Extract from the ALMA Science Requirements

1.1 Purpose[1]

The highest level science requirements for ALMA are set forth in the Bilateral Agreement, Annex B. These requirements (see Section 2 of this document) drive the technical specifications of ALMA. A highly simplified flow-down of science requirements into technical specifications is given in Annex B. In this document, the requirements are developed in detail. Specific reference is made to the science requirements at the point of discussion of specific science drivers in Section 2..

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 as early as z=10;
2. Trace through molecular and atomic spectroscopic observations the chemical composition of star-forming gas in galaxies throughout the history of the Universe;
3. Reveal the kinematics of obscured galactic nuclei and Quasi-Stellar Objects on spatial scales smaller than 300 light years [SCI-90.00.00.00-00380-00];
4. Image gas rich, heavily obscured regions that are spawning protostars, protoplanets and pre-planetary disks;
5. Reveal the crucial isotopic and chemical gradients within circumstellar shells that reflect the chronology of invisible stellar nuclear processing;
6. Obtain unobscured, sub-arcsecond images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects 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 [SCI-90.00.00.00-0360-00].

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.

ALMA is conceived and designed to be a long-lived user observatory. Its scientific impact at any time will be determined by the quality of its instruments 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 equal in clarity of detail to the imaging capability of 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, instruments which image light from stars and collections of stars such as galaxies.

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[1] From Project Plan v2.0

1.2 General Requirements

One can write down a few generic high level requirements derived from the full suite of desired scientific experiments ([RD4],[RD5]):

1. ALMA shall cover all available millimeter and submillimeter atmospheric windows [SCI-90.00.00.00-0020-00];
2. ALMA shall be able to observe in both narrow (``spectral line") and wide (``continuum") bandwidth modes [SCI-90.00.00.00-0030-00];
3. ALMA shall maximize sensitivity over its frequency bands [SCI-90.00.00.00-0110-00, SCI-90.00.00.00-0120-00, SCI-90.00.00.00-0130-00, SCI-90.00.00.00-0140-00, SCI-90.00.00.00-0150-00, SCI-90.00.00.00-00040-00, SCI-90.00.00.00-00160-00, SCI-90.00.00.00-0200-00];
4. ALMA shall maximize the flexibility of spectral line capability [SCI-90.00.00.00-00030-00, SCI-90.00.00.00-0040-00, SCI-90.00.00.00-0050-00, SCI-90.00.00.00-0060-00];
5. ALMA shall maximize imaging capability, both as an interferometer and as a collection of single antennas, at both large and small angular resolutions [SCI-90.00.00.00-0220-00, SCI-90.00.00.00-0230-00;

6. ALMA shall be able to measure all polarization cross-products simultaneously [SCI-90.00.00.00-0310-00].

In the following text, these requirements are developed into more explicit requirements. First, examine the highest level scientific experiments.

2. Level-1 Scientific Requirements[2]

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 decade's 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 Level-1 primary science requirements are the following:

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 tidal gaps created by planets undergoing formation in the disks.
3. The ability to provide precise images at an angular resolution of 0."1. 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. In this document, the requirements are developed in detail.

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[2] Text from ALMA Project Plan v2.0

2.1 Detecting the Milky Way at z=3

For high redshift galaxies, 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 three major terms: the atmospheric transparency, the noise performance of the detectors, and the total collecting area. Compared to current millimeter arrays the contribution of the atmosphere will be minimized by locating ALMA at the Chajnantor altiplano in the Atacama Desert of northern Chile at an elevation slightly over 5000m [SCI-90.00.00.00.00-060-00]. The noise level of the detectors cannot be reduced by much more than a factor of two, because these receivers are approaching fundamental quantum limits [SCI-90.00.00.00-0160-00]. 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 [SCI-90.00.00.00-0310-00]. 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 7000 m^2 of collecting area [SCI-90.00.00.00-0100-00], from the following arguments ([RD12-16]). ALMA sensitivity calculations are detailed in [RD14]; these result in a number of requirements as listed in §1.7.3 above.

