Astronomical Requirements for the Millimeter Array Correlator

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Abstract:

Taking full advantage of the sensitivity and flexibility of the Millimeter Array (MMA) will require an impressive correlator. The signals from 40 telescopes (possibly as many as 128, if major foreign collaborations materialize) must be correlated over bandwidths of at least 2 GHz, and preferably 8 GHz, per polarization, producing $4 - 32\,\mathrm{GHz}$ of (bandwidth times polarizations). This should be split amongst at least 4, and preferably 8, independently-tunable baseband pairs. There should be 500-1000 channels (with two polarization products each) over the full 8 GHz, and one should be able to trade bandwidth for channels in a fairly flexible way. Standard sustainable integration times of 0.1 second are required, with sustainable integration times of $40\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)^2\,\mathrm{msec}$ being highly desirable. This gives a required sustainable data rate of at least 250 million visibilities per second. The spectral dynamic range, measured either as the accuracy of continuum subtraction or the ratio of the peak to the spectral sidelobes of a narrow signal, must be $10^5 - 10^6 : 1$. The prospect of a collaborative project with international partners leaves several of the most important correlator requirements uncertain.

Introduction

This memorandum aims to set forth the astronomical requirements for the correlator of the proposed Millimeter Array (MMA). The current working design for that correlator is described in *MMA Memorandum 166* (Escoffier 1997) and *MMA Memorandum 194* (Rupen & Escoffier 1998), the latter of which also discusses the limits on the expansion of that design. Here we step back to ask what astronomers would like to be able to do with the instrument, and what requirements those desires set for the correlator. The emphasis is naturally on the more challenging projects, those which push the correlator to its limits; at the same time we try to specify a reasonable minimal as well as the ``dream'' correlator. The underlying philosophy is that the correlator should not rule out plausible experiments which would otherwise be allowed by the design. Obviously not all of these experiments will be doable when the MMA first opens; but if the VLA experience is any guide, the original correlator will remain in use for many decades following first light.

To avoid confusing what is intended primarily as a scientific discussion, and to restrict the length of an already-lengthy document, we defer consideration of cost equations and other practical matters of correlator design to a later memorandum. Similarly, we do not here compare the requested to the current design specifications.

Some Notes on Nomenclature

We use the same terminology as *MMA Memo 194*. The numbers given here are for reference only, to make a somewhat confusing discussion more concrete, and are based on the current notional design of the MMA system.

- **Channel:** the resolution element of frequency; also referred to as a *spectral point*. A channel may be have associated single, dual (XX & YY), or full (all Stokes) polarization correlator products. We have tried to be careful to state specifically which is required in each instance: *e.g.*, 4000 channels dual polarization, which means 4000 frequency elements with two polarization products each. Other authors sometimes refer to this as ``8000 channels''; here 8000 channels always means 8000 chunks which do not overlap in frequency.
  In this notation, the total number of complex correlator products is the number of channels times the number of Stokes parameters required for each channel (4000 channels dual polarization corresponds to 8000 complex correlator products).
- **IF:** abbreviation for ``intermediate frequency''; a terribly confusing term we try to avoid, as it is used to mean so many different things. Insofar as it must be used, an IF is a wire coming out of a receiver package. In the current design for the MMA, each wire carries an 8 GHz bandwidth. There is provision for switching halves of the IFs (that is, a 4 GHz bandwidth) independently, and each half is sometimes called an IF. The current plan has a total of 16 GHz being sent down from each antenna to the correlator, for a total of 4 independent (4 GHz) IFs.
- **Baseband (BB):** the signal presented to a sampler. In the MMA case, each BB has a bandwidth of 2 GHz or less, and can be flexibly positioned within an IF band, or switched between IFs. The canonical design has 4 pairs of basebands, with the two basebands of each pair having the same frequency but different (linear) polarizations.
  We often refer to `independently-tunable' basebands or baseband pairs. This is intended to mean, ``capable of being tuned to different frequencies, with reasonable flexibility.'' There could be some restrictions on which exact frequencies are possible, and the LO chains for the BBs need not be totally independent (e.g. they might share a first LO or some such). The MMA will require much more flexible tuning than the VLA; for the correlator this doesn't matter, and discussion of the LO system, tuning capabilities, and the like, is outside the scope of this document.
  In this parlance the VLA currently has two 50 MHz BB pairs.
- **Total bandwidth:** in this memo, the total bandwidth is the total frequency coverage, *NOT* the total frequency coverage times the number of correlator products. Again the required polarization products will usually be stated explicitly; for instance, an observation covering 230-232 GHz with all four Stokes parameters recorded simultaneously will be referred to as ``2 GHz full polarization.''
- **Correlator:** one source of confusion is the dividing line between the correlator and the other electronics systems. Here we do not maintain a rigorous distinction, but have generally drawn the line at the samplers. The correlators takes as input the sampled signal from each antenna, and gives as output spectra (either frequency or lag) for each baseline and polarization product. There have been many discussions about how much processing is done within the correlator itself, with the tendency being to do as little as possible; so for instance resampling or smoothing the spectra, either in frequency or in time, will probably be done after the correlator.

We assume throughout that the MMA will eventually observe through all atmospheric windows between ~ 30 GHz and ~ 850 GHz, although it will probably not be equipped with all of the requisite receivers initially. For concreteness we also assume that linear polarizations (X and Y) are recorded.

Correlator Requirements

Number of Antennas

The lower limit to the number of antennas is set by the desire for excellent `snapshot' uv-coverage. Snapshot observations are of more importance to the MMA than to other interferometers for several reasons. First, the atmosphere at millimeter and submillimeter wavelengths is highly variable both in opacity and in phase coherence, and one wishes both to take advantage of brief periods of exceptionally fine weather, and to image large regions on the sky rapidly to minimize systematic effects across the resulting maps. This becomes progressively more important at higher frequencies. Second, the MMA's excellent sensitivity makes very short observations attractive, if the instantaneous uv-coverage is good enough to ensure accurate images. Finally, mosaics are expected to become rather common with the MMA, given the small primary beams at these frequencies; the quality of those mosaics will be set in part by the consistency and completeness of the uv-coverage of each pointing. The second and third of these points were quantified in Cornwell, Holdaway, and Uson (1993) and further elaborated in a series of MMA memoranda by Holdaway and others (Holdaway 1990, 1992; Holdaway & Foster 1994; Wright 1997). All three *desiderata* considered together led to the design goal of 40 antennas for the MMA (cf. the original MMA proposal to the NSF [1990]).

Another, less strong argument for a large number of antennas is the desire for multiple subarrays, each with very good mapping capabilities. This is discussed further below (§3.7).

More significant are the recent discussions between NRAO, ESO, and Japan's NAO concerning possible partnership(s), which would result in a much larger array. The most recent European proposal (Downes *et al.* 1997b) suggests $64 \times 12\mathrm{m}$ dishes, set by the desire to maximize collecting area while minimizing the number of antennas, subject to the constraint that the antennas maintain excellent performance for mosaicing and for high frequency work. The complexity of the correlator itself, and the resulting data rates, are the main arguments for minimizing the number of dishes. On the other hand, it is clearly easier to build superb small dishes than superb big ones, and alternative suggestions range from $\sim 128 \times 8\mathrm{m}$ to $\sim 90 \times 10\mathrm{m}$ dishes. Since we will probably not know until at least the end of 1999 whether ESO and/or NAO will actually fund the proposed joint project, the number of telescopes could be a factor two lower than suggested here. So the bottom line is that the MMA correlator should be able to handle at least 40 antennas, and perhaps as many as 80-128 if these major foreign partnerships materialize.

