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Observing with ALMA: A Primer for *Early Science* *(Cycle 1)*

www.almascience.org

ALMA, an international astronomy facility, is a partnership of Europe, North America and East Asia in cooperation with the Republic of Chile.

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Revision History:

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1.0	18 May 2012	G. Schieven
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Contributors

This document was produced by the National Research Council of Canada with the National Radio Astronomy Observatory, with contributions from staff of the European and East Asian ALMA Regional Centers (ARCs) and the Joint ALMA Observatory (JAO).

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Figure 2: *Panorama showing the Chajnantor Plain over which ALMA antennas will be located. Chajnantor Volcano is the peak to centre right. Licanbur is the nearly perfect cone-shaped volcano toward the left. (Photo G. Schieven)*

Purpose of this Document

This document is designed to provide background information on ALMA and its capabilities during the *Early Science* stage of operations (when the telescope is available on a best-efforts basis to the general community but with limited capabilities compared to the completed array) plus basic terminology and concepts related to radio interferometry. Our goal is that, with all the basic information in one place, and a few examples of how to plan a science observation, this document can help all astronomers become familiar with ALMA's capabilities and to start planning their own ALMA observations during *Early Science*. Sections specific to *Early Science Cycle 1* are indicated in this document with an orange background.

Some Relevant Acronyms

ALMA	Atacama Large Millimeter/submillimeter Array
ACA	Atacama Compact Array
AOS	Array Operations Site (at 5000 m elevation)
ARC	ALMA Regional Center
CASA	Common Astronomy Software Applications
DSO	ALMA Division of Science Operations
ES	Early Science
FOV	Field of View
JAO	Joint ALMA Observatory
NAASC	North American ALMA Science Center
NAOJ	National Astronomical Observatory of Japan
NRAO	National Radio Astronomy Observatory
OSF	Operations Support Facility (at 2900 m elevation)
OT	Observing Tool
SCO	Santiago Central Office, headquarters of the JAO
SB	Scheduling Block
SV	Science Verification
TP Array	Total Power (or Zero Spacings) Array (part of the ACA)

Learn More

Go to http://www.almaobservatory.org/en/about-alma/acronyms for a list of the most commonly used ALMA acronyms.

Figure 3: *Another ALMA antenna takes its place at Chajnantor, carried by one of the two ALMA transporter vehicles. (Photo J. Guarda, © ALMA (ESO/NAOJ/NRAO)*

What is ALMA?

The Atacama Large Millimeter/submillimeter Array (ALMA) will be a single research instrument composed of 66 reconfigurable high-precision antennas (see Figures 7 & 8), located on the Chajnantor plain of the Chilean Andes at an elevation of about 5000-m and at a latitude of -23°.

> **Learn More**
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> Click on
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> www.almaobservatory.org/en/alma-virtual-tour
>
> for a virtual tour the ALMA site and vicinity.

Figure 4: *Map of Chile, showing the location of ALMA (red star).*

ALMA will consist of the 12-m Array, made up of fifty 12-m diameter antennas, plus the Atacama Compact Array (ACA), made up of twelve 7-m antennas packed closely together and four 12-m antennas (the Total Power (TP) Array).

ALMA will be a complete imaging and spectroscopic instrument for the millimeter/submillimeter regime, providing scientists with capabilities and wavelength coverage which complement those of other research facilities of its era, such as the Jansky Very Large Array (JVLA), James Webb Space Telescope (JWST), and planned extremely-large-aperture optical telescopes. 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 forming.

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

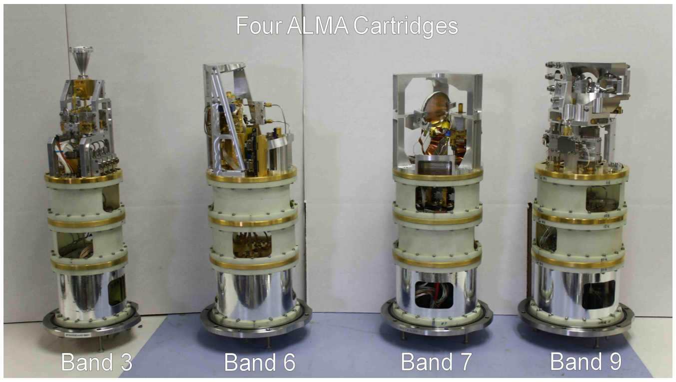


Figure 5: *Four of the ALMA receiver cartridges. Eventually ALMA antennas will be equipped with at least seven receiver cartridges, covering Bands 3-10 (see Table, page 10). The Band 3 cartridges were constructed in Canada by NRC, Band 6 in the U.S. by NRAO, Band 7 in France by IRAM, and Band 9 in the Netherlands by SRON. Bands 4, 8, and 10 are being constructed in Japan by NAOJ in collaboration with U. Tokyo.*

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.

Unlike most radio telescopes, the ALMA antennas are at a very high altitude of 5000 m on the Llano de Chajnantor in northern Chile (see Figure 4). This is more than 750 meters higher than Mauna Kea and more than 2300 meters higher than Cerro Paranal. Decade-long monitoring studies of the sky above this site have shown it to have the dryness and stability essential for ALMA (Figure 6). The site is large and open, allowing easy re-positioning of the antennas over an area at least 16 km in extent.

ALMA Chilean operations are the responsibility of the JAO. The telescope array itself is located at the Array Operations Site. 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, retrieve, or move equipment and antennas. OSF site facilities include the array control room, offices, labs, staff residences, and a contractor camp. The OSF will handle the ongoing operations, maintenance, and repairs of ALMA antennas and receivers. The JAO has a central office in Santiago .

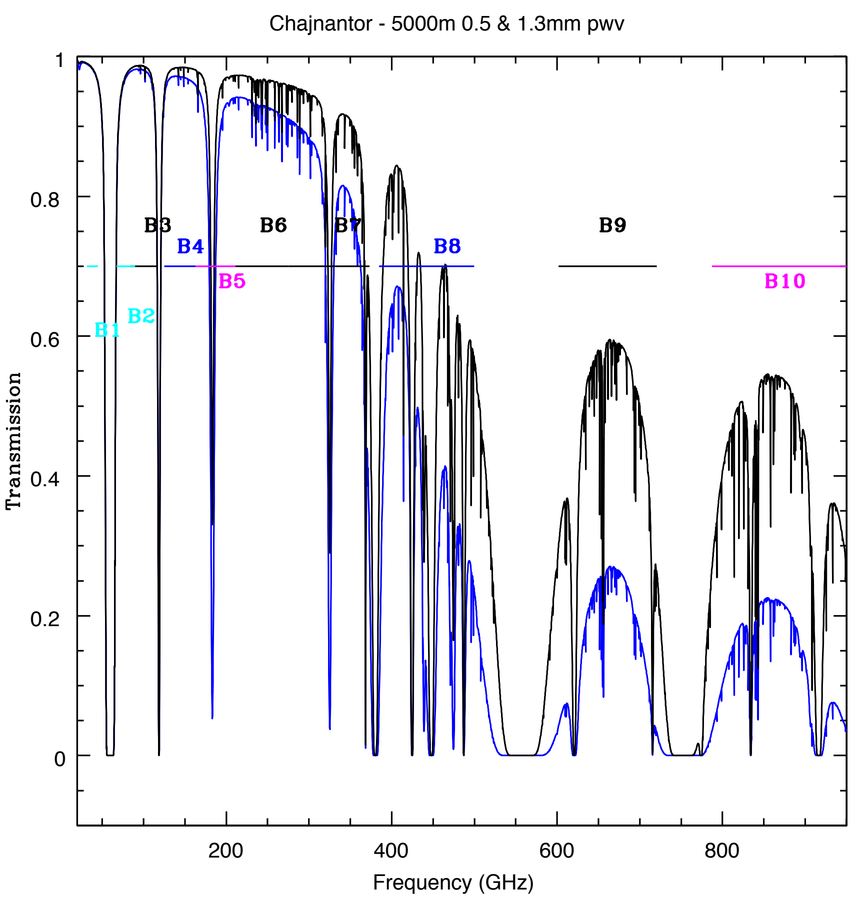


Figure 6: *Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency. Plotted in blue and black are the transparency values for the 50th, and 12.5th percentile weather conditions respectively averaged over the year. This means that 50% of the time the sky transparency is better than shown in the blue line, and 1/8 of the time is better than the black line. The horizontal lines represent the frequency coverage of the ALMA receiver bands. Bands 3, 6, 7 and 9 (black) are available on all antennas in Cycle 1. Plots such as this can be generated via the Science Portal (under "About ALMA" -> "Weather") for any frequency range and value of water vapor.*

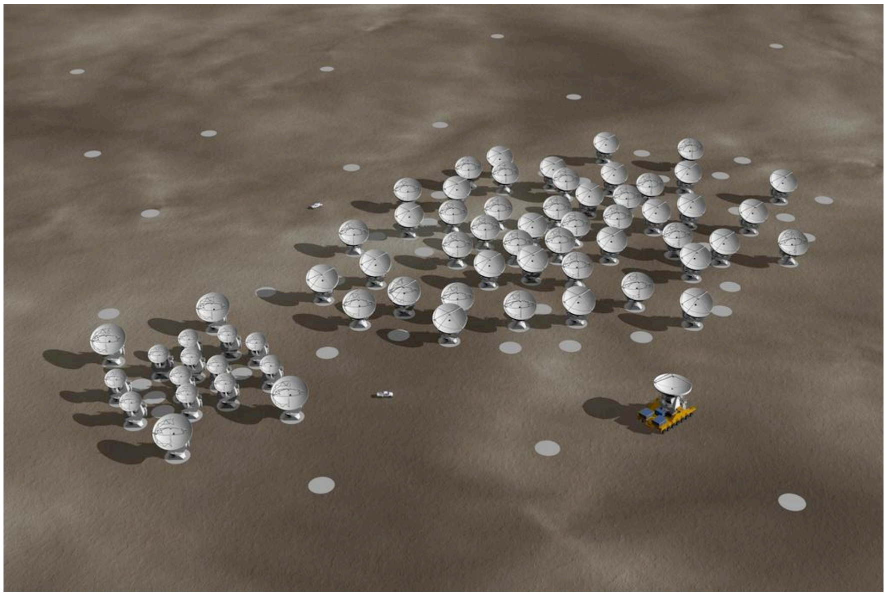


Figure 7: *Artists conception of the ALMA 12-m Array in its compact configuration, with the ACA toward the left, and the transporter in the lower right. A few unoccupied pads can be seen, to which antennas of the 12-m Array can be moved by the transporter as the array is being reconfigured. At its most extended configuration, antennas in the 12-m array will be up to 16 km apart (see Figure 8).*
© ALMA (ESO/NAOJ/NRAO)

What is Interferometry?

In contrast to direct imaging technology like a CCD camera, the image quality from an interferometer depends on more than pure sensitivity. An interferometer reconstructs an image of the sky from measurements of specific spatial frequencies, i.e. measurements of the Fourier transform of the sky brightness. The raw data, called "visibilities", correspond to measurements at single positions in Fourier transform space, and thus the reconstructed image quality is very sensitive to the "*uv*-coverage" — how completely the raw visibility data covers the range of real angular scales on the sky. For example, if you take a very short "snapshot" observation with an interferometer, the "*uv*-coverage" will be a set of points corresponding to each independent baseline, with positions in Fourier space related to the distance between each pair of antennas and the position angle of the baseline vector; the resulting image quality will be much poorer than implied by a sensitivity calculation. One increases the *uv*-coverage by changing the relative positions of the antennas as projected in the source direction, by (1) the rotation and foreshortening of baselines due to Earth rotation over time; (2) reconfiguring the telescopes to provide new baselines and observing again (see figs. 7 & 8); and/or (3) adding more antennas to the array to improve the instantaneous *uv*-coverage. With ALMA both (1) and (2) are possible and (3) is why ALMA will ultimately have 66 antennas (50 in the 12-m Array, 12 in the 7-m Array, and 4 in the TP Array). For a more detailed description of these terms, see “Interferometry Concepts for ALMA” starting on page 34.

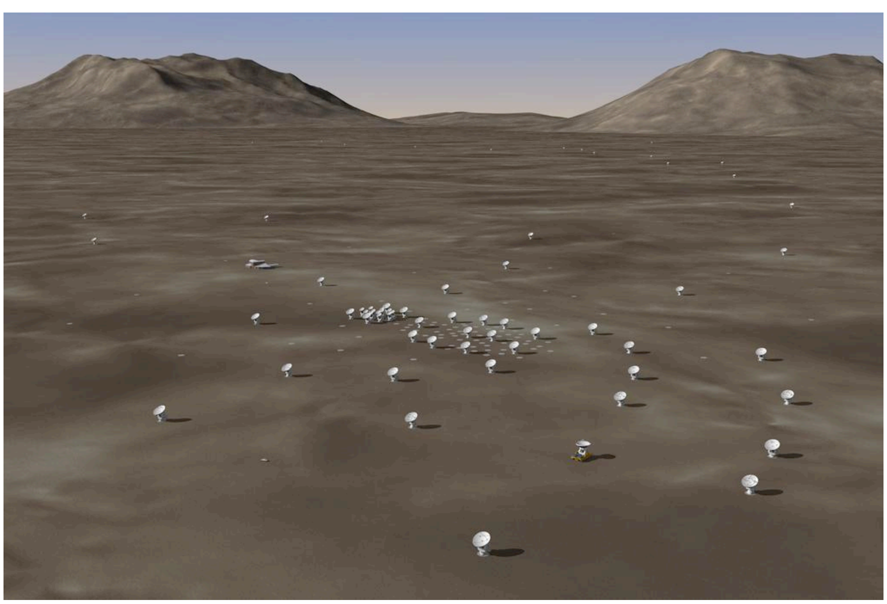


Figure 8: *The 50 antennas of the ALMA 12-m array will be reconfigurable by moving them to pads scattered across the Chajnantor plain. Here we see an artist’s conception of an extended configuration, where antennas are spaced as far apart as 16 km. The AOS is the small building left of center of the picture, and the tight clump of antennas near the center is the ACA. © ALMA (ESO/NAOJ/NRAO)*

Learn More

The Science Portal is your gateway to ALMA at

http://almascience.org/

What is *Early Science*?

Though the construction phase of ALMA will not be completed until 2013, by late 2011 the facility was already the world's most powerful millimeter/submillimeter telescope. *Cycle 0* was the astronomical community's first opportunity to propose to observe with the facility with reduced (but still substantial) capability. *Cycle 1* gives the community access to the facility with many more antennas and capabilities than *Cycle 0*, though still with somewhat less support than will be available during Full Operations.

