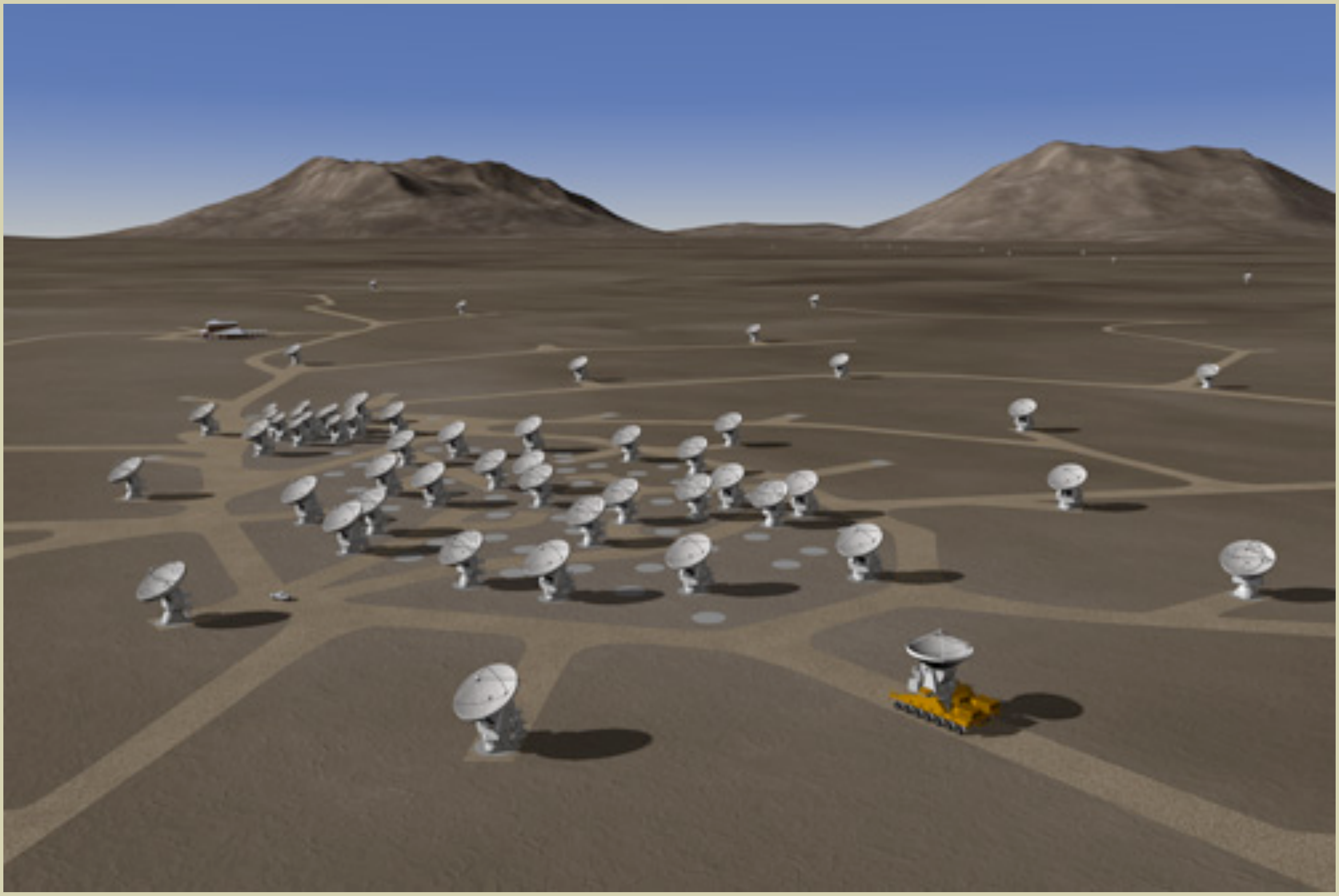
Observing with *ALMA*

A Primer



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Purpose of this Document

This document is designed to provide background information on ALMA and its capabilities, and basic terminology and concepts related to radio interferometry. Our goal is that, with all the basic information in one place, and a few well-chosen examples of how to plan a science observation, this document can help even non-experts in interferometry become familiar with ALMA's capabilities and proficient in planning their own ALMA observations.

It should be noted that this document draws heavily upon a number of sources, including the Executive ALMA websites, the ALMA brochure produced by NRAO, and the ALMA Design Reference Science Plan (DRSP).

For more information on ALMA go to www.almaobservatory.org.

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A List of Relevant Acronyms

ALMA	Atacama Large Millimeter/Submillimeter Array
ACA	ALMA Compact Array
AOS	Array Operations Site
ARC	ALMA Regional Center
CASA	Common Astronomy Software Applications
FOV	Field of View
JAO	Joint ALMA Observatory
NAASC	North American ALMA Science Center
OSF	Operations Support Facility
OT	Observing Tool

What is ALMA?

The Atacama Large Millimeter/submillimeter Array (ALMA) will be a single research instrument composed of at least 66 high-precision antennas, located on the Chajnantor plain of the Chilean Andes. ALMA will enable transformational research into the physics of the cold Universe, regions that are optically dark but shine brightly in the millimeter portion of the electromagnetic spectrum. Providing astronomers a new window on celestial origins, ALMA will probe the first stars and galaxies and directly image the disks in which planets are formed.

ALMA will be a complete imaging and spectroscopic instrument for the millimeter/submillimeter regime, providing scientists with capabilities and wavelength coverage that complement those of other research facilities of its era, such as the Expanded Very Large Array (EVLA), James Webb Space Telescope (JWST), Thirty Metre Telescope (TMT), European Extremely Large Telescope (E-ELT), and Square Kilometer Array (SKA).

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO), in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan. ALMA construction and operations are led on behalf of Europe by ESO, on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI) and on behalf of East Asia by the National Astronomical Observatory of Japan (NAOJ). The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

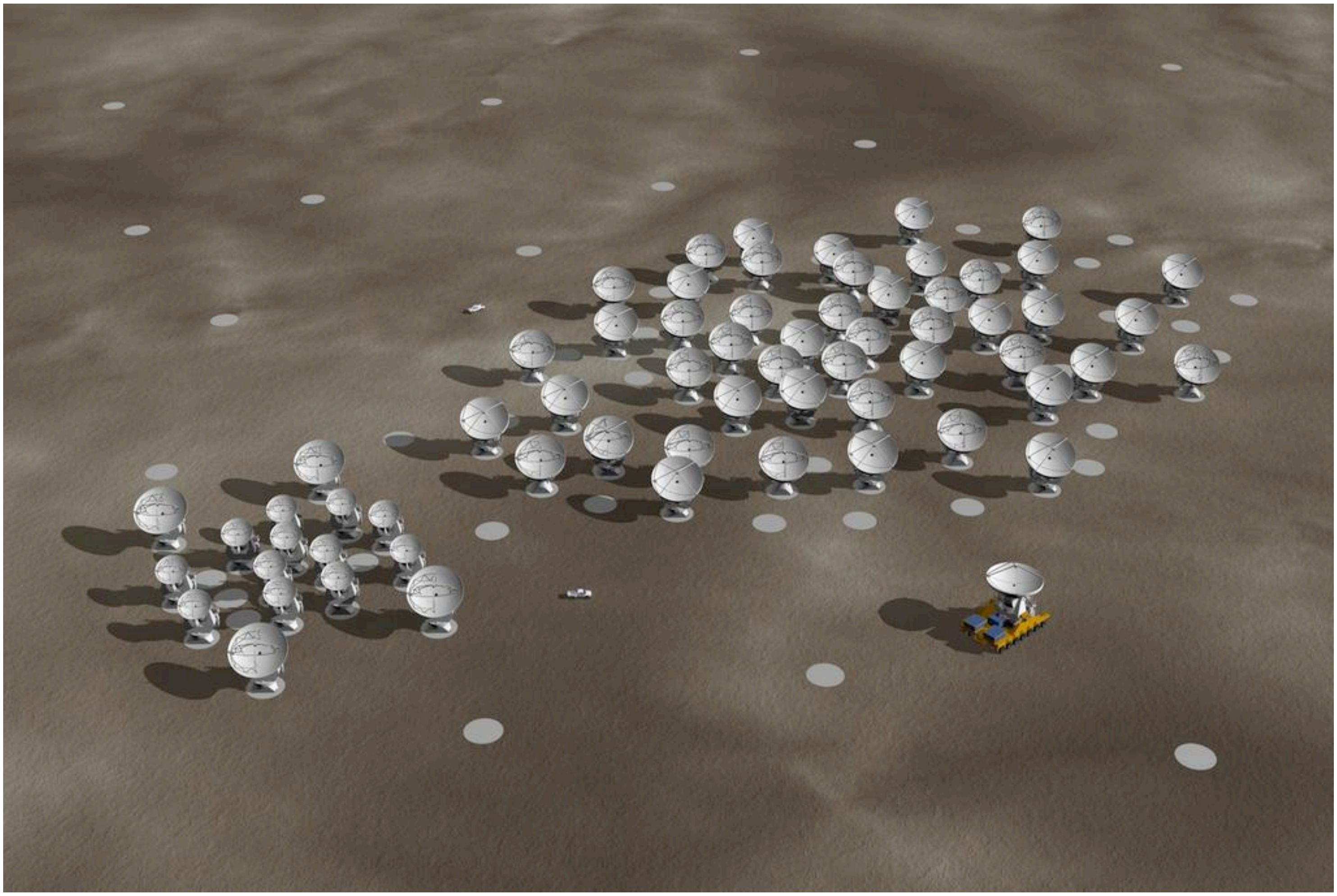


Figure 1: *Artists conception of the ALMA compact configuration, with the ACA and "total power" array on the left, and the transporter in the lower right. © ALMA (ESO/NAOJ/NRAO)*

