Doc 2.1, ver. 2 | October, 2013

Observing with ALMA: A Primer for *Early Science* *(Cycle 2)*

ALMA

www.almascience.org

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Revision History:

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1	9 Oct 2013	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 1: *Antennas at the ALMA high site, the AOS, December 2012. (Credit: C. Malin, ALMA (ESO/NAOJ/NRAO))*

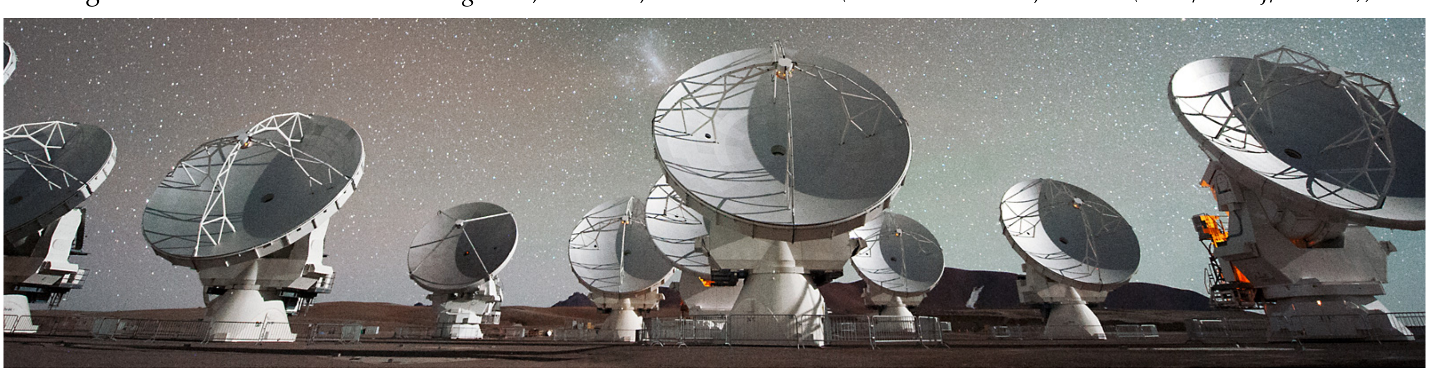


Figure 2: *A panorama of the Chajnantor Plain. The "half-way" point of ALMA was reached on May 12, 2012, with 33 antennas at the summit. (Credit: ALMA (ESO/NAOJ/NRAO), J. Guarda (ALMA))*

Purpose of this Document

This document is designed to provide basic introductory information on the Atacama Large Millimeter/submillimeter Array (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 Full Operations 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 2* are indicated in this document with an orange background.

Some Acronyms Used in this Document

ALMA	*Atacama Large Millimeter/submillimeter Array*	**LAS**	*Largest Angular Structure*
ACA	*Atacama Compact Array*	**NAOJ**	*National Astronomical Observatory of Japan*
AOS	*Array Operations Site (at 5000 m elevation)*	**NRAO**	*National Radio Astronomy Observatory*
ARC	*ALMA Regional Center*	**MRS**	*Maximum Recoverable Scale*
CASA	*Common Astronomy Software Applications*	**OSF**	*Operations Support Facility (at 2900m elevation)*
CfP	*Call for Proposals*	**OT**	*Observing Tool*
DDT	*Director's Discretionary Time*	**SCO**	*Santiago Central Office, headquarters of the JAO*
DSO	*ALMA Division of Science Operations*	**SB**	*Scheduling Block*
ES	*Early Science*	**SG**	*Science Goal*
ESO	*European Southern Observatory*	**S/N**	*Signal to Noise Ratio*
FOV	*Field of View (or Primary Beam)*	**SV**	*Science Verification*
JAO	*Joint ALMA Observatory*	**TP Array**	*Total Power Array (part of the ACA)*

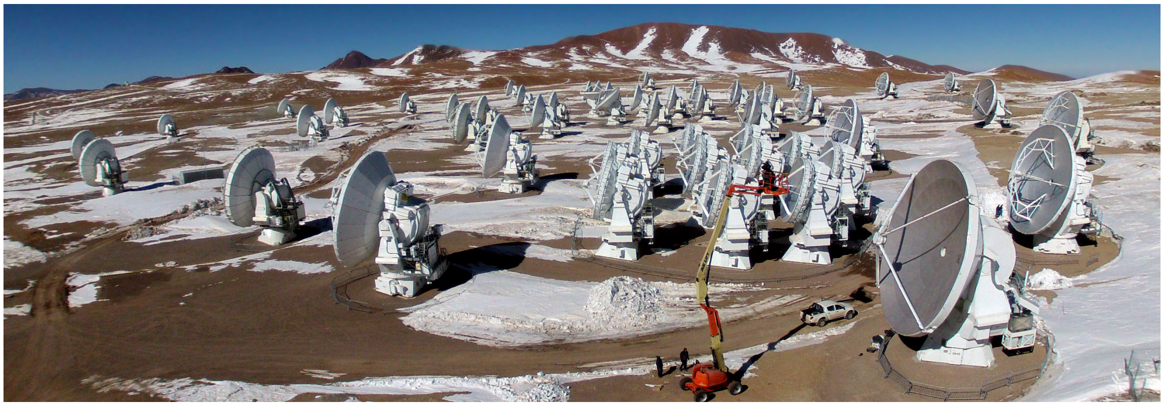


Figure 3: *An aerial photo of the ALMA Cycle 1 array, taken with a camera mounted on a hexacopter. Note the ACA 7-m Array in the center foreground. (Credit: EFE/ Ariel Marinkovic)*

What is ALMA?

The Atacama Large Millimeter/submillimeter Array (ALMA) is one of the largest multi-national science projects to date. When construction is complete in late 2013, it will be a single research instrument composed of 66 high-precision antennas located on the Chajnantor plain of the Chilean Andes at an elevation of about 5000-m and at a latitude of -23°. ALMA consists of the 12-m Array, made up of fifty 12-m diameter antennas, plus the Atacama Compact Array (ACA), also known as the Morita Array, made up of twelve 7-m antennas packed closely together (the 7-m Array) and four 12-m antennas (the Total Power or TP Array).

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

ALMA is a complete imaging and spectroscopic instrument operating at millimeter/submillimeter wavelengths, 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 and radio 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.

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 repositioning of the antennas over a region at least 16 km in extent.

Learn More

Click on

www.almaobservatory.org/en/visuals/alma-virtual-tour

for a virtual tour the ALMA site and vicinity.

Figure 5: *The flags of 20 nations fly over the plaza at the OSF, representing the ALMA partnership. (Credit: J. Di Francesco)*

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

Array operations are the responsibility of the Joint ALMA Observatory (JAO). The telescope array itself is located at the Array Operations Site (AOS) at an elevation of 5000m. Due to the limited oxygen at this elevation, the array is 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 is where ongoing operations, maintenance, and repairs of ALMA antennas and receivers take place. The JAO has a central office in Santiago. The interface between the observatory and the astronomical community is through the ALMA Regional Centers.

