ALMA Scientific Requirements
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Abstract

Executive Summary The primary science goals for ALMA are strong and form the root cause for the endorsements of the instrument as the highest priority astronomical telescope to be built by the communities of six nations. These primary science goals were distilled into those identified in the ALMA Project Plan, which were endorsed by representatives of fourteen countries committed to the construction of ALMA; Japan will shortly join this community. The three primary goals include:

The ability to image normal galaxies at cosmological distances

The ability to image the gas kinematics in protostars and protoplanetary disks about nearby sun-like stars

The ability to provide precise images at an angular resolution of 0.1 arcseconds to complement images from contemporary facilities including the eVLA, the JWST and the GMST.

In order to meet these goals, ALMA must have sensitivity (proportional to collecting area) and imaging capability (proportional to number and diameter of telescopes) provided by its design goals–64 twelve meter antennas. In this document it is shown that this design meets the scientific goals set by the communities building ALMA

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 It draws from a long list of historical documents describing the desired scientific emphasis of ALMA (and the MMA and LSA) (see, e.g., Owen et al. 1983; Barrett et al. 1983; Wootten & Schwab 1988; Shaver 1995;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). ALMA was formally endorsed during the 1990s as the highest priority for the decade by the astronomical communities of the United States, Canada, the United Kingdom, France, the Netherlands and Japan.

ALMA-90.00.00.00-001-C- SPE is 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 are to be laid out in separate documents.

As with every astronomical telescope project, the scientific requirements are the result of a long and complicated trade-off between scientific dreams and technical and budgetary reality. For ALMA, much of this trade-off has taken place years ago. For example, the antenna size and its pointing and surface accuracy specifications are the result of iterations between the scientists and the engineers and antenna vendors. Nevertheless, it was still felt useful to collect all of the requirements and supporting arguments into a single document.

1.1 Purpose

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:

1. Image the redshifted dust continuum emission from evolving galaxies at epochs of formation throughout the Universe;
2. Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies deeply into the epoch of reionization;
3. Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects (QSOs) on spatial scales smaller than 300 light years;
4. Image gas rich, heavily obscured regions that are spawning protostars, protoplanetary disks and protoplanets, as well as remnant debris disks;
5. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
6. 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;
7. Image solar active regions and investigate the physics of particle acceleration on the surface of the sun[haw1].

No instrument, other than ALMA, existing or planned, has the combination of angular resolution, sensitivity and frequency coverage necessary to address adequately these science objectives. ALMAs scientific impact at any time will be determined by the quality of its instrument and the creativity and industry of its scientist users.

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 Keck Telescopes, 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.

1.2 General Requirements

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

1. ALMA will cover all available millimeter and submillimeter atmospheric windows;
2. ALMA will be able to observe in both narrow ("spectral line") and wide ("continuum") bandwidth modes;
3. ALMA will maximize the sensitivity;
4. ALMA will maximize the flexibility of the spectral line capability;

5. ALMA will maximize the imaging capability, at both large and small angular resolutions;

6. ALMA will be able to measure all polarization cross-products simultaneously .

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.

2 Primary Scientific Requirements

The primary science requirement for ALMA is the flexibility to support the breadth of scientific investigation to be proposed by its creative scientist-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 CO or C II in 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 0.1These requirements have driven the concept of ALMA to its current technical specifications. In the following sections, a simplified flowdown of science requirements into technical specifications is presented.

2.1 Detecting the Milky Way at z=3

For galaxies at high redshift, 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 m2. These arrays can detect CO emission from the brightest starburst 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. ALMA's Chajnantor site minimizes the contribution of the atmosphere compared to what is possible with current millimeter arrays. The surface accuracies of current millimeter arrays are quite good, but we expect to improve on that so that the wavelengths at which the reflectors have reasonable surface accuracy is matched to the wavelengths at which reasonable atmospheric transparency is measured at Chajnantor. 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 ?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 m2 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. Initially, the Project will support observations in the four highest-priority bands. Additional capabilities can be added in the operational phase of ALMA. Since the redshift of the galaxies will initially be essentially unknown, the instantaneous bandwidths of the receivers should also be as large as possible.

2.2 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. In addition, proper study of the kinematics requires spectroscopy with velocity resolutions finer than 0.05 km/s, or a few times 10 kHz. Imaging the terrestrial planet regions in nearby debris disks requires few milliarcsecond resolution. 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 10milliarcsecond resolution or better. This can be obtained by combining high frequency (650 GHz and above) observations with array configurations approximately 10 km in physical dimension.

The sensitivity of ALMA highlighted above will allow, 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 kinematics1 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.

2.3 Precise Images

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. High fidelity imaging also requires the ability to perform calibrations to freeze the atmospheric turbulence which distorts the radiation coming from celestial sources.

2.4 Other Implications

The combination of these three major requirements calls for a reconfigurable array covering baselines from a few meters up to several kilometers, observing over the full millimeter and submillimeter 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 m2 of total collecting area, 64 antennas are needed, which is a large enough number to guarantee excellent imaging performance.

Finally, to allow cancellation of atmospheric disturbances, the antennas must be equipped with water vapor radiometers to measure atmospheric pathlength variations and correct the image distortions such phase variations create. This is a technique identical in its purpose and application to adaptive optics as used for ground-based telescopes operating at visual and infrared wavelengths. In addition, ALMA is designed to be able to detect calibration sources such as quasars in a time short enough to minimize the atmospheric phase fluctuations so that the needed correction may be as small as possible. Detecting weak sources requires wide instantaneous bandwidth for all the front end receivers to maximize the continuum sensitivity.