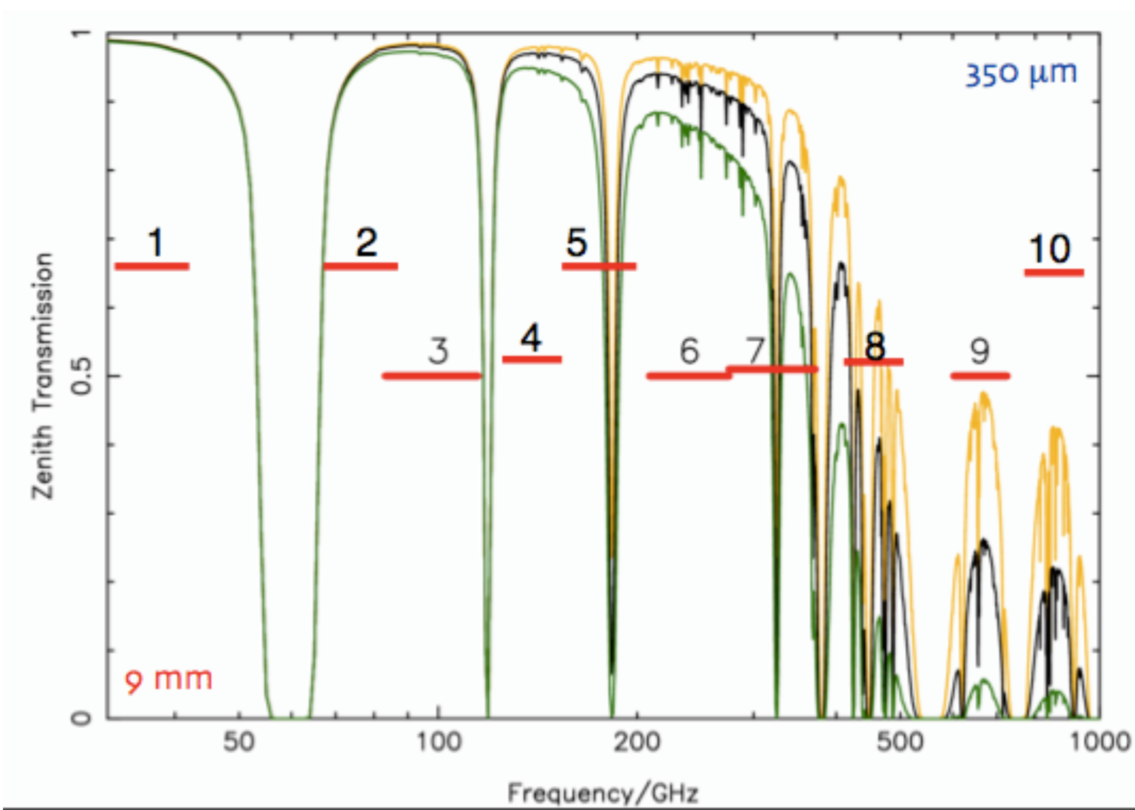
ALMA's superior capabilities will include:

- At least fifty 12-meter antennas for sensitive, high resolution imaging
- Four additional 12-meter antennas, providing total power, and twelve 7-meter antennas comprising the ALMA Compact Array (ACA), enhancing the fidelity of wide field imaging
- Imaging ability in all atmospheric windows from 3.5 mm to 300 microns (84 to 950 GHz), with coverage down to 10 mm (30 GHz) possible through future receiver development
- Array configurations from about 200 meters to 16 km, maximum baseline
- Ability to image sources many arcminutes across (i.e. accurately recover diffuse structures up to arcminutes in size) at arcsecond resolution
- Maximum spatial resolution of 5 milli-arcseconds (better than the VLA and HST)
- Maximum velocity resolution better than 0.05 km/s

Figure 2: *Map of northern Chile, showing the location of ALMA.*

Unlike most radio telescopes, the ALMA antennas will be at a very high altitude of 5000 m on the Llano de Chajnantor in northern Chile. This is more than 750 meters higher than Mauna Kea and more than 2300 meters higher than Cerro Paranal. The U.S. NRAO, the European ESO, and Japan's NAOJ have collected atmospheric and meteorological data at this site since 1995. These studies show the sky above the site has the dryness and stability essential for ALMA (Figure 3). The site is large and open, allowing easy repositioning of the antennas over an area at least 16 km in extent.

Figure 3: *Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency. Plotted in orange, black, and green are the transparency values for the 25th, 50th, and 75th percentile weather conditions. The numbered red horizontal lines represent the frequency coverage of the ALMA receiver bands.*



ALMA Chilean operations will be the responsibility of the JAO. The telescope array itself is located at the Array Operations Site (AOS). Due to the limited oxygen at 5000 m, the array will be operated from the Operations Support Facility (OSF) at an elevation of 2900 m, with trips to the AOS to install, reinstall, or retrieve equipment or antennas. OSF site facilities are being completed with offices, sleeping facilities, and a contractor camp. The OSF will handle the ongoing operations, maintenance, and repairs of ALMA antennas and receivers and will include a public Visitor Center. The JAO has a central office in Santiago.

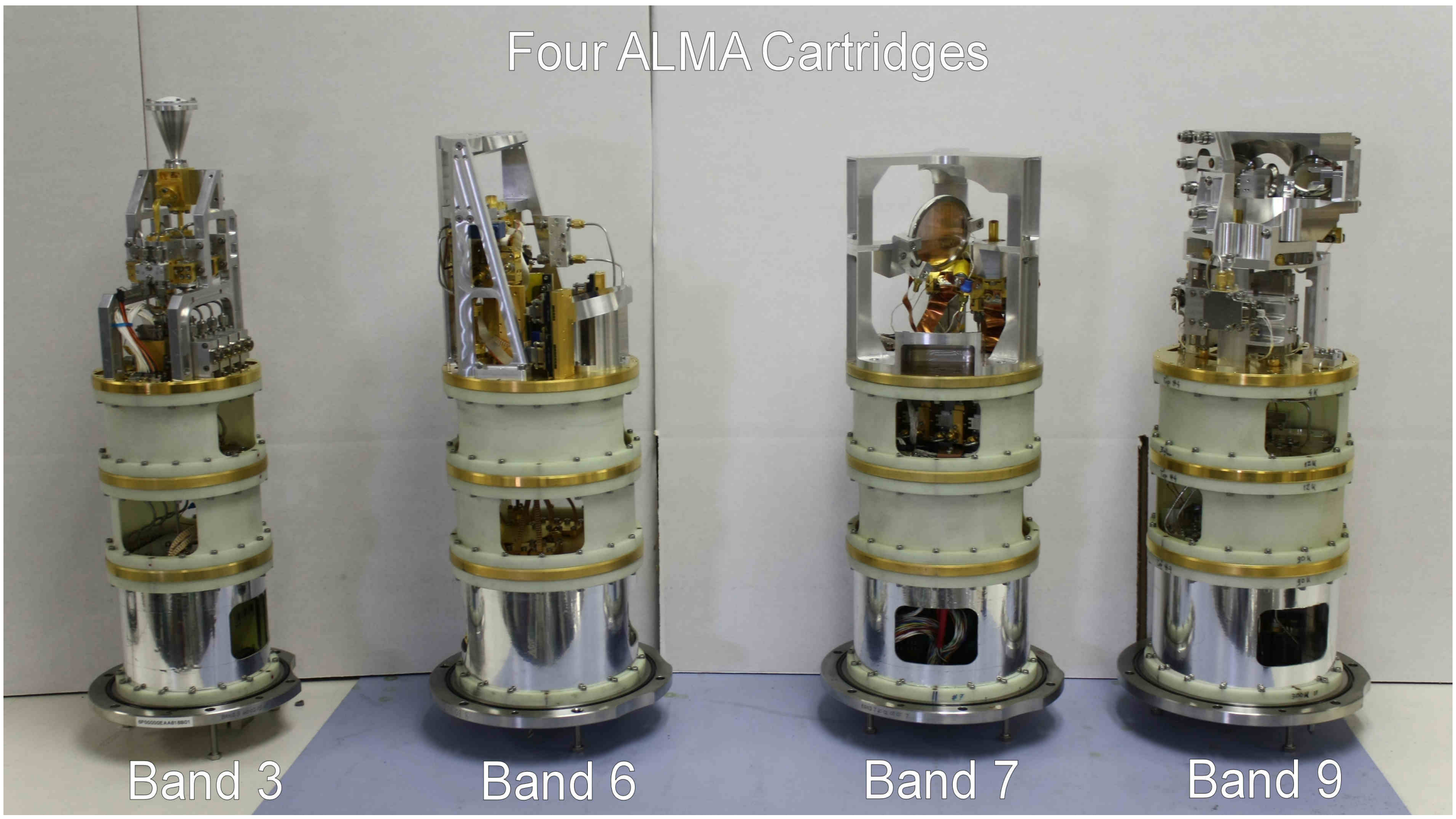


Figure 4: *Four of the ALMA receiver cartridges before being placed in the cryostat. Eventually ALMA antennas will be equipped with at least seven receiver cartridges, covering Bands 3-10 (initially Band 5 will be available for only six of the antennas, while Bands 1 and 2 remain possible future developments). The Band 3 cartridges are being constructed in Canada by HIA, Band 6 by NRAO in the U.S., Band 7 in France by IRAM, and Band 9 by SRON in the Netherlands.*

ALMA Specifications

Hardware	Specification
Antennas	
Number of Antennas	*at least 50 (12m) [ALMA] + 12 (7m) & 4 (12m) [ACA]*
Maximum (RMS) Baseline Lengths	*0.2 - 16.3 km (Equiv. to B_{RMS} = 0.079 - 6.6 km)*
Angular Resolution (")	*0.08" × (300 / ν[GHz]) × (1 km / B_{RMS})*
12m Primary beam (")	*21" × (300 / ν[GHz])*
Correlator	
Number of Baselines	*up to 2016*
Bandwidth	*16 GHz (2 polarizations × 8 GHz)*
Velocity Resolution	*0.5 × (300 / ν[GHz]) km/s with 8 GHz bandwidth* *0.008 × (300 / ν[GHz]) km/s with 125 MHz bandwidth*