ALMA *Cycle 1* Capabilities

During *Cycle 1*, some of ALMA's capabilities will include:

- Thirty-two antennas in the 12-m array, plus nine 7-m and two 12-m antennas in the Compact Array
- A range of configurations with maximum baselines from 160 m to 1 km
- The ability to recover some extended structure with the ACA
- Wavelength coverage in Bands 3, 6, 7 & 9 (see table page 10)
- Single field imaging, and mosaics (of up to 150 pointings)
- Ability to use more complicated correlator modes, for example allowing both high spectral resolution and continuum simultaneously
- Users should consult the *Proposer's Guide* issued at the *Call for Proposals* by the JAO and ARCs for an exact description of capabilities that will be available.

During Full Operations, some of ALMA's capabilities will include:

- Fifty 12-meter antennas (the *12-m Array*) for sensitive, high-resolution, high fidelity imaging
- Four additional 12-meter antennas providing total power (TP Array) and twelve 7-meter antennas comprising the ACA, enhancing the fidelity of wide field imaging
- Imaging ability in all atmospheric windows from 3.5 millimeters to 300 microns (84 - 950 GHz), with coverage extending to 10 millimeters (30 GHz) possible through future receiver development
- 12-m Array configurations with maximum baselines from 150 m to 16 km
- ACA configurations with baselines ranging from 9 m to 50 m
- Ability to image sources many arcminutes across (i.e. accurately recover structures up to arcminutes in size) at sub-arcsecond resolution
- Angular resolution as small as 5 milliarcseconds at 950 GHz
- Flexible spectrometer (correlator) modes, with as many as 32 separate spectral windows within the 8 GHz passband (per polarization)
- Velocity resolutions as fine as 8 m/s ($\times$ 300/ν GHz)
- Ability to "split" the array into several sub-arrays, which could observe different frequencies/ targets simultaneously
- Full Stokes polarization capability

The ALMA Correlator is an immensely powerful and flexible instrument, but during *Early Science* a limited set of modes will be supported. The following are available for *Cycle 1*.

ALMA *Early Science* Correlator Modes

Mode	Polarization	Bandwidth (MHz)	Nchan	Chan. Spacing (MHz)	Velocity Resol'n† 300 GHz (km/s)	Mode	Polarization	Bandwidth (MHz)	Nchan	Chan. Spacing (MHz)	Velocity Resol'n† 300 GHz (km/s)
FDM	***Dual***	***1875***	***3840***	**0.488**	**0.98**	***FDM***	***Single***	**1875**	**7680**	**0.244**	**0.49**
FDM	***Dual***	***938***	***3840***	**0.244**	**0.49**	***FDM***	***Single***	**938**	**7680**	**0.122**	**0.24**
FDM	***Dual***	***469***	***3840***	**0.122**	**0.24**	***FDM***	***Single***	**469**	**7680**	**0.061**	**0.12**
FDM	***Dual***	***234***	***3840***	**0.061**	**0.12**	***FDM***	***Single***	**234**	**7680**	**0.0305**	**0.061**
FDM	***Dual***	***117***	***3840***	**0.0305**	**0.061**	***FDM***	***Single***	**117**	**7680**	**0.0153**	**0.031**
FDM	***Dual***	***58.6***	***3840***	**0.0153**	**0.031**	***FDM***	***Single***	**58.6**	**7680**	**0.00763**	**0.015**
TDM	***Dual***	***2000‡***	***128***	***15.625***	***31.2***	***TDM***	***Single***	***2000‡***	***256***	***7.8125***	***15.6***

†Note: Resolution is 2 × the spacing due to a Hanning filter applied to the data. Quoted resolution is at 300 GHz (1 mm).
‡Note: Because of filtering, the useful (effective) bandwidth of this mode is 1875 MHz.

Each receiver outputs four 2 GHz-wide basebands in each polarization, which are fed into the correlator. The correlator can further split each baseband into multiple spectral windows, whose bandwidths and channel spacings are defined by correlator modes (table above). In *Cycle 1*, the correlator is limited to one spectral window per baseband, but the spectral windows can have different modes. For example, one might want to use one window for a high resolution narrow-bandwidth observation of a spectral line, and set up the other three in TDM mode for continuum (see example, page 26).

During *Cycle 1*, thirty-two 12-m antennas will be available, in a range of configurations from "most compact" (maximum baseline 160 m) to "most extended" (maximum baseline 1 km). In the table below, the sensitivities assume an integration time of 60 seconds, a continuum bandwidth of 7.5 GHz, and a spectral resolution of 0.976 MHz. (From the on-line ALMA Sensitivity Calculator adopting the default weather conditions*) See pp. 14-16 for a discussion of resolution and maximum scales with the ACA.

Cycle 1 Capabilities					Most Compact			Most Extended		
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy/beam)	Angular Resolution (")	Approx. Max. Scale (") (see P.14)	ΔT_{line} (K)	Angular Resolution	Approx. Max. Scale (") (see P.14)	ΔT_{line} (K)
3	***84-116***	***2.6-3.6***	***72-52***	**0.11**	**4.4-3.2**	**29-21**	**0.09**	**0.7-0.5**	**10-7**	**3.4**
6	***211-275***	***1.1-1.4***	***29-22***	**0.14**	**1.7-1.3**	**12-9**	**0.11**	**0.27-0.21**	**4.1-3.1**	**4.5**
7	***275-373***	***0.8-1.1***	***22-16***	**0.24**	**1.4-1.0**	**8.9-6.6**	**0.18**	**0.21-0.15**	**3.1-2.3**	**7.5**
9	***602-720***	***0.4-0.5***	***10-8.5***	**2.2**	**0.6-0.5**	**4.1-3.4**	**1.8**	**0.09-0.08**	**1.4-1.2**	**80**

*Note: These sensitivities were calculated using the expected receiver temperatures at the time of writing, and may not represent the values that are currently available. For the most up-to-date values, use the ALMA Sensitivity Calculator.

ALMA *Full Array Specifications*

	Specification
Number of Antennas	***At least 50×12-m (12-m Array), plus 12×7-m & 4×12-m (ACA)***
Maximum Baseline Lengths	***0.15 - 16 km***
Angular Resolution (")	***~0.2" × (300/ν GHz) × (1 km / max. baseline)***
12-m Primary beam (")	***~20.6" × (300/ν GHz)***
7-m Primary beam (")	***~35" × (300/ν GHz)***
Number of Baselines	***Up to 1225 (ALMA correlator can handle up to 64 antennas)***
Total Bandwidth	***16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)***
Velocity Resolution	***As narrow as 0.008 × (ν/300 GHz) km/s***
Polarimetry	***Full Stokes parameters***

In the table below, the sensitivities assume an integration time of 60 seconds, a continuum bandwidth of 7.5 GHz, a spectral resolution of 0.976 MHz, and 50 antennas in the 12-m Array in the "compact" vs. most "extended" array configurations. (From the on-line ALMA Sensitivity Calculator adopting the default weather conditions†):

Full Science Capabilities						**Most Compact**		**Most Extended**	
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Approx. Max. Scale (")	Continuum Sensitivity (mJy / beam)	Angular Resolution (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
1‡	***31.3-45***	***6.7-9.5***	***145-135***	***93***	***‡***	***13-9***	***‡***	***0.14-0.1***	***‡***
2‡	***67-90***	***3.3-4.5***	***91-68***	***53***	***‡***	***6-4.5***	***‡***	***0.07-0.05***	***‡***
3	***84-116***	***2.6-3.6***	***72-52***	***37***	***0.07***	***4.9-3.6***	***0.04***	***0.05-0.038***	***430***
4	***125-163***	***1.8-2.4***	***49-37***	***32***	***0.06***	***3.3-2.5***	***0.048***	***0.035-0.027***	***330***
5	***163-211***	***1.4-1.8***	***37-29***	***23***	*	*	*	*	*
6	***211-275***	***1.1-1.4***	***29-22***	***18***	***0.09***	***2.0-1.5***	***0.05***	***0.021-0.016***	***490***
7	***275-373***	***0.8-1.1***	***22-16***	***12***	***0.15***	***1.5-1.1***	***0.08***	***0.016-0.012***	***814***
8	***385-500***	***0.6-0.8***	***16-12***	***9***	***0.40***	***1.07-0.82***	***0.28***	***0.011-0.009***	***1900***
9	***602-720***	***0.4-0.5***	***10-8.5***	***6***	***1.4***	***0.68-0.57***	***0.9***	***0.007-0.006***	***8900***
10	***787-950***	***0.3-0.4***	***7.7-6.4***	***5***	***1.2***	***0.52-0.43***	***1.6***	***0.006-0.005***	***—***

‡To be developed in the future. *Available on a limited number of antennas

†Note: These sensitivities were calculated using the expected receiver temperatures at the time of writing, and may not represent the values that are currently available. For the most up-to-date values, use the ALMA Sensitivity Calculator.

ALMA Regional Centers (ARCs)

Each of the three ALMA regional partners (Executives) maintain an ALMA Regional Center (ARC) within its respective region. The ARCs provide the gateway to ALMA for astronomers, whether for information, assistance through the Helpdesk, for submitting proposals and science goals through the OT, or acquiring data through the archive.

Learn More

The three ARCs can be reached through their web sites:

NAASC http://science.nrao.edu/facilities/alma/

EU-ARC http://www.eso.org/sci/facilities/alma/arc.html

EA-ARC http://alma.mtk.nao.ac.jp/e/forresearchers/ea-arc/

The North American ARC is part of the North American ALMA Science Center (NAASC) based at NRAO headquarters in Charlottesville, VA, USA, and with the assistance of the National Research Council of Canada (NRC), is responsible for supporting the science use of ALMA by the North American and Taiwan astronomical communities, and for research and development activities in support of future upgrades to ALMA.

European researchers are supported by the EU-ARC, based at the ESO headquarters in Garching, Germany, along with regional nodes based in Germany, Italy, Sweden, France, the Netherlands, the United Kingdom, and the Czech Republic.

The East Asian ARC (EA-ARC) is based at the NAOJ headquarters in Tokyo, in collaboration with Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), and supports the astronomy communities of Japan and Taiwan.

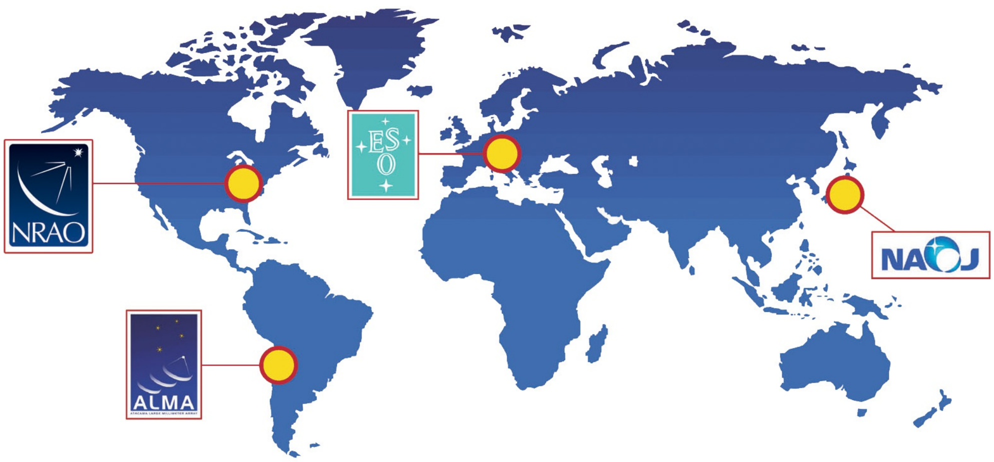


Figure 9: *ARCs are located in North America, Europe, and East Asia. The ALMA headquarters are located in Santiago, Chile © ALMA (ESO/NAOJ/NRAO).*

Figure 10: *Array in the moonlight. Image courtesy of Stéphane Guisard (© 2011, www.astrosurf.com/sguisard)*

Science with ALMA

Level One Science Aims for Full Operations

While ALMA will revolutionize many areas of astronomy, the ALMA Project has three Level One Science Aims for Full Operations that drive its 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 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 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

When completed (i.e. during Full Operations), ALMA will also be able 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

Figure 11: *The Antennae, a pair of interacting galaxies in Corvus, was the subject of Science Verification observations by ALMA. Shown here are an optical picture (blue) taken by the HST, and ALMA data taken in Band 3 (red) and Band 7 (pink/yellow). These data are publicly available from the ALMA Science Portal, and are the subject of the very first refereed science article to appear from ALMA (Herrera et al., 2012, A&A 538, L9). (Images © ALMA (ESO/NAOJ/NRAO) and NASA/ESA (HST)).*

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.

• Reveal the details of how stars form from the gravitational collapse of dense cores in molecular clouds. The spatial resolution of ALMA will enable 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. For example, establishing the role of the freeze-out of gas-phase species onto grains and the re-release of these species back into the gas phase in the warm inner regions of circumstellar disks. ALMA will have the large total bandwidth, high spectral resolution, and sensitivity needed to detect the myriad lines associated with the heavy, pre-biotic molecules that 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.

• Study physics of the Sun; refine dynamical and chemical models of the atmospheres of planets in our own Solar System and provide unobscured images of cometary nuclei and hundreds of other Solar System objects.

• Countless other science goals, including unforeseen discoveries which always occur when exploring new wavelength/sensitivity/resolution regimes.

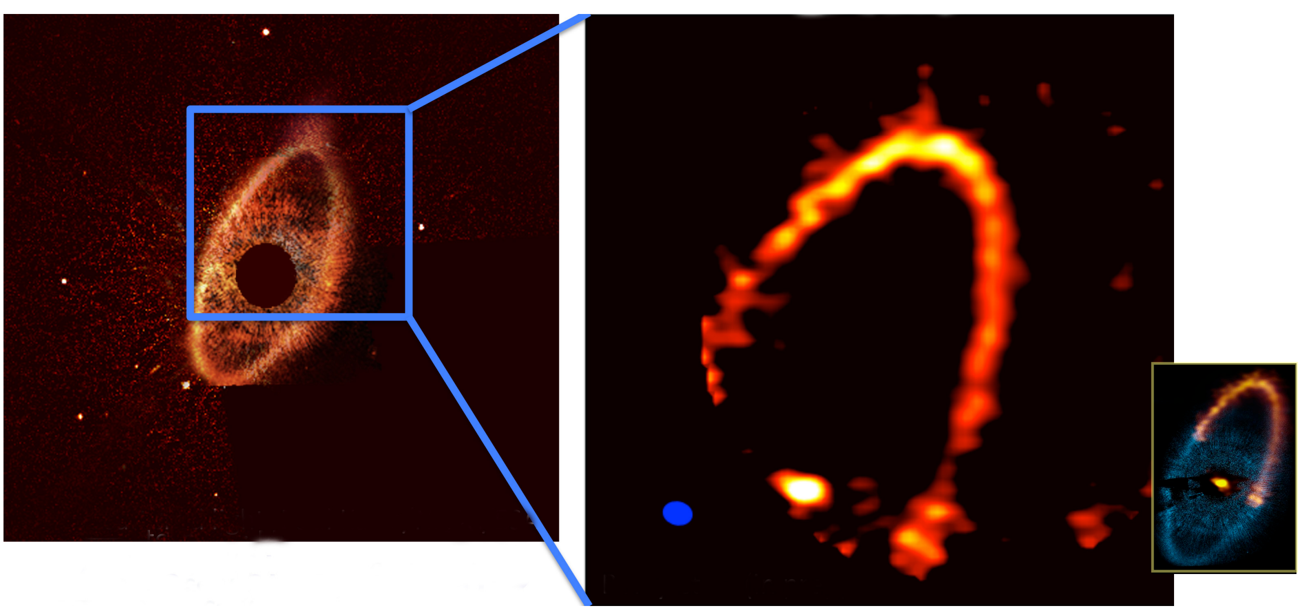


Figure 12: *(Left) HST coronographic image (credit: Paul Kalas/NASA/ESA) showing scattered light from the debris ring surrounding Fomalhaut. (Right) ALMA Cycle 0 Early Science image of 850 μm dust emission from (part of) the ring itself. (Inset lower right: The two images superposed.) The ring's morphology and blobby appearance is consistent with its being dominated by "shepherd planets". The bright "blob" to the lower left is emission from Fomalhaut itself. The blue oval represents the size of the synthesized beam. The image is about 30" on a side. (Image from Boley et al., 2012, ApJ, 750, L21.)*

ALMA During *Early Science*

From the start of *Early Science* observing in late-September 2011 (*Cycle 0*), ALMA was already a powerful millimeter/submillimeter interferometer. A number of *Early Science* example projects suitable for *Cycle 1* has been compiled by the world-wide ALMA science staff and can be found on pages 17 to 26.