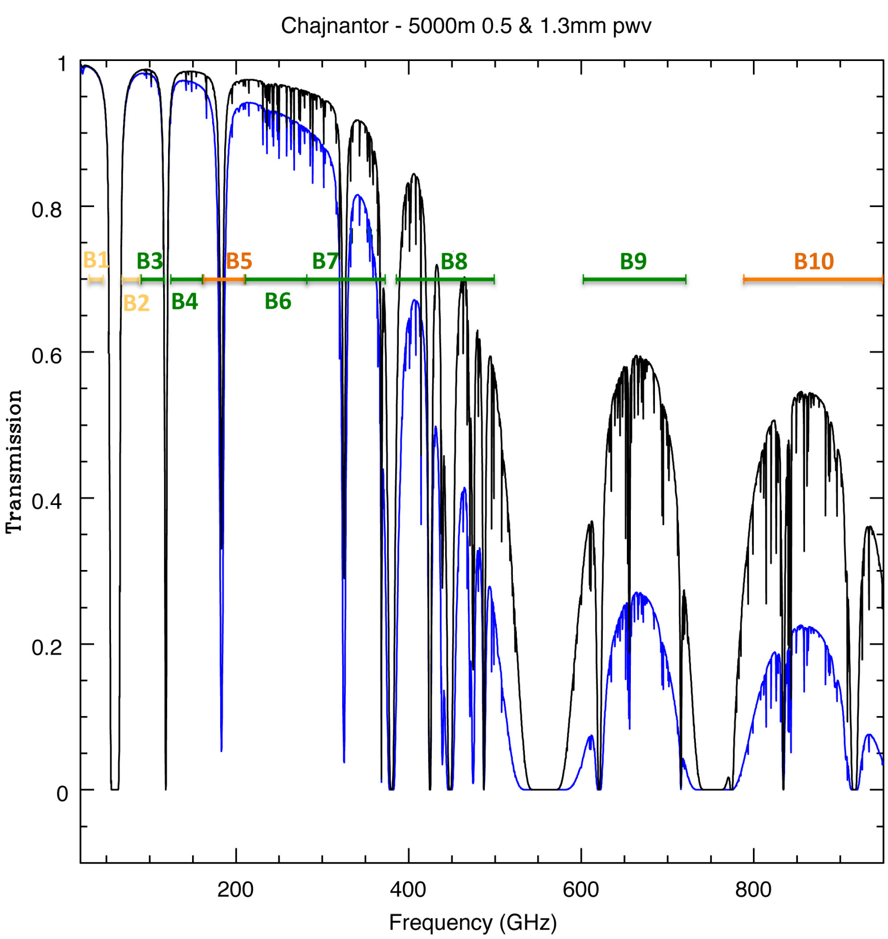


Figure 6: *Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency. Plotted in blue and black are the transparency values for the 50th and 12.5th percentile conditions respectively averaged over the year. This means that 50% of the time the sky transparency is better than shown in the blue line (corresponding to a precipitable water vapour (PWV) of 1.3 mm), and 1/8 of the time is better than the black line (transparency at 0.5 mm of PWV). The horizontal lines represent the frequency coverage of the ALMA receiver bands. Bands 3, 4, 6, 7, 8 and 9 are available on all antennas in Cycle 2. Plots such as this one can be generated via the Science Portal (under "About" -> "Atmosphere Model") for any frequency range and value of water vapor.*

Learn More

The Science Portal is your gateway to ALMA at

http://almascience.org/

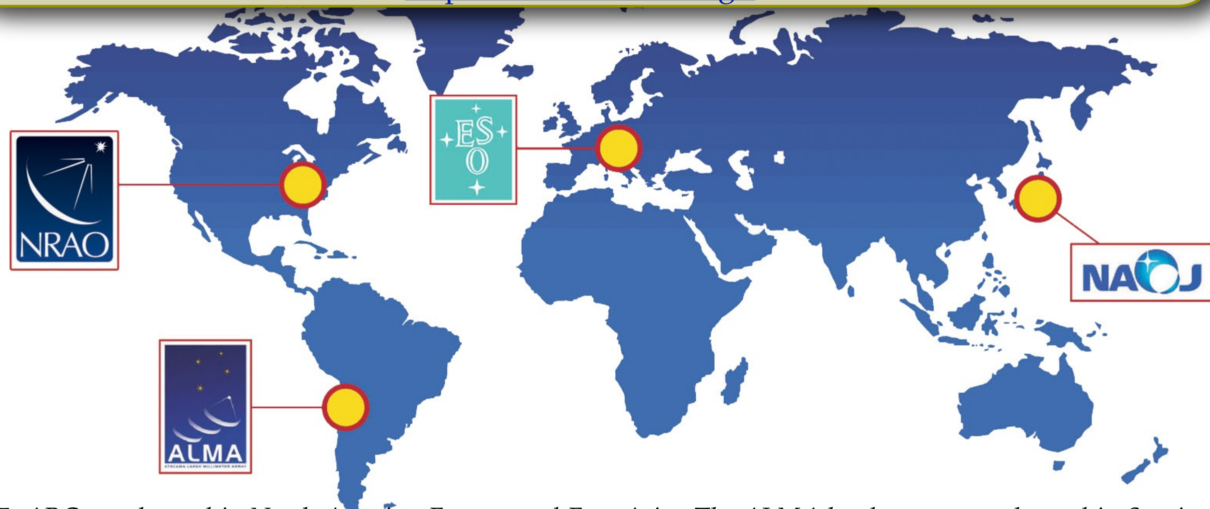


Figure 7: *ARCs are located in North America, Europe, and East Asia. The ALMA headquarters are located in Santiago, Chile .* *(Credit: ALMA (ESO/NAOJ/NRAO))*

ALMA Regional Centers (ARCs)

Each of the three ALMA regional partners (Executives) maintains an ALMA Regional Center (ARC) within its respective region. The ARCs provide the interface between the JAO and their respective communities, either through the ALMA Helpdesk or face-to-face at the ARC. In addition, the ARCs provide operational support to the JAO, and for research and development activities in support of future upgrades to ALMA.

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.

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 the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), and supports the astronomy communities of Japan, Taiwan and South Korea.

Chilean astronomers may be supported by any of the three ARCs. Similarly, astronomers from non-partner countries may choose any of the three ARCs for their support.

Learn More

The three ARCs can be reached through the Science Portal or via 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/

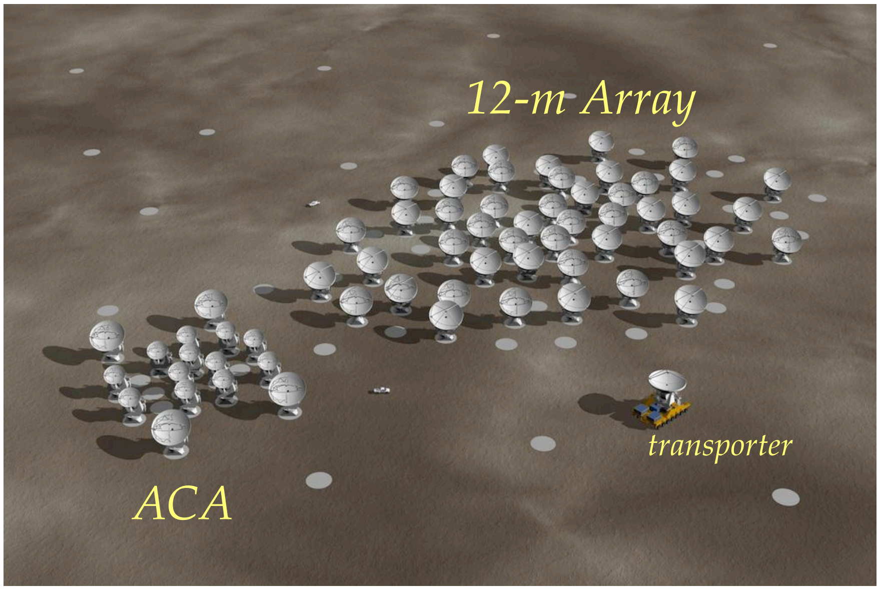


Figure 8: *Artist's conception of the Full Operations ALMA 12-m Array in its most compact configuration, with the ACA (including the 12 antennas of the 7-m Array and 4 12-m antennas of the Total Power Array) toward the left, and the transporter in the lower right. A few unoccupied pads can be seen, to 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 9). (Credit: ALMA (ESO/NAOJ/NRAO))*

What is Interferometry?