For an integration time of 60 seconds and a spectral resolution of 1 km/s, the brightness temperature sensitivity ΔT, with a 50 antenna array and "compact" vs. most "extended" array configuration, will be:

					Compact		Most Extended	
Band	**Frequency**	**Primary Beam (FOV; ")**	**Largest Scale (")**	**Continuum Sensitivity (mJy)**	**Angular Resolution (")**	**ΔT_{line} (K)**	**Angular Resolution (")**	**ΔT_{line} (K)**
Band 1	*31.3 - 45 GHz*							
Band 2	*67 -90 GHz*							
Band 3	*84 - 116 GHz*	*56*	*37*	*0.05*	*3.18*	*0.07*	*0.038*	*482*
Band 4	*125 - 163 GHz*	*48*	*32*	*0.06*	*2.5*	*0.071*	*0.03*	*495*
Band 5	*163 - 211 GHz*	*35*	*23*					
Band 6	*211 - 275 GHz*	*27*	*18*	*0.10*	*1.52*	*0.104*	*0.018*	*709*
Band 7	*275 - 373 GHz*	*18*	*12*	*0.20*	*1.01*	*0.167*	*0.012*	*1128*
Band 8	*385 - 500 GHz*	*12*	*9*	*0.40*	*0.86*	*0.234*	*0.01*	*1569*
Band 9	*602 - 720 GHz*	*9*	*6*	*0.69*	*0.52*	*0.641*	*0.006*	*4305*
Band 10	*787 - 950 GHz*	*7*	*5*	*1.1*	*0.38*	*0.940*	*0.005*	

To be developed in the future. Available for early science.

Science with ALMA

Level One Science Goals

While ALMA will revolutionize many areas of astronomy, the ALMA Project has three Level One Science Goals that drive the technical requirements:

I. The ability to detect spectral line emission from CO or C^+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

II. The ability to image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.

III. The ability to provide precise images at an angular resolution of 0.1″. Here the term "precise image" means an accurate representation of 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.

ALMA's Breadth of Science

This remarkable instrument will be able, but is not in the least limited, to:

• Image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as $z = 10$. The inverse K-correction on the Rayleigh-Jeans side of the spectral energy distribution of a dusty galaxy compensates for dimming at high redshift, making ALMA the ideal instrument for investigating the origins of galaxies in the early universe, with confusion minimized by the high spatial resolution.

• Use the emission from CO to measure the redshift of star-forming galaxies throughout the universe. The frequency spacing between successive transitions of CO shrinks with redshift as $1/(1 + z)$, and the large instantaneous total bandwidth of ALMA will make possible blind surveys in order to establish the star-forming history of the universe, without the uncertainties inherent in optical and UV studies caused by dust extinction.

• Probe the cold dust and molecular gas of nearby galaxies, allowing detailed studies of the interstellar medium in different galactic environments, the effect of the physical conditions on the local star formation history, and galactic structure. The resolution of ALMA will reveal the kinematics of obscured active galactic nuclei and quasars on spatial scales of 10-100 pc and will be able to test unification models of Seyfert galaxies.

• Image the complex dynamics of the molecular gas at the center of our own Galaxy with unprecedented spatial resolution, thereby revealing the tidal, magnetic, and turbulent processes that make stellar birth and death at the Galactic Center more extreme than in the local Solar neighborhood.

• Reveal the details of how stars form from the gravitational collapse of dense cores in molecular clouds. The spatial resolution of ALMA will allow the accretion of cloud material onto an accretion disk to be imaged and will trace the formation and evolution of disks and jets in young protostellar systems. For older protostars and (pre-)main sequence stars, ALMA will show how (proto)planets sweep gaps in protoplanetary and debris disks.

• Uncover the chemical composition of the molecular gas surrounding young stars, including establishing the role of the freeze-out of gas-phase species onto grains, the re-release of these species back into the gas phase in the warm inner regions of circumstellar disks, and the formation of complex organic molecules. ALMA will have the large total bandwidth, high spectral resolution, and sensitivity needed to detect the myriad of lines associated with heavy, pre-biotic molecules such as those which may have been present in the young Solar System.

• Image the formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae. ALMA will resolve the crucial isotopic and chemical gradients within these circumstellar shells, which reflect the chronology of the invisible stellar nuclear processing and early seeding of the ISM.

• Refine dynamical and chemical models of the atmospheres of planets in our own Solar System and provide unobscured images of cometary nuclei, hundreds of asteroids, Centaurs, and Kuiper Belt Objects.

• Answer a myriad of other questions of current interest in astrophysics.

• Delve into as yet unanticipated, transformational science questions which arise whenever an entirely new realm of spectral coverage, resolution, and sensitivity is opened up.

Figure 5: *Panorama of the OSF. Left to right: (foreground) European Site Erection Facility (SEF), showing part of one antenna structure; (background) Japanese AEF with three antennas; North American SEF with the large erection hall and two antennas; ALMA base camp; and the the OSF technical building. © ALMA (ESO/NAOJ/NRAO)*

ALMA Science Operations

Observations will be performed in service observing mode with flexible (dynamic) scheduling, 24 hours per day. All observations will be executed in the form of scheduling blocks (prepared by the astronomer using the Observing Tool (OT)), each of which will contain all the information necessary to schedule and execute the observations. The astronomer will then be provided with reliable images, calibrated according to a detailed calibration plan. The JAO will be responsible for the data product quality. All science and calibration raw data will be captured and archived.

ALMA Regional Centers (ARCs)

The North American ALMA Science Center (NAASC, Figure 5) based at NRAO, with the assistance of the Herzberg Institute of Astrophysics, is responsible for supporting the science use of ALMA by the North American astronomical community, and for research and development activities in support of future upgrades to ALMA.

The NAASC will provide North American astronomers with support during the creation and submission of ALMA proposals, including help with observation modes and capabilities, validation of scheduling blocks, and support of the Proposal Submission and Scheduling Tool, also called the Observing Tool (OT). Post-observations, the NAASC will support data reduction and examination, as well as help with ALMA Common Astronomy Software Applications (CASA), the software package for reducing and analyzing data.

Figure 6: The North American ALMA Science Center (NAASC) in Charlottesville, Virginia.

Observations and Data Reduction *

The Basic Set-Up of an Observation

ALMA will manage projects through a two phase project system that will be handled through the ALMA OT. Phase I will consist of a detailed observing proposal with a scientific and technical justification, that will be submitted to the Observatory through the OT. The OT will have calculators for determining sensitivities, viewers for assisting with correlator setups, and suites of optical, IR, etc. images available for help in setting up single pointing and mosaic fields. Additionally, one can simulate ALMA observations in CASA , including realistic effects of noise, antenna configurations, atmospheric phase delay, and other instrumental effects. A library of model images and synthesized observations of them is being assembled. (For more information see "simdata" on the tools web site (p. 36).) Phase I submissions will be peer-reviewed by committee, and time will be awarded appropriately. Phase II will consist of the development of a detailed observational plan, using other features in the OT to develop a series of small blocks of observing time, which can be run by the array operators when conditions are appropriate above the Llano de Chajnantor. Support staff at the ALMA Regional Centers (ARCs) will provide technical assistance to project teams during Phase II to optimize the execution of their respective projects.

While considering a possible ALMA project, it is important to understand that ALMA is a very flexible instrument. Data can be obtained over a wide range of observational parameters: angular resolution, field-of-view, spectral resolution, and sensitivity. These quantities must be specifically defined and justified for a given project during Phase I of the proposal process, and proper choices are required to ensure that the project's scientific goals can be met. These quantities are also used during Phase II, to guide in planning the execution of the project. Depending on the nature of a given project, these quantities may be interrelated. In the following, we describe the bases for choosing these parameters.

Angular resolution (or "synthesized beam") is the minimum angular separation whereby adjacent and independent spatial features can be distinguished. Angular resolution fundamentally varies as the inverse of the product of observational frequency and distances between the antennas used to make the image; higher frequencies or longer antenna baselines result in data of higher angular resolution. An important concept to remember about interferometers is that they can only observe emission on a discrete set of

* For the non-expert reading this section, a list of Interferometer Concepts is included at the end of the document.

spatial scales (i.e., frequencies), as measured by the antenna pairs making up an array. Since the number of spatial scales measured is finite, the resulting image is "filtered" spatially and only reflects the emission on the observed spatial scales. (The effective maximum baseline defining the angular resolution is called the “RMS” baseline, B_{RMS}.) The actual angular resolution achieved in a reconstructed image depends on how the data are weighted during the imaging process. During imaging, interferometer data are commonly weighted "naturally," i.e., by the relative densities at which angular scales on the sky have been sampled in the data ensemble. Naturally weighted images have the highest sensitivity possible for a given bandwidth and integration time but they may have lower angular resolution than would be expected simply from the separation of the furthest antennas. Other weighting schemes can yield images of higher resolution but at an expense to sensitivity.

Another property of an array configuration is the largest observable scale that can be reconstructed during image processing. This quantity is related to the minimum distance between antennas. Interferometers are insensitive to emission on large angular scales because the telescopes cannot be moved arbitrarily close to one another. To recover emission that has been "resolved out," additional observations are needed, including observations with more compact arrays with smaller-sized antennas (such as the ACA) or large single-dish telescopes (ALMA will will have four specially outfitted 12m antennas that can be used to sample large-scale emission by scanning over fields in a non-interferometric, “total power”, mode). One can explore with the ALMA simulator in CASA whether the ACA will be required for a particular project, and the ACA can be requested in the proposal at Phase I.

