MILLIMETER ARRAY
MEMO NO. 71

MMA Systems Engineering Questions and Comments

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The major parameters of the Millimeter Array that define the overall capability have been specified in the proposal document. These include such things as the number and size of the antennas, the range of antenna spacings, and the observing frequency bands. Now, as we are beginning to think about the design of the hardware, it is necessary to consider the receiving system in greater detail. The goal is to produce a block diagram that shows details of the signal flow and breaks the hardware down into units with well defined characteristics that are feasible to construct. Developing this block diagram is a task of the Systems Engineering group.

This memorandum outlines some of the questions that are encountered at a fairly simple level of detail when considering such a block diagram. A number of these questions concern the way in which the received signals are handled between the front ends and the correlator. The questions have been discussed by NRAO staff involved in the MMA project and many of the resulting ideas are included below. However, this memorandum is intended to stimulate discussion rather than to indicate that any firm decisions have yet been made. Initial answers obtained can in many cases be expected to be modified before the array is built, as techniques and components improve. Thus the aim is to produce and maintain an optimum plan for implementation of the receiving system, revising it as necessary.

(1) First Intermediate Frequency and Bandwidth.

It will be assumed that the front ends contain mixers and the outputs are at an intermediate frequency. What are the frequencies and bandwidths of the IF's at this point? The proposal indicates a total bandwidth of 2 GHz per antenna, so the bandwidth for single-band observing would be 1 GHz for each polarization. It has been pointed out in MMA Memo 67 that a wide bandwidth for the first IF could reduce the required tuning range of the first LO. This would require IF bandwidths of tens of GHz, and the resulting high intermediate frequencies could also result in increased system temperature. Use of a high IF seems to be a future possibility that would require some development. It has been recommended that with a 1 GHz bandwidth the IF center frequency should be 2.5 GHz (rather than 1.5 GHz) to reduce the fractional bandwidth of the IF input circulator, if one is needed. More importantly, the higher intermediate frequency would improve the image rejection obtainable with a Martin-Puplett interferometer. Note that the 1 GHz bandwidth, which can be used for planning at this early stage, is a minimum requirement and is likely to be increased as the technology allows.

(2) Image Suppression.

For most spectral line observations, and for continuum observations in the larger configurations, the array will be required to operate in a single sideband mode. However, for continuum operation, simultaneous reception in both sidebands reduces the receiver noise temperature by an approximate factor of two. It also results in increased bandwidth smearing, and so would probably only be usable at the smallest configurations. The front ends should therefore be designed to allow operation in either double or single sideband modes.

In single sideband operation, how will the image response be suppressed? Image suppression could be implemented at the front end by means of a Martin-Puplett interferometer or by development of a sideband separating configuration for the SIS mixer. With a Martin-Puplett interferometer the image rejection increases with the intermediate frequency: for a signal frequency near 230 GHz the image rejection at the band edges is 12, 16 or 19 dB for IF bands 1-2, 2-3 or 3-4 GHz respectively (see memo by T. Kerr, 9/19/91). Degradation of the system noise temperature would limit the IF to a few GHz. Also, the achievable image rejection with a sideband separating mixer might be no better than 10 dB at some points in the band. Image rejection in the range 10-20 db would be sufficient to prevent degradation of the system temperature by atmospheric noise at the image frequency, which is an important requirement. However, it would not be sufficient for the required spectral dynamic range. Thus sideband separation at the correlator (which does not remove atmospheric noise) may also be required. This technique involves quadrature phase switching of the first LO and doubling the number of integrators at the correlator output. It appears that we should plan to include both image suppression by hardware at the front end and by phase switching. A Martin-Puplett interferometer at the front end would be remotely adjustable to allow the rejection band to be placed over the unwanted sideband for any particular local oscillator tuning. It could also be adjusted to allow both sidebands to be accepted by the mixer when required.

(3) First LO Tunability.

With an IF bandwidth of 1 GHz the minimum tuning increment of the first LO should be about 500 MHz which will require an LO reference of the same frequency. A scheme like that used for the VLBA in which the lock frequencies are (Nx500 +/- 100) MHz is convenient to implement and would be appropriate. At the highest observing frequencies the multiplication factor for a 500 MHz reference frequency would exceed 700, so considerations of phase noise may require a use of an additional, higher reference frequency. Note that distributing fixed reference frequencies and synthesizing required frequencies at the antennas should, in practice, result in better phase stability than distributing tunable reference frequencies. Also, in a complicated system it can be extremely difficult to avoid spurious responses if tunable reference frequencies are used.

(4) Number of IF Signals at each Antenna.

The project book indicates that dual band observing using a dichroic system at the feeds is a requirement of the array. The number of IF's to be handled at each antenna should thus be no less than four to allow for simultaneous observations at two frequencies, each with dual polarization.