In contrast to direct imaging like with a CCD camera on an optical telescope, an interferometer essentially samples the Fourier transform of the sky brightness. In a single integration (typically a few seconds or less), each pair of antennas, called a *baseline*, samples a single point in this power spectrum, at a position in Fourier space related to the distance between the pair of antennas and the position angle of the baseline vector. Antennas which are close together (short baselines) sample large-scale angular structure, while long baselines sample very small-scale angular structure. By combining these data, called *visibilities*, over a large number of baselines (the *uv*-coverage), the Fourier plane is sampled, which can then be inverted to reconstruct an image. 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. Even a few minutes of observations with the 34 12-m antennas (561 baselines) available in *Cycle 2* provides good coverage, and in full operations more than twice as many baselines will be available. During longer observations, more of the *uv*-plane is filled in by the rotation and foreshortening of baselines as the Earth rotates on its axis. Antennas are periodically moved (reconfigured) to provide a wide range of array configurations with different baselines lengths; observations with different configurations may be combined to improve the *uv*-coverage. Furthermore, to recover very large-scale structure, the short spacings gap in the *uv*-coverage can be filled in by adding ACA observations. For more detailed descriptions of these terms, see the Glossary starting on page 33.

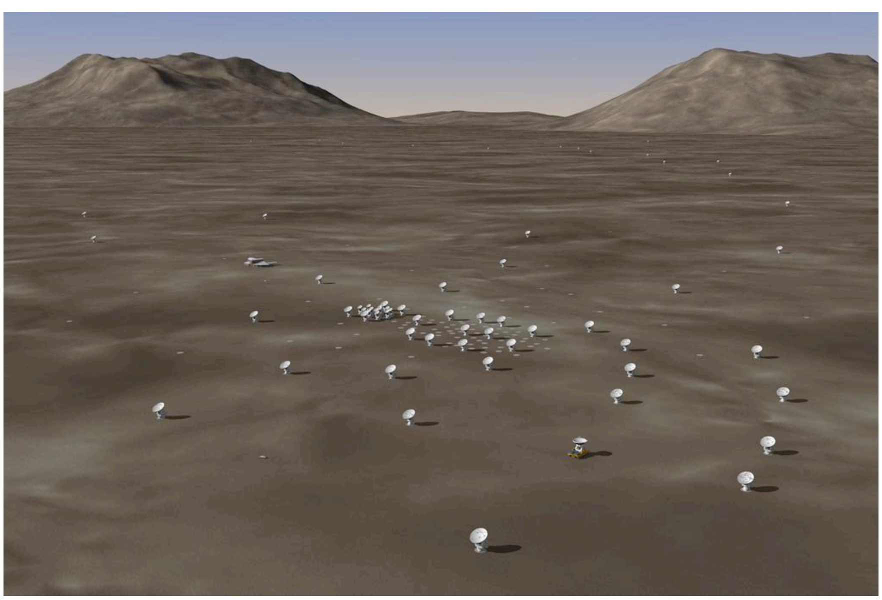


Figure 9: *The 50 antennas of the ALMA 12-m Array will be reconfigurable by moving them to pads scattered across the Chajnantor plain. Here we see an artist's conception of an extended configuration, where antennas are spaced as far apart as 16 km. The small building to the left of center contains the ALMA correlators, and the tight clump of antennas near the center is the ACA. (Credit: ALMA (ESO/NAOJ/NRAO))*

What is *Early Science*?

The construction phase of ALMA will conclude in late 2013, and full commissioning of its many capabilities will take some time more. Nevertheless by late 2011 the facility was already the world's most powerful millimeter/submillimeter telescope, and astronomers were given the opportunity to observe with ALMA with reduced (but still substantial) capability. This is called *Early Science*, and *Cycle 2* is the community's third window to utilize the facility. The full extent of the capabilities being offered in *Cycle 2* are described in the *Proposer's Guide* issued with the Call for Proposals.

Figure 10: *His Excellency, Sebastián Piñera, President of Chile, addressing the Inauguration of ALMA, March 13 2013. (Credit: ESO)*

Did you Know? In *Cycle 2*, ALMA can…

…resolve molecular structures in M83:	
6pc clouds of excited CO (J=3-2) gas across the central 400pc	***in < 2 hours***
…detect the ISM in high-redshift galaxies:	
major cooling [CII} line in a lensed Milky Way type galaxy at z=4.2	***in 30 minutes***
…reveal the behavior of solar system objects:	
obtain wind patterns in the atmosphere of Mars with 300 km resolution	***in 30 minutes***
measure Kuiper Belt Object sizes and albedos from their thermal emission	***in 1 hour***
…survey Galactic Clouds and star forming regions:	
detect thousands of lines over 60 GHz with < 1 km/s resolution toward Orion-KL	***in 10 minutes***
…reveal the nature of planetary disks around nearby stars:	
resolve the "snow line" in the disk around the T Tauri system HD 163296	***in 15 minutes***
…measure stellar activity from low-mass to high-mass stars:	
investigate heating mechanisms of red giant stars	***in 2 minutes***
image molecular outflows from pre-planetary nebulae	***in 5 minutes***
…study black holes and their environments, near and far:	
measure black hole mass of NGC 4526 from molecular gas kinematics	***in 1 hour***

Learn More

To see *more* quick facts like these, as well as the calculations that went into them, check out

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

ALMA *Cycle 2 Capabilities*

ALMA's capabilities will include (in *Cycle 2*):

- 34 antennas in the 12-m Array, plus nine 7-m and two 12-m antennas in the ACA
- Receiver Bands 3, 4, 6, 7, 8, & 9 (at wavelengths of about 3, 2.1, 1.3, 0.8, 0.66 and 0.45 mm)
- Both single field interferometry and mosaics
- Limited polarization capability
- Mixed correlator modes allowing both high- and low-spectral resolution in the same observation
- An automated Spectral Scan setup
- Baselines up to 1.5 km for Bands 3, 4, 6, & 7, and up to 1 km for Bands 8 & 9
- See the *Proposer's Guide* on the Science Portal for a full list of *Cycle 2* capabilities

Each ALMA antenna is equipped with a set of receivers, each of which covering a certain frequency range (or band). In *Cycle 2*, Bands 3,4,6,7,8, and 9 are available. See Table 1 below with the frequency ranges of each band.

During *Cycle 2*, thirty-four 12-m antennas will be available, in a range of configurations from "most compact" (maximum baseline 160 m) to "most extended" (maximum baseline 1.5 km (Bands 3-7) or 1.0 km (Bands 8-9)). In Table 1 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. 14-15 for a discussion of resolution and maximum scales with the ACA.

Table 1: *Receiver Bands and Selected Properties*

Cycle 2 Receiver Bands					Most Compact			Most Extended		
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy/beam)	Angular Resolution (")	Approx. Max. Scale (") (see P.14)	Spectral Sens. ΔT_{line} (K)	Angular Resolution	Approx. Max. Scale (") (see P.14)	Spectral Sens. ΔT_{line} (K)
3	84-116	2.6-3.6	73-53	0.097	4.4-3.2	31-22	0.08	0.48-0.35	11-8	6.1
4	125-163	1.8-2.4	49-38	0.11	3.0-2.3	21-16	0.08	0.32-0.24	7.3-5.6	7.0
6	211-275	1.1-1.4	29-22	0.13	1.8-1.4	12-9	0.10	0.19-0.14	4.3-3.3	8.6
7	275-373	0.8-1.1	22-16	0.22	1.4-1.0	9.5-7	0.17	0.14-0.11	3.3-2.4	14
8	385-500	0.6-0.8	16-12	0.41	0.97-0.75	6.8-5.2	0.32	0.15-0.12	2.4-1.8	14
9	602-720	0.4-0.5	10-8.5	1.69	0.6-0.5	4.3-3.6	1.25	0.15-0.08	1.4-1.3	54

*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. To convert sensitivity in *K* to sensitivity in *Jy/beam*, see page 38.

