MMA Memo 213:
MMA Frequencies Working Group:
Frequency Band Considerations and Recommendations

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1. Introduction

This report summarizes deliberations of the MMA Frequencies Working Group, charged with reporting on the priorities for the frequency bands of the MMA receivers. This includes consideration of the positions of the rest wavelengths of important lines in the millimeter and submillimeter bands. as well as redshifted lines and continuum emission, especially dust.

In the first section, we discuss previous considerations of the siting of MMA frequency bands. In the second sections, we consider the positions of the rest wavelengths of important lines relative to the atmospheric absorption in the millimeter and submillimeter bands, including redshifted lines and continuum emission, especially dust. For the centimeter window, the Sunyaev-Zeldovich effect drives the science, which is discussed in relation to placement of that band.

2. MMA Bands – Previous Discussion

In Table I, I reproduce a recommendation made by a small committee of R. Brown, A. Kerr and A. Wootten in November 1996, which forms a starting point for discussions. We have assumed that the extent of a band $\mathcal{R}$ is defined by the ratio of frequency maximum within a band to frequency minimum.

$$\mathcal{R} = \frac{\nu_{upper}}{\nu_{lower}} \tag{1}$$

On the recommendations of A. Kerr and M. Pospieszalski, we take this to be $\mathcal{R}$=1.3 for SIS receivers, $\mathcal{R}$=1.3 for HFET higher frequency receivers, and $\mathcal{R}$=1.5 for the Qband HFETs. Goals of the 1996 recommendation were to:

• ensure good performance at the wavelengths of astrophysically important transitions as well as complete coverage of the bands.

• cover atmospheric windows blocked from low elevations but which promise usable transparency from excellent sites,

• minimize the number of receivers, to keep costs and maintenance difficulties small,

• conservatively assume that the ratio $\mathcal{R}$ between a receiver's upper frequency limit and its lower frequency limit be no larger than $\mathcal{R}$=1.3 for SIS or HFET HFET receivers in most instances, and to

• provide best performance at frequencies where the atmosphere is most transparent.

We have also attempted to site the receivers near the frequencies covered by standard waveguide components which results in a somewhat lower receiver development cost. Note that the maximum single moded bandwidth for a corrugated feed is about 1.68 and does not pose a problem for the smaller bandwidths covered here.

We note that Erickson has pointed out that in practice, the local oscillator coverage may limit the range of frequencies of receivers also. The final arrangement of bands will depend upon many interlinked system parameters; the goal here is only to provide guidelines based upon the science. Ideally, frequency coverage should be complete.

Table 1 provides for complete coverage of the millimeter range in five receivers. If bandwidth to frequency ratios of $\mathcal{R}$=1.5 could be ensured, four receivers might cover this range. In the table, frequencies corresponding to ratios of both $\mathcal{R}$=1.3 and 1.4 are given to illustrate that a slight increase in bandwidth to frequency ratio would cover the few holes in spectral coverage. The proposed bands in Table 1 were modified in subsequent MMA Memos.

At the lower frequency end covered by the Cassegrain receivers MMA Memo No. 163 suggested a strawman optics layout for the MMA antenna. It only considered seven receivers, with central frequencies which would leave large holes in frequency coverage at astrophysically important frequencies under the assumptions we have adopted here. We believe that plan to be unacceptable.

MMA Memo No. 183 elaborated upon this strawman layout to present a plan for the focal plane of the antenna. In the receiver plan proposed in this memo, the frequency coverages are as given in Table 2. Complete frequency coverage is attained with ten receivers in this plan. Differing only marginally from the suggestions in Table I, gaps might remain between 92 and 99 GHz, 128 and 137 GHz, and 178 and 182 GHz, if $\mathcal{R}$=1.4 cannot be achieved at the low frequencies. Table 2 will be the starting point of discussion for this memo.