> **Learn More**
> Resources for Scientists (including the Science Portal and ALMA Science Archive) can be found at
> http://almascience.org/

Observations during *Early Science* will be performed in service observing mode by ALMA Operations personnel on a "best efforts" basis. A high priority will be placed on completing projects, but completion cannot be guaranteed during *Early Science*.

Before You Propose for Early Science

In order to be able to submit proposals using the OT, or request help from the Helpdesk, you will need to be registered through the ALMA Science Portal.

When putting together a proposal for *Early Science* using the OT, one should have at hand:

- A Science Case
- Source coordinates
- Observing frequency, bandwidth, velocity resolution
- Required spatial resolution and largest angular scale. In inter-

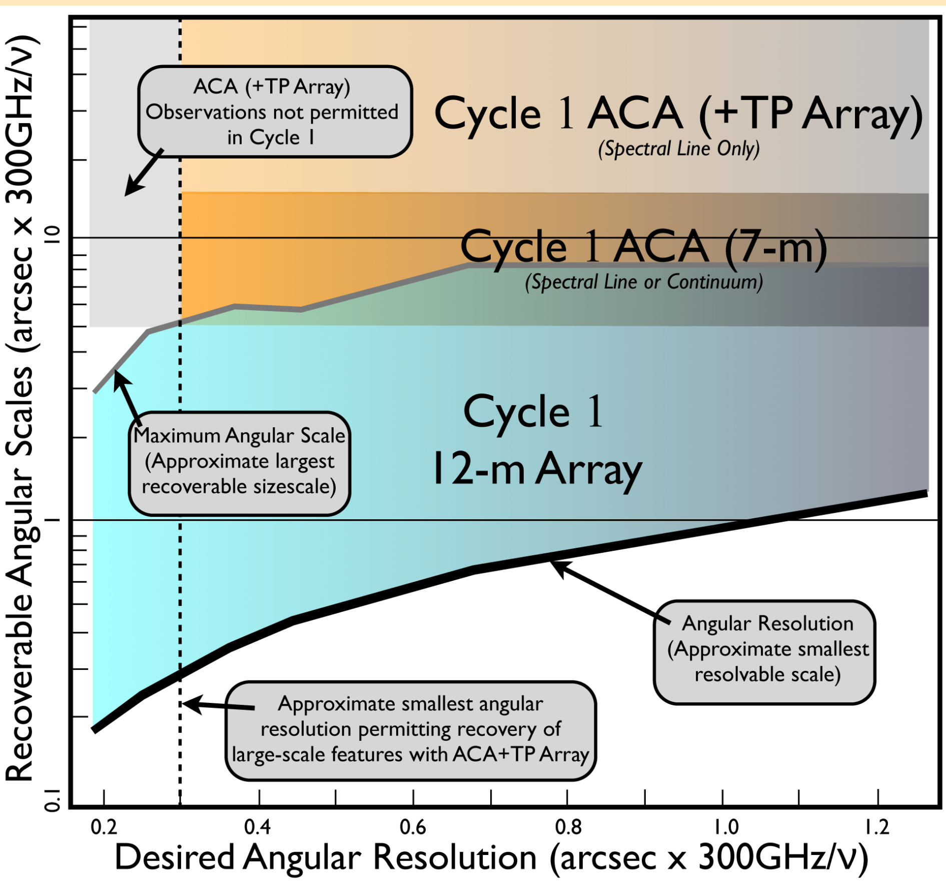


Figure 13: *With 32 antennas available in the 12-m Array during Cycle 1, when one selects a desired angular resolution (e.g. 0.7″ at 300 GHz), an observation can recover structure over a range of angular scales (e.g. from 0.7″ to ~8″; blue region). Larger structures are "resolved out" by the interferometer, but may be recovered, if needed, by combining observations from the ACA (dark orange region). With the ACA 7-m Array combined with 12-m Array, structures from 0.7″ to ~15″ (at 300 GHZ) can be recovered from the data. Still larger structure (up to the size of the 7-m primary beam) can be reconstructed using data from the TP Array (pale orange), but only for spectral line observations (the TP Array does not support continuum observations in Cycle 1). However, for resolutions requiring the most extended 12-m Array configurations (indicated by the vertical dashed line) there is little baseline overlap between the 12-m and 7-m Arrays, and ACA observations will not be permitted for Cycle 1. Values quoted here are only approximate, and full uv-simulation using the CASA Simulator or the Observation Support Tool may be needed.*

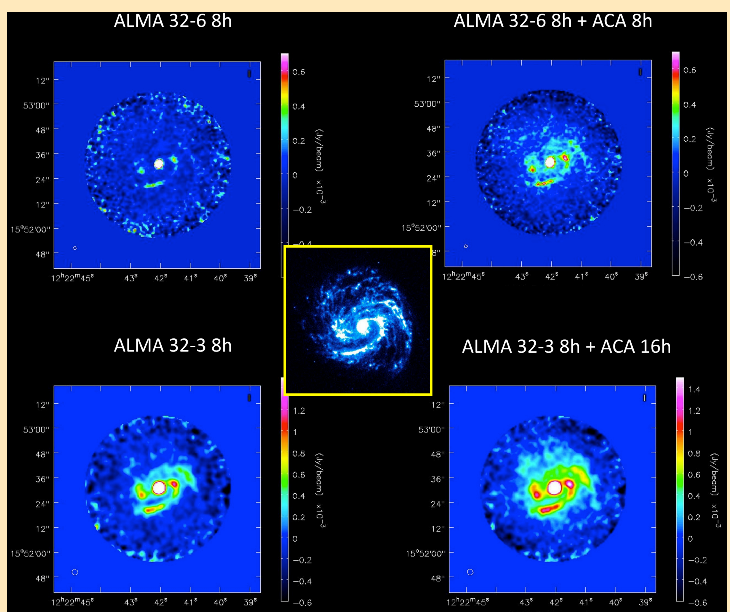
ferometry, the angular resolution (i.e. the smallest scale structure that can be resolved) is governed by the largest distances between antennas (largest baselines), but the maximum size-scale structure that can be observed and recovered depends on the size of the smallest baselines, i.e. the distances between the closest antennas. (See *uv-coverage* and *maximum angular scale* in the Glossary of Terms starting on page 34.) ALMA 12-m Array plus ACA observations (including the TP Array to give *zero spacings*) allow both large- and small-scale structure to be recovered from the data because the antennas of the ACA can be packed much closer together than the 12-m array. Figure 13 shows the approximate range of angular scales which can be recovered when observing with the 12-m ALMA array alone, and when coupled with ACA (including the TP Array to give *zero spacings*), for a given angular resolution during *Cycle 1*. Note that these are only approximations, and that full *uv* simulations using the CASA *Simulator* or the Observation Support Tool may be necessary. Figure 14 shows an example of simulated observations of a galaxy, and Figure 15 shows examples of when the ACA would or would not be necessary.

> **Learn More**
> about the ALMA Sensitivity Calculator
> and simulating ALMA data with the *CASA Simulator*
> or Observation Support Tool at
> http://almascience.org/documents-and-tools/

- Required sensitivity. Care must be taken when estimating the sensitivity needed per synthesized beam, particularly if estimating the source brightness from single-dish observations. A source which is bright in, say, a 30″ beam, may be difficult to detect in a 0.5″ beam if the emission is spread out over a few arcseconds.
- Dynamic range needed. The dynamic range in an image improves with the length of the observation and the number of baselines (which goes nearly with the square of the number of antennas). Fields where there is a bright source but where the faint emission is of interest may be better observed during Full Operations.

During *Cycle 1* with 32 antennas, ALMA will have 496 baselines (roughly 40% of the 1225 baselines with the 50 antennas of the full array), so has more than four times better "snapshot" (< 1h observation) *uv*-coverage than during *Cycle 0* when only 120 independent baselines were available. Thus even in *Cycle 1* the array should be able to image most "simple" fields with good fidelity. However, if your science aim involves imaging a complex field, one with a nearby bright source, or requires very high signal-to-noise, then the *uv*-coverage is as important to consider as sensitivity. If you have a reasonable model for your source structure and brightness, an ALMA simulator (e.g. CASA *Simulator* or the web based Observation Support Tool) can be used to test and demonstrate the *uv*-coverage needed to achieve your imaging requirements. As an example of what the CASA *Simulator* can do, see Figures 14 and 15.

Figure 14: *Simulation of an ALMA Cycle 1 spectral-line observation of an M100-like galaxy at a redshift of 0.05. Inset: IRAC 8μm image of M100 used as a proxy of how the CO would appear if the galaxy were moved to z=0.05. The leftmost images show a simulated 8-hour observation of the redshifted galaxy in Band 3, using just the 32 antennas of the 12-m array in the most extended (top) and a moderately compact (bottom) configuration. The right images show the same observation after including ACA 8-hour (top) and 16-hour (bottom) data. Such simulations can be made using the Simulator in CASA, or using the on-line Observation Support Tool.*



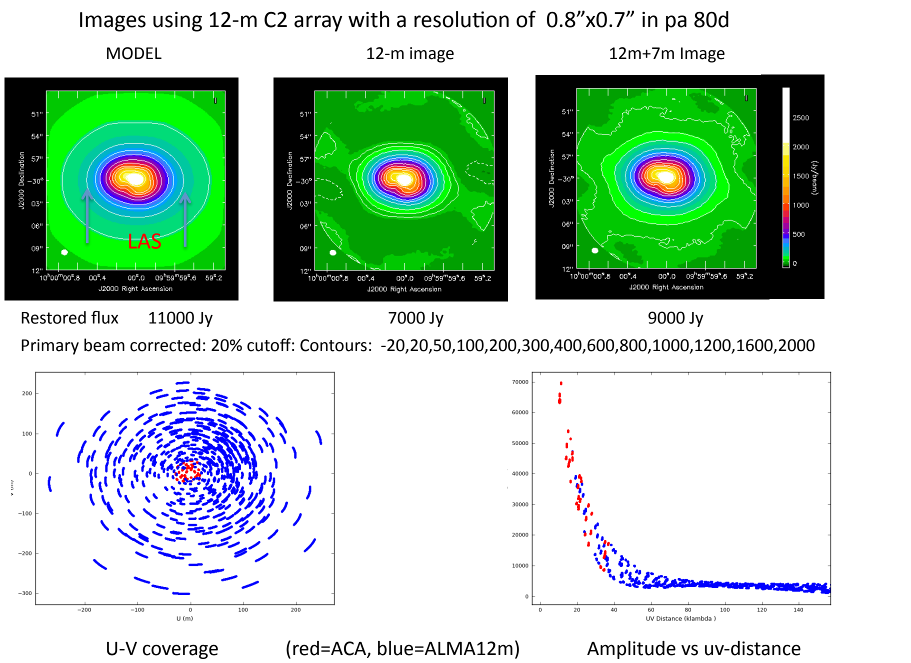


Figure 15(a)

Observing sources with a range of spatial scales (such as power-law envelopes) requires careful consideration of the effects of finite baselines and the respective uv-coverage as shown by the following analysis of reconstructed maps of complex regions. These simulations were generated using the CASA Simulator. The largest angular scale (LAS) of structure is shown by the arrows in the model image (top left image in Figures 15(a) and (b).

Figure 15(a) [above left]: *Demonstrated here is a simulated observation of a source with structure on very large angular scales. This theoretical model of e.g. a protostellar disk has a power-law envelope, so in principle has power on all spatial scales (top left). In this case, for a high-sensitivity observation, the LAS is clearly as large as the field of view.*

When observed at 345GHz with a desired resolution of 0.75″, the 12m-only ALMA observation (top center) shows that significant large-scale structure has been resolved out; this cleaned image has negative bowls, and a significant amount of restored flux is missing. The OT will recommend use of the ACA in this case, and indeed the combined 12-m Array + ACA 7-m image (top right) shows that more, but not all, of the large-scale structure is recovered (incorporating the TP Array 12-m data will add in the missing flux density). The bottom row shows the u-v coverage of the ACA (red) and ALMA-array (blue) (left) and the amplitude versus u-v spacing for the ACA and 12-m Array baselines (right). The correlated flux densities for the ACA baselines are significantly larger than that for the shortest ALMA baselines.

Figure 15(b) [below]: *Here we show simulated observations of a source which has structure only on small spatial scales, such as a cluster of compact galaxies or protostars (top left). The LAS is well-within the range of the shorter 12-m Array baselines.*

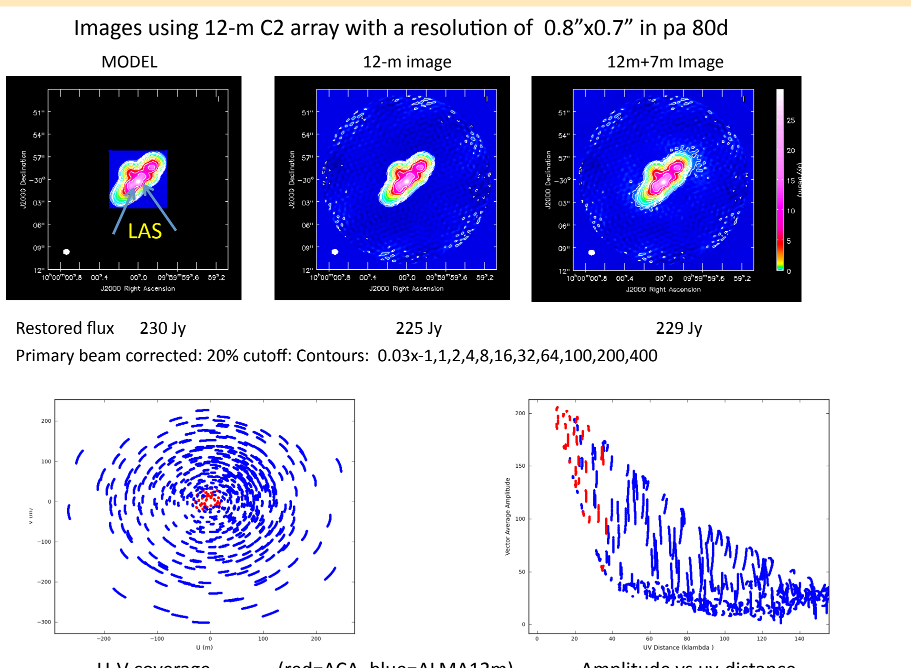


Figure 15(b)

When observed at a desired resolution of 0.75″ with just the 12-m Array (top center), we see no negative bowls in the cleaned image and the recovered flux is within 95% of the total flux density. Adding the ACA (top right) makes no significant difference.