The ALMA Correlators

ALMA Correlators are immensely powerful and flexible instruments; in *Cycle 2*, astronomers will be able to use more of the correlators' features than in previous cycles.

Each receiver outputs four 2 GHz-wide *basebands* in each *polarization*, which are fed into the correlator. (See the *Glossary* starting on page 33 for an explanation of unfamiliar terms.) These basebands can be tuned independently of each other, so for example one might place the centers of two basebands 1.8 GHz apart so as to get a contiguous spectrum 3.6 GHz wide. Alternatively, one might tune two basebands to the same frequency so as to completely overlap, and use one baseband to focus on small sections of the baseband at very fine spectral resolution (small channel spacing) and the other baseband to look at a large velocity range with very coarse spectral resolution.

Table 2: *Spectral Capabilities per baseband for observations in dual polarization*

Mode	Polarization✣	Bandwidth (MHz)	Nchan	Chan. Spacing (MHz)	Spectral Resolution† 300 GHz (km/s)
FDM	*Dual*	*1875*	*3840*	*0.488*	*0.98*
FDM	*Dual*	*938*	*3840*	*0.244*	*0.49*
FDM	*Dual*	*469*	*3840*	*0.122*	*0.24*
FDM	*Dual*	*234*	*3840*	*0.061*	*0.12*
FDM	*Dual*	*117*	*3840*	*0.0305*	*0.061*
FDM	*Dual*	*58.6*	*3840*	*0.0153*	*0.031*
TDM	*Dual*	*2000‡*	*128*	*15.625*	*31.2*

†*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.*

✣*Note: Single polarization modes are available for all bandwidths, which yield double the number of channels and half the channel spacing. Full Stokes polarization mode yields half the number of channels.*

Each baseband is sampled by the correlator according to a given correlator mode, defining the total bandwidth, number of channels, and spectral resolution (see Table 2 right).

The channels within a mode may be set up as one contiguous *spectral window*, or split up into two or four narrower windows. For example, one could choose to observe a contiguous 234 MHz range within a baseband, with 3840 channels of width 61 kHz (fourth entry in Table 2 above). If there were two lines of interest in that baseband, one might choose to have two *spectral windows* in that baseband, each with 1920 channels covering 117 MHz, or one might choose to have four *spectral windows* in that baseband, each with 960 channels covering 58.5 MHz.

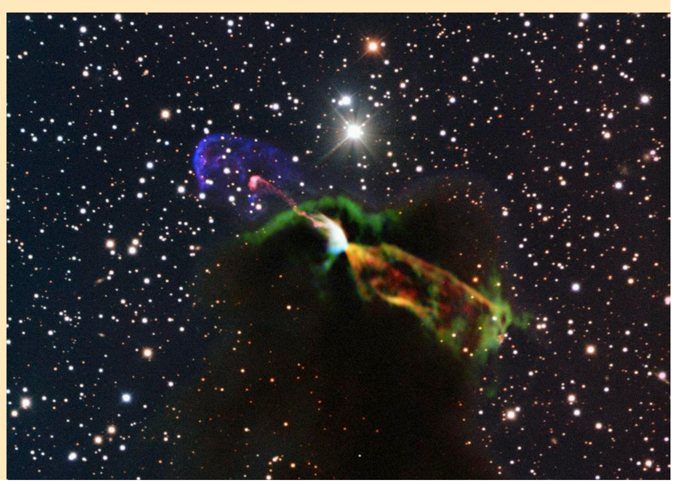


Figure 11: *This exquisite image of Herbig-Haro object HH 46/47 combines ALMA Band 3 observations with visible light observations obtained by ESO's New Technology Telescope (NTT). The ALMA observations of CO J=1-0 emission (orange, lower right) toward the protostar reveal a large energetic jet moving away from us, which in the visible is hidden by dust and gas. To the left (in pink and purple) the visible part of the jet is seen, streaming partly towards us. The green is CO emission tracing the edge of the dark cloud. (Credit: ESO/ALMA (ESO/NAOJ/NRAO)/Arce et al., 2013, ApJ, 774, 39)*

ALMA *Full Array Specifications*

	Specification
Number of Antennas	***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 correlators can handle up to 64 antennas)***
Total Bandwidth	***16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)***
Spectral Resolution	***As narrow as 0.008 × (ν/300 GHz) km/s***
Polarimetry	***Full Stokes parameters***

In Table 3 below, the sensitivities assume an integration time of 60 seconds, dual polarization, 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):

Table 3: *Full Science Receiver Bands and Selected Properties*

Full Science Capabilities					**Most Compact**		**Most Extended**	
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ")	Continuum Sensitivity (mJy / beam)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)	Angular Resolution (")	Spectral Sensitivity ΔT_{line} (K)
1	*31.3-45*	*6.7-9.5*	*197-137*	0.04	*13-9*	0.006	*0.12-0.08*	255
2	*67-90*	*3.3-4.5*	*92-69*	0.06	*6-4.4*	0.009	*0.06-0.04*	413
3	84-116	2.6-3.6	73-53	0.07	4.8-3.4	0.04	0.045-0.032	430
4	125-163	1.8-2.4	49-38	0.06	3.2-2.4	0.048	0.030-0.023	330
5	163-211	1.4-1.8	38-29	0.11	2.5-1.9	0.06	0.027-0.021	641
6	211-275	1.1-1.4	29-22	0.085	1.9-1.5	0.05	0.018-0.014	490
7	275-373	0.8-1.1	22-16	0.15	1.5-1.1	0.08	0.014-0.01	814
8	385-500	0.6-0.8	16-12	0.28	1.04-0.8	0.28	0.01-0.008	1900
9	602-720	0.4-0.5	10-8.6	1.1	0.66-0.55	0.9	0.006-0.005	8900
10	787-950	0.3-0.4	7.8-6.5	1.2	0.51-0.42	1.6	0.005-0.004	—

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 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, where the rising flux density on the Rayleigh-Jeans side of the spectral energy distribution of a dusty galaxy compensates for dimming at high redshift, makes ALMA the ideal instrument for investigating the origins of galaxies in the early universe, with confusion minimized by the high angular resolution.

