ALMA Scientific Requirements

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1 Scope and Description

This document is meant to describe and specify the scientific requirements for ALMA. It draws from a long list of historical documents describing the desired scientific emphasis of ALMA (and the MMA and LSA) (see, e.g., Barrett et al. 1983; Wootten & Schwab 1988; Shaver 1995; Brown et al. 1995; ESO Proposal 1999; Brown et al. 2000; Wootten 2001; Vanden Bout et al. 2003), and a number of technical memos and documents (many of them in the formal MMA and ALMA memo series). It is meant to be the defining document for the high level science requirements for ALMA. The implications of these requirements on the instrumental hardware, software, and operations (including calibration) plan is to be laid out in separate documents.

As scientists, if given free reign on specifying the requirements, we would tend to "ask for the sky", i.e., ask for too much. However, what we desire must be confronted with the reality of the available technology and budget. In that case, we often simply want "as good as we can get." This is often hard to quantify into a proper requirement (one which is very useful in terms of designing the instrument). As an example, we would like the antenna pointing to be as good as possible. To get it as good as we really want it, however, would be prohibitively expensive, and might not even be technically feasible. We have iterated with antenna vendors on what is reasonable and affordable to arrive at the current specification. This is not a new phenomenon - it has been true for basically every astronomical telescope constructed. To quote Sebastian von Hoerner (in VLA Test memo 129, 1981): "In summary, the astronomical demands are not so well-suited for deriving a well defined specification for the pointing error... Thus, it comes back to wanting the pointing error just as small as possible, and then to live with what one can get." So, given the time at which this document is being written, many of these "requirements" were decided upon long ago, and have already been incorporated into the design of the instrument. As such, there has already been a feedback of both technical and budgetary reality into the setting of the requirement. However, it was still felt that it would be beneficial to collect all of the requirements and supporting arguments into a single document.

2 Introduction

ALMA should provide astronomers with a general purpose telescope which they can use to study at a range of angular resolutions millimeter and submillimeter wavelength emission from all kinds of astronomical sources. ALMA will be an appropriate successor to the present generation of millimeter wave interferometric arrays and will allow astronomers to:

- Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z = 10$;
- Trace through molecular and atomic spectroscopic observations the chemical composition of star forming gas in galaxies throughout the history of the universe;
- Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects (QSOs) on spatial scales smaller than 300 light years;
- Image gas rich, heavily obscured regions that are spawning protostars, protoplanetary disks and protoplanets;
- Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
- Obtain unobscured, subarcsecond images of cometary nuclei, and thousands of asteroids, Centaurs, and Kuiper Belt Objects (KBOs) in the solar system along with images of the planets and their satellites;
- Image solar active regions and investigate the physics of particle acceleration on the surface of the sun.

ALMA will have the capability to extend the high resolution imaging techniques of radio astronomy to millimeter and submillimeter wavelengths to achieve an astronomical imaging capability better in clarity of detail than the Hubble Space Telescope (HST) and large ground based telescopes. It will do so at wavelengths where the richness of the sky is provided by thermal emission from the cool gas and dust from which stars and all cosmic objects form. In this sense, ALMA is the appropriate scientific complement to the Very Large Telescope (VLT) and Gemini, to the HST, and its successor instrument, the James Webb Space Telescope, and to the Space InfraRed Telescope Facility (SIRTF), instruments which image light from stars and collections of stars such as galaxies.

3 General Requirements

We can write down a few generic high level requirements derived from the full suite of desired scientific experiments:

- cover all available millimeter and submillimeter atmospheric windows;

- be able to observe in both narrow ("spectral line") and wide ("continuum") bandwidth modes;
- maximize the sensitivity;
- maximize the flexibility of the spectral line capability;
- maximize the imaging capability, at both large and small angular resolutions;
- able to collect full polarization data.

But in order to be very useful we must turn these somewhat vague requirements into more concrete numbers. Let us start to do this by first examining a few particularly important scientific experiments.

4 Primary Scientific Requirements

The main science requirement for ALMA is the flexibility to support the breadth of scientific investigation to be proposed by its creative users over the decades long lifetime of the instrument. However, three science requirements stand out in all the science planning for ALMA done in both Europe and in North America. These three primary science requirements are:

1) The ability to detect spectral line emission from a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

2) The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the gaps created by planets undergoing formation in the disks.