The bottom row shows the u-v coverage of the ACA and ALMA-array (left) and the amplitude versus u-v spacing for the ACA and ALMA-array baselines (right).

In a case such as this, provided an appropriately small LAS is entered into the OT, the OT will recommend not using the ACA. However, if an erroneously large LAS is entered, or the PI requests the ACA anyway, the large increase in the time needed for the project may lead the review panel to find the request unnecessarily large to meet the science goal.

Examples of *Cycle 1* Observing With ALMA

In the following sections we provide a few examples of observations that could be done with ALMA during *Cycle 1 Early Science*. **Note that these examples use the sensitivities and capabilities of ALMA for *Early Science* as they were known at the time of the *Cycle 1* Announcement. Any astronomer proposing observations with ALMA for *Cycle 1* should carefully check the published capabilities and sensitivities at the time of the Call for Proposals**.

For each example below, we start with a brief *science aim* and discuss the required *receiver band* at which the observations should be undertaken. Next, we determine the *angular resolution* and required maximum baselines needed. Where multiple frequencies are requested, the angular resolution obtained will vary with frequency. The necessary *spectral resolution* is discussed to provide the appropriate *correlator settings* (see table page 9). As well, the *continuum* or *channel sensitivity* is quantified so the on-source *observing time* can be calculated. Users who are unfamiliar with these terms, or who would like a "refresher" on radio interferometry terms and concepts, should first read "Interferometry Concepts for ALMA" starting on page 34.

A Survey of Submillimeter Galaxies

Science Aim: ***To measure accurately the positions of SMGs***

A large fraction of the star formation activity at the epoch of galaxy evolution ($1 < z < 3$) is traced by sub-millimeter galaxies (SMGs). SMGs are typically detected with single-dish telescopes with coarse resolution; identification of a counterpart has required deep radio (centimeter) observations followed by deep optical or near-infrared spectroscopy. With ALMA, we can precisely locate SMGs very rapidly. In this example we lay out a strategy to pinpoint a large number of sources with Band 7 continuum.

Receiver Band: **Band 7 (Continuum, 345 GHz)**

Angular Resolution: ~0.25" at Band 7. A good rule of thumb is that 1" corresponds to ~ 8 kpc for z ~ 1, so spatially resolved observations could be made during *Early Science Cycle 1*. The ACA is not needed for these observations since the sources are small.

Spectral Resolution: These are purely continuum detections, so only the TDM mode (15.6 MHz channels) is required.

Continuum (Band 7) Sensitivity: In *Cycle* 1, up to 15 sources may be observed in one science goal (provided the sources are less than 15° apart) and one proposal may have up to five science goals, meaning up to 75 sources may be observed in one project. As an example, there are ~70 COSMOS-AzTEC sources (Aretxaga et al. 2011) with $S_{1.1mm} > 5$ mJy and S/N > 5. Given the exceptional atmospheric conditions at ALMA, we choose to pinpoint these sources at a higher frequency (345 GHz or 0.8 mm) where they are significantly brighter ($S \propto \nu^{\beta}$, typically β~2 at z~2). Therefore, these sources should have $S_{0.8mm} > 8$ mJy. It is possible that these sources may be extended or may resolve into more than one source, so we aim to get a S/N ~ 40, adequate to identify the counterparts and obtain excellent relative astrometric accuracy, which is usually estimated as ~ θ/(S/N).

Band 7 Observing Time: For Band 7, the ALMA sensitivity calculator, assuming thirty-two 12-m antennas and an effective 7.5 GHz continuum bandwidth per polarization, predicts 1.5 minutes integration per source to reach a 1 σ = 0.2 mJy. Each science goal of 15 sources would require about 22 minutes of on-source integration, not including overheads and calibration.

In the Future: More antennas will permit even more sensitive detections of SMGs, plus a relaxing of the restrictions on source numbers will mean much larger samples of these objects. In addition, redshift surveys will be practical when a special "spectral scan" observing mode is released, which will permit relatively simple searches for redshifted spectral lines over roughly the entire frequency range of each receiver Band.

Mapping a Lensed High Redshift, Gas-Rich Galaxy

Science Aim: ***To resolve the continuum and molecular gas in a distant lensed starburst galaxy***

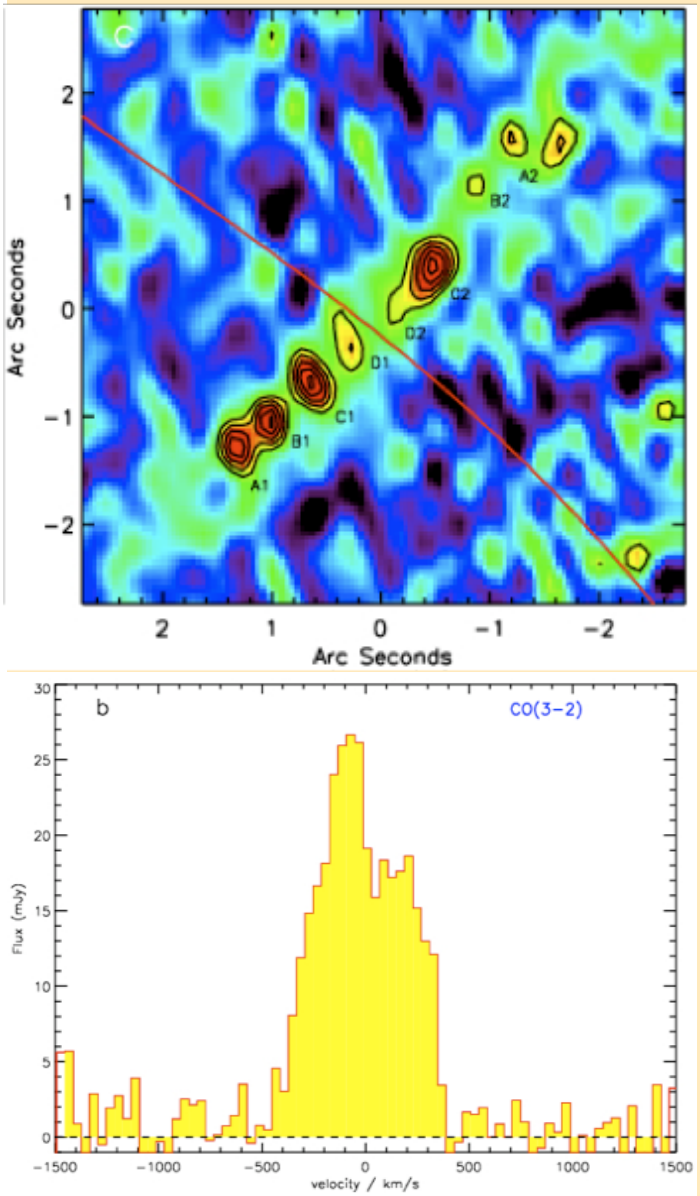


Figure 16*: (above) SMA (very extended configuration) 870 μm image of the Cosmic Eyelash. The red line marks the division between the two images of the background source. (below) Spectrum of CO(3-2) taken with the Plateau de Bure interferometer. Both figures are from Swinbank et al. (2010, Nature, 464, 733).*

At high redshift there is a population of gas-rich starburst galaxies that are relatively bright in the submillimeter, but extremely faint in the optical due to dust obscuration. The small number that has been observed with mm/submm interferometers are unresolved, but increasing numbers are now being discovered that are gravitationally lensed and therefore brighter and larger than would otherwise be the case. A pre-eminent example of this is the so-called "Cosmic Eyelash". This starburst galaxy at z=2.3 has been gravitationally lensed into two “images” (Figure 16) that have a combined extent of ~5". Each image has been resolved into at least four components (Fig. 16a) and large amounts of molecular gas have been detected (Fig.16b). Although resolved, the source is small and dominated by relatively compact structures and therefore well-suited to ALMA during *Cycle 1*. As an example project, we will attempt to map both the continuum and the molecular gas at high frequencies where the ALMA *Early Science* array may be able to resolve the source structure.

Receiver band: Band 7 (spectral line and continuum, 312 GHz).

Angular Resolution: 0.3" (spectral line [CO(9-8)] and continuum, Band 7). This resolution is sufficient to spatially resolve the components revealed by the SMA. ACA observations should not be required.

Spectral Resolution: For Band 7, we use the TDM correlator mode to provide 14 km/s channels (i.e., 27 km/s resolution) and a total bandwidth of 1.875 GHz (~1800 km/s) in one baseband. The remaining 5.6 GHz (3 basebands) can be used for mapping continuum.

Spectral (Band 7) Sensitivity: The peak flux density of the redshifted CO J=9-8 line is expected to be ~10 mJy. To detect the line at a sufficient S/N across the entire width of the line, we aim to achieve a S/N~20 at the peak in a 100 km/s channel. This requires a 1 σ noise level of 0.5 mJy/beam. We use the TDM correlator mode and average the channels to achieve the 100 km/s channel width. The ALMA sensitivity calculator with thirty-two 12-m antennas predicts 13 minutes of integration to reach 1 σ = 0.5 mJy/beam (not including overheads). (This is more than 7 times faster than during *Cycle 0*!) This amount of time will also produce a sensitivity of 59 μJy/beam in a map of the remaining 6 GHz of line-free continuum providing a S/N > 15 for the continuum signal (~1 mJy).

Molecular Absorption Lines at z=0.9

Science Aim: ***To study high-redshift absorption lines toward a bright background quasar***

Observing gas in absorption against a bright background continuum source can provide detailed information on the molecular interstellar medium of the foreground galaxy. Observations of absorption lines are very powerful because the detectability of the intervening gas depends only on the brightness of the background source. Many molecular species have already been detected in the few known intermediate-redshift absorbers, but ALMA's sensitivity and bandwidth will allow an unbiased survey for absorption lines in selected distant galaxies.

Here we prepare a spectral survey in Band 3 of PKS1830-211, where a spiral galaxy at z~0.9 is detected in front of the bright background quasar at z~2.5. The background source is sufficiently bright (~2 Jy in Band 3) that short observations with the *Early Science Cycle 1* array will result in very good optical depth limits of about 1%. By covering a wide range of frequencies with several spectral settings, we expect to detect many molecular lines, enabling detailed comparison with the interstellar chemistry of the Milky Way interstellar medium.

Receiver band: Band 3. The molecules HCN, HNC, HCO+, HOC+, CS, HC_3N have transitions redshifted into this band.

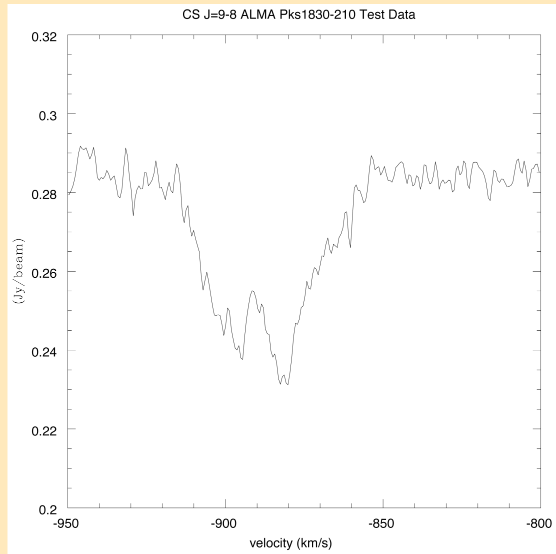
Angular resolution: In principle, angular resolution is not important for this experiment because we are looking for absorption lines against a bright background point source. However, an angular resolution of at least ~1.5″ is needed so that the two lensed components of the quasar can be separated.

Spectral resolution: We want to cover a large bandwidth but with adequate spectral resolution to resolve the absorption lines of a few km/s width. The 1875 MHz bandwidth FDM correlator mode gives a velocity resolution of ~3 km/s.

Line sensitivity: In order to reach 1% optical depth limits at 5 σ significance, an rms noise level of 4 mJy per channel is required in Band 3. Additional spectral smoothing can be applied to search for broader, weaker absorption features.

Continuum sensitivity: N/A: The background source is very bright (~2 Jy) and well-studied, so additional continuum observations are not required.

Band 3 observing time: Covering most of the entire Band 3 frequency range requires setting the LO to ~5 frequencies, namely 91.75, 95.5, 99.25, 103.0 and 106.75 GHz. To reach our target line sensitivity, a total integration time of 6 minutes per LO setting is required, or ~30 minutes (plus overheads) to cover most of the Band 3 frequency range.



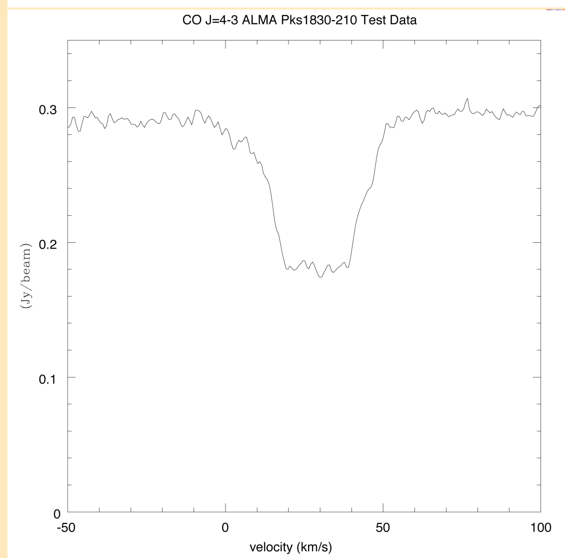


Figure 17: *Examples of molecular absorption lines detected toward PKS1830-211. These observations were made by ALMA in late 2010 when there were only a few antennas.*

In the future: A spectral scanning observing mode is expected, making such observations much simpler. Furthermore, with longer baselines it will be possible to resolve the structure of the background source and detect absorption against the different lensed components.