Unfortunately the number of antennas is *not* something that can readily be changed in the correlator at some later date; see *MMA Memo 194*. If we are to have e.g. 80 telescopes eventually it is far preferable to design the correlator to handle them from the start. Of course a correlator which can handle more telescopes than are actually built would allow the addition of further dishes after the completion of the original project (cf. Downes *et al.* 1997b).

Maximum Total Interferometric Bandwidth

Many observations will benefit from the widest possible bandwidths. For continuum experiments this is important mainly for sensitivity, and so will directly affect virtually all such observations. Projects for which sensitivity is paramount, even for the ``maximal'' combined US and European array, cover every area of millimeter astronomy: the detection of proto-Jupiters in other solar systems; high-resolution dust mapping around young stellar objects (YSOs); the observation of pulsar emission at wavelengths which minimize the effects of dispersion; the search for dust emission in high-redshift galaxies and proto-galaxies; and so on and on. Sensitivity becomes progressively more important at higher frequencies, as the atmospheric contribution leads to higher and higher system temperatures; and at higher resolutions, since the same total flux is spread over a larger number of synthesized beams. Some of the most interesting science expected to come from the MMA depends on high-resolution, low-noise images. The importance of wide bandwidths in achieving the desired sensitivity cannot be stressed enough.

Wide-band continuum observations will also provide accurate single-band ``colours'' (spectral indices). While a few narrow basebands spread across the band might suffice for bright sources (the Sun, the planets, Sgr A$_*$, M87), wider bandwidth (e.g., 1 GHz) `chunks' spread over a receiver's frequency window would allow similar analysis of more standard sources, in particular the measurement of thermal dust temperatures in Galactic YSOs and extragalactic disks.

The above argues for a wide continuum bandwidth using dual polarization for sensitivity. Full polarization imaging is also important, primarily for stellar emission, dust polarization mapping, Faraday rotation observations, and planetary work (where the polarization fraction is of order 1%). The signals are expected to be quite faint, but the results will be well worth the effort, particularly in mapping the magnetic fields in molecular clouds and accretion disks.

A number of spectral line experiments also require or benefit from wide bandwidths.

- *Pressure-broadened planetary lines* can be up to 3 GHz across. In general one would like to measure a line-free continuum at the same time as well.
- *Solar radio recombination lines* are expected to be broad and shallow, requiring total bandwidths of 1 to 2 GHz.
- *YSO outflows* could cover up to 600 km/s (full-width at zero intensity, FWZI), including the extremely-high-velocity CO `bullets' in sources like HH111. This corresponds to $\sim 1.7\,\mathrm{GHz}$ at 850 GHz, the highest frequency proposed for the MMA. Adding a reasonable area for continuum subtraction brings this to $\sim 2\,\mathrm{GHz}$ total bandwidth.
- *Radio recombination lines in ultracompact H II regions* may be up to 250 km/s broad, for the most energetic ionized outflows. Observing H, He, and C recombination lines at once adds another 150 km/s; adding a bit for baseline determination brings the total to $\sim 550\,\mathrm{km/s}$, or 1.6 GHz at 850 GHz.
- *Large-scale surveys of Galactic gas* need to cover $\sim 600\,\mathrm{km/s}$ total bandwidth, allowing for the full range of Galactic rotation. However, it seems unlikely that these will be carried out at the highest frequencies, so the total required bandwidth is more modest, 0.7 GHz at 345 GHz.
- *Radio recombination lines arising from narrow line regions of active galactic nuclei* (including Sgr A$_*$) require a total velocity coverage of at least 1500 km/s, or $\sim 5\,\mathrm{GHz}$ at 850 GHz. These high-frequency lines, observed at high resolution with high sensitivity, are expected to prove very interesting in constraining models of the dense gas surrounding AGNs (Anantharamaiah 1997, priv. comm.).
- *Surveying a galaxy cluster* covering $\sim 10,000\,\mathrm{km/s}$ in CO J=2-1 at 230 GHz, expected to be the most sensitive transition for such searches, requires 8 GHz total bandwidth. Higher frequency transitions would demand even wider bandwidths. Of course the full bandwidth need not be observed simultaneously.
- *Spectral line surveys* in general, either local (Galactic) or at high redshifts, benefit from the widest possible bandwidths. For example, 8 GHz at 45 GHz covers CO J=1-0 emission from redshifts of 1.5 to 2.1. Again such surveys could be carried out by time-sharing among several frequency settings.

Most of these experiments would involve dual polarization for sensitivity. The case for full polarization wide-band spectral line measurements is much less clear, confined to Zeeman splitting observations of masers covering a wide range of velocities; however this could easily be done in a series of frequency settings, and will probably be a rare enough project that the additional time required will not be an issue.

In sum, a bandwidth of 2 GHz, producing two correlator polarization products (XX & YY), is necessary for a wide variety of spectral line experiments. Observations of pressure-broadened planetary lines and radio recombination lines associated with the Sun or AGNs require double that bandwidth (4 GHz with two polarization products) to fit the line into a single frequency setting, while the very broadest of such lines at the highest frequencies might require up to 5 GHz. For continuum observations sensitivity demands the widest bandwidths possible. A large number of experiments would also benefit from the ability to sacrifice polarization products for bandwidth; most experiments not involving linear polarization measurements would prefer to cover, e.g., 16 GHz producing only the parallel-hand (XX, YY) polarization products, to always getting full Stokes information but only over 8 GHz. In any event the correlator should match the rest of the instrument in allowing the maximum bandwidth permitted through the receivers, backends, etc; with the current systems design, with $2 \times 8\,\mathrm{GHz}$ sent to the correlator from each antenna, this would imply all four polarization products for an 8 GHz bandwidth.

Spectral (Frequency) Resolution

The highest frequency resolution needed for the MMA is set by the possibility of future millimetric bistatic radar observations of solar system objects, which would require a few hundred $\sim 10\,\mathrm{Hz}$ channels. Apart from this the highest velocity resolution required is $0.02 - 0.05\,\mathrm{km/s}$ (2-5 kHz at 30 GHz), needed for a wide variety of experiments: measuring wind velocities on Venus; sampling thermal and/or dynamical line widths of comets, planetary satellites, protostellar disks, and dark cloud cores; finding and characterizing the structure of narrow absorption lines; and measuring magnetic field strengths via Zeeman splitting (of order 1 Hz splitting per microGauss). SETI observations would benefit from 1 Hz or even finer resolution (J. Tarter 1997, priv. comm.), but this should not be allowed to drive the correlator design.