3) The ability to provide precise images at an angular resolution of 0.1 arcseconds. Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements have driven the concept of ALMA to its current technical specifications.

4.1 Detecting the Milky Way at $z = 3$

The translation of the science requirement into a performance specification can be made by comparison with the results obtained by current millimeter arrays, which have collecting areas between 500 and 1000 m^2. These arrays can detect CO emission from the brightest galaxies, amplified by gravitational lensing in one to two days of observation. Emission from normal, unlensed objects will typically be 20-30 times fainter.

The sensitivity of ALMA for a given integration time is essentially controlled by five major terms: the atmospheric transparency, the surface accuracy of the antenna, the noise performance of the detectors, the bandwidth available, and the total collecting area. This is explained in much more detail in Appendix A. Compared to current millimeter arrays, by locating ALMA on a better site, the contribution of the atmosphere will be minimized. The surface accuracies of current millimeter arrays are quite good, and we do not expect to improve much on that. The noise level of the detectors cannot be reduced by much more than a factor of two, because these receivers are approaching the fundamental quantum limit. An important factor of $\sqrt{2}$ will be gained by the requirement that ALMA support front end instrumentation capable of measuring both states of polarization. No gain from bandwidth differences is realized, since this is a spectral line detection. The remaining factor of 7-10 can only be gained by increasing the collecting area by a similar amount. Hence the ALMA goal is to achieve at least 7000 m^2 of collecting area. A much more detailed derivation of this requirement is presented in Appendix B.

The spectral lines of scientific interest as diagnostics of the gas content and dynamics of a galaxy early in the history of the universe have frequencies that are fixed in the rest frame of the galaxy, but we observe these lines at a frequency that depends on the redshift of the particular galaxy. Since galaxies are found at every redshift (i.e., age), the goal of the ALMA Project is to provide the capability to observe in all atmospheric windows from 30-950 GHz so that galaxies of all ages may be studied. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers should also be as large as possible.

4.2 Protoplanetary Disks

A similar sensitivity argument can also be made for the studies of protoplanetary disks: going from the 0.5 arcsecond angular resolution obtained in the best images with current millimeter arrays to the 0.1 arcsecond resolution comparable with that of optical telescopes requires a factor of 25 improvement in sensitivity, similar to that mentioned above. A more detailed derivation of this is provided in Appendix C.

Gaps created by giant planets in their early stages of formation ("proto-Jupiters") in protoplanetary disks are expected to be of order 1 AU in width. Combined with the distance of the nearest star forming regions (60-140 pc), this implies that ALMA needs to provide 10 milliarcsecond resolution or better. This can be obtained by combining high frequency (650 GHz and above) observations with array configurations approximately 10 km in physical dimention.

ALMA will provide, for the first time, the opportunity to investigate the structure of the magnetic field both in the larger protostellar regions and in the small protoplanetary disks, by observing polarized emission from dust. The spatially resolved kinematics of a rotating, infalling protostellar envelope provides insight into the hydrodynamics of star formation, whereas the morphology of the magnetic field probes the magnetodynamics. The combination of the two will allow astronomers to discover the physical process by which magnetic fields accelerate or impede the process of star and disk formation. The requirement to support these observations emphasizes again the firm requirement for the ALMA receiving system to have full simultaneous polarization capability. The formation of stars and planets also causes changes in the density, temperature and chemistry in the envelopes and disks. Wide frequency coverage is essential to probe these different conditions.

4.3 Precise Imaging

High fidelity imaging requires a sufficient number of baselines, in order to cover adequately the uv plane (i.e., the time/frequency domain plane in which the data are sampled). Detailed studies of the imaging performance of aperture synthesis arrays have shown that imaging performance implies a minimum number of antennas, 40 or more, and accurate measurements of the shortest baselines, as well as of the large scale emission measured by total power from the antennas. Such accurate measurements can only be obtained with high quality antennas, with superior pointing precision.

4.4 Other Implications

The combination of these three major requirements calls for a reconfigurable array covering baselines from a few meters up to several km, observing over the full millimeter and sub-millimeter atmospheric windows. The maximum size of the individual antennas is driven by the required pointing and surface precision: a choice of 12 meter diameter antennas offers an excellent technological compromise. To provide no less than 7000 m^2 of total collecting area, 64 antennas are needed, which is a large enough number to guarantee excellent imaging performance.