Figure 7: First interferometry at the AOS (high site), early November 2009. © ALMA (ESO/NAOJ/NRAO)

Field-of-view (FOV) is the area on the sky over which an interferometric image is obtained. The instantaneous FOV is formally the angular size of the half-power width of the Gaussian beam (FWHM) of the individual antennas and is also called the width of the "primary beam". The size of the FOV depends on the inverse of the product of the frequency of the observation and the diameter of the individual antennas used; larger antennas or higher frequencies result in smaller FOVs. For a single pointing, the sensitivity of the observation is not uniform across the FOV; it declines with angular separation from the center position with the approximately Gaussian responsivity of the main antenna beam. Larger FOVs and flatter map sensitivities across images can be attained by observing in series many adjacent locations on the sky (best separated by ~FOV/2.4 to achieve Nyquist sampling) and using the resulting data to create a "mosaic" map. In order to have constant sensitivity across the mosaic, each pointing must be observed to the same relative sensitivity. Thus, mosaics can be quite costly in terms of observing time. Deciding whether a mosaic or a single pointing should be observed requires an understanding of the expected source structure and size, i.e., whether or not the observed emission will be extended, based on previous, often inferior data from other telescopes. Furthermore, if multi-band images over the same FOV are needed for a given project, mosaics may be required with higher frequency bands in order to match the areal coverage of a single pointing with lower frequency bands. Mosaics can also aid in recovering some emission on scales larger than those that are sampled by single pointings.

Spectral resolution is the minimum separation in frequency whereby adjacent independent features can be distinguished. The digitized data from ALMA allows for an incredible range in spectral resolution. Spectral resolution depends on how the correlator has been configured prior to observations. ALMA's correlator can be configured to provide data cubes with up to 8192 independent spectral channels. The width of these channels can be defined from 3.8 kHz to 25 MHz. For continuum observations, low spectral resolution (i.e., large total bandwidth) channels are averaged to achieve high sensitivity; the total bandwidth of all correlator settings used cannot exceed 8 GHz. For line observations, high spectral resolution (i.e., small bandwidth) is used to achieve high velocity resolution. For example, a 0.01 km/s velocity resolution of R=30,000,000 can be achieved for ^{13}CO 1-0 at 110 GHz by utilizing the narrowest channels (3.8 kHz). There is, however, a cost to sensitivity in using small bandwidth channels. Sensitivity can be improved after the observations by averaging channels together, i.e., by the inverse square root of the number of channels averaged, but at the expense of the spectral resolution. The ALMA correlator is highly complex and extremely flexible and can be configured to observe simultaneously several spectral lines within the 8 GHz band at high spectral resolution while additional correlator channels can be simultaneously used to observe continuum emission at low spectral resolution. In addition, a combination of high and low resolution correlator windows can be chosen over the same bandwidth to determine how emission from lines at these frequencies is contributing to the emission observed at low spectral resolution.

Sensitivity is usually defined as the 1 sigma rms variation of noise in the data and so serves as a threshold for the detection of emission. For ALMA, basic sensitivity depends strongly on receiver performance and atmospheric conditions (i.e., water vapour content, atmospheric turbulence, and target elevation). These effects are quantified by one parameter called "system temperature" (T_{sys}). High T_{sys} values (in K) indicate low sensitivity and vice versa. Note that atmospheric opacity and stability are very frequency dependent, and thus the ability to observe with any particular receiver will usually depend strongly on the weather conditions. These conditions include the water content of the atmosphere which attenuates astronomical emission and atmospheric turbulence which results in phase instability. The magnitude of these problems generally increases with observing frequency.

Two other aspects of the observational set-up strongly affect sensitivity: spectral resolution and angular resolution. Continuum intensities are often given in units of Janskys per beam where 1 Jansky (Jy) = 10^{-26} W s^{-1} m^{-2} Hz^{-1} while line intensities are given in units of Kelvin (K). Converting from one unit to another requires knowledge about the angular resolution of the data, where the sensitivity in K is proportional to the sensitivity in Jy divided by the angular size of the beam (see p. 22). For a given ΔS_{ν}, the corresponding ΔK increases with decreases in beam size; it is harder to detect extended line emission at high angular resolution. The quantity ΔS_{ν} itself varies as the inverse-square root of the product of total integration time and the total bandwidth of the observation. (How data are weighted during imaging also affects sensitivity; see above.) The total bandwidth of the observation is determined by the correlator settings and how many spectral channels, i.e, resolution elements, are averaged together. For continuum data, up to 16 GHz (8 GHz in each polarization) bandwidth can be used. Sensitivity also depends on the inverse square root of the number of observed polarizations; all ALMA bands have two polarization channels. There is an on-line sensitivity calculator available (see tools p. 36), as well as one built into the OT. One can also explore the required sensitivity in more detail using the “simdata” tool.

Calibrating and Reducing Your Data

Once the data are taken, the project team will want to see what they have observed. ALMA data will be reduced using the Common Astronomy Software Applications (CASA) package. ALMA will have a pipeline that will process its data in a reasonable but routine manner, and the project team will want to optimize reduction of their data to get the most out of them. During Early Science, the pipeline will still be under development, and ALMA Science Operations (DSO) and ARC staff will help calibrate and reduce data for the project team. In the following, we describe the basic concepts of reducing interferometer data. This process can be boiled down to two stages, calibration and imaging, and we discuss these below in turn.

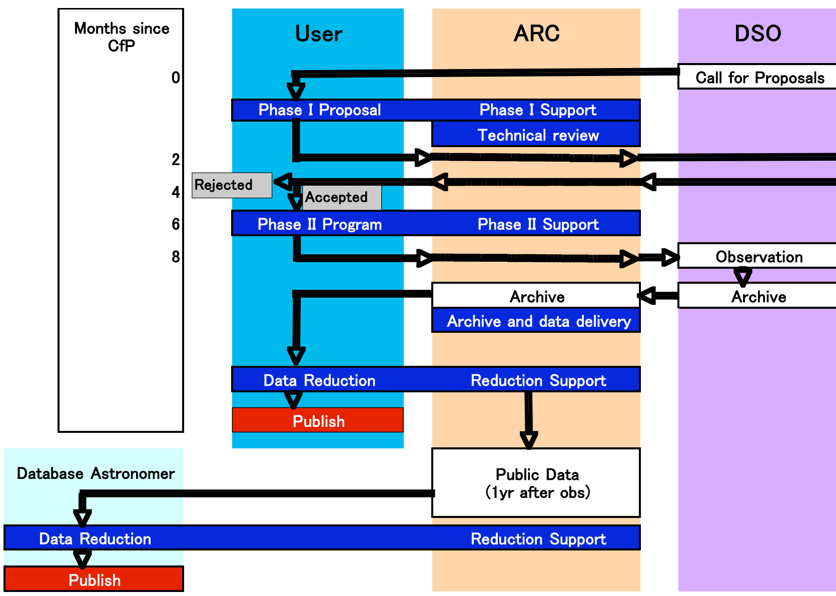


Figure 8: *Schematic showing the various steps and support available for proposal generation, acceptance, and observation. The ALMA Department of Science Operations (DSO) will make the call for proposals and the ALMA Regional Centers (ARCs) will support the user in generation, observation, and reduction. The ALMA Project will also maintain an archive of all ALMA observations.*

Calibration: ALMA observing will be heavily constrained by weather conditions on the Llano de Chajnantor. Therefore, ALMA projects will be divided up into small blocks of time that can be executed dynamically by the on-site array operators when appropriate conditions are available. These blocks will contain observations of other, well-characterized, typically bright objects (calibrators) either before, during or after the target source observations are made. The calibrator data will be used to calibrate the target data during post processing. During reduction, all calibration measurements will be obtained using these calibrator data and then applied to the target data.

Target data will require calibration of its amplitudes and phases. Moreover, spectral line data will require calibration for how these quantities vary with frequency. Amplitude calibration requires observations of at least one or two bright sources of known angular extent. The brightnesses of these objects should vary only relatively slowly, so that an accurate estimate of their fluxes can be determined. Typically, very bright and compact radio sources (3C273 or 3C84), planets (Uranus), and even moons (Callisto) are used for this measurement. (Asteroids may be useful amplitude calibrators at high frequencies.) The observed data from these objects can be used to scale accurately the intensities recorded at the target. In addition, amplitude calibration devices (ACDs), which will be fitted to all antennas, will be used for relative calibration. Bandpass (or passband) calibration, sometimes called frequency calibration, also requires observations of bright sources with the same correlator setup as the target. If bright enough, variations of amplitude and phase with frequency will be also captured by these observations; typically amplitude calibrators are also used to gather these data. Phase calibration requires periodic (e.g. every few minutes) observations of a moderately bright, very compact source at relatively small angular distance from the target. These data are used to correct for phase drifts that occur with time, e.g., small changes in the path length between antennas or through the atmosphere. The best sources for phase calibration are unresolved at the angular scales probed by the array; since such objects are point sources, their data have intrinsically zero phase (no emission at any angular offsets), and any phase changes recorded in the data are due only to changes in the system. The pace at which the phase calibrator will be observed will depend on the stability of the atmosphere, the observational frequency, and the maximum baseline length. At longer baselines, atmospheric phase varies more rapidly while at higher frequencies the variations are larger. The ALMA antennas will need to "fast-switch" between the target and phase calibrators every few minutes to capture these variations.

Imaging: ALMA datasets will be processed through a reduction pipeline so that project teams will be able to see quickly preliminary results. (Of course, the project teams will also be able to reduce the data themselves.) There are many approaches to reducing and imaging interferometer data but these are the basics.

The heart of imaging is a Fourier Transform (FT) of the interferometer data (termed "visibilites") into images. The reduction process itself is twofold: first, poor quality data must be removed from the ensemble before the FT, and second, the image is made from the FT. Removing poor quality data ("flagging") is important because their inclusion in the data ensemble can have a large effect on the quality of the image made by the FT. For example, a high-amplitude spike in the visibilities will produce a high-amplitude ripple in the resulting image. In the past, such poor quality data have been located within the ensemble by manually comparing data from different antennas and antenna pairs as well as over time and frequency, and noting features that are significantly different from other data. The sheer size of ALMA data products will make this kind of close inspection impractical, and tools are being developed to streamline the process. Flagged, poor quality data can be ignored by the reduction software and are then effectively removed from the data ensemble. It is important to search for aberrant data to flag for the calibrators and the targets; it is typically harder to see poor quality target data as targets are typically weaker than calibrators, and unusual variations of amplitude and phase are harder to identify.