At the other end of the scale, very wide channels are desirable primarily to reduce the data rate and the total data volume produced by an experiment. Most continuum observers would be happy with as few as one channel per baseband pair, corresponding (in the current design) to 1-2 GHz channels. However, there are a number of constraints on how wide a channel is actually usable:

- *Bandwidth smearing:* Assuming one wishes to lose at most 5%\ in sensitivity at the half-power point of the primary beam due to bandwidth smearing, the frequency resolution must be better than
$$\mathrm{d}\nu = 49 \left(\frac{\mathrm{D}}{8\mathrm{m}}\right) \left(\frac{140\mathrm{m}}{\mathrm{B_{max}}}\right) \left(\frac{\nu}{850\,\mathrm{GHz}}\right)\,\mathrm{GHz}$$
(see, e.g., Rupen 1997a), where the parameters used are those appropriate to the smallest proposed configuration and the highest proposed observing frequency. These parameters give the largest channel width one might ever wish to use; even for the most extended proposed configuration (10km) at the lowest observing frequency (30 GHz), the required frequency resolution is only 24 MHz. Clearly this is not much of a constraint.
- *Delay errors:* Delay errors will cause phase slopes across the band; the corresponding decorrelation across a channel should not be too large. 5% decorrelation seems a reasonable limit (high dynamic range observations will use more channels), corresponding to about $18°$ across a single channel. At the VLA, the delays seem to be stable to about 1 nsec, arguing for 50 MHz channels. At OVRO, using analog delay lines, the phase errors due to delay errors are negligible over a full 1 GHz (Woody, priv. comm.). In part this

comes down to how often one wishes to reset the delays; a very rough guess for the MMA might be a drift of 5-10 picoseconds per hour, or 5-10 times worse than that in a week (Clark 1997, priv. comm.). This would imply channels a few hundred to a few thousand MHz wide.

- *Instrumental structure in the bandpass:* The receiver and signal transmission will themselves introduce gain and phase errors which one would like to calibrate out even for continuum experiments. Since the RF and IF components will all be very broad band there should be no instrumental structure on frequency scales less than a few hundred MHz.

This suggests that the broadest practicable channels will be $\sim 100\,\mathrm{MHz}$ wide. Of course for a lag correlator this number is not very important for the design.

Finally, between these two extremes one must be able to choose frequency resolution (and bandwidth) in geometric (factor two or whatever is convenient) intervals; preferably these choices could be made independently for each baseband or baseband pair.

Number of Basebands

There are two main arguments for having as many baseband pairs as possible. First, to the extent that each baseband may be positioned independently in frequency, more basebands imply more flexibility in observing several lines or several `chunks' of continuum within a single band. Second, to zeroth order the size of a lag correlator goes inversely as the number of basebands, since one can use proportionately fewer lags to cover the same total bandwidth with a given frequency resolution (see e.g. *MMA Memo 194*). Of course there are counter-arguments which suggest a smaller number of basebands. Astronomically, it is difficult to keep consistent calibration between different basebands, particularly for single-dish data; this implies that the maximum bandwidth of a baseband should roughly match the width of the broadest lines that would regularly be observed. From considerations like those in §3.2 above, this probably corresponds to 1-2 GHz per baseband. Practically, correlators with many basebands (e.g., the analogue correlator at the 12m) have not been terribly successful, and the ideal number of basebands from an engineering point of view is a subject of current debate. That debate however is outside the scope of the present paper, which purports to concentrate on astronomical needs, and the remainder of this subsection is addressed to the question of how many independently-tunable basebands are necessary to allow the observer to take good advantage of the capabilities of the MMA.

For continuum work one wants a number of baseband pairs for two reasons: first, to allow one to position individual `chunks' of continuum bandwidth to avoid strong lines, atmospheric contamination, and strong interference; and second, to allow single-band spectral index (or colour temperature) mapping. Four independently-tunable baseband pairs is probably the maximum necessary for these sorts of experiments. Note that each BB pair will be made up of a number of channels (see the next section), so while one would want to avoid broad interfering lines, narrow ones are not a problem, since the contaminating lines can simply be deleted from the data set.

Line experiments in general benefit from having as many BB pairs as possible, as this maximizes the observing efficiency by allowing many lines (as well as the continuum) to be observed at once. This is particularly important at high frequencies and for the larger array configurations, since one wishes to take the best advantage of periods of good phase stability, low wind conditions, and/or low opacity. For similar reasons very long integrations, which may be quite common (Evans *et al.* 1995), should also be carried out simultaneously in as many lines as possible. That many interesting lines are available is very clear; for instance, Schilke *et al.* (1997) found an average of 26 reasonably strong lines per GHz in the 350 GHz window towards Orion K-L. Obvious choices for multi-line studies include a set of different isotopes and transitions of a single molecule, which could easily add up to 8 or more lines in a single band.

Many experiments require, or would benefit greatly from, simultaneous wide and narrow bandwidths; measuring accurate line-to-continuum ratios, referencing the phase of a line to a strong continuum or vice versa, observing a single line at multiple velocity resolutions (e.g., observing both a protostellar disk and the associated outflow at the same time), and `piggy-back' surveys (e.g., doing a pencil-beam survey for CO while mapping the emission in a nearby galaxy) are all examples of observations of this type.

Finally, VLBI observations using the MMA would benefit from having the same flexibility as the VLBA system provides, i.e. 8 independently-tunable basebands.

Based on the above considerations, the ideal correlator would allow for a minimum of 4 BB pairs, and preferably 8. Note that this is one of the aspects of the correlator which is modular - it would be relatively easy to add more basebands later (*MMA Memo 194*). At least one of these BB pairs should have a maximum bandwidth of at least 1-2 GHz, and together they should of course span the full bandwidth discussed in §3.2. Insofar as possible, since even broader lines will be observed occasionally, and perforce be split amongst several basebands, one should be able to join these basebands together smoothly over frequency, with little loss in sensitivity and minimal systematic errors. The bandwidth and channelization of each baseband (or, at a minimum, each baseband pair) should be set independently, allowing e.g. one BB pair to cover 1 GHz with 100 channels while another covers 10 MHz with 1000 channels.

Multibeam feeds, if used, would represent an additional complication, as presumably one would want to correlate all the beams from one telescope with the corresponding beams from all others. To first order this would be similar to having additional (sets of) BBs. This should probably not drive the initial correlator design.

Number of Channels

A number of experiments benefit from a large number of channels; many of these involve wide (several GHz) total bandwidths. Among the most obvious are:

- *Mapping molecular clouds:* The maximum linewidth for a molecular cloud (ignoring outflows) might be about 50 km/s, while protostellar disks embedded in such clouds benefit from velocity resolutions as high as 50 m/s. Blind searches for such disks, looking through the entire velocity range of the cloud, could then be done with ~ 1000 channels per BB pair; the total number of channels would then be 4000-8000 spread over the 4-8 BB pairs (see above). Similar *desiderata* obtain for mapping the Zeeman splitting in a cloud, for which one wants spectral resolutions of order $10\,\mathrm{kHz}$. Note however that for most of these experiments the total bandwidth would only be about 0.14 GHz, even when observing at 850 GHz; assuming one can trade bandwidth for channels in at least a proportional rate (i.e. half the bandwidth implies twice the number of channels), 4000-8000 channels in 0.14 GHz corresponds to only 70-140 channels over 8 GHz.
- *Searching for molecular clouds in ellipticals and AGNs:* Several nearby dwarf ellipticals have CO emission with total linewidths of only a few km/s (e.g., Wiklind and Rydbek 1986), corresponding to a single molecular cloud; some have also been observed with very patchy dust emission, implying that their interstellar media (ISM) may consist mainly of small, independent clumps of gas. Similarly, HI absorption observations of AGNs (e.g. van Gorkom *et al.* 1989) often show fairly narrow lines, or lines with significant substructure. Searching for such narrow lines in a giant elliptical requires a velocity resolution of order 1 km/s (to match the linewidth of a single cloud) over 2000 km/s (the dynamical width of the elliptical), implying of order 2000 channels, spread over 2.3 GHz at 345 GHz, or 5.7 GHz at 850 GHz (the highest operating frequency of the array). Again, if one can trade bandwidth for channels, this corresponds to 575-1425 channels spread over 8 GHz.
- *An unbiased search for CO in galaxy clusters:* An unbiased 230 GHz search for CO in a

galaxy cluster would require covering $\sim 10,000\,\mathrm{km/s}$ at 10 km/s resolution, implying about 1000 channels spread over 8 GHz. This will however be an unusual experiment, as the array, even with the largest areas currently under consideration, will not be sensitive enough to make such searches fruitful for other than the closest clusters.