Observing a GRB Afterglow (A Target of Opportunity)

Science Aim: ***Detect & monitor the mm/sub-mm afterglow of a GRB from its burst to one month later***
Long-duration gamma-ray bursts (GRBs) are the most energetic phenomena in the universe. The broadband afterglow emission accompanying GRBs can be described quite robustly as non-thermal emission from electrons accelerated in relativistic shocks that occur as the GRB-generated outflow is decelerated by the ambient medium. At mm and sub-mm wavelengths, we can observe the synchrotron emission directly, where it is free from interstellar scintillation. Continuum monitoring at mm and sub-mm wavelengths provides information on GRB physics, not only for normal GRBs but also dark GRBs, and it sets constraints on theoretical models of GRB phenomena as well.

Only a few GRB afterglows have been detected at mm and sub-mm wavelengths, because instruments at these wavelengths have had limited sensitivity. GRB 030329, the second nearest (z=0.1685) GRB to date, was intensively monitored at mm and sub-mm wavelengths. The GRB 030329 afterglow light curve at 100, 250, and 345 GHz showed a "plateau" for about one week after the burst, followed by a steep decline (Sheth et al. 2003, ApJ, 595, L33; Kuno et al. 2004, PASJ, 56, L1; Kohno et al. 2005, PASJ, 57, 147; Smith et al. 2005, A&A, 439, 981). Theses data support a model with a two-component, jet-like outflow (Berger et al. 2003, Nature, 426, 145).

Receivers: Bands 3, 6, 7: (100 GHz, 230 GHz, and 345 GHz)

Angular Resolution: The sources will be unresolved, since they are about the size of a star. Hence any array configuration can be used.

Spectral Resolution: N/A. Each measurement will use the largest bandwidth possible in dual polarization.

Sensitivity and Observing Time: With 32 antennas and with 7.5 GHz of bandwidth in two polarizations, extraordinary sensitivities are possible in only a few minutes of integration time. For this project, however, observation cadence is required. For proper sampling, the target must be observed every two or three days for the first two weeks, followed by two additional epochs over the final two weeks.

Triggering Target of Opportunity (ToO) Observations: As an observation target that can be anticipated but not specified in detail, this would be an archetypal ToO project. The proposal must specify in detail the observing modes, sensitivities, the observing cadence, and the trigger needed to initiate the observations. The trigger must include an accurate position (within ~10"). During *Cycle 1*, however, the observing cadence requested by this project will be very difficult to do, since ToO observations will be permitted only during *Cycle 1* Science Operations. No science observations will be permitted during engineering/commissioning periods, which can last for a few weeks.

Figure 18: *Santiago Central Office (SCO) of the JAO. © ALMA (ESO/NAOJ/NRAO).*

Mosaicing the Nearby Spiral Galaxy M100

Science Aim: *Map the distribution and kinematics of molecular gas in a nearby spiral galaxy*

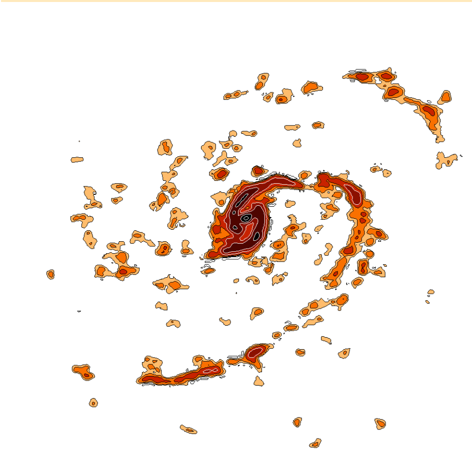


Figure 19: *ALMA Science Verification Data on M100. This image shows CO (1-0) integrated intensity in M100 from Science Verification observations (publicly available from the ALMA Science Portal).*

M100 (NGC 4321) is a bright, fairly face-on spiral galaxy in the Virgo Cluster. As one of the nearest (d ~16 Mpc) spiral galaxies with well-defined arms and active star formation, M100 has been studied at virtually every wavelength, including the millimeter. These studies reveal a rich molecular interstellar medium (ISM) fueling the star formation visible at optical and IR wavelengths. A bar funnels gas to the center of M100, leading to a nuclear concentration of molecular gas and star formation while fainter molecular emission traces the spiral arms. ALMA imaged M100 as a science verification target and the data are available from the Science Portal (see Figure 19).

In *Cycle 1*, ALMA's excellent imaging fidelity, mosaicing capabilities, and sensitivity to large angular scale (via the ACA) make a wide-field, high-resolution image of a galaxy like M100 a viable project. Such data would probe the dynamical effects of spiral arms and the nuclear bar on molecular gas, map the density distribution of the molecular ISM, and allow comparisons of molecular material to the distributions of dust, recent star formation, stellar populations, and other phases of the ISM.

Receivers: Band 3 (115 GHz): We consider a mosaic to observe CO (1-0) emission (~115 GHz, Band 3) across most of M100.

Angular Resolution: We target a resolution of 2", or about 150 pc at M100. This is suitable for comparison to a wide variety of multiwavelength data and sufficient to resolve spiral arms, the bar, and large molecular complexes. At this resolution in Band 3 ALMA can achieve surface brightness sensitivity well matched to the brightness of M100 in a reasonable amount of time.

Mosaic Coverage: We know the overall extent of CO from previous observations, including wide field single dish maps (see Figure 20). A single ALMA beam covers only a small part of the galaxy, but a rectangular grid of 126 pointings spaced by ~half of the primary beam does manage to encompass most CO emission. We show our proposed mosaic pointings in Figure 20. Mosaics of up to 150 pointings are allowed by the *Cycle 1* call.

Spectral Sensitivity: Large molecular clouds like the Orion complex have masses ~5×10^5 $M_\odot$ or more. We design our survey of M100 to detect such clouds. For a CO-to-H_2 conversion factor of ~2×10^{20} cm^{-2} $(K\ km\ s^{-1})^{-1}$ and assuming a CO line width of 10 km s^{-1}, a 1σ sensitivity of 3 mJy $beam^{-1}$ corresponds to a 1σ molecular mass sensitivity of 8×10^4 $M_\odot$ per beam per 10 km s^{-1} channel, enough to detect Orion-like clouds at S/N ~ 5 or more.

Sensitivity and Mosaicing: Entering the mosaicing parameters and a required sensitivity of 3 mJy $beam^{-1}$ directly into the OT, the integration time calculator (which takes into account the overlapping of the mosaic fields) estimates an observing time of ~4 minutes per

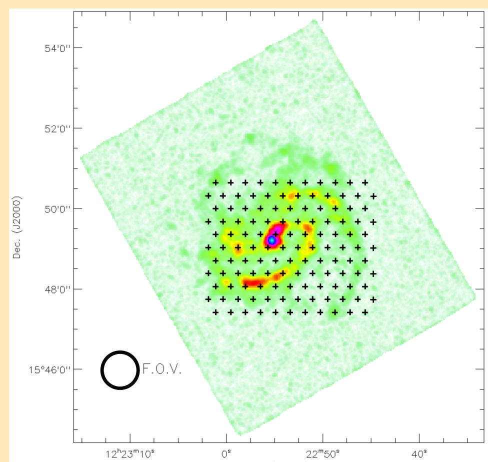


Figure 20: *Planning a large mosaic of M100. The color shows a low-resolution peak intensity map of CO (2-1) emission in M100 (HERACLES survey, Leroy et al. 2009). We plan a rectangular grid of hexagonally-packed pointings spaced by half of the ~54" field of view (shown as a circle). With 126 pointings, shown as crosses, we cover almost all of the bright CO*

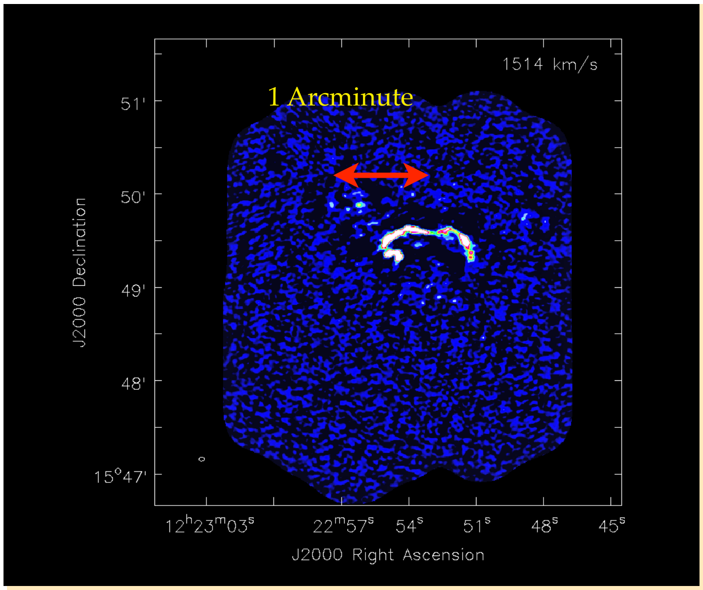


Figure 21: *Estimating the largest angular scale of CO (1-0) emission in M100. We examine individual channels of the ALMA Science Verification data and look for the largest angular extent of emission in any direction. Within this channel we see contiguous emission extending at least an arcminute. This is larger than the maximum angular scale sampled by the main 12-m array at Band 3, so ACA observations will be a necessary complement to the main array data.*

mosaic position. With 126 fields we expect that the program will need about 8 hours on source. The OT estimates that 39 overlapping pointings will be needed for the ACA.

Largest Angular Scale: For a spectral line data set like we propose here, the key metric for "largest angular scale" is the extent of emission in an individual channel map. We can estimate this from a model of the source, similar observations, or previous observations of the same object. In the case of M100 we use the Science Verification data and note that emission in an individual channel often shows contiguous features up to 60″ long in their most extended direction (see the map of a single channel in Figure 21). Because 60″ exceeds the maximum angular scale sampled by the main 12-m array, the project will automatically involve complementary observations with the ACA (7-m array). (It should be noted that the required integration time for the ACA will be about three times larger than that needed for the 12-m array.) To recover the total flux of the system we would also request observations with the total power antenna (this is possible for this project in *Cycle 1* because this is a spectral line map).

Multi-wavelength Continuum Survey of Protostellar Disks in Ophiuchus

Science Aim: *To investigate the evolutionary states of protostellar disks in the nearby Ophiuchus molecular cloud by measuring the global variation in their dust spectral energy distribution (SED) to infer dust properties.*

The characteristics of dust in a disk around a protostar are expected to evolve over time as dust grains settle to the disk mid-plane, accumulate onto larger solid bodies, and eventually, perhaps, form planets within the disk. The evolutionary state of the disk may be traced by determining the continuum SED of a coherent sample of protostellar disks. Wide frequency coverage is necessary to measure the SED of the disk. The SED is determined by a combination of the dust temperature and density distribution, and the optical properties of the dust grains. During Early Science *Cycle 1*, ALMA will just be able to resolve nearby protostellar disks, and will allow high-sensitivity observations of the disk-averaged SED in short observations. Here we discuss a potential project to observe a set of six Class II protostellar disks in Ophiuchus, selected from the catalogue presented by Evans et al. (2009, ApJS, 181, 321).

Receivers: Bands 3, 6, 7 and 9: (100 GHz, 230 GHz, 345 GHz and 690 GHz)

Angular Resolution: In Early Science Cycle 1, ALMA will observe with a variety of antenna configurations. The most extended configuration will feature maximum baselines of 1 km, at which the telescope will achieve resolutions ranging from 0.1″ at Band 9 to 0.6″ at Band 3. The typical size of a protostellar disk is ~ 100 AU. At the distance to the nearby Ophiuchus molecular cloud (125 pc), 100 AU subtends 0.8″, so it is just resolved at Band 3 with the 1 km baselines.

In this experiment we aim to measure global properties of the disks, including the SED. We therefore seek observations at each frequency that match the 0.6″ resolution achieved in Band 3 from the most extended configuration. Using the ALMA Observing Tool, we simply request a resolution of 0.6″ for each frequency band. The observations would then be executed in more compact configurations for the higher frequencies, while Band 3 data would be observed in the most extended configuration. If necessary, we can fine-tune the angular resolution achieved in each band by applying a uv taper during the data analysis. It should be noted however that such a taper suppresses the contribution from the longest baselines and changes the sensitivity.

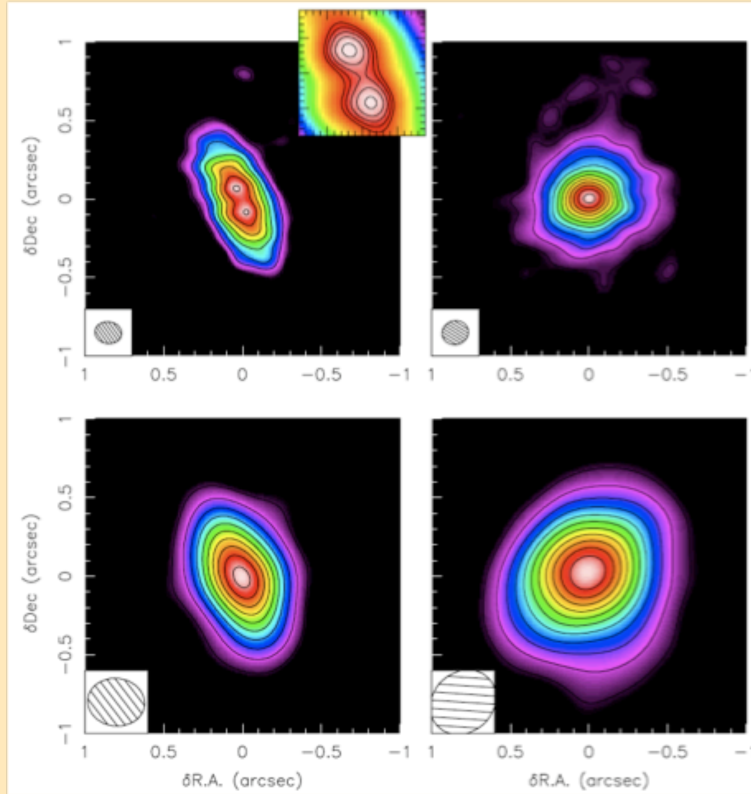


Figure 22: ***Top***: *CARMA aperture synthesis images of 1.3mm (228 GHz) continuum emission from two protostellar disks in Taurus with an inset to highlight the double structure seen in the top left panel (Isella et al. 2010, ApJ, 714, 1746).* ***Bottom***: *CARMA images of the 2.8mm (106 GHz) emission from the same two disks (Isella et al.). Each image includes ~8 hours of data for each of several different CARMA configurations, for a synthesized beam of ~ 0.15″ FWHM at 1.3mm and ~0.4″ at 2.8mm.*

Spectral Resolution: These data are observed in the continuum, so each measurement will include the largest bandwidth possible. We thus achieve 7.5 GHz × 2 polarizations = 15 GHz effective total bandwidth coverage in each frequency band.