To allow cancellation of atmospheric disturbances, it must be possible to measure atmospheric pathlength variations and correct the image distortions such phase variations create. One way of doing this is via the use of Water Vapor Radiometers (WVRs) on the antennas. This is a technique nearly identical in its purpose and application to adaptive optics as used for ground-based telescopes operating at visual and infrared wavelengths. Another possibility is to switch very quickly back and forth between the source of interest and a calibrator source. In order for this to work, the calibrator source must be near the source of interest, and as such, it is required that they can be very weak (10's of mJy). Detecting such weak sources requires wide instantaneous bandwidth for all the front end receivers to maximize the continuum sensitivity.

In order to take full advantage of the excellent site chosen for ALMA, it is required that ALMA be dynamically scheduled, i.e., the project to be observed at any given time is determined by the set of all available project and their demands, along with the current observing conditions at the site. The VLT and VLBA are two instruments that are already using dynamic scheduling, demonstrating that it is possible. This is a critical component of the proper functioning of ALMA.

The final major scientific requirement is related to the diverse community that will use and benefit from the scientific capabilities that ALMA brings to extend their research endeavors: ALMA should be "easy to use" by novices and experts alike. Users certainly should not need to be experts in the techniques of aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the most demanding experiments requiring expert intervention.

5 Detailed Requirements

In this section we list specifically and in some more detail the requirements necessary to undertake the scientific investigations ALMA should enable.

5.1 Frequency

- ALMA should be able to observe in all atmospheric windows between 30 and 950 GHz.
- In order to achieve this technically, the receiving system will be separated into 10 bands: band 1 = 31.3-45 GHz; band 2 = 67-90 GHz; band 3 = 86-116 GHz; band 4 = 125-163 GHz; band 5 = 163-211 GHz; band 6 = 211-275 GHz; band 7 = 275-370 GHz; band 8 = 385-500 GHz; band 9 = 602-720 GHz; band 10 = 787-950 GHz.
- It shall be possible to tune ALMA completely across the observable windows, i.e., reach a spectral line transition at any arbitrary frequency.
- channel width reqs here... TBC...
- It shall be possible to retune ALMA to a new frequency within a band in a time not greater than 100 milliseconds.
- It shall be possible to retune ALMA to a new frequency in a different band that is currently "warm" in a time not greater than 1.5 seconds.
- It shall be possible to retune ALMA to a new frequency in a different band in a time not greater than 1 minute.
- The required spectral dynamic range is 10000:1 for a few experiments, more generally 1000:1.

5.2 Sensitivity

- ALMA shall routinely obtain sub-millijansky point source sensitivity at all observing frequencies, for reasonable integration times.
- ALMA shall be sited at the Llano de Chajnantor, to take advantage of the extremely dry conditions (transparent atmosphere) there.
- ALMA shall be comprised of 64 12-m antennas.
- The antennas shall have surfaces with rms deviation from the ideal of 20 μmor less.
- The antennas shall have forward gain of at least 0.95 to minimize spillover.

- The ALMA feed systems shall be tapered to 13 dB at the edge of the antenna, to reduce spillover.

- The antennas shall have less than 3% geometric blockage.

- The antennas shall have aperture efficiency of 75% at 30 GHz.

- The ALMA receivers shall be close to quantum limited, with SSB receiver temperatures of: $\alpha h\nu/k + 4$ K, where $\alpha = 6$ for bands 1-6; $\alpha = 8$ for bands 7 and 8, and $\alpha = 12$ for bands 9 and 10.

- The ALMA data sampling and transmission system shall have IF bandwidth of 8 GHz in continuum mode.

- The full 8 GHz IF bandwidth must be processed by the correlator.

- Correlator and electronics losses shall be 0.05 or less.

- Data storage and processing must not result in a loss in sensitivity (from, e.g., not storing enough bits per number).

- ALMA shall be dynamically scheduled, with the next project to be observed being determined by a combination of the current set of available projects, their demands on conditions, and the actual current conditions.