Table 1. MMA Cassegrain Receiver Coverage - Nov 1996 Plan

Receiver	$\nu_{low,1.4}$ (GHz)	$\nu_{low,1.3}$ (GHz)	ν_{center} (GHz)	$\nu_{high,1.3}$ (GHz)	$\nu_{low,1.4}$ (GHz)	WG Band WR-xx
1	67	70	80	90	93	(WR-12-HFET?)
2	86	90	103	116	120	WR-8
3	125	130	150	170	175	WR-6
4	175	183	210	237	245	WR-4
5	225	235	270	305	315	WR-3
6	292	305	350	396	408	n-s[a]
7	375	392	450	509	525	n-s
8[b]	625	625	660	705	705	n-s

[a] n-s means non-standard

[b]Receiver band #8 is bandwidth limited by the atmosphere

Table 2. MMA Memo No. 183 Cassegrain Receiver Coverage

Receiver	$\nu_{low,1.4}$ (GHz)	$\nu_{low,1.3}$ (GHz)	ν_{center} (GHz)	$\nu_{high,1.3}$ (GHz)	$\nu_{high,1.4}$ (GHz)	WG Band
1	67	70	81	92	95	(WR-12-HFET)
2	94	99	114	128	133	(WR-8-HFET)
3	132	137	158	178	183	n-s[a]
4	174	182	209	236	244	WR-4
5	226	235	271	307	316	WR-3
6	294	305	353	400	412	n-s
7	380	397	456	515	532	n-s
8[b]	602	602	660	720	720	n-s
9[b]	787	787	869	950	950	n-s

[a] n-s means non-standard

[b]Receiver bands #8 and #9 are bandwidth limited by the atmosphere

3. Discussion

3.1. Atmospheric Considerations

For the purpose of defining atmospheric windows, we consider the sky to be effectively blocked when the system temperature rises to three times the value in the minima of the windows. Spectrally blocked regions are thus 51-68 GHz and 116-123 GHz, from oxygen lines. Even under dry conditions, the regions 181-187 GHz and 323-328 GHz are effectively blocked under this definition. However, the water line which blocks the Earth's atmosphere is a very strong maser in celestial sources, and the optical depth in the atmosphere may be as low as unity, permitting astronomical observations of both the 183 and 325 GHz water lines from dry sites. We have made no attempt to specify receiver bands which cover the oxygen-blocked 51-68 GHz and 116-123 GHz regions. Low energy (ground state) transitions of water very effectively block transmission in the 375-385 GHz, 532-602 GHz and 720-787 GHz bands. Except for 51-68 GHz, 116-125 GHz, 370-385 GHz, 532-602 GHz and 720-787 GHz, all frequencies are covered by a receiver band in the conservative plan we devise (Table 3, below).

3.2. Astronomical Considerations

For an instrument with very limited sensitivity, such as have existed in the pioneering days of millimeter radio science, one might construct a list of critical transitions, around which the frequency coverage for an instrument might be planned. For the MMA it is useless to pose the question, as thousands of clouds will be visible in thousands of lines. The number of lines of interest might be estimated to lie in between the number for which frequency protection is being sought, as a minimum number, to the number in a complete census of lines expected in a particular window.

The list of lines being considered by the IAU Committee on the Allocation of Frequencies for frequency protection runs to five pages, covering some three hundred lines considered critical to the science. No complete line list exists for any frequency window. Recently Turner (private communication) has attempted to construct such a list in order to aid in identification of emission observed in his survey of the 2mm window. This list includes ten thousand transitions in the 40 GHz covered by the survey, all of which might be expected in emission from astronomical objects. Subsets of this list have been created by Lovas (observed lines) and Pickett (observed and predicted lines) in WWW-searchable files, such as the ones reached from the homepage of IAU Commission 34 / Division VI - Astrochemistry working group (http://www.strw.leidenuniv.nl/~iau34/). We conclude that emission lines so densely cover the millimeter/submillimeter spectrum that a list abstracted within this document would be misleading. As maser emission is of particular interest for operation of an interferometer, and since known maser emission lines are scarce, we have attempted to mention them specifically. Even among these lines, we might expect more masers among the myriad of lines which have not been observed than are known.

Note that all spectral regions are equally important from an astrochemical point of view. The detection of large molecules requires very sensitive observations. At high sensitivity, weak lines from molecular interloper species fill the spectrum and cause confusion. Some of this confusion arises from line broadening, arising in components in an extended turbulent envelope, or in adjacent emission regions. The spatial frequency sensitivity of an imaging interferometric array can help alleviate this confusion, offering a significant advantage over single-element radio telescopes for astrochemical searches. This will be particularly important for searching small cores for emission from large highly saturated interstellar molecules, which may have numerous weak emission lines.