Sensitivity and Observing Time: We calculate the expected brightness of a typical disk assuming a disk mass of 0.01 $M_\odot$, an average dust temperature of 20 K, a plausible dust emissivity, and a distance of 125 pc. The flux densities we expect are 4, 30, 80, and 400 mJy for bands 3, 6, 7, and 9, respectively. We plan our observations with the consideration that the angular size of the disks can be up to a few times the size of the beam at Band 3, and we would like to measure the disks with sufficient signal to measure continuum ratios accurately. We aim for continuum sensitivities of 0.04 mJy/beam, 0.3 mJy/beam, 0.8 mJy/beam, and 4 mJy/beam for Bands 3, 6, 7, and 9, respectively. Using the ALMA sensitivity calculator with 32 main array antennas (12-m diameter) and 7.5 GHz of bandwidth, we find that these sensitivities can be achieved in 7.6 minutes per disk (Band 3), 13 s per disk (Band 6), 6 s per disk (Band 7), and 18 s per disk (Band 9). For this experiment, we are not interested in diffuse continuum emission that extends beyond the primary beam of the 12-m antennas, so we do not require observations with the Atacama Compact Array or the Total Power Array.

Figure 23: *More and more antennas, during the altaplanic winter. Note the ACA array at center right. (© ALMA (ESO/NAOJ/NRAO))*

Chemical and Evolutionary Diversity in a Massive Protostellar Cluster

Science Aim: *To observe the molecular chemistry and kinematics of the massive protostellar cluster NGC6334I*
When a massive star forms, photoionization of dust grains liberates complex organic molecules and leads to a "hot core" phase. Subsequent expansion of the ionized region leads to a detectable ultracompact HII region. In this target, SMA observations show that objects in several phases of star formation appear to be present within 10000 AU of one another, in a configuration similar to the more evolved Trapezium cluster. Here, we describe a simple spectral survey to be performed at Band 6 to observe the emission lines from many saturated molecules and probe the chemistry of this complex region. Observations of a continuous spectral region within an ALMA band will be possible in Cycle 1, using up to five consecutive receiver tunings at a fixed spectral resolution (i.e., using only one correlator mode).

Receivers: Band 6 (220 GHz) We will observe many useful molecules that provide temperature measurements including CH_3CN, CH_3OH, and C_2H_5CN, and shock tracers such as SiO and SO_2.

Angular Resolution: 0.4″. The typical separation of massive protostars in this cluster is ~2000 AU, which is about 3″ for this source (d=1.6 kpc). As the hot core emission is smaller than 1000 AU, sub-arcsecond observations are needed to avoid loss of sensitivity due to beam dilution. The 0.4″ resolution can comfortably separate the sources, as well as avoid loss of sensitivity to the hot core due to beam dilution. The 28″ FOV at Band 6 is sufficient to cover the ~12″ region of interest in a single field (though primary beam correction will be important).

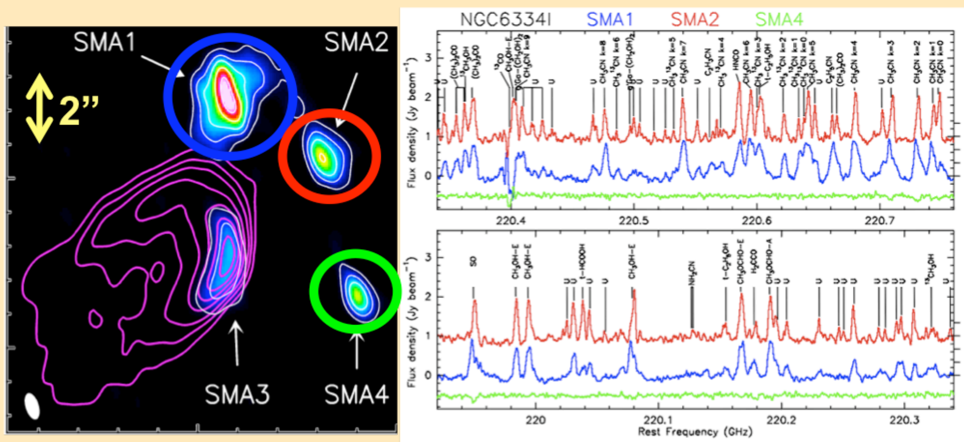


Figure 24: ***Left***: *Color-scale and white contours show a Submillimeter Array (SMA) continuum image at 1.3 mm (222 GHz) of NGC6334I (Brogan et al. 2012, in prep) with a resolution of ~ 0.5″. The magenta contours show VLA 3.6 cm continuum from a UCHII region.* ***Right***: *Spectra of three of the sources showing the diversity of chemistry toward the protostars.*

Spectral Resolution: The 230 GHz SMA observations have 0.488 MHz = 0.66 km/s wide channels (resolution 1.2 km/s). We will use a correlator mode that provides dual polarization and 1.875 GHz bandwidth in each sideband. Nearly the entire Band 6 frequency range can be covered with five LO tunings. In the future, this kind of spectral survey will be much simpler with the spectral scanning observing mode.

Sensitivity and Observing Time: We aim for a sensitivity of 10 mJy/beam rms (compared to 40 mJy/beam for the SMA observations). Using the ALMA sensitivity calculator with thirty-two 12-m antennas, dual polarization and ~0.5 MHz resolution, these point source sensitivities can be achieved at the center of the field in only 3 minutes at Band 6 for each LO setting, or ~15 minutes for the entire frequency range. Since the observed spectral windows will have line-free areas, the continuum sensitivity will correspond to a substantial fraction of the total bandwidth for continuum RMS noise levels of ~0.1 mJy/beam at Band 6.

Learn More

about the spectral line catalogue tool *Splatalogue* at http://www.splatalogue.net/

Observing Molecular Gas in a Planetary Nebula

Science Aim: *To map the structure of molecular gas (CO) in a Planetary Nebula*

In Planetary Nebulae (PNe) molecular gas is often observed 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 this 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 ($T_A^* < 5$ K) clumps that are slowly evaporating in the radiation field of the central white dwarf. The origin of these tiny clumps is still debated and to date the highest angular resolution millimeter molecular line observations have beam sizes greater than 3" (see Huggins et al. 2002, ApJ, 573, L55).

Receivers: Band 6 (230.538 GHz) For this pilot project we choose to observe the CO (2-1) line.

Angular Resolution: 0.3" Taking the Helix Nebula results as a starting point, the angular resolution desired should be below the fragmentation scale of ~1". As a pilot project, we attempt to gain a factor of one hundred in areal resolution over previous observations, requiring the maximum baseline configuration available for *Cycle 1*.

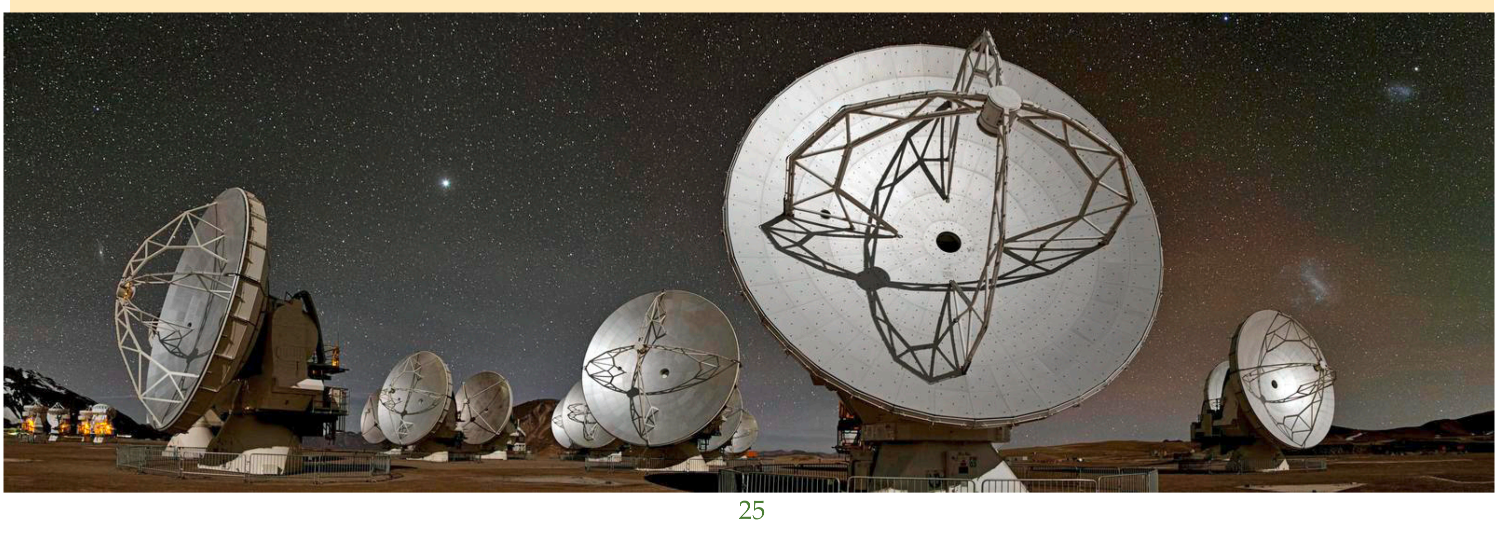
Mosaic Required: The Helix is quite large (diameter ~ 25′) and highly fragmented. However, the diameter of the primary beam at 1.3 mm is only about 27". It would take an enormous mosaic of pointings to map the entire Helix and thus in this proposal one pointing each toward the SE and NW portion of the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

Spectral Resolution: The spectral resolution is chosen to match the expected line profiles within the Helix Nebula, 0.2 km/s. We choose the 234 MHz bandwidth spectral mode with 0.061 MHz channels.

Channel (Line) Sensitivity: 0.5K. 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: For Band 6, the ALMA sensitivity calculator, assuming 32 antennas and an effective 0.2 km/s spectral resolution predicts 5 hours to reach 0.5 K. The two separate pointings will require about 10 hours of ALMA observing time, plus overheads.

Figure 25: *A nighttime panoramic view of the Chajnantor plateau, showing some of the antennas of the 12-m Array. To the far left, a cluster of 7-m antennas from the Atacama Compact Array (ACA) is illuminated. To the right, the Large and Small Magellanic Clouds are visible in the sky. (Photo B. Tafreshi © ALMA (ESO/NAOJ/NRAO))*



Continuum and CO J=3-2 Emission from the Pluto-Charon System

Science Aim: *To observe the CO line on Pluto and to measure the flux densities of both Pluto and Charon:*

N_2 is the dominant atmospheric molecule on Pluto, but the minor species of methane and CO dominate the thermal balance as they have a spectrum which better permits radiative activity, particularly when Pluto is closest to the Sun. Methane observations suggest an atmospheric temperature considerably warmer (~100 K) than the surface (~45 K) but CO has not been detected. The proposed ALMA ES observations will constrain atmospheric models; the New Horizons spacecraft will provide in situ measurements during its 2015 flyby. These observations will also constrain the surface temperature of both bodies.

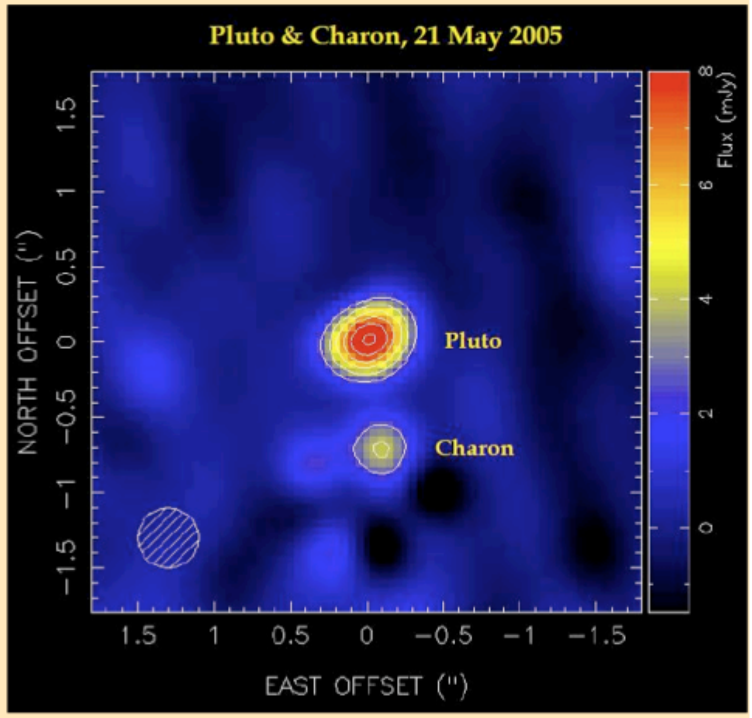


Figure 26: *Submillimeter Array (SMA) aperture synthesis images of 1.4 mm (220 GHz) continuum emission of Pluto and Charon (Gurwell & Butler. 2005 BAAS 37, 743). These observations were made with the most extended SMA configuration during an 8 hour track, achieving a synthesized beam of ~ 0.4″ FWHM.*

Receivers: Bands 7 and 9: (345 GHz and 690 GHz)

Angular Resolution: The typical separation of Pluto and Charon is ~0.9″ so we will need an angular resolution of ~0.25″ to distinguish the emission from each. In cycle 1, this resolution is achievable at both Bands. At ~0.1″ diameter, Pluto is not yet resolvable even at Band 9 in the most extended Cycle 1 configuration.

Spectral Resolution: To resolve the expected 1 km/s line width for CO (3-2) requires a spectral resolution of about 0.2 km/s, so we will use the FDM correlator mode with 469 MHz bandwidth and 0.122 MHz channel spacing (0.106 km/s at Band 7), yielding a spectral resolution of 0.21 km/s. The remaining three spectral windows will use the TDM mode to detect the continuum. At Band 9 (670 GHz), we will use the TDM mode (dual polarization) to maximize sensitivity.

Continuum Sensitivity: Pluto should have flux densities of 20 and 100 mJy respectively at Band 7 & 9 respectively, while Charon will be 40% of those values. The sensitivity required for 50 σ detections of Charon will be 0.16 mJy/beam and 0.8 mJy/beam.

Channel (Line) Sensitivity: 10 mJy km/s in Band 7: The predicted intensity of the CO (3-2) line from Pluto ranges from about 50 to 120 mJy in a 1 km/s line. By comparison, the CO (6-5) line is expected to be 10 times weaker, and thus observations of it will need to await Full Science.

Observing Time: Using the ALMA sensitivity calculator with thirty-two 12-m antennas, and dual polarization, the Band 7 CO (3-2) spectral line observations, reaching a 10 mJy rms in 0.21 km/s resolution elements, require 18 minutes of observing time. The remaining 5.625 GHz of continuum will yield a continuum sensitivity of 0.07 mJy/beam. To reach the continuum sensitivities with 7.5 GHz of bandwidth and dual polarization at Band 9 will require 8 minutes of exceptional weather.