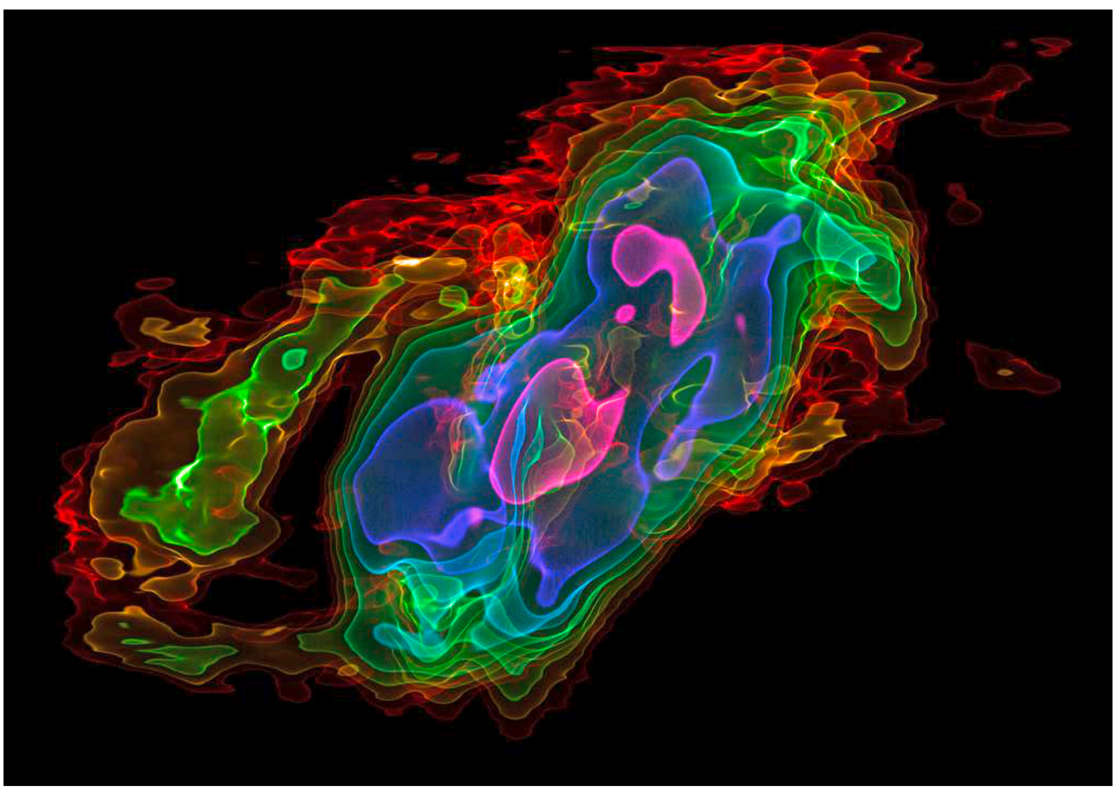


Figure 12: *This picture shows a view of a three-dimensional visualization of ALMA observations of cold CO gas in the nearby starburst galaxy NGC 253. The vertical axis shows velocity and the horizontal axis the position across the central part of the galaxy. The colors represent the intensity of the Band 3 emission detected by ALMA, with pink being the strongest and red the weakest, and show that huge amounts of cool gas are being ejected from the central parts of this galaxy, inhibiting future star formation. (Credit: ALMA (ESO/NAOJ/NRAO)/Bolatto et al., 2013, Nature, 499, 450)*

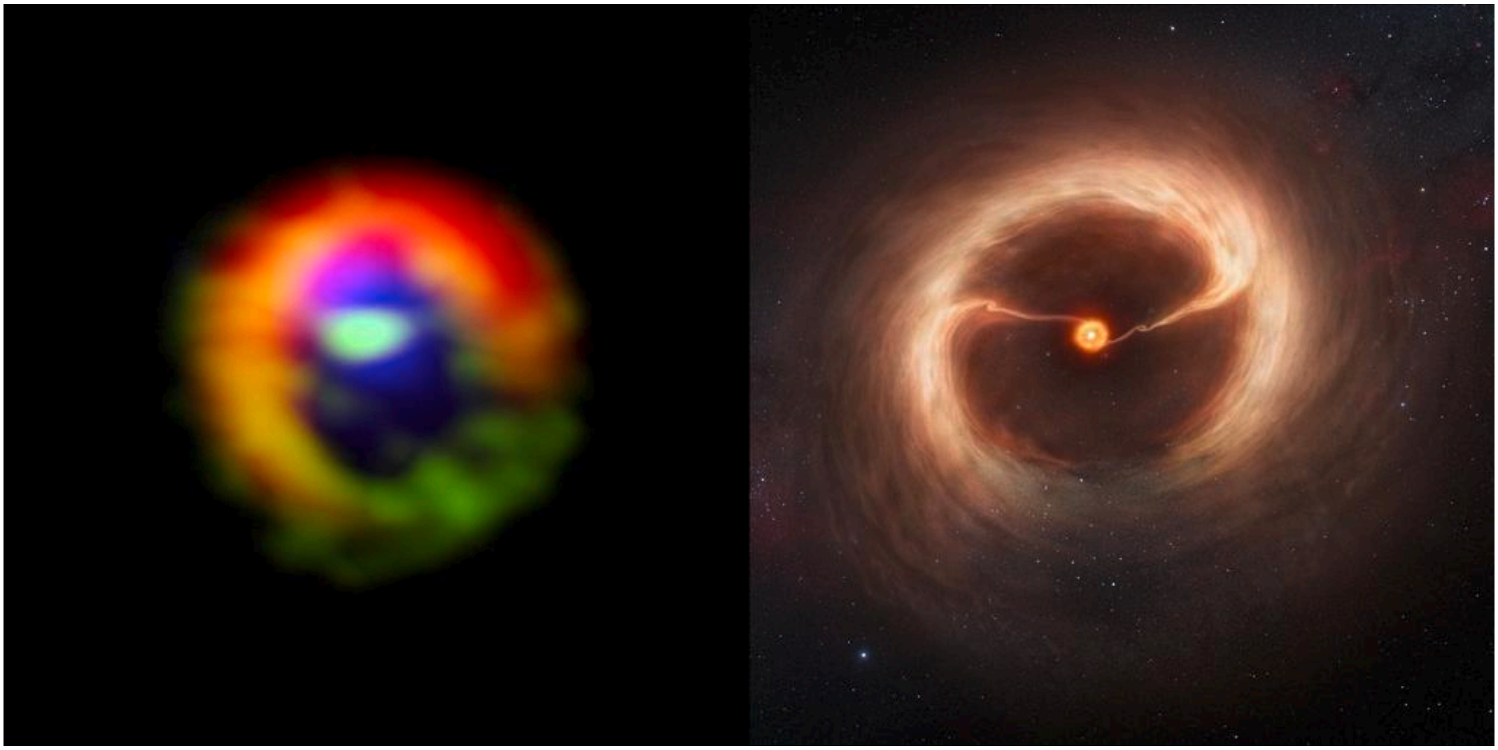


Figure 13: *(Left panel) Band 7 observations of the disk around the young star HD 142527, showing vast streams of gas flowing across the gap in the disk. The dust in the outer disk is shown in red, dense gas (HCO+) is green, and diffuse gas (CO) is shown in blue. (Right panel) An artist's impression of the disk and gas streams. (Credit: ALMA (ESO/NAOJ/NRAO)/Cassasus et al., 2013, Nature, 493, 191)*

• 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 angular 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.