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 highest-priority bands [SCI-90.00.00.00-0100-00, SCI-90.00.00.00-0020-00]. Additional capabilities may 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 [SCI-90.00.00.00-0170-00, SCI-90.00.00.00-0180-00] with rapid tuning [SCI-90.00.00.00-00040-00, SCI-90.00.00.00-00060-00].

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 will now be derived.

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 ALMA collecting area, proportional to the product ND^2, is the parameter one needs to optimize, where N is the number of antennas of diameter D in the array.

If one wishes 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 line candidate to observe is CO. The total CO luminosity of the Milky Way in the 1-0 transition has been estimated by [RD18]. This luminosity agrees roughly with the CO luminosities seen in the higher

transitions by COBE ([RD19] [RD20]. Note that COBE also measured emission from neutral and ionized carbon (CI and CII) and ionized nitrogen (NII). Given the luminosity of the CO 1-0 transition, we can calculate the expected received flux density in any transition as (see [RD21]):

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

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)v_{rest} is the rest line width in km/s. The luminosity distance can be written ([RD22]):

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

This obtains for H_0 = 75 km/s/Mpc, q_0 = 0.5 so that for z=3, d_L = 16 Gpc. For a LCDM cosmology the luminosity distance will be larger, as calculated below. Adopt L'_{CO} = 5 H 10^8 K km/s pc^2 for the 1-0 transition, which is slightly larger than that in [RD18] (where L'_{CO} = 3.7 H 10^8 K km/s pc^2), but is consistent with the COBE results. One then modifies 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 photodissociation regions [RD23]. In the Milky Way, most of the CO emission arises in clouds of several tens of Kelvin kinetic temperature. In more distant Milky Way look-alikes, the gas will be somewhat warmer owing to the relatively higher background temperature. Beyond z~5, transitions above J=5 strengthen while those below J=5 weaken somewhat. For the Milky Way at z=3, the J=3-2 and J=4-3 lines will fall within Band 3, the J=8-7 and J=9-8 lines will fall within Band 6, and the [C II] will fall within Band 8. One assumes H_0 = 75 km/s/Mpc, q_0 = 0.5 (note that under this assumption, the above equation for the luminosity distance is exactly equivalent to that in [RD24], if Σ_0 is assumed to be equal to 1.0), and that the intrinsic width of the lines is)v = 300 km/s [RD25]. One 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. One demands a 5σ detection in a 75 km/s channel in 12 hours of integration (24 hours of telescope time might yield 16 hours of usable on-source time). With these requirements, the following relationship between collecting area and maximum detectable z_{max} 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 65 12-m antennas. If one assumes a Lambda-Cold Dark Matter cosmology, the calculation for luminosity distance is more complex; taking H_0 = 71 km/s/Mpc, Σ_{tot}=1.0 and Λ = 0.7 one calculates d_L = 26 Gpc; one can reach a 4σ detection in a 75 km/s channel in a full day’s integration.

Of course, larger values of ND^2 are always desirable, as they would allow one to resolve the line flux density into more pixels (higher angular or spectral resolution) or image to higher S/N more quickly.

Note finally that lines of CI (Bands 3 and 6), and redshifted lines of NII (Band 7) and CII (Band 8) 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. The latter is the primary cooling line for the Milky Way; COBE found its emission widespread. ALMA should detect this line in a few hours of integration. The intensity of the line is relatively insensitive to the carbon abundance; because the emission is widespread the brightness temperature of the line is actually lower than that of CO although its total flux is higher.

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 about 10 kHz at 3mm wavelength.

Gaps created by giant planets in their early stages of formation (“proto-Jupiters”) in protoplanetary disks are expected to subtend about 1 AU in width. Combined with the distance of the nearest star forming regions (60-140 pc), this suggests that ALMA needs to provide 10milliarcsecond resolution or better [SCI-90.00.00.00-00220-00].