In The Future: As ALMA's maximum baseline length increases, all the moons in this example can be resolved at the shortest wavelengths. Increased sensitivity will enable the array to detect Nix and Hydra, providing estimates of the size and density of these enigmatic moons. Also, better orbital parameters will help to guide the New Horizons spacecraft during its 2015 encounter with the Pluto system.

Proposals, Observations and Data Reduction*

Proposal Submission and Observing Process

Call for Observing Proposals: The general procedure is that the Joint ALMA Observatory (JAO) prepares the Call for Proposals (CfP), which includes the anticipated capabilities of the observatory (available observing bands, correlator modes, observing modes, configurations, etc.) for the upcoming observing season.

The CfP will be broadcast to the regional and worldwide communities by the ARCs using standard broadcasting means (e.g. society and observatory newsletters and mailing lists), and will be posted to the ALMA science websites.

Registering as an ALMA User: All users who wish to be part of any ALMA proposal (either as Primary Investigator or Co-Investigator), submit tickets to the ALMA Helpdesk, track a project, or retrieve data from the ALMA Science Archive must register as an ALMA user via the ALMA Science Portal (see link page 39). Non-registered users may still access ALMA user tools, software, or browse the Helpdesk Knowledgebase archive.

Users will be associated with one of the ALMA partners (EU, NA, EA, or Chile) or as being outside the partnership based on their institutional affiliation(s). This affiliation factors into time allocation and specifies the ARC that users will be directed to for data retrieval and helpdesk support. Users from non-ALMA member regions or Chile may select any of the three ARCs for support.

> **Learn More**
>
> The Observing Tool (OT) is accessible from
>
> http://almascience.org/documents-and-tools/

Proposal Preparation & Submission (Phase I Proposal): After the CfP is issued, users will have some period (1-2 months) to prepare their Phase I materials using the ALMA OT. The OT is a java-based application based on existing tools for other observatories (Gemini, JCMT, Spitzer, Herschel), so its design should be familiar to many potential observers. Phase I consists of a detailed observing proposal with a scientific and technical justification submitted to the Observatory through the OT. The OT includes calculators for determining sensitivities, and viewers for assisting with correlator setups and mapping parameters, in order to prepare Science Goals. Users can use the ALMA Helpdesk, available from the ALMA Science Portal, to get assistance from ARC staff at any stage of the preparation and submission process (Phase I Support).

If desired, one can simulate ALMA observations using the *Simulator* tasks of the CASA software package, or using the web-based ALMA Observation Support Tool. These tools take a model image as input and simulate the resulting ALMA image, accounting for the array configuration, instrumental noise, atmospheric phase delay, as well as the data reduction process. One can also use the compilation of molecular spectral line databases provided by the *Splatalogue* on-line catalogue to help plan spectral line observations.

Proposal Review Process: Phase I submissions will be peer-reviewed by a single international committee that is divided into a number of science-themed review panels (Scientific Review). Time will be awarded based on the proposals scientific ranking and available time. The time available for projects will depend on the PI's institutional affiliation, with [33.75%, 33.75%, 22.5%, 10%] made available to projects

For the non-expert reading this section, a list of Interferometer Concepts is included on page 34.

associated with the North American, Europe, East Asian, and Chilean partners, respectively. Time will also be available to projects from non-ALMA regions through the Open Skies policy. Users should consult the ALMA websites and Call for Proposals for details. Users will receive notification of the proposal review process via email.

Phase II Program: During Phase II, successful proposers will use the OT to convert their Phase I Science Goals into a series of blocks of observing time called Scheduling Blocks (SBs). During *Early Science*, ARC and DSO staff will carry out SB generation, in consultation with the proposer. SBs will be submitted to a scheduling queue so they are available to the array operators when conditions are appropriate at the ALMA site, according to the ranked list of proposals, operations schedule and weather conditions. Once SBs have been submitted, users will be able to track the status of their project through the ALMA Project Tracker, a user application available from the Science Portal.

Archive & Data Delivery: After all SBs associated with a science target have been successfully observed, the data will be processed and quality assured by ALMA staff and deposited into the ALMA Science Archive, where they may be retrieved by observers. ALMA data have a one-year proprietary period from the date when they are placed in the ALMA Science Archive and made available to the PI. Archived data products include the raw visibilities, telescope logs, relevant data reduction scripts, and reference images and cubes.

Observing Considerations

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 in a proposal, and careful choices are required to ensure that the project's scientific aims 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, the observational pa-

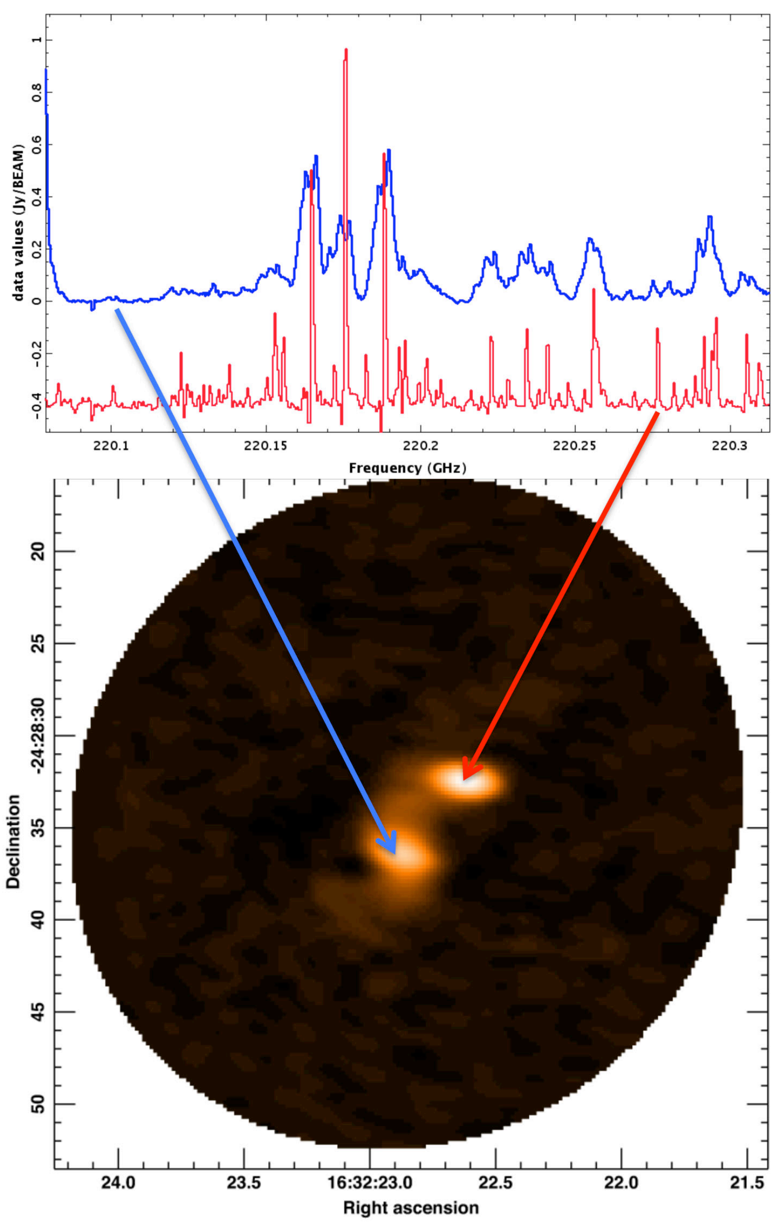


Figure 27: *ALMA Science Verification (SV) Band 6 data of a spectral survey toward the class 0 protostellar binary, IRAS16293. The image shows dust continuum emission at 1.3mm. Spectra toward the two emission peaks are also shown. Identification of the spectral lines is left as an exercise for the reader. See page 39 for a link to the Splatalogue. SV data, reference images, and reduction scripts are available to download from the Science Portal.*

rameters may be interrelated. In the following, we describe the basis for choosing these parameters.

Angular resolution (or "synthesized beam") is the minimum angular separation whereby adjacent 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 finer angular resolution. An important concept to remember about interferometers is that they can only observe emission on a discrete set of spatial scales (i.e., spatial frequencies), as measured by the antenna pairs making up an array (see "*uv*-coverage", page 36). Since the number of spatial scales measured is finite, the resulting image is spatially "filtered" and only reflects the emission on the observed spatial scales. Even for a given baseline distribution, however, the observer has some control over the effective resolution of the image during post-processing. By using different weighting schemes to reconstruct an image, it is possible to make moderate tradeoffs between effective resolution and surface brightness sensitivity.

Maximum Angular Scale (MAS) is roughly defined to be 0.6 × (wavelength/minimum baseline) (in radians, or ~124″ × (1m/D_{min}) × (300 GHz/ν), where D_{min} is the minimum distance between antennas (in meters) and ν is the observing frequency (in GHz)). MAS is a guideline for the largest angular scale on which most of the flux of a smooth structure can be reasonably recovered by the interferometer. This rule-of-thumb applies to the size scale of smoothly varying structures in both dimensions. Smooth structures larger than ~1.0 × (wavelength/minimum baseline) will be "resolved out" by the interferometer. This is the well known "missing flux" problem intrinsic to interferometry. The minimum baseline depends both on the array configuration (i.e. compactness) and source elevation. 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 (the ACA includes four specially outfitted 12-m antennas, the TP Array, 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 CASA *Simulator* or Observation Support Tool whether the ACA will be required for a particular project, and the ACA (which includes the TP Array) can be requested in the proposal at Phase I (see Figure 15). In *Cycle 1*, nine 7-m ACA antennas and two 12-m TP Array antennas will be available. Stand-alone ACA proposals will not be accepted.

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 $\lambda/2D$ where λ is the observed wavelength, and D is the diameter of the antennas, to achieve Nyquist sampling) and using the resulting data to create a "mosaic" map. Note, however, there will be only limited mosaicing (maximum 150 pointings) available for *Cycle 1*.

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 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 area 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, though they cannot compensate for emission that has been "resolved out". (See Maximum Angular Scale above.)

Learn More

Go to http://www.aoc.nrao.edu/events/synthesis/2010/lectures10.html to find out more about the fundamentals of interferometry.

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, a limited subset of which will be available during *Early Science*. (See page 9 for a table showing the correlator modes available during *Early Science*.) Spectral resolution depends on how the correlator has been configured. 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. (In *Cycle 1*, the smallest available channel spacing is 7.6 kHz.) 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 7.5 GHz. For line observations, high spectral resolution (i.e., small bandwidth) is used to achieve high velocity resolution. Note that the velocity resolution of ALMA will be 2 x the channel spacing, assuming default Hanning data smoothing. For example, a 0.02 km s^{-1} velocity resolution 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 7.5 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. Such "mixed" spectral modes will be available during *Cycle 1*.

Sensitivity is usually defined as the 1 sigma RMS variation of

Figure 28: *Aerial view of the OSF. The grey-roofed buildings in the center host offices, labs, and the array control room. Three antennas in front of the building are being commissioned before being moved to the AOS. In the mid-background are the antenna assembly facilities. Photo W. Garnier © ALMA (ESO/NAOJ/NRAO) (Acknowledgement: General Dynamics C4 Systems)*

noise in the data (ΔS) and so serves as a threshold for the detection of emission. For ALMA, basic sensitivity depends (see *Useful Equations*, page 38) on: the number of antennas; receiver performance; atmospheric conditions (i.e., water vapor content and other atmospheric gases with strong spectral lines in the submillimeter (e.g. ozone), atmospheric turbulence, and target elevation); and, of course, integration time. Receiver and atmospheric conditions 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 (see Figure 6), 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 m^{-2} Hz^{-1}, while line intensities are often 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 when the source is resolved (see p. 35). For a given ΔS, the corresponding ΔK increases with decreasing beam size; it is harder to detect extended line emission at high angular resolution. The quantity ΔS 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, a bandwidth of up to 7.5 GHz in each of two polarizations (effectively 15 GHz) 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. 39), as well as one using the same algorithms built into the OT. One can also explore the required sensitivity in more detail using the CASA *Simulator* tool.

Creating Images From Your Data

Once the data are taken, ALMA data will be reduced by the ALMA Division of Science Operations team (DSO) using a pipeline employing the Common Astronomy Software Applications (CASA) package. After the DSO has reduced the data and verified its quality, the raw and reduced data are shipped to the ARC data archives, where they are made available to the project teams. The project teams are provided with the raw data, the images (i.e. the pipeline-reduced calibrated data cube), and the scripts used by the pipeline (or, in *Early Science*, by DSO or ARC personnel).

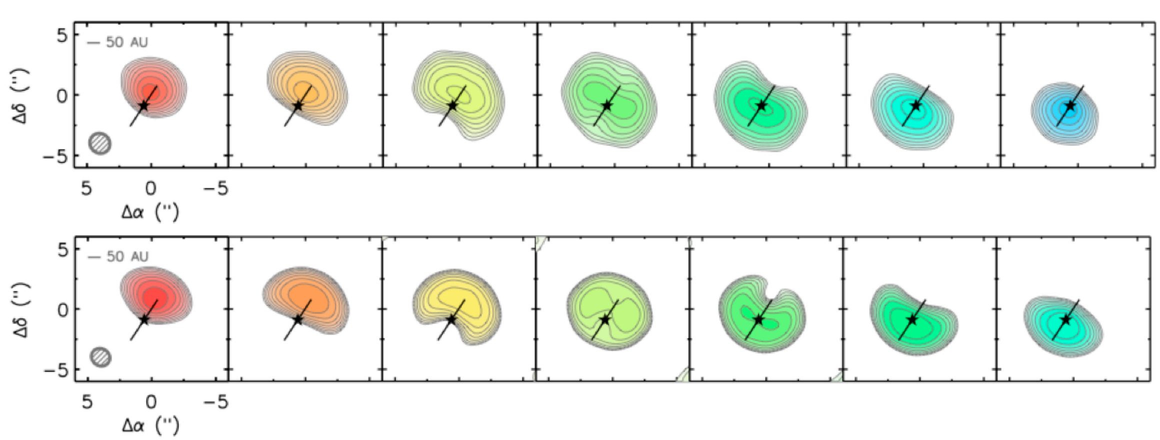
> **Learn More**
>
> Go to
> http://casa.nrao.edu/
> to learn more about using CASA to reduce and analyze ALMA data.

Once the pipeline-reduced data are released, the PI may still want to optimize the reduction and imaging to get the best possible data for the project, most likely using CASA. In the following, we describe the basic concepts of reducing interferometer data. This process can be distilled down to two stages, calibration and imaging, and we discuss these below in turn. (Science Verification data, along with reduction scripts and reduced images and data cubes, are available from the Science Portal for anyone to download and “practice” data reduction and techniques of image creation.)

Calibration: ALMA observing will be heavily constrained by weather conditions on the Llano de Chajnantor. Therefore, ALMA projects will be divided up into blocks of time (Scheduling Blocks or SBs) that can be executed dynamically by the on-site array operators when appropriate conditions are available. These blocks will contain observations of 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.