5.3 Imaging

- ALMA shall provide high fidelity imaging at spatial scales from of order degrees to 10 milliarcseconds. More precisely, images shall be thermally limited at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

- Both total power and interferometric data must be collected. All antennas must be capable of collecting total power data, and at least 4 antennas must be equipped with wobbling subreflectors in order to do atmospheric emission cancellation.

- It shall be possible to dump data at rates of X msec for total power, and Y msec for visibilities.

- The ALMA antennas shall be relocatable, so that a variety of spatial scales of interest can be imaged, from a compact configuration of maximum baseline 150 m to a spread out configuration of maximum effective baseline 15 km.

- The ALMA antennas shall point to 0.6 arcseconds with the aid of reference pointing.

- The primary beams of the ALMA antennas shall be measured to an accuracy of 6% in power out to the FWHM point.

- The ALMA antenna station locations shall be determined to an accuracy of 65 μm.
- The visibility phase fluctuations must not exceed 1 radian (57 degrees) at 950 GHz, implying:
  - antenna delay stability of 50 fs (non-repeatable component);
  - electronics stability of 30 fs (fluctuating component);
  - ability to correct atmospheric fluctuating delay to 33 (1.1 + PWV) fs, where PWV is in millimeters.
- The visibility amplitude fluctuations must not exceed 1% at frequencies less than 300 GHz, 3% at higher frequencies, implying:
  - antenna gain stability under changing wind and gravity conditions;
  - electronics gain stability;
  - ability to measure and correct for atmospheric opacity and emission fluctuations.

5.4 Polarization

- It shall be possible to observe simultaneously in full Stokes polarizations.
- It shall be possible to determine the linearly polarized flux density to 0.1% in amplitude.
- It shall be possible to determine the linearly polarized flux density to 6° in position angle.
- It shall be possible to do very precise polarization work in band 7, requiring a quarter-wave plate.

5.5 Flux Density Scale

- The final visibilities must be on a calibrated flux density scale, within 1% at frequencies less than 300 GHz, and 3% at higher frequencies.

5.6 Miscellaneous

- It shall be possible to observe the sun at all frequencies.
- It shall be possible to phase up the array, with provision of an output sum port, either hardware or software.
- It shall be possible to use ALMA for VLBI, both with a single element, or with phase array (or subarray) output.
- It shall be possible to observe in four subarrays simultaneously, where here a subarray is defined as a set of antennas tuned to a frequency within a different band.

5.7 Software

BJB - we probably need more here?

- ALMA shall be "easy to use" by both novice and expert astronomers.
- ALMA shall provide tools for preparation of proposals, preparation of observations, and reduction of data.
- There shall be a standard data reduction performed on every project successfully completed, resulting in a properly calibrated image cube (the "pipeline"). This shall require minimal input from the astronomer in most cases.

Appendix A

This appendix describes in detail the sensitivity obtained by ALMA. It is based on ALMA memos and documents (Brown 1998; Butler et al. 1999; Butler & Wootten 1999, Guilloteau 2002; Rudolph & Freund 2003).

When making an image from interferometric array data, the flux density sensitivity, or rms noise in flux density units, can be written:

$$\Delta S = \frac{4\,\sqrt{2}\;k\;T_{sys}}{\gamma\,\epsilon_q\,\epsilon_a\,\pi\,D^2\,\sqrt{n_p[N(N-1)/2]\Delta\nu\Delta t}} \quad \mathrm{W/m^2/Hz}, \tag{1}$$

where T_{sys} is the system temperature, ϵ_a is the aperture efficiency, ϵ_q is the correlator quantization efficiency, D is the antenna diameter, n_p is the number of simultaneously sampled polarizations, N is the number of antennas in the array, $\Delta\nu$ is the bandwidth, Δt is the integration time, and γ is a gridding parameter that we set equal to unity. Assume that $N = 64; n_p = 2; D = 12;$, and $\epsilon_q = 0.95$. Then equation 1 simplifies to:

$$\Delta S = \frac{290\;T_{sys}}{\epsilon_a\,\sqrt{\Delta\nu\Delta t}} \quad \mathrm{mJy}. \tag{2}$$

The aperture efficiency is:

$$\epsilon_a = \epsilon_0\,e^{-\left(\frac{4\,\pi\,\sigma}{\lambda}\right)^2} \quad , \tag{3}$$

which for the goals of ALMA ($\sigma = 20\,\mu$m, $\epsilon_0 = 0.75$) takes the values shown in Table 1 over the possible range of frequencies of operation for ALMA.