- *Imaging the primary beam:* The most extended configuration suggested for the MMA stretches to ~ 10 km baselines. Following the discussion in Rupen (1997a), making an image covering the full primary beam at the highest available resolution, with at most 5% sensitivity lost to bandwidth smearing, would require
$$333\left(\frac{\mathrm{B_{max}}}{10\,\mathrm{km}}\right)\left(\frac{8\,\mathrm{m}}{\mathrm{D}}\right)\left(\frac{\Delta\nu}{8\,\mathrm{GHz}}\right)\left(\frac{30\,\mathrm{GHz}}{\nu}\right)\quad\text{channels.}$$
Here $\mathrm{B_{max}}$ is the maximum baseline, D is the dish diameter, $\Delta\nu$ is the total bandwidth observed, and ν is the observing frequency. Note that this mode may be much more common than is the case for the VLA, since the primary beam is much smaller, and since many high-resolution experiments will also demand quite long observations (implying that sacrificing sensitivity in the outer part of the primary beam will be more painful).
- *NGC 4258:* to cover the millimeter analogues of the masers in NGC 4258, all in one observation, would require three IFs, one $\sim 500\,\mathrm{km/s}$ wide for the components near systemic velocity, and two of $\sim 200\,\mathrm{km/s}$ each for the outliers. With 0.1 km/s channels this would give a total of 9000 channels, which could be single polarization, spread over 2.6 GHz at 850 GHz (corresponding to ~ 2900 channels spread over 8 GHz). Although such an unusual source should not be allowed to drive the correlator design, it's heartening that its requirements are not much more stringent than those for the more common experiments already discussed.
- *Spectral line surveys:* Numerous single-dish line surveys have been done of active star-forming regions (e.g., Schilke's review in Shaver 1996); the availability of high spectral resolution over wide bandwidths would allow astronomers to harness the sensitivity of the MMA to do similar experiments, but at much higher angular resolution, examining the spatial distribution of (potentially) 100s of lines at a time. For instance, Schilke *et al.* (1997) found an average of 26 fairly strong lines (by MMA standards) per GHz in the 350 GHz atmospheric window in Orion KL; this implies some 200 lines over 8 GHz, which one would like to image at high spectral resolution both to follow dynamical structures and to separate the lines (and measure their frequencies) as well as possible. Schilke *et al.*'s observations were done at 1 MHz resolution, i.e. 1000 channels per GHz. Doing a similar experiment over 8 GHz in a single observation would then require perhaps 4000 channels; of course one could observe instead by time-sharing among somewhat narrower bandwidths.
- *Extragalactic absorption lines:* Both Galactic and extragalactic molecular absorption lines can have widths below 1 km/s (see e.g. the reviews by Wiklind & Combes and Lucas in Shaver 1996). Many experiments (e.g. looking for intervening galaxies towards background quasars) involve searching for these narrow lines at unknown redshifts, and hence benefit from covering as wide a band as possible at high spectral resolution. 8 GHz corresponds to some 80,000 km/s at 30 GHz, the lowest operating frequency of the array; ideally one would observe this with 0.5 km/s resolution, to match the expected line widths, implying 160,000 channels. A more reasonable project would use $8,000 \times 10\,\mathrm{km/s}$ channels, with follow-up observations to ``zoom in'' on any unresolved lines.
- *Unbiased searches for high-redshift CO:* Here one wants to cover the full available bandwidth at $\sim 10\,\mathrm{km/s}$ resolution. This corresponds to 1000 channels per GHz at 30 GHz, the lowest frequency proposed for the array ($z \sim 2.8$ for CO J=1-0). Once again one would prefer to cover as wide a bandwidth as possible in one observation, but time-sharing between frequencies is certainly an option.

Apart from line surveys and the like (most of which would benefit from as many as 1000 channels per GHz), and assuming that one can trade bandwidth for channels in a fairly flexible fashion, all of these experiments correspond to having 500-1000 channels spread over 8 GHz.

Since most of these projects are limited by sensitivity, dual polarization is essential. Only Zeeman splitting and maser observations would benefit from both the maximum number of channels and full polarization products, and we could probably get by with only half as many channels when asking for full polarization information. Line surveys of course could use as many channels spread over as wide a bandwidth as is practicable, but they should probably not drive the correlator design. It seems unlikely that any reasonable experiment would demand many more channels over a narrower bandwidth; although the sensitivity of the instrument would support this, the intrinsic linewidths are broad enough that much higher resolution does not seem necessary. The obvious exception would be SETI searches, which benefit from very high resolution over the broadest possible bandwidth; again this should probably not be allowed to drive the correlator design, though it should be allowed if it is not terribly costly.

We note that Escoffier's current (1997) correlator design would give 512 channels over an 8 GHz bandwidth for each of two polarization products (e.g., XX & YY) (see *MMA Memo 194*), nicely matching the above (independently derived) astronomical specification.

Dump Times

The shortest astronomically interesting integration period for the MMA is the subject of a lengthy discussion in *MMA Memorandum 192* (Rupen 1997b). The conclusions of that memo were:

- *On-the-fly total power observations* require writing out autocorrelation spectra every few milliseconds. A hard limit of $3.0\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)$ msec is set by the desire for good atmospheric subtraction up to 350 GHz.
- *Pulsar observations* need time resolutions as high as $10\mu\mathrm{sec}$, but only the phased array (vector sum) output must be written out. Note that while the data would have to be gated on these timescales, they may not actually need to be dumped this frequently; see *MMA Memo 192*.
- *Surveys of large regions* are the most challenging interferometric observations: a minimum dump time of more than about 100 msec will make mapping objects like the Magellanic Clouds, the Cepheus Cloud, and the Virgo Cluster virtually impossible. Ideally one would like dump times of order $40\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)^2$ msec to allow mapping these large sources in a finite amount of time.
- *A variety of other experiments*, most significantly the need to avoid significant decorrelation due to phase variation during an integration, demand integration times as short as 100 msec.

On the other end of the scale, the enormous data rate coming from an instrument with at least 40 telescopes and several thousand spectral channels argues for the availability of much longer integrations, up to perhaps some 10s of seconds or longer. The limit here will be the phase wind due to the electronics and the atmosphere, which (at the higher frequencies) may often be so fast that long integrations would require on-line phase correction, which would add significantly to the complexity of the correlator. At low frequencies (30 GHz) integrations of 30 seconds or longer will often be fine. This is discussed further in §3.9.

Subarrays

Subarrays will be much more important for the MMA than for the VLA or other existing interferometers, for a wide variety of reasons.

- *Multifrequency capability:* Some observations would benefit from the ability to observe in several bands at once. For example, solar flares vary rapidly enough that one wants to track their behavior at several widely-spaced frequencies, at identical times. Atmospheric studies (e.g. measuring the opacity at the same time at different wavelengths) could similarly benefit from simultaneous multi-frequency data. Also, subarrays will be essential if only some of the antennas are equipped with certain receivers, which will undoubtedly be the case for some time while the array is gradually fitted out with all frequency bands.