Target data will require calibration of their amplitudes and phases, and for how these quantities vary with frequency. Amplitude calibration requires observations of at least one or two sources of known flux density and angular extent. The brightness of these objects should vary only relatively slowly, so that an accurate estimate of their flux densities can be determined. Typically, very bright and compact radio sources, 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 from 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 also be captured by these observations; typically amplitude calibrators are also used to gather these data. Phase calibration requires periodic 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 and/or atmosphere. The cadence at which the phase calibrator will be observed will depend on the stability of the atmosphere, the observational frequency, and the maximum baseline length. Atmospheric phase varies more rapidly at longer baselines, while at higher frequencies the variations have larger magnitude. The ALMA antennas will need to "fast-switch" between the target and phase calibrators from every few minutes to every few seconds (depending on frequency and baseline length) to capture these variations. (Fast switching is not available in *Cycle 1*.) Phase variability is also tracked using water vapor montitors (WVM) which are installed on all antennas of the 12-m Array. These corrections will be applied when it improves the phase coherence.

Figure 29: *Science Verification (SV) data of the circumstellar disk of TW Hydrae, obtained when there were only 9 antennas. The top row is a set of CO J=3-2 channel maps from the ALMA science verification data, while the bottom row is a model of Keplerian CO emission from the disk (Hughes et al., 2011). The model is not a fit to the data, but serves to illustrate the extremely high quality of the data. SV data, along with reference images and reduction scripts, are freely available from the Science Portal. (Image courtesy M. Hughes)*



Imaging: ALMA datasets will be processed through a reduction pipeline so that project teams will be able to see preliminary results quickly. (During *Early Science*, while the pipeline is being developed, this processing will be done using a combination of the pipeline and by hand using CASA and other specially designed software, by members of the DSO and the ARCs.) 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 "visibilities") into images. The reduction process itself is threefold: first, the data are calibrated, then poor quality data must be removed from the ensemble before the FT, and finally, the image is made from the inverse 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. 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 in both the calibrator and the target data sets; however, 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. For smaller interferometers, data that need to be flagged are identified by visual inspection of amplitude and phase for antennas or antenna pairs, examined over a range of time or over a range of frequency. The sheer size of ALMA data products will make this kind of close inspection impractical, and tools are being developed to automate the process.

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 include 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. 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. The dirty beam is an image of a theoretical point source observed with the same *uv*-coverage as the actual data normalized to one. Cleaning typically continues until the flux density in the residual image is a 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; in the near future this process will be speeded up through parallelization of the imaging algorithm(s).

Interferometry Concepts for ALMA: A Glossary of Terms

Aliasing According to the Nyquist principle, aliasing occurs when a signal (the *uv*-plane) is undersampled (*uv*-coverage), shifting higher spatial frequency components to lower spatial frequency. These "aliased" components introduce false large-scale structure into the resultant image, i.e the "dirty" image. Aliasing artifacts can also be introduced by strong sources (including natural and human-generated) outside of the *primary beam*.

Angular Resolution See *Synthesized Beam.*

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 10.4 m antennas, 9 x 6.1 m antennas, and 8 x 3.5 m antennas that compose CARMA.

Band The emission frequency/wavelength range over which a given receiver is able to detect astronomical signals. For example, ALMA Band 3 is sensitive to astronomical emission over the range of 84-116 GHz (i.e., 2.6-3.4 mm). See the table on page 10 for the full list of receiver Bands that ALMA will have when completed.

Bandwidth The subrange of frequencies in a given Band over which data are obtained in a given observation. For example, a 3.75 GHz bandwidth can be sampled in each *sideband* over the 84-116 GHz range of Band 3.

Baseband A baseband is a 2 GHz wide portion of the available signal (effectively 1.875 GHZ because of filters between the receiver and correlator) which is digitized at the antenna. Up to four 2 GHz wide basebands are delivered to the ALMA correlator (see Figure 30). For the dual polarization receivers (e.g. Bands 3, 6 & 7), up to two basebands can be placed in each *sideband*, or all four in one sideband. (Double sideband receivers such as Band 9 have the basebands in both sidebands simultaneously.) The user-selected correlator configuration determines how many basebands are ultimately used, where they are placed in the available IF range, and which correlation products are produced (single, dual, or full polarization). (See *spectral window.*).

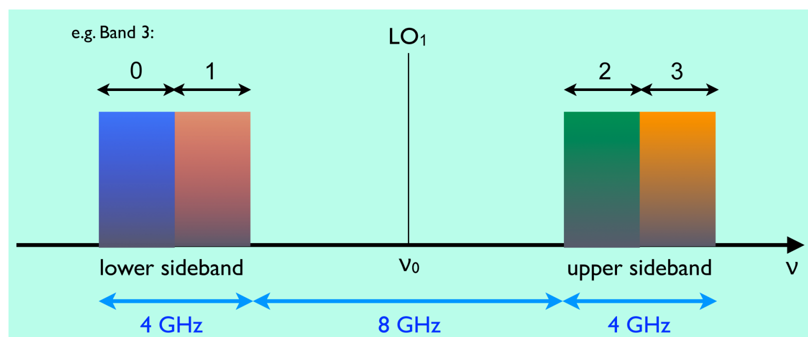


Figure 30: *A graphical view of basebands and sidebands. Basebands may be tuned to overlap if the user wishes, or may be located so as to maximize the total bandwidth (as shown). Each baseband may be further subdivided into as many as 8 spectral windows. Only one spectral window per baseband will be available during Cycle 1.*

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. In *Cycle 1*, 32 antennas provide 496 baselines, over four times more than during *Cycle 0*.

Clean Image or Cube A deconvolved image (or cube 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 depends on the science goals of the observation.

Correlator A powerful computer which cross-correlates the amplified, down-converted signals from each antenna pair to produce the interference measurement (i.e, the "*visibility*") from that pair. A user-selected correlator mode (see table page 9 for the available modes in *Cycle 1*) defines the bandwidth and resolution of the *spectral window*.

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.

Field of View See *Primary Beam.*

Fringes See *Visibilities.*

Largest Angular Scale (LAS) The largest scale structure of interest in the source to be observed. If the LAS is larger than the *maximum angular scale* which the array can recover, then a more compact array configuration, e.g. with the ACA, may be required.

Maximum Angular Scale The maximum angular scale structure that may be recoverable from observations with an interferometer, and is dependent on the minimum separation between antennas. Larger structure are "resolved out" and cannot be recovered. See *Total Power*, the discussion on page 29, and Figures 13, 14 & 15.

Nyquist Sampling This is the minimum sampling interval needed to preserve the signal content without introducing aliasing errors. For ALMA, the Nyquist sampling rate for mosaicing fields is of order $\lambda/2D$, where λ is the observational wavelength and D is the antenna diameter.

Polarization The ALMA receivers measure the two directions of linear polarization separately. When later processed by the correlator, the polarizations may be combined to give greater sensitivity, effectively "doubling" the bandwidth (dual polarization), or one may be discarded to give double the spectral resolution (single polarization), or may be processed together to give full Stokes parameters. This last mode is not available in *Cycle 1*.

Primary Beam The angular sensitivity pattern on the sky 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 ~$1.2(\lambda/D)$, 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

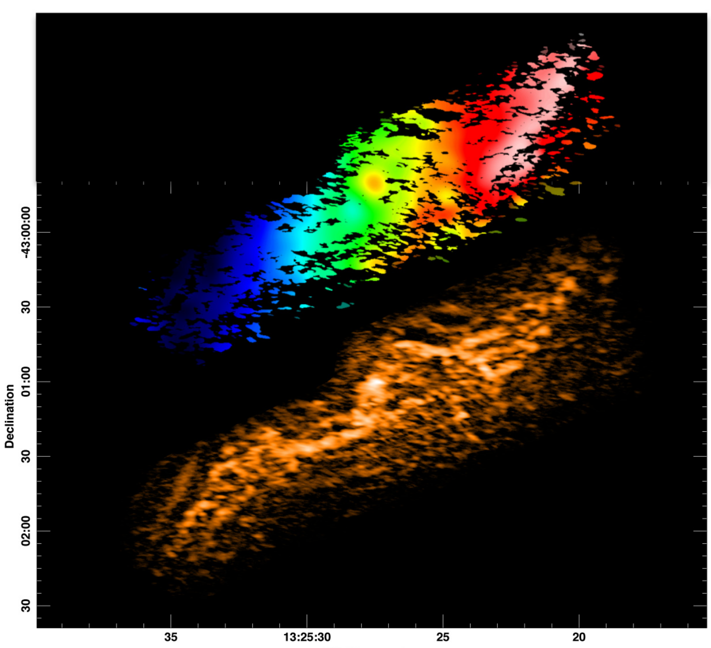


Figure 31: *ALMA SV data mosaic of the Seyfert 2 galaxy Centaurus A. The lower image shows the integrated intensity of CO J=2-1 emission. The offset image above shows the radial velocity of the CO emission. SV data and images are available to download from the Science Portal.*

these can be minimized by careful design and construction. The primary beam sets the FOV for an observation with the array, unless a larger mosaic is made. Limited mosaicing capability (maximum 150 pointings) will be offered during *Cycle 1*.

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).

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 observed for calibration which is then applied to the science target. Observations of the phase calibrator must be interspersed with observations of the science target because the phase calibration varies over time. The science target and phase calibrator must therefore be close together in the sky.

Sideband At any given tuning, each receiver is sensitive to two separate ranges of sky frequency of equal width called sidebands (see Figure 30). The four available basebands can be placed in one sideband or distributed between the two sidebands; however, baseband numbers 0 and 1 must be placed in the same sideband as must basebands 2 and 3. In Bands 9 and 10, the receivers provide no inherent separation of the sidebands, so each baseband contains signal from both sidebands simultaneously. However, one can choose to reject one sideband from each baseband by selecting an appropriate observing mode to modulate the local oscillator. (This feature is not available in *Cycle 1*.) This technique can also be used in lower frequency bands to obtain even greater sideband separation than that provided by the receiver.

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

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. The *uv*-coverage is the sampling of the spatial frequencies by the interferometer.

Spectral Window A spectral window is a frequency subrange of a baseband. Each baseband may be divided into one or more spectral windows, with the desired bandwidth and channel spacing for each spectral window de-

Figure 32: *AOS technical building at 5000 m elevation. Chajnantor Volcano is in the background. © ALMA (ESO/ NAOJ/NRAO)*

fined by a correlator mode. (For ALMA, the velocity resolution will be 2 x the channel spacing as the data will be Hanning smoothed by default.) Windows can be placed adjacent to one another to produce continuous coverage across the bandwidth or placed on individual interesting features within the band. In *Cycle 1*, each baseband may contain only one spectral window. However, different basebands may contain different spectral windows (i.e. mixed correlator modes).

Synthesized Beam or Angular Resolution 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, which can appear as significant secondary features to the synthesized beam. (Sometimes these are called synthesized beam sidelobes or dirty beams.)

Total Power, or Zero-Spacing Flux The large-scale emission which the array cannot detect. 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 12-antenna ACA or the 4-antenna TP Array to address this problem. During *Cycle 1*, the maximum baseline length of the 12-m array should be less than ~500m to give enough overlap in the *uv*-coverage of the two arrays to allow the data to be merged. See figures 13 and 15.

Track A long-duration set of integrations of an astronomical source using all *baselines*. As the Earth rotates, 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 (*uv*-coverage) and the resulting images more accurately reflect the actual emission distribution (assuming zero noise and perfect calibration).

***uv*-Coverage** The breadth of spatial frequencies sampled during an interferometric observation, so named because "*u*" and "*v*" are the spatial frequency counterparts to angular distances in Right Ascension ("*x*") and declination ("*y*") respectively (see *visibility*). Since an interferometer can only sample a finite amount of spatial frequencies, the ability to reconstruct the true sky brightness from an interferometric observation increases with the *uv*-coverage. Images made from data of low *uv*-coverage (*snapshots*) tend to have more secondary features due to *aliasing*, whereas images made from data of high *uv*-coverage (*tracks*) tend to have less aliasing. The number of points in the *uv*-coverage goes as the number of baselines (i.e. as N(N-1)/2 where N is the number of antennas), so will increase rapidly as more antennas are added to the array.

Visibility An interferometric observation of a source made 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 density and position. Visibilities are sometimes referred to as *fringes*. Each correlator channel produces its own visibilities. The ensemble of visibilities is the *uv*-coverage.

Zero Spacings See *Total Power.*

A Few Useful Equations

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, see "Tools of Radio Astronomy" by Rohlfs and Wilson.)

To convert between frequency and wavelength, a handy rule-of-thumb is to remember that the wavelength is ~1 mm (to three decimal places) when the frequency is 300 GHz. Thus, to convert frequency (in GHz) to wavelength (in mm),

$$\lambda \text{ (mm)} = (300 \text{ GHz})/(\nu \text{ GHz})$$

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

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

For example, a 1 km/s resolution at 300 GHz would require a frequency resolution of 1 MHz. Conversely a channel spacing of 0.0153 MHz (see table page 9) would correspond to a velocity spacing of 0.0153 km/s at 300 GHz, or 0.0051 km/s at 900 GHz.

The conversion from brightness temperature T to flux density S_ν with synthesized beam solid angle Ω_s is

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

An alternate formulae that is often useful is

$$\left(\frac{T}{1K}\right) = \left(\frac{S_\nu}{1 \text{ Jy beam}^{-1}}\right)\left[13.6\left(\frac{300 \text{ GHz}}{\nu}\right)^2\left(\frac{1''}{\theta_{max}}\right)\left(\frac{1''}{\theta_{min}}\right)\right]$$

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:

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

A Summary of "Learn More" Links

ALMA Science Portal / Resources for Scientists	http://almascience.org/
Cycle 1 Call for Proposals	http://almascience.org/call-for-proposals/
Science & Software Tools	http://almascience.org/documents-and-tools/
JAO Public Web	http://almaobservatory.org
ALMA Virtual Tour	http://almaobservatory.org/en/alma-virtual-tour/
Common ALMA acronyms	http://www.almaobservatory.org/en/about-alma/acronyms
NAASC	http://science.nrao.edu/facilities/alma/
EU-ARC	http://www.eso.org/sci/facilities/alma/arc.html
EA-ARC	http://alma.mtk.nao.ac.jp/e/forresearchers/ea-arc/
Intro to Interferometry	http://www.aoc.nrao.edu/events/synthesis/2010/lectures10.html
Reducing Data with CASA	http://casa.nrao.edu/
Simulating ALMA Data	http://casaguides.nrao.edu/index.php?title=Main_Page#Simulating_Observations
Observation Support Tool	http://almascience.org/documents-and-tools/
Splatalogue	http://www.splatalogue.net/
ALMA Newsletters	http://www.almaobservatory.org/en/outreach/newsletter
Press Releases	http://www.almaobservatory.org/en/press-room
ALMA Memos	http://www.alma.cl/almamemos/

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