For the weakest clouds, one might consider which lines might be observable. But among the weakest clouds are extragalactic clouds. Since the MMA is capable of imaging essentially all the galaxies in the Hubble Deep Field, again the question becomes moot, as once one gets beyond a redshift of one all frequency space is covered by the CO line alone, normally the strongest in extragalactic clouds. The committee feels that the MMA coverage should be seamless up to the upper limit set by the atmosphere.

7-10mm Science Drivers The major science driver for the 7-10mm band is the Sunyaev-Zeldovich effect which requires the lowest noise continuum frequencies in this band. However, the band will also be used for redshifted line work, continuum observations of planets, the Sun, stars and non-thermal galactic and extragalactic radio sources. It is important that the frequency coverage overlap with the VLBA including coverage of the 43 GHz SiO maser and 44 GHz methanol maser lines which are in the same 41-44 GHz band. Finally the band will be used for holographic measurements of the dish surface and baseline measurements.

The exact band which is best for the Sunyaev-Zeldovich effect also is complicated by the need to support both total power and interferometric observations. The total power requirements need to take into account the added noise from the nearby 22 GHz water line whose wings spill over into the frequencies above it up to at least 30 GHz (Holdaway, in preperation). The interferometric mode should not be as badly affected by these fluctuations and would ideally use as low a frequency as possible to be sensitive to the largest possible structures.

This situation argues for a receiver with an optimized noise temperature over about a 10 GHz window and reduced sensitivity outside this band. This best compromise right now looks like 30-40 GHz for the sensitive portion of the band.

2-3mm Science Drivers The 3mm window was among the first to be explored. At its lower end, the oxygen line blocks transmission near 67 GHz. Fundamental transitions of the important deuterated isotopomers of the abundant species HCO^+, HCN, HNC, N_2H^+ and others lie in this lower region, as well as the ground state transitions of SO_2 and H_2CO. Several masers also lie in the window, including SiO J=2-1 at 86 GHz, methanol ($8_0 \rightarrow 7_1 A^+$)at 95.2 GHz and a vibrationally excited stellar water maser ($\nu_2 = 1, 4_{40} \rightarrow 5_{33}$)at 96 GHz. Best continuum performance is expected at near 86 GHz, so receiver performance should be optimized for this region to accommodate sensitive fast switching.

Of particular concern is the 2mm window, which is marginally too wide to be covered by a single receiver with a maximum frequency ratio of 1.3. In the past, receivers have been sited in this window to avoid the wings of the oxygen line at 118 GHz, and those of the 183 GHz water line. Water line science is a driver for the MMA, a factor which tends to push the definition of the 2mm window to higher frequencies. However, the region at frequencies just above the oxygen line offers interesting science also. We note that an examination of the spectral survey of Cummings and Thaddeus (ApJ) shows that no exceedingly important transitions of critical species lie in the lower portion of the 2mm band–one exception is the J=3-2 v=0,1,2 lines of SiO at 128.5 - 130.3 which show both thermal and maser emission.

From a cosmological point of view, note that at redshifts of z=0.85 - 0.94, all three isotopes of CO are blocked by the atmosphere in their three lowest transitions. For z=0.72 - 0.83, the 1-0 line is blocked, and the J=2-1 line falls in the region 126 - 134 GHz. For z=0.84, both the 1-0 and 3-2 transitions are blocked and the 2-1 line falls at 125 GHz. Since the lowest transitions of CO are among those expected to be detectable from galaxies similar to the Milky Way at these redshifts, it should be our goal to achieve good sensitivity over the 125-134 GHz region.

We conclude that the science drivers for this region require good sensitivity. The very best sensitivity appears achieved with an SIS rather than a HFET device, and a more conservative frequency ratio. Adjustments to the band assignments in Table 2 appear necessary, particularly around 2mm.

Important scientific considerations affect band placement at higher 2mm frequencies also. With two 8 GHz IFs separated by 8 GHz, the expanse of our spectral window will be 24 GHz from top to bottom, if we can obtain both sidebands at once. It would be advantageous to be able to observe the very strong interstellar water maser at 183 GHz simultaneously with other lines, with one correlator window on the maser and another on another line of interest. The question then arises–where are the most interesting other lines? We believe that the region down to 160 GHz or so, with the J=2-1 lines of N_2H^+,C_2H, HCN, HCO^+, the J=4-3 line of SiO, the resonance line of H_2S particularly interesting. An important $H_2^{18}O$ line lies at 203 GHz and CS J=4-3 lies at 195 GHz. For these reasons, we endorse a receiver covering a broad window centering near the 183 GHz water maser line (Table 3), or two receivers with bands overlapping there (as in Table 2). The water line could be then used to improve the observations over the whole 160-206 GHz region. This frequency siting falls naturally out of the slightly modified Lugten and Welch proposal given in Table 3.