Refer T_{sys} to a point outside the terrestial atmosphere and compute it as:

$$T_{sys} = T'_{rx}\,e^{\tau_0 A} + \epsilon_l\,T'_{atm}\,\left(e^{\tau_0 A} - 1\right) + (1-\epsilon_l)\,T'_{sbr}\,e^{\tau_0 A} + T'_{cmb} \quad , \tag{4}$$

where T'_{rx} is the receiver temperature, τ_0 is the opacity of the atmosphere at zenith, A is the airmass, ϵ_l is the fraction of the antenna power that is received in the forward direction (i.e., the fraction that is on the sky in the main lobe and all the forward sidelobes), T'_{atm} is the effective atmospheric temperature, T'_{sbr} is the temperature onto which the spillover falls,

Table 1: Aperture efficiency of the ALMA antennas.

Frequency (GHz)	Wavelength (μm)	ϵ_a
35	8600	0.75
110	2700	0.74
230	1300	0.72
345	870	0.69
409	650	0.67
675	440	0.54
850	350	0.45

and T'_{cmb} is the cosmic microwave background temperature. The terms of T_{sys} represent the contributions from the receiver, the sky, the "antenna", and the CMB. The primes on the temperatures indicate that they are effective radiation temperatures, and should be calculated with a Planck correction:

$$T'_x = \frac{h\nu/k}{e^{h\nu/kT_x} - 1} \quad , \tag{5}$$

where ν is the frequency, and T_x is the physical temperature.

Assume that $T_{sbr} = T_{amb}$ where T_{amb} is the ambient surface temperature. Assume further that $T_{atm} = 70.2 + 0.72\ T_{amb}$, which has been verified to be a fairly accurate representation of the effective atmospheric temperature by comparison to detailed atmospheric emission models. Assume $T_{amb} = 269$ K, the average surface temperature at the ALMA site.

The ALMA receivers are image separating receivers (SSB) with the unwanted sideband terminated at 4 K. The noise temperature of these receivers can be written:

$$T_{rx}(\nu) = \alpha(\nu)\ \frac{h\,\nu}{k} + 4 \quad , \tag{6}$$

where α is a photon limit multiplier (the photon limit for receivers is $h\nu/2k$). The current specification for the front ends is that $\alpha = 6$ for bands 1-6 ($\nu < 275$ GHz); $\alpha = 8$ for bands 7 and 8 (275 GHz $< \nu <$ 500 GHz); and $\alpha = 10$ for bands 9 and 10 (602 GHz $< \nu <$ 950 GHz), over the central 80% of the band.

For the second two terms we adopt the ALMA antenna goal of $\epsilon_l = 0.95$, i.e., 95% of the received power comes from the forward direction. We will compute T_{sys} at an airmass of 1.3 (50° elevation) and use for the frequency dependent optical depths on the Chajnantor site the opacities produced by a model atmosphere for that site. These model opacities are taken from the Liebe model. The model contains an amount of precipitable water vapor (PWV) which decreases at higher frequencies, recognizing that observations at high frequency will occur during drier conditions in general (assuming that dynamic scheduling works correctly). The terms in the T_{sys} equation above, along with the resultant T_{sys} are shown in Table 2.

Table 2: Estimated T_{sys} for ALMA at elevation=50°.

Frequency (GHz)	PWV (mm)	τ_0	$T'_{rx}\, e^{\tau_0 A}$ (K)	$\epsilon_l\, T_{atm}\, (e^{\tau_0 A} - 1)$ (K)	$(1-\epsilon_l)\, T_{sbr}\, e^{\tau_0 A}$ (K)	T_{sys} (K)
35	2.0	0.017	13.5	5.4	13.7	35
110	1.5	0.049	35.3	16.3	14.2	67
230	1.2	0.065	70.6	21.5	14.3	107
345	1.0	0.193	165	69.3	16.8	251
409	1.0	0.382	249	155	21.3	425
675	0.5	0.640	717	306	29.1	1050
850	0.5	0.599	854	273	27.1	1150

A.1 Continuum Sensitivity

The continuum bandwidth for ALMA is 8 GHz per polarization, so assign $\Delta\nu = 8$ GHz. Using the system temperatures in Table 2, the aperture efficiencies in Table 1, and an integration time of 1 minute, the sensitivities shown in Table 3 are derived.