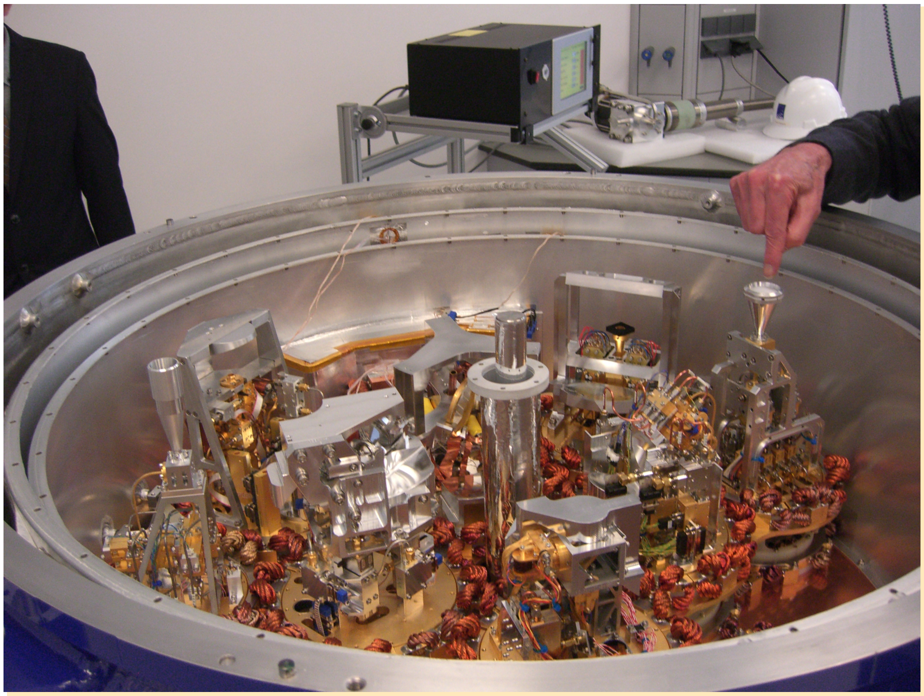


Figure 14: *An open cryostat being shown off to guests at the ALMA Inauguration in March 2013. The demonstrator is pointing to the feedhorn of a Band 3 receiver. During Cycle 2, all antennas will be equipped with receivers covering Bands 3, 4, 6, 7, 8 and 9. (Credit: J. Hesser)*

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. Some of the exciting results from *Cycle 0* are shown in figures throughout this document. A few example projects suitable for *Cycle 2* have been compiled by the world-wide ALMA science staff and can be found on page 7, or worked out in more detail on pages 16 to 25.

Observations during *Early Science* will be performed in service observing mode by ALMA Operations personnel on a "best efforts" basis. *Early science* operations, although a high priority, shall not unduly delay the construction and commissioning of full ALMA and therefore completion of projects cannot be guaranteed. However, a small number of the very highest scientific ranking may be carried over into *Cycle 3* if not completed in *Cycle 2*.

Before You Propose for *Early Science*

In order to be able to submit proposals using the Observing Tool (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:

- The Road Map. The ALMA Road Map (at http://almascience.org/proposing/road-map) provides a guide for proposing to observe with ALMA, with links to a wealth of useful documents, including this Primer.
- A Science Case. The case must demonstrate how your proposed observations will address key scientific questions.
- Source coordinates, radial velocities, proper motions (for nearby sources), ephemerides (for solar system objects).
- Observing frequency, bandwidth, and spectral resolution.
- Required angular resolution and largest angular structure

Learn More

Resources for proposers, including the OT, Technical Handbook, and Road Map can be found on the Science Portal at

http://almascience.org/proposing

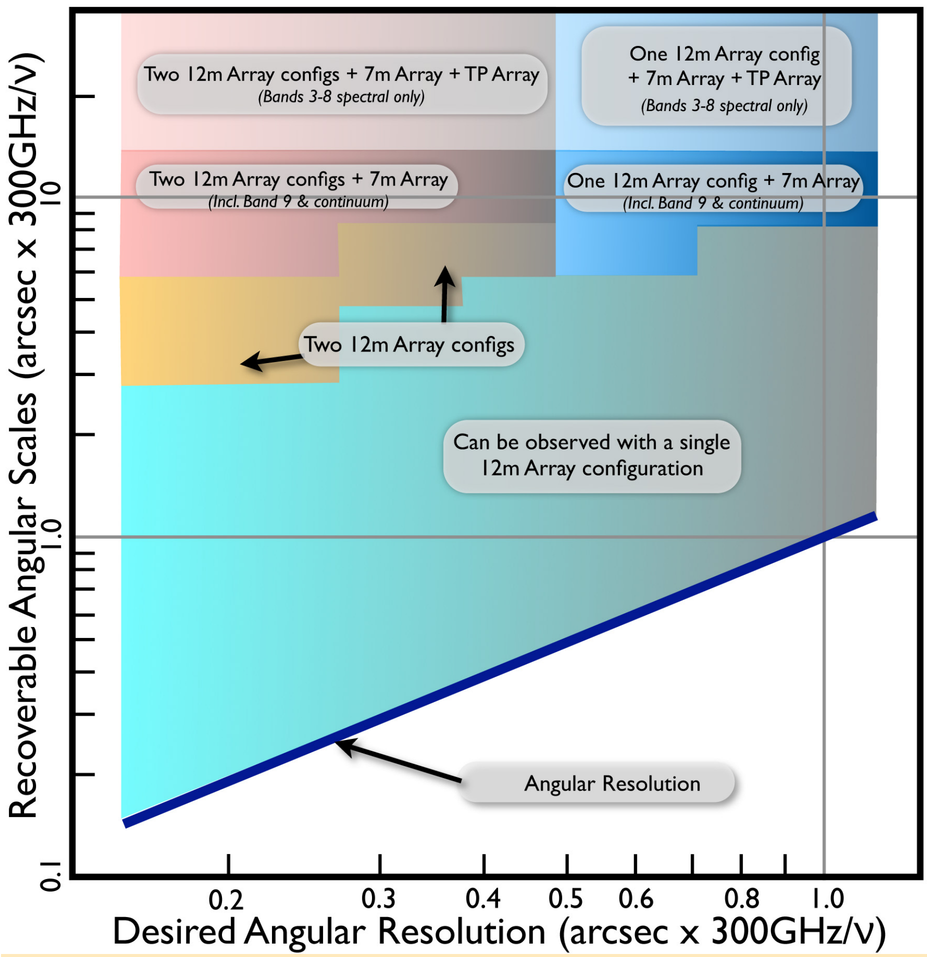


Figure 15: *The desired angular resolution determines the largest baselines (and hence the configuration) of the 12-m Array. The observations from that configuration can recover structure over a range of angular scales; for example, an observation at 0.8″ resolution at 300 GHz can recover structure over sizescales from ~0.8″ to ~8″ (cyan region). Structure larger than the "Maximum Recoverable Scale" (MRS; see p. 34) are "resolved out" by the interferometer. Structure larger than the MRS may be recovered either by adding observations using a smaller 12-m Array configuration (orange region), by adding observations using the ACA (blue regions), or by adding both another configuration and the ACA (pink regions). For example, if an angular resolution of 0.4″ (at 300 GHz) is required, and the LAS (see p. 34) in the science target is ~10″, then observations with two 12-m Array configurations plus the ACA 7-m Array will be needed. Very large angular scales require the addition of the ACA TP Array (not available in Cycle 2 for Band 9 or for continuum observations). Note that adding configurations or the ACA will significantly increase the required observing time. See the Capabilities guide in the Call for Proposals for details.*

(LAS). The angular resolution determines the largest baselines needed in the array, while the largest angular structure of interest in the source determines the shortest baselines needed (see *Glossary*, p. 33). The OT automatically determines the configurations you will need, as shown in Figure 15.

- Required sensitivity. Care must be taken when estimating the sensitivity needed per synthesized beam, particularly if estimating the source brightness from single-dish millimeter/sub-millimeter observations. A source which is bright in, say, a 30″ beam, may be difficult to detect in a 1″ beam if the emission is spread out over a few arcseconds. (Indeed, if smoothly distributed over the 30″ beam, it may have a flux density only $(1/30)^2$ as bright.)
- 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). Observations of fields where there is a bright nearby source but where the faint emission is of interest (e.g. faint sources near Sgr A*) will require great care, and may not achieve the theoretical noise level.

During *Cycle 2* with 34 antennas, ALMA will have 561 baselines (roughly 45% 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 2* 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 *simalma* 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 *simalma* can do, see Figure 16.