The final major scientific requirement affects 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. Astronomers certainly should not need to be experts in aperture synthesis to use ALMA. Automated image processing will be developed and applied to most ALMA data, with only the more intricate experiments requiring expert intervention.

Detailed requirements are given in ALMA-90.00.00.00-001-C- SPE.

3 ALMA Sensitivity

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:

$$\Delta S = \frac{4\sqrt{2}\; k\; T_{sys}}{\gamma\, \epsilon_q\, \epsilon_a\, \pi\, D2\, \sqrt{n_p[N(N-1)/2]\Delta\nu\Delta t}} \quad \text{W/m2/Hz}, \tag{1}$$

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:

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

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.

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

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, 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.

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

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.

3.1 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

3.2 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

3.3 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:

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

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

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

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.

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

	$B_{max} = 0.2$ km		0.4 km		1 km		4 km		15 km	
frequency (GHz)	ΔT_{cont} (K)	ΔT_{line} (K)	ΔT_{cont} (K)	ΔT_{line} (K)	ΔT_{cont} (K)	ΔT_{line} (K)	ΔT_{cont} (K)	ΔT_{line} (K)	ΔT_{cont} (K)	ΔT_{line} (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

4 Requirement on Total Collecting Area for Primary Science Requirement No. 1

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 $ND2$ is the parameter we need to optimize.

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 $L'_{CO} = 5 \times 108$ K km/s pc^2 for the 1-0 transition, which is slightly larger than that in Solomon and Rivolo (they give 3.7×108), 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, $q_o = 0.5$ (note that under this assumption, the above equation for the luminosity distance is exactly equivalent to that in Pen 1998, if Ω_o is assumed to be equal to 1.0), 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:

$$z_{max} \sim \frac{ND2}{3100\,\mathrm{m2}} \quad .$$

Thus, to reach $z = 3$, an $ND2$ 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 $ND2$ 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 $ND2$ of the array.

5 Requirement on Total Collecting Area for Primary Science Requirement No. 2

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).

6 Requirement on Total Collecting Area for Primary Science Requirement No. 3

We summarize in this appendix the requirements on ALMA in terms of imaging. A large number of MMA and ALMA memos present and discuss simulations of the imaging capabilities and properties of ALMA.

6.1 (u,v) coverage

The key criterion that we must consider 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, 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 the observed (u,v) points 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.

Holdaway (1998) presents a detailed analysis of the variation of FOCC depending on an array configuration and hour angle coverage. To achieve FOCC$\geq$0.5 using an array of given collecting length (ND) will require observations made out to the hour angle limits shown in Table 6.

Obviously, 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

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
400	3.9
500	2.5
600	1.7
700	1.3
800	1.0

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: in median meteorological conditions on the Chajnantor site, we need to observe out to a limiting hour angle range of no more than approximately h=2.0.

With this restriction, Table 6 shows that the specification for the "collecting length" ND for the ALMA needs to be approximately $ND \geq 560$. The full ALMA instrument (64 12-m, hence ND=768) satisfies this specification. Even considering fours antennas being used for single-dish observations (see below), and, e.g. two antennas out of order for maintenance, ALMA will still provide $ND = 696$, hence allowing FOCC larger than 0.5 to be obtain in less than 2 hours observing time.

The above requirements are derived for a 3000 m configuration. The more extended the ALMA configuration, the more hour angle coverage or the more antennas is required to obtain a high FOCC. This rapidly makes it impossible to get FOCCge0.5 . Even after optimizing extended configurations and combining them with compact or intermediate ones, the FOCC cannot be made uniform over the whole Fourier plan. This is a trade-off that has to be made between the FOCC and the angular resolution of the observations.

6.2 Short-Spacings

Whatever the hour angle coverage or combination of multiple observations, ALMA –as any array– will not be able to measure interferometrically the smallest spatial frequencies, below approximately the antenna diameter. The filtering of the short-spacings information, hence of the most extended structures, can introduce major artifacts in the resulting images. This will affect all observations of sources more extended than ~2/3 of the primary beam. For such observations, a key requirement is therefore the ability to observe in total-power mode with the ALMA antennas, and thereby derive the short-spacings information.

The optimal combination and relative weighting of the short-spacings and interferometric observations requires the signal-to-noise be equivalent in both datasets – which is a somewhat relaxed criteria as compared to matching the sensitivities. Although the exact numbers would depend on the source structure, simulations from Pety et al. have shown that this can be achieved by spending 16 more observing time on the total power than on the interferometric observations. This can in practice be obtained by using 4 antennas, which can then be optimized for single-dish measurements (wobbling secondary), each one observing 4 times more than ALMA. This would allow measuring the short-spacings for 25% of the projects.

Even after combination of the ALMA and single-dish data, there is still a "gap" in the weight distribution in the *uv* plane, in a ring located at approximately half the antenna diameter (i.e. 6 m). Depending on the amount of smooth extended structures in the source brightness distribution, this may induce significant artifacts. The addition of data from a compact array of e.g. 12 7-m antennas (ACA) allows one to obtain reliable images in all circumstances. Not only the imaging process is more robust, but the results are also more immune to pointing and primary beams errors.

References

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