Table 3: Continuum sensitivity for ALMA in 1 minute.

Frequency (GHz)	ΔS_{cont} (mJy)
35	0.019
110	0.037
230	0.061
345	0.15
409	0.26
675	0.80
850	1.1

A.2 Spectral Line Sensitivity

For spectroscopic observations we use a velocity channel width Δv and write $\Delta\nu = \nu\Delta v/c$, leaving:

$$\Delta S = \frac{5.0\ T_{sys}}{\epsilon_a\, \sqrt{\nu_{GHz} \Delta v_{km/s} \Delta t}} \quad \text{mJy}, \tag{7}$$

where ν_{GHz} is the frequency in GHz, and $\Delta v_{km/s}$ is the velocity channel width in km/s. Using the system temperatures in Table 2, the aperture efficiencies in Table 1, an integration time of 1 minute, and a velocity channel width of 1 km/s, the sensitivities shown in Table 4 are derived.

Table 4: Spectral line sensitivity for ALMA in 1 minute in a 1 km/s channel.

Frequency (GHz)	ΔS_{line} (mJy)
35	5.0
110	5.5
230	6.2
345	13
409	20
675	48
850	56

A.3 Brightness Temperature Sensitivity

Consider an observation of a source which fills the synthesized beam, and assume that the source intensity is large enough that it is in the Rayleigh-Jeans portion of the spectrum (so that no Planck correction is necessary). In this case, the brightness temperature sensitivity is given by:

$$\Delta T = \frac{\Delta S \ \lambda^2}{2 \ k \ \Omega_s} \quad , \tag{8}$$

where λ is the wavelength, and Ω_s is the synthesized beam solid angle. For an image which is restored with a circular gaussian of width θ_s (e.g., the result of CLEAN or relatives), this solid angle is given by:

$$\Omega_s = \frac{\pi}{4 \ln 2} \ \theta_s^2 \sim \frac{\pi}{4 \ln 2} \ \frac{\lambda^2}{B_{max}^2} \quad , \tag{9}$$

for maximum physical baseline length B_{max}. Substituting this into the equation for brightness temperature sensitivity yields:

$$\Delta T = \frac{2 \ln 2}{\pi \ k} \ B_{max}^2 \ \Delta S = 0.32 \ B_{max_{km}}^2 \ \Delta S_{mJy} \quad , \tag{10}$$

where $B_{max_{km}}$ is in km, and ΔS_{mJy} is in mJy. We assume configurations for ALMA with $B_{max_{km}} = 0.2$, 0.4, 1.0, 3.0, 10.0, and 20.0. Using the values for noise flux density in Tables 3 and 4 yields the brightness temperature sensitivities in Table 5.

Appendix B

We derive in this appendix the requirement on the total collecting area of ALMA in order to be able to detect spectral line emission from a Milky Way type galaxy to $z = 3$.

At cosmological redshifts the 10 kpc disk of the Milky Way is much smaller than the primary beams of reasonably sized millimeter antennas, so the product ND^2 is the parameter we need to optimize.

Table 5: Brightness temperature sensitivity for ALMA in 1 minute.

frequency	B_{max} = 0.2 km		0.4 km		1 km		4 km		15 km	
	ΔT_{cont}	ΔT_{line}	ΔT_{cont}	ΔT_{line}	ΔT_{cont}	ΔT_{line}	ΔT_{cont}	ΔT_{line}	ΔT_{cont}	ΔT_{line}
(GHz)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)
35	0.0002	0.064	0.0010	0.26	0.0061	1.6	0.098	26	1.4	360
110	0.0005	0.070	0.0019	0.28	0.012	1.7	0.19	28	2.7	390
230	0.0008	0.080	0.0031	0.32	0.020	2.0	0.31	32	4.4	450
345	0.0019	0.16	0.0077	0.64	0.048	4.0	0.77	64	11	900
409	0.0034	0.26	0.014	1.0	0.084	6.5	1.3	100	19	1500
675	0.0010	0.61	0.041	2.4	0.26	15	4.1	240	57	3400
850	0.014	0.72	0.054	2.9	0.34	18	5.4	290	76	4000