- *Calibration:* It may be useful to devote some subset (as many as half, in some proposals) of the antennas to continuous calibration measurements, at one or more frequencies. For phases the benefits of looking at a calibrator all the time are obvious; for amplitudes one might wish to monitor the opacity and/or the gain on short timescales through tipping scans or other measurements at one or more wavelengths. These sort of schemes would require at least two and possibly more subarrays.
- *Mapping large areas:* As discussed in *MMA Memo 192*, there are a number of very large sources (the Magellanic Clouds, nearby clusters, etc.) which are bright enough that the time needed to map them is set primarily by the dump time of the correlator. Splitting the MMA into *M* subarrays would shorten the mapping time by the same factor. For solar system sources, particularly the Sun, one needs to map areas much larger than the primary beam as fast as possible, either because of intrinsic variability (e.g., solar flares, planetary weather), or because the orientation of the object studied changes rapidly with time (due for instance to rotation). Obviously these considerations become more important for bigger dish diameters and longer dump times.
- *Fast-response observations:* Some objects need to be observed as rapidly after some trigger as possible, but may either be very bright, so the full array is not required, or have only a very poorly known position, requiring multiple subarrays to allow a rapid search of the entire region. Stealing only a few telescopes may also be more palatable than completely disrupting the regular observation in progress when a target-of-opportunity proposal is triggered, and would certainly allow more continuous time coverage than is typically possible at existing interferometers. Examples of interesting, potentially-bright and rapidly variable sources include gamma-ray bursts, novae, supernovae, variable stars undergoing outbursts, and lensed stars.
- *Lower data rates:* Splitting the array into *M* subarrays reduces the total number of baselines, and hence the data rate, by roughly the same factor. This may be a significant consideration for experiments that require large numbers of channels but can live with the lower sensitivity (which goes down by the same factor), and for observations (like large surveys) which require very short dump times. This tradeoff may in fact be essential in the early years of operation, when the storage media may not be able to keep up with the full data rate of the correlator.
- *VLBI:* The MMA will be in great demand as the most sensitive element in millimetric VLBI arrays. As with the VLA one will often wish to support such experiments without giving up the entire array; even a third of the MMA would still give significant collecting area, particularly if the European/American collaboration materializes.
- *Inhomogeneous arrays:* Although out of favour at the moment, if the MMA does eventually include a variety of dish sizes, it may be useful for some experiments to be able to split the array into subarrays each of which is composed solely of telescopes with a single dish size.
- *Single-dish observations:* It is quite likely that part of the array will be devoted to single-dish work, either occasionally or frequently. In this case one must be able to handle the situation where those antennas are pointing in different directions and observing at different frequencies than the remainder of the array; at times one may even wish to have, say, 10 individual telescopes all observing different things. This isn't quite the same as a regular subarray but the correlator should be able to handle the resulting data.
- *`Faking' big dish diameters:* One might occasionally wish to phase up a number of subarrays and correlate the result, either to slow down the data rate or to allow the use of fainter calibrators. To make this mode useful would require perhaps 10-30 subarrays each consisting of 3-10 antennas, as well as the correlation of the outputs of those subarrays (see *MMA Memo 165* (Thompson *et al.* 1997).

More generally, given the superb sensitivity of the array and the large number of telescopes (up to 128), many interesting projects will be so easy that it makes sense to allow for multiple subarrays. The correlator should allow for at least 4, and preferably 6-8, independent subarrays. This requirement is especially important if there are more than ~ 40 antennas, and if the collecting area is much more than $2000\,\mathrm{m}^2$. These subarrays should be as fully independent as possible; in particular, it would be very helpful to be able to specify different dump times, baseband bandwidths, and channelizations for each subarray.

Total Power Measurements

Total power measurements will be much more important than for centimeter interferometers, and require higher accuracy. Mostly this is because the primary beam will be small, and many sources will require mosaicing; single-dish observations will be needed to fill in the central hole in the uv-plane. There are various arguments that the MMA itself should provide its own short-spacing information, rather than relying on other dishes as most current interferometers do. The MMA will be the premiere millimeter telescope in the world, and as such is expected to be observing almost continuously, with high sensitivity, covering large areas of the sky. The corresponding single-dish measurements will have to match the MMA observations in both quantity and quality, over the entire spectral window covered by the MMA. It would be unreasonable to rely on any other instrument for this sort of vital support; nor are there any international, publicly-available instruments capable of providing it. Further, a series of studies (e.g., Emerson 1990) have shown that the MMA telescopes themselves can be used quite handily to fill in the missing short spacings, without any need for larger dishes. Finally, there is a software/post-processing advantage to having a `standard' source for total power data, rather than allowing for a wide variety of possible instruments; one could optimize the (automatic?) routines for mosaicing and the like, for the case of MMA single-dish data.

The correlator must therefore be prepared to handle total power measurements from all MMA dishes simultaneously, or at least from all dishes equipped to produce such data. The single-dish data should be allowed at least the same number of channels, bandwidths, etc. as provided for the interferometric data. A number of special observing modes must be supported as well:

- *On-the-fly mapping:* Much more efficient that standard ``point and shoot'' mapping, particularly for big, bright sources. May be useful or necessary for removing the atmosphere. Requires dump times for the autocorrelations as short as $3.0\left(\frac{8\mathrm{m}}{\mathrm{D}}\right)\,\mathrm{msec}$. Useful for both line and continuum work.
- *Beam switching:* Standard method for removing the atmosphere. Requires labeling data as ON or OFF, on short ($< 1\,\mathrm{sec}$) timescales, or (more likely) storing the changing position; this would of course also imply short dump times. May involve a nutating subreflector.
- *Frequency switching:* Useful for subtracting the atmosphere in spectral line work when there is no obvious off-source position for beam-switching. Requires labeling data as ON or OFF, on short ($< 1\,\mathrm{sec}$) timescales, or (more likely) storing the changing central frequency.
- *Multi-beam feeds:* While these are becoming common on single-dish telescopes, and the idea of SCUBA-type arrays on 40 JCMTs sitting on the Altacama plateau is almost unbearably attractive, it's not clear whether the MMA telescopes will ever have or need multi-beam feeds. If they do, the correlator must be able to support multiple feeds off a single dish. The number of pixels per telescope might easily approach 100 (cf. SCUBA, with 91 at $450\mu\mathrm{m}$). Presumably one would only equip a small number of dishes with such multi-beam arrays, but this has not yet been discussed.

Although it would seem easiest to use the same correlator for the auto- and the cross-correlations, there is no strong reason that the same correlator must handle both.

Finally, one must distinguish between spectroscopy and continuum total power data. One may well want to do both at the same time (usually to be able to subtract the line emission from the continuum), but they are quite different things. One does single dish spectroscopy with the usual autocorrelations, with level controls etc. used in the same way as one does for interferometry; but this may either destroy or severely injure the absolute amplitudes used for continuum measurements. The current plan is to do continuum single dish measurements based on detectors located in the antennas, far ahead of all the stuff that might bother the gain stability. This detector system would then be well outside the correlator.