This can be obtained by combining high frequency (650 GHz and above) observations with array configurations reaching 18.5 km in longest physical dimension [SCI-90.00.00.00-00250-00].

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 kinematics[3] 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.

One can now derive 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).

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[3] The most interesting narrow lines are those which have self-absorption which indicates infall ("infall asymmetry"). In that case the minimum number of channels across the line needed to model the line properly increases, from perhaps 2 resolution elements = 1 sigma for a simple gaussian line to something like 4 resolution elements = 1 sigma for a line with a dip or a red shoulder. If one applies these criteria to an extreme case (low frequency, heavy molecule, low temperature), then one should consider e.g. an HC_3N line at 100 GHz, in a cold, slowly contracting starless core with a central temperature of 8 K. The thermal velocity dispersion would be 0.036 km/s and so the spectral resolution should be about 0.018 km/s to resolve a gaussian line or 0.01 km/s to resolve a self-absorbed gaussian line [SCI-90.00.00.00-00030-00]. The baseline correlator provides a resolution of 0.011 km/s, meeting this need.

One needs 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[SCI-90.00.00.00-00011-00].

Using the brightness temperature sensitivity numbers from [RD14] (divided by $\sqrt{720}$ to account for 720 minutes in 12 hours), one can see that the required ND^2 is roughly what

one gets from 64 12-m antennas (for the 1-0 and 2-1 transitions of CO, around 110 and 230 GHz).

Now consider a continuum protoplanetary disk imaging experiment. A one solar mass Jovian protoplanet orbits at 5 AU from the star, creating a gap. With ALMA, one would like to image the disk, the gap and hopefully the planet. Wolf and D'Angelo (2005) performed a simulation showing that this might be done. In the model, the total flux is about 0.24 Jy. The brightness of the ring just outside the planet is fairly constant, at 0.28 mJy; the gap has a minimum flux level of 0.03 mJy and the inner ring has a flux level peak of 0.08 mJy. In a one day integration with all 64 ALMA antennas the ALMA sensitivity calculator shows that the flux in a beam of size 0.0065" at 650GHz is 0.027 mJy. For 50 antennas this is 0.035 mJy (for 40 it is 0.044 mJy); including the ACA in the array would improve this to 0.030 mJy. This sensitivity is sufficient to image the disk and its gap in a day. Detection of the gap would be much more significant, as the flux could be summed azimuthally about the star, though the planet signal would be lost in this process (planet detection is not an explicit goal of the level one science goal number 2). We conclude that ALMA is capable, within a one day integration, of imaging the continuum in a protoplanetary system including a gap. While it is not a requirement that this be done in 24 hours in Level One science item no. 2, it is comforting to know that both items one and two in the level one science goals may be accomplished in a similar integration time with ALMA.

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, several dozen 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. The relative positions of the antennas must be determined accurately so the geometrical delay can be correctly calculated [SCI-90.00.00.00-00280-00]. Residual delays due to incorrect antenna locations will result in phase errors which change across the observing band and differential phase errors between two different sources on the sky (for example, a calibrator and target source). High fidelity imaging also requires the ability to perform calibrations to “freeze” the atmospheric turbulence which distorts the radiation coming from celestial sources. ALMA will incorporate two techniques to effect this “freeze” of the turbulent atmospheric screen: fast switching of the antenna between target object and nearby calibrator both spatially and in frequency [SCI-90.00.00.00-0050], and monitoring of a water vapor line along a direction near to the observation by a water vapor radiometer (WVR) [SCI-90.00.00.00-0290-00]. Precise images require accurate calibration [SCI-90.00.00.00-00300-00, SCI-90.00.00.00-00350-00].

In this section the requirements on ALMA to provide precise imaging are summarized. A large number of MMA and ALMA memos present and discuss simulations of the imaging capabilities and properties of ALMA.