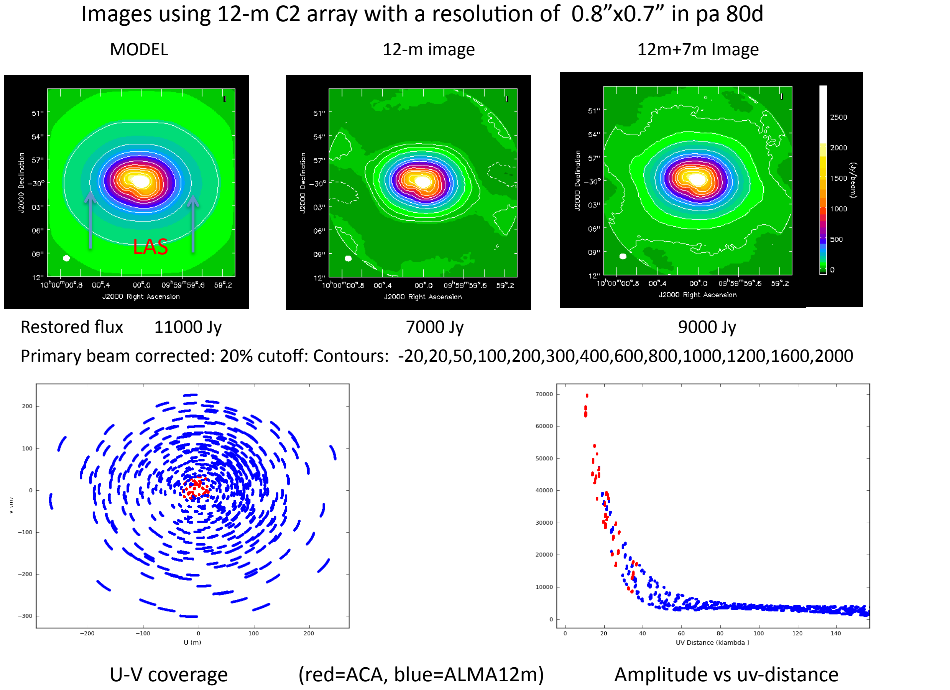


Figure 16(a)

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 *simalma*. The largest angular structure (LAS) of structure is shown by the arrows in the model image (top left image in Figures 16(a) and (b).

Figure 16(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.

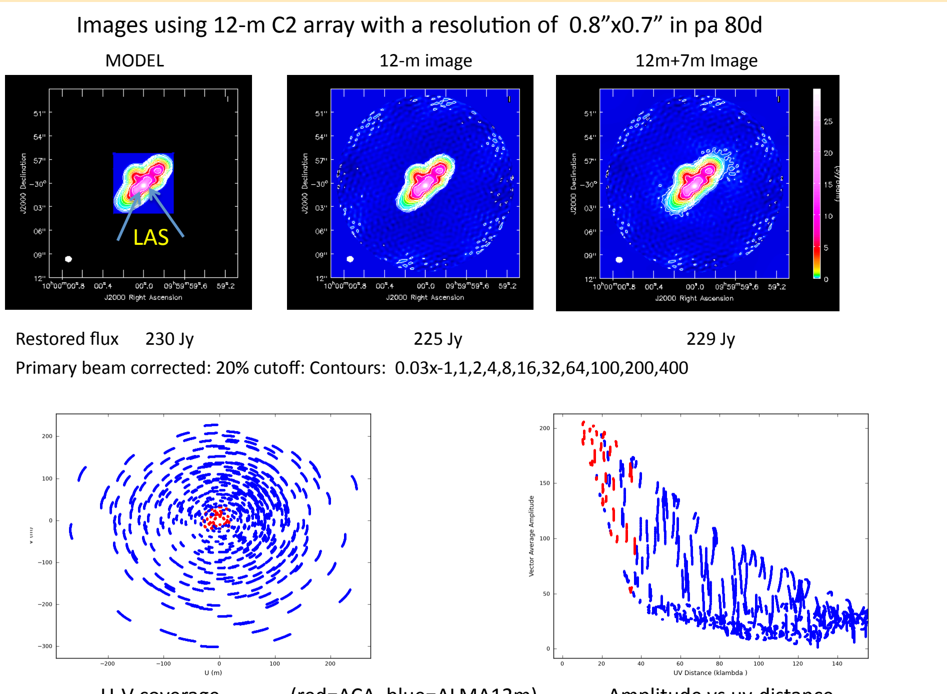


Figure 16(b)

Figure 16(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.*

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, the OT will recommend not using the ACA.

Examples of *Cycle 2* Observing With ALMA

In the following sections we provide a few examples of observations that could be done with ALMA during *Cycle 2 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 2* Announcement. Any astronomer proposing observations with ALMA for *Cycle 2* 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 *LAS* needed. The necessary *spectral resolution* is discussed to provide the appropriate *correlator settings* (see Table 2 page 9). As well, the *continuum* or *channel sensitivity* is quantified so the on-source *observing time* can be calculated. Note that the examples don't include overheads (calibration, telescope movement, etc.) which, for short observations in particular, can add a significant amount of time to an observation. 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 33.

Mapping a Lensed, High Redshift, Gas-Rich Galaxy

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

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 few that have 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 17) that have a combined extent of ~5". Each image has been resolved into at least four components (Fig. 17a) and large amounts of molecular gas have been detected (Fig.17b). Although resolved, the source is small and dominated by relatively compact structures and therefore well-suited to ALMA during *Cycle 2*. 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(s): 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 Harvard-Smithsonian Submillimeter Array (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 3 can be used for mapping continuum.

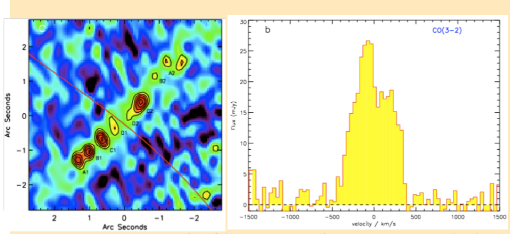
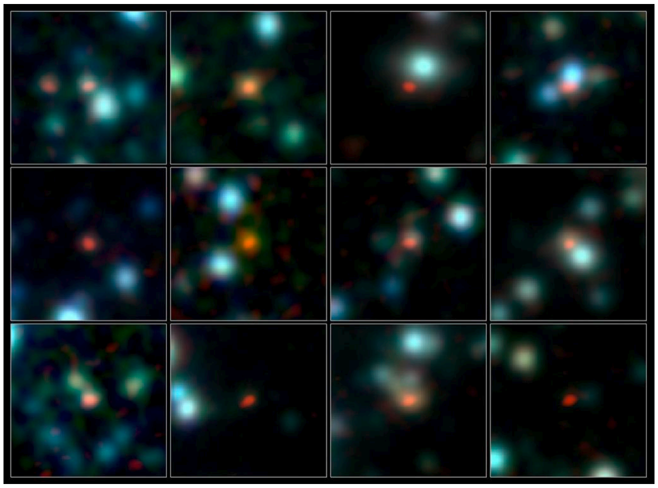


Figure 17: *(left) SMA (very extended configuration) 870 μm image of the Cosmic Eyelash. The red line marks the division between the two images of the background source. (right) Spectrum of CO(3-2) taken with the Plateau de Bure interferometer. Both figures are from Swinbank et al. (2010, Nature, 464, 733).*

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-four 12-m antennas predicts 12 minutes of integration to reach 1 σ = 0.5 mJy/beam (not including overheads). This amount of time will also produce a sensitivity of 70 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).