Ancillary Data and On-line Corrections

Operating at very high frequencies requires monitoring the atmosphere on short timescales. There are two issues: correcting the amplitudes for atmospheric opacity fluctuations, and maintaining phase coherence. Based on the extensive site testing database and atmospheric transmission models, Holdaway (1998; in prep.) concludes that short timescale (i.e., 30 seconds) amplitude fluctuations will typically be only a few percent rms at 650 GHz. On longer time scales (600 seconds) amplitude fluctuations rise to about 10% rms at 650 GHz. This implies that opacity corrections need only be calibrated out on time scales of 30 seconds or longer. Similar modelling gives atmospheric coherence times at 650 GHz of ~ 4 seconds for median weather conditions and 90% coherence (<1 second for 98% coherence), rising to longer than 10 seconds (90% coherence; about 3 seconds for 98%\ coherence) during the best 20% of the weather, which is presumably when most high-frequency work will be carried out. There is thus little need to make phase corrections on time scales less than about a second. Other simple arguments give similar time scales. For instance, assuming peak wind speeds aloft of 10 m/s, a given atmospheric perturbation will cross an antenna in $0.8\left(\frac{D}{8\mathrm{m}}\right)$ sec; it seems unlikely that one will be able to sensibly correct phases any faster than that. It is also questionable whether one could measure the phase any more frequently than this.

So, at the highest frequencies one might want to correct the phase every second or so, and the amplitude every 30 seconds. This implies that all statistics related to the atmospheric phase - radiometric measurements of the water line, opacities, wind velocities, temperatures, on-site water vapor measurements, pressure - together with pointing information, must be written out with the data, on that timescale. This basically increases the size of the output data set and the corresponding data volume, without requiring much of the correlator. However, integrations which are longer than about a second at high frequencies may require *on-line* corrections to the phase, to avoid decorrelation within an integration period. This is a major issue, because such corrections may be complicated, and because long integrations would be very helpful in reducing both the data rate and the total volume of data which has to be stored on disk and eventually analyzed. Such on-line corrections would make the correlator significantly more complicated. One option would be to have the correlator always produce a data stream with a maximum integration time of one second, and allocate a special-purpose processor to do the corrections and average the data in time after the correlation. Unfortunately that processor would have itself to be fairly complex. This is an area which needs further study fairly quickly.

Spectral Dynamic Range

The term ``spectral dynamic range'' (SDR) is used to mean at least three different things:

1. The ratio of the peak continuum signal to the root-mean-squared (rms) noise in a continuum-subtracted image. A high SDR in this sense corresponds to having a very flat

frequency response.

2. The ratio of the peak continuum signal to the accuracy with which one can measure a very deep absorption line. A high SDR in this sense corresponds to correctly measuring a very wide range in correlation coefficient.
3. The ratio of the peak of a narrow (in frequency) signal to its spectral sidelobes. A high SDR in this sense corresponds to very little cross-talk between frequency channels.

The MMA, especially in the larger versions suggested for the collaboration with the Europeans, will be a very sensitive instrument, with noise levels at 230 GHz in one minute as low as $30\mu\mathrm{Jy}$ in the continuum and $7\,\mathrm{mJy}$ ($15\,\mathrm{mK}$, for the smallest configuration) in a 0.2 km/s channel. One will often be looking for weak signals in the presence of strong confusing sources, either continuum or line (e.g., masers), requiring a high SDR potentially in all three senses.

1. *Flatness:* the ratio of the continuum brightness to the noise level in a channel map will often need to be as high as $10^5:1$ and for many experiments $10^6:1$ or higher in observations of faint lines on top of very bright continuum sources. Examples include rarefied species near bright YSOs, H II regions, and the like; radio recombination lines in ionized outflows; and searches for faint absorption lines against very bright AGNs.
2. *Absorption:* This is probably the least important type of SDR to an astronomer, as it limits the accuracy of a measurement rather than the possibility of a detection. The cases where this would matter a great deal are probably limited to searches for faint substructure in high-opacity lines, for instance searching for very weak emission superposed on very strong absorption. Probably one would like to be able to believe 1% variations in highly opaque lines, but it seems unlikely that even higher accuracy would regularly be required.
3. *Spectral sidelobes:* the desired limit on the leakage of a strong signal in one channel into other channels in the same baseband, is set primarily by deep observations of emission in line wings of sources with very bright emission at the line center. Examples include many of the most interesting objects in the sky: planetary absorption lines (e.g. Gurwell 1996); molecular outflows (e.g. Yu & Chernin 1997 [VLA 1623/CO], Cernicharo & Reipurth 1996 [HH111/CO]); YSOs (e.g., Hogerheijde *et al.* 1997 [T Tauri/HCO+], Olmi *et al.* 1996 [G10.47+0.03/CH_3CN]); star forming regions (e.g. Wink *et al.* 1994 [W3(OH)], Shepherd, Churchwell, & Wilner 1997 [ON2]); stars (e.g., Dayal & Bieging 1995 [IRC+10216]); and even external galaxies (e.g. Shen & Lo 1995 [M82], Sofue & Irwin 1992 [NGC 3079]). In all these cases the line centers peak at some 10s of Kelvin, while the rms noise in one minute on source might be a few milliKelvin (for the most compact configuration). This neglects even more difficult cases, such as looking for thermal emission around masers, searching for faint (rarefied?) species in the same BB as stronger lines, planetary radar experiments (where the strong zero-velocity return signal creates a problem similar to the maser case), and observations (at the lower frequencies at least) in the presence of strong radio frequency interference. This suggests that $10^5:1$ will be desired fairly often, and $10^6:1$ may not be that unusual a requirement.
Of course, achieving these levels is not purely a correlator problem; at the VLA we almost always Hanning smooth the raw spectra to beat down the spectral sidelobes, and (so long as one has enough bits) one can do this or more sophisticated apodisation after the correlator. The discussion here refers to the SDR after such apodisation.

High-quality Imaging

Although it is not clear how to relate image quality to the correlator design, for completeness it may be worth mentioning the dynamic range (peak to off-source rms noise level) MMA images will achieve. With noise levels as in the last section and taking 10 hours as a reasonable long integration, one expects dynamic ranges of

- $10^7:1$ for a few special sources - planets, masers, strong AGNs;
- a few to 10 times $10^5:1$ for many sources - including continuum and strong line emission from young stellar objects, AGB stars, H II regions, the Galactic center, and less impressive AGNs;
- $10^4:1$ fairly routinely, in many cases in only a few minutes of integration.

The above dynamic ranges assume the joint US+European project with a collecting area of $\sim 7,000\,\mathrm{m}^2$; for the MMA alone ($2,000\,\mathrm{m}^2$) they should be reduced by a factor ~ 3.5. Such excellent images will be useful scientifically in many contexts, ranging from searching for extragalactic counterjets at frequencies where the core is not so bright as to limit the imaging, to looking for proto-Jupiters around main sequence stars, to mapping faint, extended gas around young stellar objects. Most of these projects require not simply high dynamic range, but high on-source accuracy as well, with peak on-source errors of 1% being a good target (cf. Cornwell, Holdaway, and Uson 1993). Nothing in the correlator should prohibit making such high-quality images.

Another kind of dynamic range relates to the total range of data within a single uv-data set - the ratio of the peak short-spacing flux to the rms noise on the longest baseline. This is in some ways a more difficult number to derive, since it involves comparing the integrated flux density of a source to the rms noise in an integration period. Probably the brightest sources for which one might achieve thermal noise on the longest baselines are the planets, with brightness temperatures of 200-300 K (for Jupiter and Venus). The flux density measured on the shortest baseline would then be of order $15,000\left(\frac{T_B}{250\,\mathrm{K}}\right)\left(\frac{8\mathrm{m}}{D}\right)^2$ Jy where D is the telescope diameter. With a noise level between 5 and 20 mJy on a single baseline in 1 second for frequencies up to about 230 GHz, the peak ratio of flux density on the shortest baseline to rms noise on the longest baseline would be of order $10^6:1$.