Figure 9: *Three of the 12m Vertex (North American) antennas being readied for testing at the OSF in Chile.*

Data that have gone through flagging are ready to be imaged through an FT of the ensemble. Images need to be large enough to cover the field of view of ALMA, which varies with frequency, and sampled finely enough such that the structures observed at the high spatial resolution of the data can be accurately represented. Various spatial and spectral frequency weights can also be applied to the data during the FT to emphasize certain characteristics. For example, resolution and sensitivity can be traded-off by weighting the data in various ways, and "natural" weighting, where data are weighted relative to the number of spatial scales observed in the ensemble, typically provides the highest sensitivity. In addition, spectral channels can be averaged prior to the FT to improve sensitivity. The resulting image may consist of significant artifacts, depending on the complexity and brightness of the target region, and the amount and quality of data obtained; such images are sometimes called "dirty images". Since interferometers cannot measure all spatial frequencies, there will be gaps in the data ensemble that will translate into image artifacts after the FT. Even dirty images of point sources have these artifacts, and these images are sometimes referred to as representations of the "dirty beam". The workaround to deal with these artifacts has been to model the data through various deconvolution techniques. A common algorithm is called "CLEAN". It works by iteratively subtracting low-amplitude versions of the dirty beam from the dirty image, starting at the brightest part of the dirty image and working down in intensity until only a residual image is left. A residual image may contain intensities of some small multiple of the noise in the dirty image but other thresholds are possible. The sky locations of the beam subtractions, called "clean components," are saved. The clean components are placed on a blank image, and these are all convolved with a Gaussian of size equal to that fit to the inner part of the dirty beam, i.e., a "clean beam". Finally, the residual image is added to the convolved component image to produce a "clean image". There are many approaches to deconvolving images, even Clean has many variations, but this is the basic idea. Of course, data will need to be deconvolved one spectral channel at a time, and this can be quite time consuming if the images are large or if there are many channels with emission.

Figure 10: *ALMA is a partnership of Europe (through ESO), North America (through NSF in cooperation with NRC and NSC), and East Asia (through NINS in cooperation with Academia Sineca), in cooperation with the government of Chile.*

ALMA Early Science

The first call for ALMA proposals is expected to be in late 2010, while construction is still underway. This "Early Science" phase of ALMA will feature at least sixteen antennas, four receiver bands, baselines out to 1 km, and single dish mapping of extended objects in continuum and spectral line modes. At this point, ALMA will already represent a significant gain over present-day interferometers. While Early Science time will be shared with further commissioning of the complete array, at least 33 percent of available time will be used for science observations. Many of the examples given later in this document will require the full capabilities of ALMA. Nevertheless, numerous exciting projects will be possible during this short preliminary stage.

Full Science Operations

ALMA inauguration will occur when there are fifty antennas available and at least 75 percent of the time is dedicated to science observations. Inauguration is expected in late 2012. At this point, ALMA will have two scheduling periods per year, and the antenna configurations will be changed from the most compact to the most extended configuration over a timescale less than a year.

Figure 11: *The first ALMA antenna was transported to the AOS on 17 September 2009. The transporter and antenna climb above 4000m, leaving behind the OSF and the 21km that separate it from the Chajnator plateau. © ALMA (ESO/NAOJ/NRAO)*

EXAMPLES OF OBSERVING WITH ALMA

In the following sections we provide some examples of science observations with ALMA, taken from the Design Reference Science Plan (DRSP). While the DRSP projects were usually large in scope and required hundreds of hours of telescope time, we have selected portions of these programs which best illustrate how the ALMA telescope will be set up to perform the observations.

For each example below, we start with a brief *science goal* and then discuss the required *receiver band* (frequency) at which the observations should be undertaken. Next, we determine the *angular resolution* needed and the array configuration which allows for this set up. In some cases, where multiple frequencies are required, the angular resolution obtained will either vary with frequency or the observations at each frequency may require different array configurations (and thus will not be coincident in time). The necessary *spectral resolution* is discussed in order to determine the appropriate *correlator settings*. As well, the *continuum* or *channel sensitivity* is quantified in order for the *observing time* to be calculated. In a few cases, where mosaicing observations are required, the *number of pointings* and *total-power and/or ACA use* are also presented.

Figure 12: *Some of the uncompleted antenna pads of the compact configuration at the AOS. One of the antennas already at the summit can be seen on the horizon.*

Converting Units: In radio astronomy one is often converting between different units of measurement and computing the required integration time for varying spectral resolutions. Here we provide a few important reference equations (for further details, we point readers to the textbook "Tools of Radio Astronomy" by Rohlfs and Wilson).

To achieve a particular velocity resolution Δv at a given observing frequency ν, requires a frequency resolution $\Delta\nu$ of

$$\Delta\nu = \left(\frac{\Delta v}{c}\right)\nu.$$

The conversion from brightness temperature T to surface brightness S_ν with synthesized beam area Ω_s is

$$S_\nu = \frac{2\,\nu^2\,k\,T}{c^2}\Omega_s.$$

An alternate formulae that is often useful is

$$\left(\tfrac{T}{1K}\right) = \left(\frac{S_\nu}{1\ \mathrm{Jy\ beam^{-1}}}\right)\left[13.6\left(\tfrac{300\ \mathrm{GHz}}{\nu}\right)^2\left(\tfrac{\theta_{max}}{1"}\right)\left(\frac{\theta_{min}}{1"}\right)\right]$$

Finally, the noise ΔS_ν, in an integration time Δt, varies with system temperature T_{sys}, frequency resolution $\Delta\nu$, number of antennas used N, diameter of the antennas D, and number of polarization measurements obtained n_p, in the following manner:

$$\Delta S \propto \frac{T_{sys}}{D^2\left[n_p\,N(N-1)\,\Delta\nu\,\Delta t\right]^{1/2}}\ \mathrm{W\,m^{-2}\,Hz^{-1}}.$$

1. Cosmology & Extragalactic Astronomy

1.1 - CO and Dust Continuum in Distant Submillimeter Galaxies

Science Goal: ***To determine the redshift distribution of submillimeter galaxies via the detection of CO.***

It is now clear that a significant fraction, approximately half, of star formation in the cosmos occurs in galaxies that are heavily obscured by dust, and that this fraction may rise with redshift. With ALMA, an unbiased redshift survey of these galaxies can be performed in parallel with continuum measurements. Using the Band 3 receiver, it is possible to search for redshifted CO while simultaneously obtaining deep continuum observations. For redshifts $z > 2$, there will be at least one CO line within the receiver passband. Over all redshifts there are only two blind spots $0.4 < z < 1$ and $1.7 < z < 2$ in which no CO line falls within the Band 3 frequency range.

Receiver Band: **Band 3**

Angular Resolution: **3"** No attempt will be made to resolve the structure of the galaxies. Thus, the default compact configuration angular resolution suffices.

Spectral Resolution: 50 km/s For this project, the requirement is full spectral coverage within the receiver band (since the goal is to achieve an unbiased redshift survey). Galactic CO lines are expected to be broad - typically a few hundred km/s linewidth. Therefore, a low spectral resolution (50 km/s) can be used and 8 GHz of bandwidth obtained for each tuning. To cover the entire Band 3 range, 84 to 116 GHz, requires 4 tunings of the receiver. The continuum flux can be measured simultaneously with the spectral survey.

Sensitivity: **Continuum 1 μJy (S/N ~ 100); Channel 0.1 mJy (S/N ~ 100)** Given a 1 mJy continuum flux at 1 mm (i.e. the bright end of the observed SCUBA source count) observations to date suggest an integrated CO line strength of a few Jy km/s. (or ~ 10 mJy per 50 km/s channel if the line is 200 km/s in width) (Solomon & Vanden Bout 2005, ARA&A, 43, 677). In this survey, we aim for clear detections of lines ten times less bright. At the same time, assuming a continuum spectral index of 2-3 for dust emission, these sources should have 3 mm continuum fluxes of order 0.1 mJy. In this survey we aim to find sources more than ten times fainter and thus set a continuum sensitivity of 1 μJy (which is achievable in the same observing time as required for the line observations).

Observing Time: A spectral sensitivity of 0.1 mJy per 50 km/s channel provides a line sensitivity of 10-20 mJy km/s integrated over the line (widths of a few hundred km/s) and requires about 4 hours of integration per tuning, or 16 hours to cover the entire Band 3 range. Each 4 hour integration provides a continuum sensitivity of a few μJy and the results can be combined to achieve approximately 1 μJy continuum rms.

Comment: It is worth noting that in this configuration ALMA will detect all submillimeter galaxies with continuum fluxes at 3 mm greater than 10 μJy within the one arcminute primary beam. Current number counts suggest that in each field there should be approximately a dozen such sources. Obviously this proposal lends itself well to a large survey mode (i.e. many overlapping pointings to increase the observed area).

[Based on a DRSP submitted by Stephane Guilloteau.]

1.2 - Imaging Molecular Material in the Vicinity of an AGN

Science Goal: ***To detect and probe the kinematics of CO 2-1 in the nucleus of a nearby Seyfert Galaxy.***

Molecular gas has been detected in the nucleus of several Seyfert Galaxies (e.g. Casasola et al. 2008, A&A, 490, 61). With the high sensitivity and spatial resolution of ALMA, this CO line emission can be mapped on small spatial scales (< 10 pc), providing a test of dynamical models of gas flow in the presence of central black holes (BH). Ultimately, this method should allow the measurement of BH masses using molecular line kinematics. Using the Band 6, 250 GHz, receiver the CO 2-1 (230 GHz) line can be readily detected in nearby (~20 Mpc) Seyfert Galaxies.

Receiver: Band 6 The most easily observed molecular species in Galaxies is CO. The CO 2-1 line lies at 230 GHz, within the Band 6 receiver frequency range.