(5) Channelization.

Should the 1 GHz-wide IF bands be further subdivided into narrower channels before digital sampling? If the observer wants to use only a part of the full 1 GHz IF bandwidth then narrower channels must be provided that will be tunable across the IF bands to allow the desired frequencies to be selected. There should perhaps be more than one channel for each IF to allow for cases in which two or more parts of the IF band are of interest. A system with one or two such channels per IF (i.e. this means four or eight per antenna) was suggested in MMA Memo No.65. It has been noted that with modern circuitry it should be possible to sample and digitize a bandwidth of one or two GHz with a single sampler. This would be good for continuum observing, but breaking the IF down into a number of tunable narrower channels is likely to be necessary to provide flexibility of bandwidth for line observations. Filtering by digital techniques would add considerable complexity to the system. Channelization considerations also depend upon the design of the correlator. A preliminary figure for the minimum spectral channel bandwidth (i.e. the spectral resolution) that has been mentioned in earlier discussions is 6 kHz. (This figure is equal to the Doppler shift for a radial velocity of 0.02 km/s at 100 GHz.) If the correlator produces 1000 spectral channels, the IF channels prior to sampling would require bandwidths variable down to 6 MHz.

(6) Analog or Digital Transmission.
Should the signals be transmitted from the antennas to the correlator location in analog or digital form? The advantage of analog transmission is that it simplifies the equipment at the antennas since selection of the final frequency channels and sampling can then be performed at the correlator location. Advantages of digital transmission are that distortion in the analog transmission system is avoided, high linearity of the transmission system is not necessary to maintain high dynamic range, and after digitization the signals are not susceptible to pickup of low-level spurious components. Also, the stability of the delay in the transmission is less important because, in principle, the time at which each sample was taken is known. In the VLA, which uses waveguide as an analog transmission medium, the dependence of the passbands on the flatness of the waveguide response is a limiting factor in the dynamic range achievable in the images. Of the advantages given above, those of digital transmission seem to outweigh those of analog.

It also appears that for fiber optic systems digital transmission can, in some circumstances, handle a higher signal bandwidth than analog transmission. In analog transmission the noise introduced in the laser diode imposes a lower limit to the power spectral density of the signal at the modulator input to avoid degradation of the signal-to-noise ratio. In addition, there is a maximum input power limit set by linearity requirements. The effect of these two limits is a limit on the bandwidth. This bandwidth limit depends inversely upon the required signal-to-noise ratio and the dynamic range required in the link. Since a lower signal-to-noise ratio and dynamic range can be tolerated for digital bits, the signal bandwidth transmitted in the digital case can be higher if the number of bits per sample is not too high. However, for the MMA the limit on the analog bandwidth resulting from this effect should be at least several gigahertz, and so it may not be an important consideration.

(7) Use of Fiber Optics in the Delay System.
The possibility of using switched lengths of fiber optic transmission line as delay elements has been pointed out in MMA Memo No. 66. If the signals are carried in digital form in the transmission line, adding further sections for delay purposes would not cause distortion. This would be an analog delay of a digital signal. The relative advantages of performing some delay steps in the transmission line rather than making the whole delay system in digital

circuitry are mainly related to cost and reliability, so a choice would rest largely on engineering considerations. With analog signal transmission the temperature coefficient of the delay in the fiber would be important. The practicability of the fiber optic delay system would depend strongly on the availability of fiber optic switches with adequate performance.

(8) What is the Minimum Tuning Increment for the Final LO?
This tuning increment determines how closely the channels discussed in (5) could be set relative to a particular frequency in the IF band. This should be some fraction, say 1/10, of the narrowest analog bandwidth which, as suggested in (5) above, might be 6 MHz. Thus the LO should be tunable in increments of about 0.5 MHz.

(9) Fringe Rotation.
How should the fringe rotation be implemented? Possible methods are by offsetting a local oscillator, or digitally in the correlator as in VLBI. Fringe rotation in a lag correlator usually involves a small loss in sensitivity as a result of the use of a two- or four-level representation of the waveform with which the signal is multiplied. More importantly, it has been pointed out in VLBA Memo No. 593 that phase shifting after coarse quantization does not compensate accurately for phase shifts incurred before sampling. It works alright in most cases, but calculations in the Memo demonstrate that for high correlation coefficients (>0.2), which could occur in observations of maser lines, spectral dynamic range is lost. These problems are avoided by fringe rotation at one of the local oscillators, as in the VLA. The system for fringe rotation in a local oscillator also provides a means of real time phasing of the array, which is presumably a requirement for the MMA. Discussions in some early VLA memos (VLA Electronics Memoranda Nos. 116 and 122) concluded that both fringe rotation and phase switching should be introduced in an early LO in the receiver chain. Fringe rates for the MMA will be very similar to those for the VLA, in which a fringe frequency synthesizer at each antenna is used to offset the reference in an LO phase-locked loop. Is there any reason not to use a similar scheme for the MMA? It should be noted that since the VLA may be re-outfitted in the foreseeable future, it would simplify design and maintenance if some units were identical in both instruments. The fringe rate generator is a possible case for such a unit.