If we wish to detect spectral line emission in a galaxy that is similar to the Milky Way but at redshifts up to $z = 3$ then the most obvious candidate to observe is CO. The total CO luminosity of the Milky Way in the 1-0 transition has been estimated by Solomon and Rivolo (1989). This luminosity agrees roughly with the CO luminosities seen in the higher transitions by COBE (Bennett et al. 1994; Wright et al. 1991). Note that COBE also measured emission from neutral and ionized carbon (CI and CII) and ionized nitrogen (NII). We presume here that the desire is to measure the neutral species, so concentrate on CO. Given the luminosity of the CO 1-0 transition, we can calculate the expected received flux density in any transition as (see e.g. Solomon et al. 1992):

$$S_{CO} = 3.08 \times 10^{-8} \frac{L'_{CO}\, \nu_{rest}^2\, (1+z)}{\Delta v_{rest}\, d_L^2} \quad ,$$

S_{CO} is the flux density in Jy, L'_{CO} is the CO luminosity in K km/s pc^2, ν_{rest} is the rest frequency of the transition in GHz, d_L is the "luminosity distance" in Mpc, and Δv_{rest} is the rest line width in km/s. The luminosity distance can be written (Weinberg 1972):

$$d_L = \frac{c}{H_o\, q_o^2} \left[z q_o + (q_o - 1)\left(-1 + \sqrt{2 q_o z + 1}\right)\right] \quad .$$

We use $L'_{CO} = 5 \times 10^8$ K km/s pc^2 for the 1-0 transition, which is slightly larger than that in Solomon and Rivolo (they give 3.7×10^8), but is consistent with the COBE and lensed ULIRG results. We then modify the luminosity as a function of transition and redshift according to a model which accounts for the proper radiative transfer given the higher background temperature at higher z, and assuming that 90% of the CO is in clouds similar to our galactic dark clouds and 10% is in regions similar to strong PDR's (H. Liszt provided this calculation). We assume $H_o = 75$ km/s/Mpc, $q_o = 0.5$, and the intrinsic width of the lines is $\Delta v = 300$ km/s (Solomon et al. 1997). We can then calculate, given any array collecting area, the maximum z to which any of the transitions of CO (we calculate up to the 8-7 transition) can be detected by that array. We demand a 5-sigma detection in a 75 km/s channel in 12 hours of integration (24 hours of telescope time might yield 12 hours of usable on-source time). With these requirements, the following relationship between collecting area and maximum detectable z is derived:

$$z_{max} \sim \frac{ND^2}{3100\,\mathrm{m}^2} \quad .$$

Thus, to reach $z = 3$, an ND^2 of 9300 m^2 is required. This is satisfied with an array of 93 10-m antennas or 65 12-m antennas. Of course, larger values of ND^2 are always desirable, as they would allow us to resolve the line flux density into more pixels (higher angular or spectral resolution) or image to higher S/N more quickly.

We note finally that lines of CI, and redshifted lines of NII and CII will also be observable and will provide important probes of the IMF and the Lyman continuum luminosity from the most luminous stars in early galaxies. However, because so little is known about the luminosity of these lines as a function of redshift in galaxies of differing Hubble type we have not used them here to help us place limits on the needed ND^2 of the array.

Appendix C

We derive in this appendix the requirement on the total collecting area of ALMA in order to be able to image protoplanetary disks.

Consider an observation of the gas distribution and kinematics in a protoplanetary disk by observation of CO. A velocity resolution of 1 km/s (or slightly better) might be desired. A spatial resolution of 0.1 arcseconds or so might be desired, implying a maximum baseline length on the order of 4 km. Assume 12 hours of on-source time (same as the high-z case above).

We need to achieve a brightness temperature sensitivity of $\Delta T \sim 1$ K - sufficient to image marginally optically thick lines in cool (10's of K) protoplanetary disks.

Using the brightness temperature sensitivity numbers in Table 5 from Appendix A (divided by $\sqrt{720}$ to account for 720 minutes in 12 hours), we can see that the required ND^2 is roughly what we get from 64 12-m antennas (for the 1-0 and 2-1 transitions of CO, around 110 and 230 GHz).