Studies demonstrate the utility of having one receiver available for monitoring of atmospheric conditions above each antenna. Most thought has focussed on the 183 GHz water line as the most useful for this sort of atmospheric monitoring for the MMA, though the 325 GHz line has similar opacity and may offer similar capabilities. Monitoring might be achieved in either of two ways. 1) A receiver operating at 183 GHz may be turned on, though not centered on the optical path of the telescope, when atmospheric monitoring is desired but observations occur at a different band. When observations occur in the band containing the 183 GHz line, the monitoring function might be carried out by the 325 GHz receiver. However, the calibration of this line will be somewhat different, and receiver sensitivity at higher frequencies may be poorer. A preferred solution might be 2) to place a dedicated receiver for atmospheric monitoring among the focal plane detectors.

1mm Science Drivers The Science Workshops have consistently selected this window as the most scientifically important window for the MMA. The window contains fundamental transitions of most important molecules, as well as stong dust emission. This window is defined by the atmospheric water absorption lines ($3_{13} \rightarrow 2_{20}$) at 183 GHz and ($5_{15} \rightarrow 4_{22}$) at 325 GHz. Both of these lines mase in a variety of astrophysically interesting sources (Cernicharo *et al.* 1996 A&A 305, L5 and Menten *et al.* 1990 ApJ 363, L27). Additionally, the ($10_{29} \rightarrow 9_{36}$) 321 GHz line has been observed toward a number of oxygen rich stars (Menten and Melnick 1991 ApJ 377, 647). The vibrationally excited water line ($\nu_2 = 1, 5_{50} \rightarrow 6_{43}$) at 233 GHz has been observed toward W Hya (Menten and Melnick 1989 ApJ 342, L91).

0.3mm to 0.6mm Science Drivers Higher excitation transitions of abundant molecules, as well as fundamental transitions of lighter molecules, are the most important spectroscopic targets in this band. Dust emission from cool condensations and redshifted galaxies will provide important continuum targets. Despite the incomplete exploration of the window, several water masers are known: the $6_{43} \rightarrow 5_{50}$ line at 471 GHz and the $6_{42} \rightarrow 5_{51}$ line at 439 GHz toward stars and star-forming molecular clouds, and the $7_{53} \rightarrow 6_{60}$ line at 437 GHz toward evolved stars (Melnick *et al.* 1993 ApJ 416, L37). Very strong emission has been observed at 658 GHz in the $\nu_2 = 1, 1_{10} \rightarrow 1_{01}$ line towards evolved stars also (Menten and Melnick 1995 ApJ 450, L67). Melnick (1993, in *Astrophysical Masers* , Clegg and Nedoluha, editors (Berlin: Springer-Verlag), p. 41) has predicted that maser emission might be observed from the $9_{28} \rightarrow 8_{35}$ line at 906 GHz toward many sources; this has not yet been confirmed. Hence, strong water maser emission has been found, or is expected, in all of the MMA bands and will provide a useful phase reference.

3.3. Receiver Detector Technologies – 2-3mm Performance

Over what frequency range might HFET receivers be used, and over what frequency range should SIS receivers be planned? This is a question to be left to engineering progress but some science issues enter peripherally.

At 3mm frequencies, SIS or HFET amplifiers may suffice. Dick Thompson points out that an 8 GHz bandwidth is achievable with an HFET amplifier but has not been demonstrated with SIS mixers; that HFETS are more robust and less likely to be overloaded by interference, and provide an inherently single sideband input.

At WRC-97, the band 94-94.1 GHz was allocated to the Earth-exploration service for the use of a very limited number of cloud-profiling radar satellites. It is important that the 92-99 GHz region be covered, because it contains the low-lying lines of a number of important heavy species (CS 2-1, N_2H^+ 1-0, CH_3OH $2_{K-1,K}$). A most important consideration is the input power levels at which compression occurs in 3mm systems (A. R. Thompson, private communication). The millimeter wavelength spectrum is beginning to be developed for various commercial usages, and will begin to fill up at the lower frequencies first. Note that the 90-115 GHz band is one of those that may be switched to for phase calibration when observing at higher frequencies, so it would be serious if an interfering signal in some part of the band caused compression. Thompson's impression is that the HFET amplifiers are superior in this respect. Thompson suggested that the receiver group should obtain measurements of the -1dB compression point on HFETs and SIS mixers at this frequency to provide quantitative data to consider.