Angular Resolution: 0.1'' To reach size scales less than ~10 pc for sources at a distance of 20 Mpc, an angular resolution ~ 0.1'' is required.

Spectral Resolution: 5 km/s Since the goal is to understand the kinematics of the region, a spectral resolution of 5 km/s is desired.

Channel Sensitivity: 0.3 mJy A typical line brightness of 5 - 10 K at 230 GHz might be expected. Thus, if a signal to noise level of 10 is desired in order to decode the kinematics from the spectrum one requires a brightness sensitivity of ~500mK (in a 0.1'' beam).

Observing Time: Using the integration time calculator, 8 hours is needed per pointing to achieve the required sensitivity.

***[Based on a DRSP submitted by E. Schinnere*r]**

Figure 13: *Technical support building at the OSF.*

1.3 - GMC Scale Chemical Inventory of a Nearby Galaxy

Science Goal: ***To detect and identify molecular lines from a single GMC in a nearby galaxy.***

Little is known about the molecular content on the scales of GMCs (~10 pc) inside external galaxies. For the nearest galaxies, within 2 Mpc, a census of the molecular species abundant in these clouds will yield important insight into the large-scale chemistry as well as providing diagnostics for many additional physical properties of these clouds. For example, cosmic ray rates and ionization fractions can be measured from molecular ions. The prevalence of shocks within the molecular gas can be probed by consideration of the intensity of energetic transitions. Comparison of the molecular lines and dust continuum can yield insights into grain surface processing (Meier & Turner 2005, ApJ, 618, 259).

Receivers: Band 6 The Band 6 receiver is ideal for this project as many low excitation molecular lines fall within the bandpass.

Angular Resolution: 1" For relatively nearby galaxies, a physical scale of 10 pc requires only a 1" angular resolution.

Spectral Resolution: 5 km/s As this is a molecular line survey within an individual cloud, a large bandwidth is desired, along with a moderate spectral resolution. For this band, a 5 km/s spectral resolution provides 8 GHz of available bandwidth, and thus 4 tunings achieve 32 GHz of coverage.

Channel Sensitivity: 0.5 mJy Typical line brightnesses are expected to be > 0.1 K (and up to 10 K). A typical signal to noise greater than 10 is desired to be confident of individual line detections and thus we aim for 10mK in a 1" beam.

Observing Time: Using the integration time calculator, 2.4 hours of observations per tuning is required, or 10 hours for the entire Band 6 census.

[Based on a DRSP submitted by D. Meier and J. Turner]

Figure 14: *Part of the team of technicians, engineers and scientists who involved in the ALMA antenna's first movement to the AOS on the Chajnator plateau. © ALMA (ESO/NAOJ/NRAO)*

2. Galactic Astronomy

2.1 - Chemical Survey of the Innermost Environment of a Protostar

Science Goal: ***To observe a variety of molecular transitions at high spatial resolution.***

In the innermost regions of a highly embedded protostellar core, complex chemistries are at play that are driven by the sublimation of ice mantles from dust grains that have been significantly warmed by the young central source. The subsequent reactions at high temperatures (100 K) can lead to complex organic species. Such regions, named hot cores, have been observed with present millimeter telescopes but have not yet been well resolved. ALMA, with its enhanced spatial resolution and sensitivity, will be able to map the radial distributions of many molecular species near individual protostars, providing observational constraints for complex chemistry models.

Receivers: Bands 6, 7 and 9 Among the interesting species that have been observed in hot cores are methanol, formaldehyde, and even more complex hydrocarbons. Strong spectral features for these molecules are found in Band 6 (211 - 275 GHz) and Band 7 (275 - 373 GHz). As well, at the high temperatures reached in the inner zones significantly excited lines also may be observed. These transitions tend to lie at higher frequencies and thus Band 9 (600 - 720 GHz) is included in this proposal.

Angular Resolution: ~0.25'' FWHM The nearest protostars are about 200 pc away and the zones of interest are located within about 100 AU of the central heating source. Thus, an angular resolution of ~0.25'' should suffice for these observations. Reaching this resolution at 200 - 400 GHz requires roughly 1 km baselines while at 600 GHz the same baselines yield a factor of 2 better angular resolution (or alternatively, maximum baselines of only 0.5 km would suffice for the required resolution).

Spectral Resolution: 0.25 km/s At the moderate temperatures found inside the protostellar core, the sound speed of the gas should be only a fraction of a kilometer per second. Non-thermal motions, however, tend to broaden the lines. This proposal aims to survey a range of molecules and thus a moderate spectral resolution is chosen to provide a larger instantaneous bandwidth (at the expense of high spectral resolution).

Channel Sensitivity: ~1 K Observations of hot cores have shown that there are myriad molecular lines from very strong to quite weak. In this survey, a moderate threshold of 1 K per correlator channel (or velocity bin) is set in order to keep the integration times reasonable. Follow-up observations looking for particular molecular features would likely aim for much deeper integrations (and possibly higher spectral resolution).

Correlator Settings: To sample the large number of molecular lines, several pre-defined correlator settings will be used in each band, i.e., 3 settings in Band 6, 4 in Band 7 and 2 in Band 9. Given the desired spectral resolution, the maximum instantaneous bandwidth available is 500MHz , 1GHz, and 2GHz respectively, due to the trade-off between spectral resolution and bandwidth imposed by the correlator.

Observing Time: Using the ALMA integration time calculator and the above parameters, we get ~1 K per channel in ~1 hour per correlator setting. Thus to observe all 9 correlator settings will require about 9 hours per target.

[Based on a DRSP project submitted by E. van Dishoeck, et al.]

2.2 - Multiwavelength Continuum Survey of Circumstellar Disks

Science Goal: T*o observe the dust SED as a function of position within a circumstellar disk.*

The characteristics of dust in a circumstellar disk around a protostar are expected to evolve over time, especially if planets form within the disk. This evolution of the disk may be traced by determining the radial variation in the dust emissivity, requiring high angular resolutions and brightness sensitivities. Wide frequency coverage is necessary to achieve these aims, since the Spectral Energy Distribution (SED) of the disk, at any radius, is determined by a combination of the dust temperature, the dust emissivity properties, and the optical depth through the disk. ALMA, with its wide frequency coverage, extended baseline configurations, and large collecting area, is well designed for this type of observation.

Receivers: Bands 3, 6, 7 and 9 To disentangle the dust emissivity properties from the dust temperature and optical depth, observations are required at several different frequencies, preferably from either side of the thermal emission peak. In this proposal, observations are to be made at ~110 GHz, 230 GHz, 345 GHz, and 690 GHz.

Angular Resolution: 0.1" The typical size of a protoplanetary disk is ~100 AU and thus the desire to analyse individual radial annuli leads to a size scale ~20 AU. With the nearest protostars 200 pc away, this requirement enforces a 0.1" angular resolution (for all receivers the size of the primary beam will remain >5" or 1000 AU ensuring that the entire disk is observed within a single pointing). Note, however, that the large frequency range (100 GHz - 700 GHz) ensures that either the attained angular resolution will vary dramatically between receiver bands or the observations will be taken over a wide range of dates, as the ALMA array moves through its configuration cycle.

Spectral Resolution: N/A As the purpose of this proposal is the determination of the SED through sensitive measures over a large frequency range, each measurement will include the largest bandwidth possible (sacrificing spectral resolution for continuum sensitivity).

Continuum Sensitivity: 33 mK, 60 mK, 0.1 K, and 0.2 K for Bands 3, 6, 7, and 9, respectively. We wish to probe the surface brightness of the disk, which is likely to have a temperature of ~20 K. The disk will be optically thin at the observed frequencies, with the possible exception of Band 9. As the optical depth increases with decreasing frequency, higher sensitivity is needed for the lower bands.

Observing Time: Using the ALMA integration time calculator, it will take 4.5 hours of observing with Band 3 (110 GHz), 0.25 hours of observing with Band 6 (230 GHz), 0.10 hours of observing with Band 7 (345 GHz) and 0.02 hours of observing with Band 9 (690 GHz), for a total of 5 hours per disk observed. The Band 3 observation takes most of the observing time but is especially required as this frequency will have the lowest optical depth and thus will provide the most valuable information for determining dust emissivity properties..

[Based on a DRSP project submitted by S. Guilloteau, et al.]

2.3 - Magnetic Field Geometry in Protostellar Envelopes

Science Goal: ***To detect continuum polarization from the innermost regions of a protostellar core.***

Magnetic fields are hypothesized to play a significant role during the dynamical infall of circumstellar material onto the central protostar. For example, the ambipolar diffusion of neutrals within the protostellar envelope may weaken the local magnetic support, allowing collapse. At the same time, the details of the mass accretion may be significantly affected by the residual magnetic flux.

Submillimeter continuum polarimetry presents an excellent method for tracing magnetic fields. Nonspherical, charged dust grains aligned by ambient magnetic fields will emit thermal emission that is polarized along the long axes of the grains. By tracing this polarized emission with extremely high sensitivity, the ALMA Band 7 receivers can be used to map the direction of magnetic field projected onto the plane of sky from the innermost radii of the circumstellar envelopes around individual protostars.

Receivers: Bands 7 For this experiment the Band 7 receiver (345 GHz) provides the highest sensitivity to polarized dust emission.

Angular Resolution: 1.0" The typical envelope size is thousands of AU and thus angular resolution is not a signficant concern. Adopting 1.0" angular resolution ensures that at a distance of 200 pc the envelope is resolved at the 200 AU length scale.

Number of Pointings: 7 At 345 GHz, the instantaneous field of view is about 18" but the sensitivity varies dramatically from the center to the edge. Given the large extent of the protostellar envelope, an hexagonal mosaic around the central pointing, seven fields in all, will provide uniform coverage over an ~20" field of view (4000 AU at a distance of 200pc).

Continuum Sensitivity: 100 μK Assuming an envelope has a simple R^{-2} radial density profile, the inner envelope should have emission of ~10s of mK or more. Taking a 3% polarization, yields a polarized signal of > 500 μK. To attain a ~5 sigma level therefore requires a sensitivity of 100 μK.