Appendix D

BJB - this needs to be updated! Perhaps we should get Frederic (and the imaging group) to do it?

We derive in this appendix the requirement on the total collecting length of ALMA in order to be able to perform precise imaging.

Holdaway (1998) assesses the ability of the MMA to provide precision imaging in all the array configurations and at all the frequency bands planned for the MMA. Here the consideration for imaging is the ability of the instrument to achieve good coverage of the (u,v)-plane. Morita and others have emphasized that excellent imaging, imaging limited by dynamic range, can be achieved when 50% of the (u,v)-cells are filled. Morita calls this quantity FOCC, the "fraction of occupied cells." It is calculated by simulating (u,v)-points taken in short integrations by the array in a particular configuration and gridding them onto the Fourier plane with a cellsize equal to the antenna diameter. The fractional area of the gridded (u,v)-plane out to the diameter of the longest array baselines that is filled by observations is the quantity FOCC. Clearly, FOCC is a function of hour angle that asympotically approaches a value of one.

For the three shorter MMA configurations–the compact array(s), the 240-m and 860-m arrays, the MMA achieves FOCC=0.5 in less than two hours of observations. But for the longest array, the 3000-m diameter A-array, FOCC=0.5 can be realized only with 8 hours of hour-angle tracking. Such long tracks can only be obtained at the expense of observations being made well off the meridian at increasingly low elevation angles. At low elevation the sensitivity is compromised by the increasing atmospheric contribution to the system temperature making the weights of the (u,v)-points so obtained very low. This compromises the fidelity of the image and reduces its signal-to-noise. The situation worsens at higher frequencies where the atmospheric contribution to T_{sys} is larger. The ALMA, however, should have a sufficiently large number of antennas such that FOCC=0.5 can be achieved even in the highest resolution 3000-m array with suitably short hour-angle tracks taken near the meridian where the sensitivity always remains high.

In Figure 2 of Holdaway (1998), the FOCC as a function of hour angle for the 3 longer MMA configurations is shown. As hour angle increases all these curves asympotically approach one as an increasing number of the gridded (u,v)-cells are sampled redundantly. However, as Holdaway notes, the non-redundant FOCC (i.e., the FOCC for "snapshots") for each of the arrays is approximately proportional to

$$\mathrm{FOCC} \propto \left(\frac{ND}{B_{max}}\right)^2 \quad ,$$

where B_{max} is the maximum baseline length in the array. "Hence, to achieve optimal Fourier plane coverage, one wants to optimize the so-called 'collecting length' ND" (Holdaway 1998).

The function that is plotted in Figure 2 of Holdwaway (1998) for FOCC as a function of hour angle for the 3000-m array has the form

$$\mathrm{FOCC} = 1 - e^{-10\,h\,(ND/3000)^2} \quad ,$$

where h is the hour angle and we've explicitly used $B_{max} = 3000$. To achieve the precision imaging for which FOCC$\geq$0.5 is the figure of merit using an array of given collecting length (ND) will require observations made out to the hour angle limits shown in Table 6.

As noted above, observations taken at large hour angles will be given low weight in the imaging owing to the increase in system temperature at low elevation. To avoid corrupting the image with such low weight points, let us restrict our observations to hour angles such that the lowest weight points are reduced from those on the meridian by no more than $\sqrt{2}$. Let us also retain the opportunity to do such imaging in the submm. Then in median meteorological conditions on the Chajnantor site (Figure 4b of Holdaway [1998]) we conclude

Table 6: Hour Angle Limits to Achieve FOCC=0.5 for an Array of N Antennas of Diameter D(m) in a Configuration with B_{max}=3000 m.

ND	h
300	6.9
350	5.1
400	3.9
450	3.1
500	2.5
550	2.1
600	1.7
650	1.5
700	1.3
750	1.1

that we need to observe out to a limiting hour angle range of no more than approximately h=2.0.

With the restriction that $h < 2$ hours, we can return to Table 6 above and conclude that the specification for the "collecting length" ND for the ALMA needs to be approximately $ND \geq 560$. A joint array of 56 10-m antennas or 47 12-m antennas will satisfy this specification.

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