Radio Frequency Interference

Although radio frequency interference (RFI) has not in the past been much of a problem for millimeter interferometers, RFI has been increasing even at the high frequencies used by the MMA, and will certainly be an issue for at least the lower observing bands by the time it is built. Currently the main frequency allocations above 30 GHz have been to satellites, with a few areas in Q band going to stratospheric balloons and automobile radar systems. Little use has yet been made of the frequency space already allocated, but some important features are already clear. First, most services proposing to operate at these high frequencies do so because they need fairly wide bandwidths. This implies that typical RFI signals will be at least a few MHz wide. Second, at millimeter wavelengths it is more difficult to generate high transmitter power, while high gain beams require only small antennas. Thus one would expect most transmissions to be highly beamed at specific areas. Most importantly, the sidelobe levels of radio astronomy antennas are likely to have similar gain to those at centimeter wavelengths, i.e. of order 10 dB for those near the main beam and order 0.1 dB at angles greater than about 50 degrees from the main beam. Since the collecting area for a given gain is proportional to wavelength squared, the sidelobe sensitivity to interference decreases with increasing frequency. This leads to the third point, that the bulk of the worrisome interference will come from satellite downlinks. Since those satellites are likely to surround the globe, we will not escape their transmissions however remote the observatory site. If the satellite downlinks use time multiplexing like IRIDIUM, they will transmit in brief bursts (IRIDIUM uses 4.5 msec packets) which we may be able to flag if the signal can be recognized and discarded on $\sim$ msec timescales. Such time-sharing may not be very common however, since most satellite allocations are designated specifically as space-to-Earth or Earth-to-space, whereas IRIDIUM takes advantage of an unusual secondary uplink allocation within a primary downlink band.

While the RFI situation is currently fairly benign, we cannot afford to be complacent. At the VLA the bulk of the interference above $\sim 15\ \mathrm{GHz}$ is internally generated, due mostly to the LO systems (the 100-200 MHz `birdies'). This should be avoided if at all possible at the MMA; it will do us little good to have clear skies if we bring with us our own headlights. Further, although no allocations have yet been made above 300 GHz, those are to be discussed in the 1999 World Radiocommunications Conference.

Miscellaneous Constraints

In addition to the major requirements discussed above, the correlator must allow for a number of more specific constraints:

- *Fast telescope motions:* Slew speeds of order $1^\circ/\mathrm{sec}$, and the correspondingly fast dump times, will require rapid updates to the correlator model. In the (common) fast switching case there may be savings because one is switching between only two positions, but OTF (or even `point and shoot') maps will be more challenging. Unlike the VLA, the MMA will often be pointing at significantly different positions during adjacent integration periods (dump times).
- *Rapid frequency switching:* several experiments would benefit from rapid frequency switching within a single band, though the availability of more than the minimal 4 BB pairs would take care of most cases. More important and more difficult is the problem of phase-referencing one band to another, e.g. to take advantage of a strong maser transition. In this case one might want to switch between frequency bands in a few seconds (for the more extreme examples). Whether this mode should be considered vital, and how often it might be used, will be discussed in an upcoming memo on phase calibration (Holdaway *et al.*, in prep.).
- *Maximum baseline:* Many of the most interesting MMA observations require high resolution, between several 10s of milliarcseconds and an arcsecond. Examples are legion, including e.g. searches for proto-Jupiters (or tell-tale gaps in disks) around YSOs, imaging of stellar photospheres, and resolving AGN accretion disks out to Virgo and beyond. The desired resolution corresponds to baselines ranging from a few to 10s of kilometers, with 10km being the maximum currently discussed. The correlator should therefore allow for baselines up to 10km long. Although it is unlikely that the initial array will include such long baselines, the existence of prospective international partners specifically interested in such high-resolution experiments is a strong argument for allowing for this capability from the start. Even longer baselines have occasionally been discussed in the context of major international partners.
- *Phased-array output:* For some types of experiments, most notably gated pulsar and VLBI observations, one wishes to phase up the array in real time and write out the summed data. For VLBI one wants the raw summed data, not averaged over time; for pulsars one can average down (see *Gating*, below).
- *Gating:* Pulsars are very weak (but detectable; Kramer *et al.* 1997) at MMA frequencies; writing out the (phased array) correlator output in time bins sufficient to phase resolve the pulse profile would therefore be useful in increasing the signal-to-noise of their emission. This sort of gating in time would also be useful for on-line RFI excision, particularly of periodic interference. Various flux calibration schemes (measurements of ON/OFF loads and the like) might benefit as well from the availability of multiple data streams. The required time resolution for pulsars would be a tenth of a millisecond or better, and one might want to employ 10 or 20 different time bins across the $\sim$ msec pulse, to sample the pulse profile. RFI may require time samples as fine as $\sim 1\,\mathrm{msec}$ (IRIDIUM for instance pulses with a 45 msec period, and its individual data packets are a tenth as long).
- *Burst mode:* Some objects (e.g. solar flares) vary so rapidly that it might be advantageous

to write out partial data at a much higher rate than normally allowed. One might also consider trading baselines for time resolution, for instance for large scale surveys limited by total observing time rather than sensitivity, at least during the early days of the instrument. A special burst mode is probably not necessary if dump times of some 10s of milliseconds are considered `standard' (see §3.6).

- *The Sun and Other Bright Sources:* The Sun is an example of a source which dominates the system temperature; during bursts, that system temperature will vary dramatically. Similarly other sources contribute significantly to the system temperature (e.g., planets), and there too T_{sys} will vary somewhat as the source wobbles around in the primary beam of each antenna. That variation must be monitored and the visibility data corrected. This affects the correlator because its power inputs may not be held at constant and optimum levels. The consequent less-than-optimum performance is probably not a big issue, as this should affect only a small number of sources.

Summary

From the above discussion, the main requirements for the MMA correlator are as follows:

- *Number of antennas:* ≥ 40: at least 40 for good imaging, up to **80-128** if we can afford more collecting area but don't want huge dishes.
- *Maximum bandwidth:* There are several obvious break points for this.
  - ≥ 2 **GHz with two polarization products**, corresponding to ≥ 4 GHz of (bandwidth times polarization products), for a wide variety of spectral line experiments.
  - ≥ 4 **GHz with two polarization products** for pressure-broadened planetary lines and wide RRLs.
  - **8 GHz with full (4) polarization products** to match the maximum bandwidth sent down from each antenna in the current systems design.
  - **As wide as possible** to maximum continuum sensitivity and the efficiency of spectral line surveys.
- *Frequency resolution:* **10 Hz - 100 MHz**, with the ability to select in factors of two or something similarly flexible. A few to 10 Hz is needed (but only over a few hundred channels) for bistatic radar; other experiments require only **2 kHz** resolution, for sampling thermal/dynamical linewidths of low-mass systems (comets, YSOs, dense cores, etc.), resolving molecular absorption lines, and Zeeman splitting. SETI searches on the other hand would benefit from **0.1 - 1 Hz** resolution, over as wide a band as possible, but this should not be permitted to drive the correlator design. The lowest interesting resolution is that corresponding to features in the bandpass, due to poor delay settings or to the RF/IF systems themselves. One wants this low resolution for continuum experiments, to keep the data rate down as much as possible.
- *Number of basebands:* **4-8 independently-tunable baseband pairs**. Desirable for flexibility in placement of continuum bandwidth (for spectral index studies, and to avoid atmospheric emission and RFI) and choice of multiple line transitions. This last is crucial to the MMA, not so much because its lack would disallow vital experiments, but because observing several lines at once is a far more efficient use of the instrument.
- *Number of channels:* **500-1000 (with dual polarization products) spread over 8 GHz**, desirable for a wide variety of line experiments, ranging from searching for molecular clouds in elliptical galaxies, to imaging the entire primary beam with negligible sensitivity losses due to bandwidth smearing. Spectral line surveys and unbiased line searches could benefit from as many as **1000 channels per GHz** over the entire band, but these can be carried out by time-multiplexing amongst several frequency settings; it is however interesting to note that there is no obvious experiment which would benefit greatly from *more* than this number of channels. These numbers assume that one can trade bandwidth

for frequency in a fairly flexible way, i.e. obtain more channels across a narrower bandwidth.