Single-Dish/ACA Use: Given the desire for high fidelity across the spatial scales, from 1.0” to 20”, total-power single dish measurements and the ACA should be utilized in tandem with the ALMA array.

Observing Time: Using the ALMA integration time calculator, it will take 14 hours to reach 100 μK brightness sensitivity for one pointing, while cross correlating all polarization information. Thus, the combined seven pointing mosaic will require almost 100 hours of observing time. (Note: to obtain large-scale polarization data of similar sensitivity, greater than 100 hours would be required with the ACA).

[Based on a DRSP project submitted by J. Richer]

3. Solar System Astronomy

3.1 - Direct Detection of Jupiter Around a Nearby Solar-like Star.

Science Goal: ***To directly detect Jupiter-like planets around nearby solar-type stars.***

A Jupiter analogue at the distance of α Centauri will have a 345 GHz flux density of 6 μJy, while α Cen A itself is expected to have a flux density of 19 mJy at this frequency. Such a planet, moving on the same orbit around α Cen A as Jupiter does around the Sun (~5 AU), will have a maximum elongation projected distance of 3.9" from α Cen A.

Angular resolution: 0.1" The primary beam of an ALMA antenna is >15", at 345 GHz, and thus a single pointing will suffice to capture both sources. High angular resolution is beneficial in this case since the objects under investigation are effectively point sources. From the angular resolution formula the array baseline should be about ~ 2 km.

Receivers: Band 7 For this proposal we are interested in maximizing our ability to observe the Jupiter analogue and thus choose a high frequency receiver band where the planet will appear brightest. At the highest frequency bands, however, the atmosphere becomes a major obstacle and thus as a compromise we settle on Band 7.

Spectral Resolution: N/A There will be no attempt to resolve individual spectral features and thus the correlator will be set to cover the broadest bandwidth possible, 16 GHz.

Continuum Sensitivity: 2 μJy The expected brightness of the source is only ~ 6 μJy at 345 GHz. A 3 sigma detection requires a 2 μJy RMS (equivalent to 4 mK in a 0.1" beam at 345 GHz).

Observing Time: Using ALMA, this planet could be detected at the 3 sigma level (rms = 2 μJy) in ~175 hours. The dynamic range of ~10000 (i.e. maximum signal from the star over rms noise) necessary for this observation should be easily reachable, given that self-calibration can be employed using α Cen A as a reference.

[Based on a DRSP submitted by K. Menten]

Figure 15: *Panoramic view of the OSF. © ALMA (ESO/NAOJ/NRAO)*

3.2 - Albedo & Surface Properties of a Trans-Neptunian Object

Science Goal: ***To measure the variations in continuum flux from a Kuiper Belt object.***

The distribution of object sizes in the Kuiper Belt is an indicator of their formation and collisional evolution processes. Knowledge of the albedo of these objects is needed to interpret correctly their spectra, and to search for possible correlations in the albedo-size-color space that would trace their dynamical and collisional history. This knowledge can be obtained by measuring the continuum thermal flux of these objects. For the largest of these objects, millimeter lightcurves (i.e. the variation of the thermal flux with the object rotational phase) can be obtained, providing additional information on the object surface properties, particularly their thermal inertia.

Angular resolution: 0.05" Kuiper Belt Objects are effectively point sources for ALMA and thus the highest resolution possible is preferred. From the angular resolution formula the array baseline should be ~4 km to avoid significant beam dilution.

Receivers: Band 7 For this proposal we are interested in maximizing our ability to observe Kuiper Belt objects and thus choose a high frequency receiver band where the object will appear brightest. At the highest frequency bands, however, the atmosphere becomes a major obstacle and thus as a compromise we settle on Band 7.

Spectral Resolution: N/A There will be no attempt to resolve individual spectral features and thus the correlator will be set to cover the broadest bandwidth possible, 16 GHz.

Continuum Sensitivity: 0.1 K Placing the Kuiper Belt object at 40 AU yields an expected surface temperature of ~ 40 K. If the object is 1000 km in diameter, it subtends only 0.01" on the sky and the significant beam dilution yields a brightness temperature of about 1 K.

Observing Time: Using the ALMA integration time calculator we find that it takes about an hour to reach the required continuum rms noise level of 0.1 K (0.03 mJy). To study such objects in depth would require either a dedicated campaign in time (lightcurves) or in space (census of sources), with about an hour spent per measurement..

[Based on a DRSP submitted by E. Lellouch]

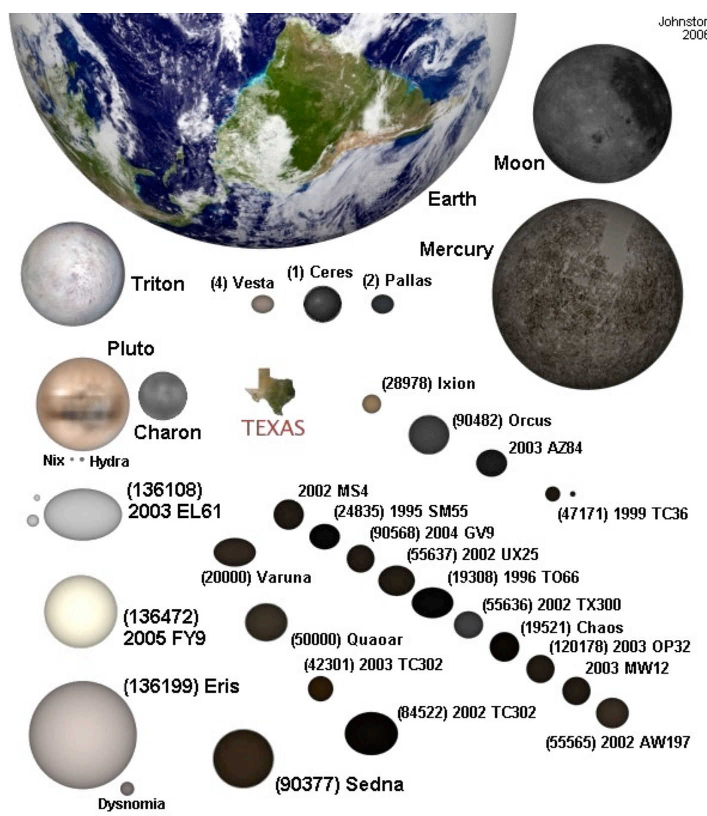


Figure 16: *Comparison of the largest TNOs, depicting relative sizes, colors, and albedos. © 2006 Johnston*

4. Stellar Astronomy

4.1 Molecular Gas in a Planetary Nebula

Science Goal: ***To map the structure of molecular gas in a Planetary Nebula using CO J = 2-1 (230 GHz).***

In most Planetary Nebulae (PNe), molecular gas is found in a torus surrounding a core of ionized gas. The detailed structure of molecular gas in PNe, however, is of great interest since it contains information on the physical processes that created the nebulae. High resolution observations of a few PNe show that the molecular gas is characterized by a high degree of fragmentation. For example, the Helix Nebula has been found to be made of thousands of small (Diameter < 1"), dense (n ~ 10^5 cm^{-3}), quiescent ($\Delta V < 1$ km/s FWHM), and faint ($T_A^* < 1$ K) clumps that are slowly evaporating in the radiation field of the central white dwarf. The origin of these tiny clumps is still debated.

Angular resolution: 0.3" Taking the Helix Nebula results as a starting point, the angular resolution needs to be set below the fragmentation scale of ~1". From the angular resolution formula the array baseline should be about 1 km.

Mosaic Required: The Helix is quite large (diameter ~ 25′) and highly fragmented. However, the diameter of the primary beam at 1.3 mm is only about 27". It would take an enormous mosaic of pointings to map the entire Helix and thus in this proposal one pointing each toward the SE and NW portion of the nebula are chosen.

Receiver: Band 6

Spectral Resolution: 0.2 km/s The spectral resolution is chosen to match the expected line profiles.

Sensitivity: 0.2 K The fragments observed in the Helix Nebula are quite faint. In this scenario, a moderate sensitivity is desired, which would detect the brighter Helix Nebula fragments.

Observing Time: Using the ALMA integration time calculator, it takes almost 20 hours to reach the required sensitivity over a single pointing. The two separate pointings will require about 40 hours of ALMA observing time.

[Based on a DRSP submitted by P. Cox.]

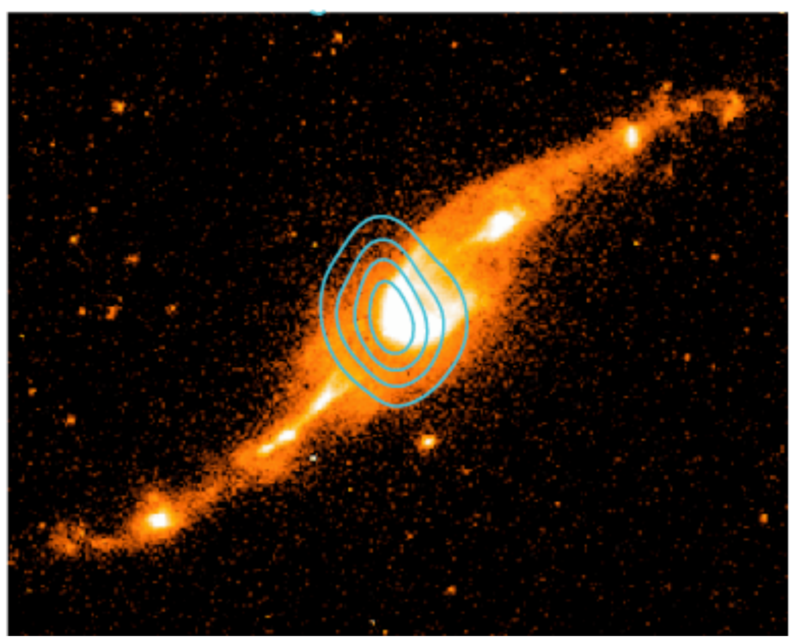


Figure 17: *Proto-planetary nebula He 3-1475, with contours of CO 2-1 emission, the latter obtained at the Plateau de Bure interferometer. © Patrick Huggins (2004, A&A, 414, 581)*

Interferometer Concepts for ALMA

Array An ensemble of antennas where signals measured by each antenna are cross-correlated with signals from all others to obtain data of high angular resolution. A homogenous array consists of antennas of the same diameter, like the 50 x 12 m antennas of ALMA. A heterogeneous array consists of antennas of different diameters, like the collection of 6 x 10 m antennas, 9 x 6 m antennas, and 8 x 3.5 m antennas comprising CARMA.