Some cloud-radar satellites, such as approved by WRC-97 may even pose a survival threat to devices, according to Lamb (private communication). Discussions at WRC-97 considered the need for measures to reduce satellite emissions when the radar satellites were overhead to major 3mm facilities, but the facilities would be well-advised to consider defensive measures also. Inband interference (i.e., the 4 or 8 GHz being used) will have the same effect on the HFET and SIS systems (for a single telescope; for a long baseline interferometer the output of antenna pairs may be decorrelated). The main difference would be where the signals are in the RF band but downconverted outside the IF band. High powers can then affect the in-band signals. In this respect it is not just the HFET which must be considered but its wideband mixer(s) also.

We conclude that the best possible available performance can be achieved in this critical upper 3mm band by SIS devices. HFET devices offer advantages in simpler receiver technology, broader bandwidth coverage and probable superior performance in a hostile interference environment. If HFET sensitivity can be improved, particularly in the 120-135 GHz range, to be comparable to that achieved by SIS devices, then the bands in Table 2 are optimal. Since it does not appear that HFET devices of sufficient sensitivity will be available on the timescales during which they are needed, we revise the bands of Tables 1 and 2 to the conservative valuyes given in Table 3.

3.4. Polarization Considerations

Polarizers might be necessary for measuring weakly polarized signals; these devices may compromise receiver performance and bandwidth. Generally, for observations of weak linear polarization, such as might be observed from interstellar dust, cross-correlation of circularly polarized signals will be less sensitive to systematic calibration errors than observing linear polarizations directly. To measure circular polarization, useful for measuring the Zeeman effect, planetary radar signals or for VLBI work, cross correlation of linearly polarized signals may be desireable. To date, available polarizers have limited bandwidths; they also may degrade sensitivity. At present, the subreflector is planned to be symmetric, illuminated by feeds which are slightly off axis. We are uncertain how much uncertainty this may introduce into polarization observations. Alternatively, signals may be combined to produce the desired polarization at a later stage, though perhaps with some loss in accuracy owing to systematic effects.

Polarization observations with the BIMA array is achieved through placing quarter wave plates in front of the receivers for converting linear to circular polarization, At OVRO a reflecting wire grid polarizer allows transformation of receiver linear polarization to any other polarization state on the sky (Akeson and Carlstrom 1997 ApJ, 10 Dec).

There is a consensus that linear polarization will suffice if the penalty for circular polarization is to be decreased sensitivity and/or bandwidth.

3.5. Recommendation and Implementation

We present, in Table 3, a plan for receiver coverage which leaves only one hole in astrophysically interesting frequency coverage around the (opaque) 383 GHz atmospheric water line. Stretching from 360-385 GHz, this hole contains six important transitions of formaldehyde, a transition of H_3O^+, and some other lines. We have therefore stretched the allowable bandwidth for this band only to a ratio of 1.35, to enable coverage of these important lines. This shrinks the hole in coverage to the region 370-385 GHz, a band lying between an atmospheric oxygen line and a strong water line, but which still contains the potentially useful ground state H_2D^+ line.

Table 3. Recommended Receiver Coverage[a]

Receiver	ν_{low} (GHz)	ν_{center} (GHz)	ν_{high} (GHz)	WG Band/Detector	comments
1	30	35	40	WR-22 HFET[b]	
2	67	79	90	WR-12 HFET	
3	89	103	116	WR-8 HFET or SIS	Pending HFET development
4	125	144	163	WR-6 SIS	
5	163	187	211	WR-5 SIS	
6	211	243	275	n-s[c] SIS	
7	275	323	370	n-s SIS	Bandwidth ratio of 1.35
8	385	442	500	WR-2.2 SIS	
9[d]	602	660	720	n-s SIS	
10[d]	787	869	950	n-s SIS	

[a]Band definitions are for good sensitivity degrading increasingly beyond edges

[b]Some sensitivity is needed through the VLBA band, to 45 GHz

[c] n-s means non-standard

[d]Receiver bands #8 and #9 are bandwidth limited by the atmosphere