- *Dump times:*
  - *Autocorrelation spectra:* $\mathbf{3.0\left(\frac{8m}{D}\right)\ msec}$, to allow good atmospheric subtraction during on-the-fly measurements at 350 GHz
  - *Phased-array data:* $\mathbf{10\mu sec}$ for pulsar work
  - *Interferometric data:* $\mathbf{40\left(\frac{8m}{D}\right)^2\ msec}$ to allow surveys of large regions on the sky.

    This requirement, if it must be relaxed, should at least be kept below **100 msec**, to avoid significant decorrelation due to phase variation.
  - *Max. dump time:* **10 seconds or longer**, if one can hold the phase steady during that time. Without active phase correction the maximum dump time would probably be about 1 second.
- *Subarrays:* **at least 4; prefer 6-8**. Desirable for many reasons, most importantly for flux/phase calibration, to speed up mapping large areas, to lower the data rate, and to allow the use of part of the array for single-dish measurements. More important if there are more telescopes and for larger total collecting areas.
- *Total power measurements:* **must be fully supported for taking data similar to those from the interferometer**. Vital for flux calibration and mosaicing.
- *Ancillary data:* **must record a variety of weather, telescope, and related information with the visibilities.** Important primarily for calibration (phase, flux, and pointing) and flagging.
- *Spectral dynamic range:* $\mathbf{10^5 - 10^6 : 1}$, for many projects (weak lines near strong thermal sources (stars, YSOs, H II regions), faint line wings, etc.). Conveniently this numerical requirement is roughly the same for both the flatness of the frequency response and the limit on spectral sidelobes.
- *RFI excision:* allow for very strong, transient signals; possibly employ on-line flagging and masking, particularly for the longer integration times. May require flexible, programmable on-line flagging.
- *Maximum baseline:* **10 km**, to allow eventual resolutions of a few milliarcseconds. Might be even longer if a major foreign collaboration materializes.

Remaining Uncertainties

As the astute reader will have noticed, several areas of these correlator specifications would benefit from more careful study. While the need for ancillary data (§3.9) is obvious, whether it would be useful to apply any calibration derived therefrom on-line is not. Although doing this in the correlator would significantly complicate the design, the prospect of averaging down the data before writing them out is very attractive. Perhaps one could employ an intermediate, real-time processor directly after correlation to do some simple calibration and flagging before the data are written to disk. Similarly the maximum channel width is important in limiting the output rate, but will be determined by the accuracy of the delay settings and the frequency characteristics of the LO and related systems.

By far the largest source of uncertainty however is the possibility of significant foreign partners. If either the European LSA or the Japanese LMSA does in fact merge with the MMA, the budget will grow considerably, and a rather different instrument will result. This uncertainty is reflected in several areas of the correlator specifications. The most obvious is the number of antennas, which might go from 40 to a hundred or more. This together with the larger collecting area leads to a desire for more subarrays and more stringent dynamic range limits. Larger antennas have smaller primary beams, which make one want shorter integrations to allow mapping a given sky area in the same total time. Some of the joint proposals, particularly the Japanese, also push for longer baselines.

End Notes

The MMA correlator will be an impressive and complex instrument. Assuming 100 MHz channels and 1 second integrations, the *minimum* data rate for a full-bandwidth, 8 GHz continuum experiment will be $\sim 250,000 \left(\frac{N}{40}\right)^2$ visibilities per second. For an 8000-channel line observation using 0.1 second integrations this jumps up by a factor of 1000. By contrast the VLA produces at most 3,300 visibilities per second, the VLBA about 3.3 million. A standard figure of merit (or at least size!) for a correlator is the number of multiplications per second, computed as $N_{ant}^2 \, BW \, N_{\mathrm{Stokes}} \, N_{chan}$. Using the requirements given above, the proposed MMA weighs in at $\sim 1 \times 10^{16} \left(\frac{N_{ant}}{40}\right)^2$ multiplies per second, compared to 1×10^{12} for the current VLA, and $2 - 4 \times 10^{15}$ for the VLBA and the GBT.

The MMA will be a great leap forward for millimeter astronomy, much as the VLA was for radio astronomy in the '70s. Almost 30 years later the VLA is limited primarily by its original correlator, which both restricts the total bandwidth and severely constrains the number of channels one can use to cover that bandwidth. Unless the budgetary process changes significantly we can expect the initial MMA correlator to be similarly long-lived. We are designing this instrument therefore not for the 1990s, nor yet for first light in 2005 or beyond, but for the maturity of the instrument 40 years hence. What seems ambitious now may by then seem merely prudent.

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About this document ...

The command line arguments were:
latex2html `-split 0 no_navigation -info 0 -address 0 rupen.latex.`

The translation was initiated by Kate Weatherall on Tue Feb 17 13:40:41 MST 1998

...design.

Although radio frequency interference (RFI) can be quite narrow, most services operating at these high frequencies do so because they need broad bandwidths, a few MHz or more. High spectral resolution is therefore not needed for finding and excising interference signals (see §3.11). An exception is internally-generated interference, which tends to be quite narrow; hopefully the MMA will try to avoid the kind of internal emissions which currently plague the VLA.

...simultaneously,

One might be able to simply define a small number of single-dish subarrays and use those, rather than recording data from all MMA dishes at once. But it is more efficient to time-multiplex by using the full array consecutively for interferometric and single dish measurements, because the number of interferometric baselines goes as the number of antennas squared; and it is quite possible that a non-negligible fraction of the array's time may have to be used for single-dish observations (as much as 10-25%, for large-scale mosaics; see *MMA Memo 128*, Holdaway & Rupen 1995). The use of the MMA antennas for single dish observations clearly needs much more attention than it has yet received.

...data.
Some have proposed outfitting only a subset of the full array with special single-dish equipment, such as nutating subreflectors, total power continuum detectors, and multi-beam feeds.

...data.
This paragraph is taken almost verbatim from an email from Barry Clark (30 December 1997). Thanks Barry!

...timescale.
Of course, current interferometers often do not provide this sort of information. But the high operating frequencies of the MMA, together with the availability of sophisticated algorithms (currently under development; T. Cornwell 1998, priv. comm.) which explicitly take these data into account when imaging, make this information much more important for the MMA than for existing telescopes.

...phase,
Amplitude corrections can be made on much longer timescales (C. Carilli 1998, priv. comm.).

...frequency.
Thanks to Dick Thompson for making this point.

...model.
The correlator model refers to the model of the telescope geometry and atmosphere used during correlation.

...Sources:
With thanks as always to Tim Bastian.

...3.3 million.
Note that the VLBA correlator is currently limited by disk write times to actually writing out only 64,000 visibilities per second.

Kate Weatherall
Tue Feb 17 13:40:41 MST 1998