(10) A Special Wideband Correlator for Continuum Observing?
Data processing for spectral line observing will be done in a digital correlator, the capacity of which will limit the bandwidth that can be used for continuum observations. To obtain wider bandwidths for maximum sensitivity in continuum observing it is likely to be cheaper to build a special continuum correlator rather than to expand the spectral correlator. The continuum correlator would perform only multiplying and integrating functions without lags or real time FFT's. Correlation of wide bandwidth signals in a single channel has the effect of smearing the image in the outer parts of the field of view. With the 3 km configuration of the array the smearing would begin to be noticeable at a bandwidth of about 1/200 of the observing frequency, e.g. 500 MHz for the 3 mm band. Thus to obtain an overall bandwidth of several GHz at the larger configurations several narrower channels would be processed in parallel. For the purpose of detecting narrow,

weak sources some degradation in the resolution would be acceptable in return for higher sensitivity. However, these factors need to be carefully weighed to decide what the maximum channel bandwidth for a continuum correlator should be. Although the additional correlator would perhaps be a feature to be added later in the design of the array, it should be considered at this point because it would affect the bandwidth requirements of the signal transmission system.

In principle, a continuum correlator could be implemented in either analog or a digital hardware. An analog system would also require analog signal transmission and compensating delays. A bandwidth of 1 GHz, for example, would require delay adjustment to an accuracy of 31 ps (1/32 of the reciprocal bandwidth, as in the VLA delay system) which is equivalent to an air path length of 9.7 mm. To avoid rapid switching of short lengths of optical fiber the fine delay elements might have to use moving mirrors to provide a variable path length. The usefulness of an analog system would depend upon how accurately the signal passbands could be maintained, and the extent to which bandpass mismatch would limit the dynamic range achievable in imaging. The reason for considering an analog correlator is that it might be somewhat cheaper since some parts of the system such as the signal multiplying elements could be quite broadband. However, if image smearing considerations require that the overall bandwidth be broken down into a number of parallel channels, the possible advantage of the analog approach is reduced, since very broad bandwidth components would no longer be needed. As in the case of double sideband observation, the size of the array configuration should be included in any consideration.

(11) Total Power Measurements.
Measurement of the total power received at each antenna is required for a number of purposes. These are, (1) determination of total flux density from an area being mapped, (2) pointing calibration, as an alternative to interferometer-mode pointing, (3) measurement of system temperature, (4) operation of the array as a set of independent single dishes. Measurement of system temperature is a way of monitoring variations in the atmospheric component noise power, and might in the future provide a correction for atmospheric phase. Four total power measurement units should be provided at each antenna to cover the four IF channels mentioned in section (4). Each total power unit would contain a square-law detector, and also a synchronous detector to extract the switched component from a noise source or nutating subreflector. This system would provide for continuum measurements of total power. If spectral line measurements of total power are required these would have to be implemented in the correlator using an autocorrelation mode. They would therefore be made on the IF signals after digital sampling. The level of the IF signals at the sampler input will be controlled by an ALC circuit, but a measurement of the unlevelled IF power would be provided by the continuum total power system.

(12) Pulse Calibration Scheme.
A feature that may be desirable for the MMA is a pulse calibration scheme to facilitate bandpass calibration of the IF signal channels from the antennas to the correlator. This would be similar to the calibration systems used in VLBI in which a series of narrow pulses is injected into the front end inputs. The

spectrum of such a pulse train is a series of lines that are harmonics of the pulse repetition frequency, which is commonly one or five megahertz, i.e. a comb spectrum. In VLBI the pulses are derived from the maser at each antenna site, and can be used to calibrate the instrumental phase responses. The pulse generators use tunnel diodes to produce pulses of width approximately 25 ps, which result in a useful comb spectrum up to about 30 GHz. It is not within the current state of the art to generate trains with lines of useful strength as high as the observing frequencies of the MMA, but pulses could certainly be injected into the IF stages immediately following the SIS mixers. The system would not help to calibrate drifts in the first local oscillator, but a series of lines across the passband could be used to measure the variations in amplitude and relative phase with frequency. During spectral line programs such calibration could be performed at convenient intervals since one would not generally want the calibration lines present when astronomical data was being taken. Measurement of the calibration lines might be done in the correlator, or a special line-frequency extraction system, and these considerations would determine whether it would be possible to calibrate all antennas and all IF's simultaneously. Pulse calibration schemes were considered for the VLA but never implemented, and various possibilities are described in VLA Electronics Memo No. 172.