Receiver The instrument at each antenna in the array where astronomical signals are collected. The signals are combined with a highly accurate frequency signal at each antenna (the local oscillator) to produce a lower frequency (downconverted) signal that can be handled more effectively by array system electronics (e.g., amplification or transmission).

Band The emission frequency/wavelength range over which a given receiver is able to detect astronomical signals. For example, ALMA Band 3 will be sensitive to astronomical emission over the range of 84-116 GHz (2.6-3.4 mm).

Bandwidth The subrange of frequencies in a given Band over which data are obtained in a given observation. For example, Band 3 can sample 8 GHz over the 84-116 GHz range.

Correlator The component of the instrument which cross-correlates amplified, down converted signals from each antenna pair in order to produce the visibility measurement for that pair.

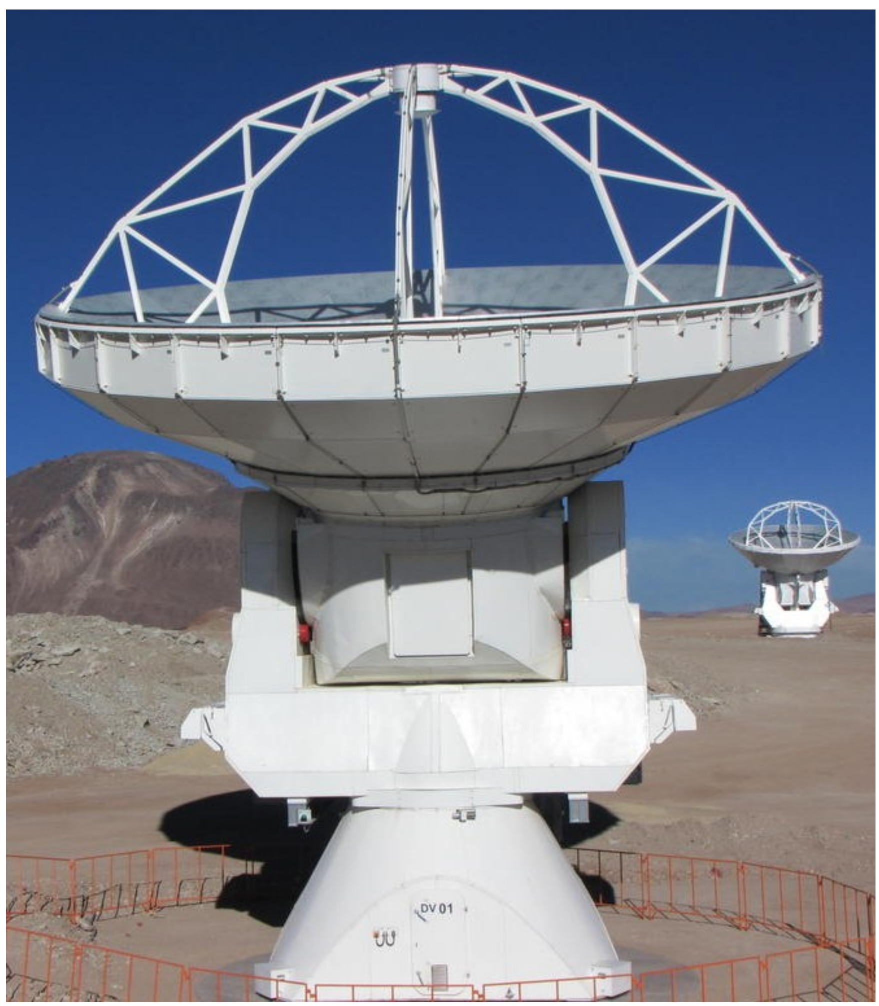


Figure 18: *First interferometry at the AOS. © ALMA (ESO/NAOJ/NRAO)*

Spectral Window (or Correlator Window) Windows are a frequency subrange of the bandwidth. Depending on the receiver/correlator specifications, the bandwidth can be sampled by a number of windows that can be moved within the bandwidth. Furthermore, each window can be divided into channels of fixed number and width. At a given window frequency, the number and width of these channels determines the velocity range and velocity resolution sampled by each window. Windows can be overlapped to produce continuous coverage across the bandwidth or placed on individual interesting features within the band.

Spatial Frequency The inverse of an angular distance scale on the sky. As in Fourier analysis, any distribution of emission can be decomposed into information over a set of such spatial frequencies. Low spatial frequencies equate to large angular scales and high spatial frequencies equate to small angular scales.

Visibility An observation of a source at a specific spatial frequency. The ensemble of (calibrated) visibilities is what is Fourier transformed to produce an image. Correspondingly, visibilities are complex numbers with amplitudes and phases that are related to the brightness and position of the emission relative to the position where the antennas are pointed. These amplitudes and phases need to be calibrated during observations by observing bright sources of known flux and position. Visibilities are sometimes referred to as fringes. Each correlator channel produces its own visibilities.

Baseline A pair of any two antennas in the array. The spatial frequency that a given baseline measures is related to the instantaneous foreshortened distance between the two antennas relative to the source and the wavelength of the observed emission. An array of N antennas will have N(N-1)/2 baselines, so the 50-antenna 12 m antenna array will have 1225 baselines.

Snapshot A short-duration set of integrations of an astronomical source using all baselines. Since only a limited number of spatial frequencies is sampled the resulting image quality can be relatively poor, unless the number of baselines is large.

Track A long-duration set of integrations of an astronomical source using all baselines. As the Earth turns, the instantaneous foreshortened distances between antennas change. Obtaining integrations over different hour angles, i.e., "tracking the source," thus allows visibilities over a larger number of spatial frequencies to be measured and the resulting images more accurately reflect the actual emission distribution (assuming zero noise and perfect calibration).

Nyquist Sampling This is the minimum sampling interval in order to preserve the signal content without introducing aliasing errors. The exact rate depends on the edge taper, but for ALMA, the Nyquist sampling rate for mosaicing fields is of order 1/2.4 × FOV.

Zero-Spacing Flux (Total Power) The large-scale emission the array cannot sample. A pair of antennas cannot be physically separated by a distance less than the antenna diameter. Hence, there is a range of low spatial frequencies (from 0 to the lowest spatial frequency sampled by the array) in any snapshot or track where emission has not been sampled, or has been "resolved out" by the array. Emission at large scales (low spatial frequencies) can be restored to images by combining array data with those from single-dish telescopes or an array of smaller antennas. For example, data from the 50-antenna extended array can be combined with data from the 16-antenna ALMA compact array to address this problem.

Primary Beam The angular sensitivity pattern of each individual antenna in the array, i.e., the sensitivity to emission relatively close to their pointing direction. The primary beam is typically approximated by a Gaussian of FHWM equal to ~1.02(λ/D), where λ is the observational wavelength and D is the antenna diameter. Parabolic radio antennas can have significant secondary angular sensitivities called sidelobes or the error beam, but these can be minimized by careful design and construction. The primary beam sets the field of view for an observation with the array, unless a larger mosaic is made.

Synthesized Beam The effective angular resolving power provided by the ensemble of transformed visibilities given its range of spatial frequency coverage. The synthesized beam is analogous to the point spread function in an optical image. A typical observation will result in a synthesized beam with a primary feature that can be approximated by a Gaussian whose FWHM is typically given as the achieved high resolution of the image or cube. Incomplete spatial frequency coverage in the observation, however, results in aliasing in the angular sensitivity, which can appear as significant secondary features to the synthesized beam. (Sometimes these are called synthesized beam sidelobes or dirty beams.)

Figure 19: *AOS technical building.* © *ALMA (ESO/NAOJ/NRAO)*

Dirty Image or Cube The dirty image is produced by the appropriate Fourier transform of the measured visibilities. A single image is produced from a given window if all channels are combined (e.g., through averaging, summing, etc.). A cube is the ensemble of images, typically ordered in velocity or frequency, where visibilities from each channel have been Fourier transformed independently of those from other channels. The image or cube is considered "dirty" because the secondary sensitivity features of the synthesized beam have distorted the location and brightness of the true emission distribution, producing unphysical artifacts. Essentially, the dirty image is the convolution of the true brightness distribution with the synthesized or dirty beam.

Clean Image or Cube A deconvolved image or ensemble of images, where the emission in each has been modeled in some manner so that distortions induced by secondary features to the synthesized beam are minimized. The optimal method of deconvolution is very dependent on the science goals of the observation.

Self-Calibration Self-calibration is the use of a bright source to solve for the relative gains of the individual antennas in phase (and, optionally, amplitude). A minimum of three antennas is required to self-calibrate phase; four antennas are required to self-calibrate amplitude. In effect, the data are compared to an input model and the observed phases are corrected to reproduce the model as well as possible. For self-calibration to work, however, the data themselves must be fairly well characterized, i.e., they must have high S/N over a wide range of spatial frequencies.

If a science target is bright enough, it can be used for self-calibration. If not, another target must be used and then the gains derived applied to the science target. Observations of the self-calibration target (a.k.a. a "phase calibrator") must be interspersed with observations of the science target because the phase gains change over time, so proximity of the two targets is desirable.

A Few Useful Links

i) **International ALMA website:** [www.almaobservatory.org]

ii) **North American ALMA Science Center:** science.nrao.edu/alma/index.shtml

iii) **Science and software tools:** science.nrao.edu/alma/tools.shtml

iv) **Canadian ALMA website:** www.almatelescope.ca