2.3.1 (*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 [RD26] 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 cell size 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; it asympotically approaches a value of one.

Holdaway ([RD27]) presents a detailed analysis of the variation of FOCC depending on an array configuration and hour angle coverage. To achieve FOCC ≥0.5 using an array of given collecting length (ND) will require observations made out to the hour angle limits shown in Table 3.

Table 3 Hour Angle Limits to Achieve FOCC=0.5 for an Array of N Antennas of Diameter D(m) in a Configuration with Maximum Baseline of 3000m

ND	*h*
300	6.9
400	3.9
500	2.5
600	1.7
700	1.3
800	1.0

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, the observer should restrict observations to hour angles such that the lowest weight points are reduced from those on the meridian by no more than √2. One would wish to retain the opportunity to do such imaging in the submillimeter spectral windows: in median meteorological conditions on the Chajnantor site, one needs to observe out to a limiting hour angle range of no more than approximately h=2.0.

With this restriction, Table 3 shows that the specification for the ``collecting length" ND for the ALMA needs to be approximately ND ≥ 560. The full ALMA instrument (64 12-m, hence ND=768) satisfies this specification. Even considering four 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. These parameters also ensure ALMA will constitute an excellent survey instrument, capable of forming excellent high resolution images in a short period of time.

The above requirements are derived for a 3000m configuration. The more extended the ALMA configuration, the more hour angle coverage or the more antennas one requires to obtain a high FOCC. This rapidly makes it impossible to get FOCC ≥0.5. 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.

2.3.2 Short Spacings

Whatever the hour angle coverage or combination of multiple observations, ALMA--as for 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[SCI-90.00.00.00-0230-00].

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 criterion as compared to matching the sensitivities. Although the exact numbers would depend on the source structure, simulations from [RD28, RD29] have shown that this can be achieved by spending a factor of 16 more observing time on the total power than on the interferometric observations. This can in practice be obtained by using 4 12-m antennas, which can then be optimized for total power measurements (using the nutating secondary), each one observing 4 times more than ALMA. This would allow measuring the short-spacings for 25% of the projects observed by the interferometer. These data, combined with the interferometric data, then provide the final ALMA image. For these images to meet the standards in [AD1], the ALMA antennas must point to 0.6 arcseconds [RD30], the primary beam must be accurately measured [RD30], and total power mapping must be accomplished quickly relative to atmospheric fluctuations [RD31][SCI-90.00.00.00-00240-00, SCI-90.00.00.00-00260-00, SCI-90.00.00.00-00270-00]

Even after combination of the ALMA and total power data, there is still a “gap” in the weight distribution in the (*u,v*) plane, in a ring located at approximately half the antenna diameter (*i.e.* 6m). 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 allows one to obtain reliable images in all circumstances [RD29]. Not only is the imaging process more robust, but the results are also more immune to pointing and primary beam errors. Calibration of these smaller antennas may be most effectively accomplished when they are cross-correlated with the four 12-m elements of the Total Power Array or with all antennas, as allowed by the capacity available in the correlator. Cross correlation of any antennas in any array accomplishes more accurate calibration, more timely calibration of smaller antennas and greater sensitivity for the whole array; this is the Combined Array mode of ALMA.

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. In addition to this large spatial dynamic range, ALMA science requires high image dynamic range [SCI-90.00.00.00-00070-00]. 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 7238 m^2 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. This step will require accurate atmospheric modeling, which in turn requires local sensing of the atmosphere. Accurate pointing of the antennas also requires weather data from local sensors. The requirements for these atmospheric sensors are detailed in [RD34]. 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 [sci-90.00.00.00-00400-00]. 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 [SCI-90.00.00.00-00410-00, SCI-90.00.00.00-00420-00]. Flexible (dynamic) scheduling is essential for ALMA, and this defines the overall science operations concept [SCI-90.00.00.00-0210-00].