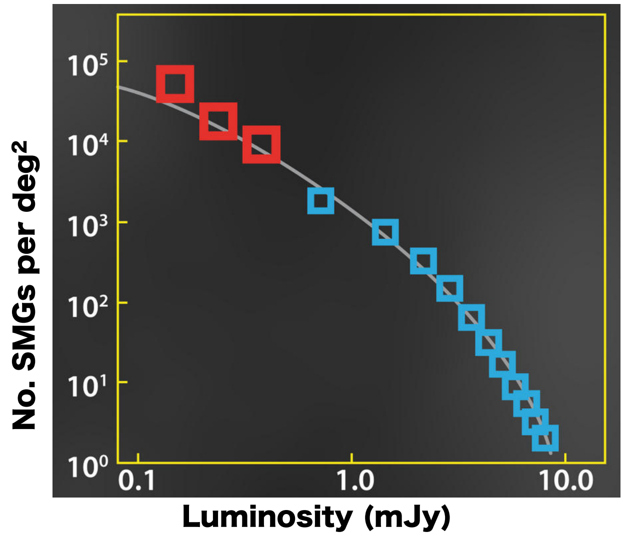


Figure 18: *(Left) ALMA was used in Cycle 0 by several teams to pinpoint the locations of star-forming galaxies in the early Universe. This image shows close-ups of a selection of these galaxies from one such study. ALMA Band 7 data (orange/red) are overlaid on an infrared view of the region as seen by the Spitzer Space Telescope. Each ALMA observation took only 2 minutes per galaxy. (Credit: ALMA (ESO/NAOJ/NRAO), J. Hodge et al., 2013, ApJ, 768, 91, NASA Spitzer Science Center)*

(Right) In a related study, another Cycle 0 project measured the number density of sub-mm galaxies a factor of ten less luminous than previously observed. The Band 6 observations revealed that approximately 80% of the unidentified millimeter wave light from the Universe is actually emitted from galaxies. (Credit: ALMA(ESO/NAOJ/NRAO) / B. Hatsukade et al., 2013, ApJ, 769, L27)

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

Angular Resolution: ~0.2” 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 2*. 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 2,* up to 150 sources (see *Proposers Guide* for restrictions) may be observed in one science goal, provided the sources are less than 10° apart. As an example, there are ~150 sources in the COSMOS-AzTEC catalogue (Aretxaga et al. 2011) with (de-boosted) flux densities > 3.3 mJy. 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 $S_{0.8mm} >$ 5 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-four 12-m antennas and an effective 7.5 GHz continuum bandwidth per polarization, predicts 2.7 minutes integration per source to reach a 1 σ = 0.125 mJy. Each science goal of 150 sources would require about 6.8 hours of on-source integration, not including overheads and calibration.

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 2* 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(s): 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 spectral resolution of ~3 km/s, but to decrease the data rate, we will use *Spectral averaging* factor of 2, which still yields a resolution of ~3.4 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.

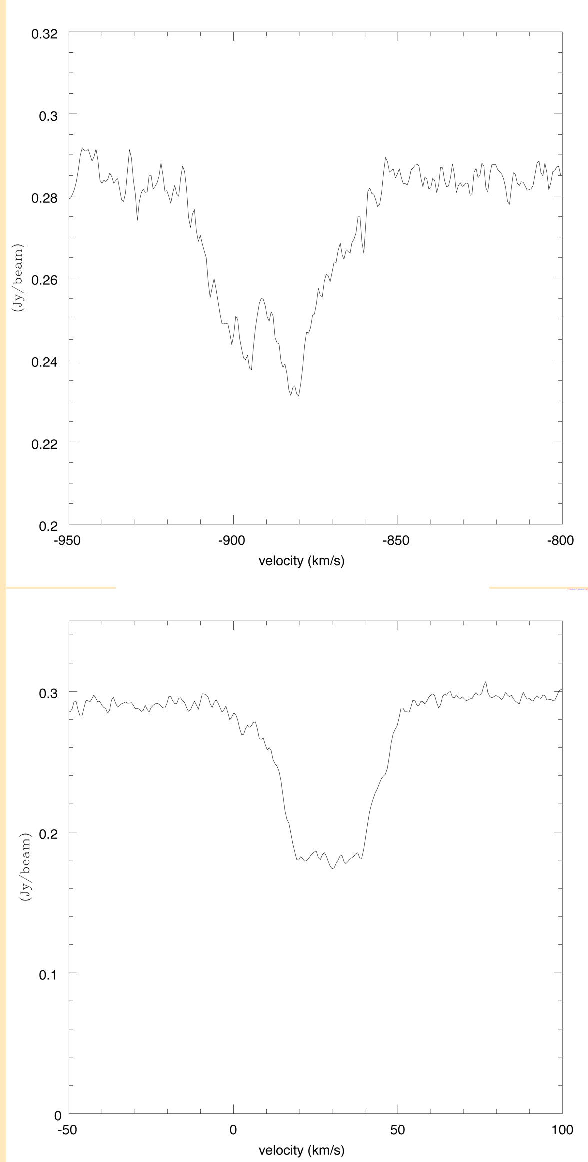


Figure 19: *Examples of molecular absorption lines detected toward PKS1830-211. These observations were made by ALMA in late 2010 when there were only a few antennas.*

Continuum sensitivity: N/A: The continuum sensitivity of the spectral line observations is sufficient for the present purposes given that a single spectral line channel has only a 1% error in the continuum level. Continuum imaging would also be useful for self-calibration

Band 3 observing time: With the release of the spectral scan mode in *Cycle 2*, setting up such spectral surveys is now much simpler. In the OT in the *Spectral Setup* frame, we request a start and end sky frequency of 85.0 and 115.5 GHz respectively, which is nearly the entire frequency range of the Band 3 receiver (84-116 GHz). The OT automatically sets up a set of five tunings to cover the requested interval. To reach our target line sensitivity, a total integration time of 22 minutes (plus overheads) will be required to cover this frequency range.

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 broad-band 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). These data support a model with a two-component, jet-like outflow (Berger et al. 2003, Nature, 426, 145).

Receiver(s): 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 34 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 over a four week period. 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 2*, no science observations will be permitted during engineering/commissioning periods, which can last for a few weeks. PIs should indicate whether fewer observations would still be useful.

Figure 20: *Part of the ALMA 12-m Array and, in the center, the 7-m Array, as they appeared in mid-November 2012. In the background the AOS support facility is visible. (Credit: ALMA (ESO/NAOJ/NRAO), C. Padilla)*

Mosaicing the Nearby Spiral Galaxy M100

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

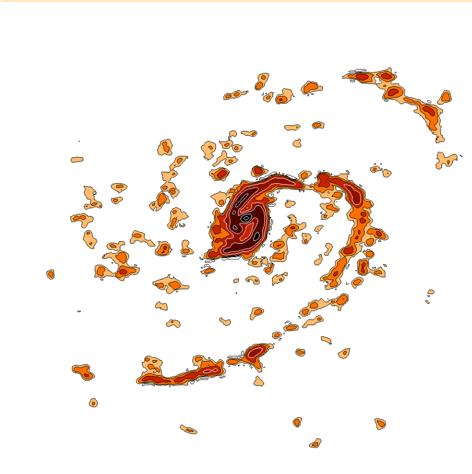


Figure 21: *ALMA Science Verification Data on M100. This image shows CO (1-0) integrated intensity in M100 from Science Verification observations (publicly available from the ALMA Science Portal).*

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.

In *Cycle 2*, 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.

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

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} $(K\ km/s)^{-1}$ and assuming a CO line width of 10 km/s, 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 channel, enough to detect Orion-like clouds at S/N ~ 5 or more.

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.

LAS: For a spectral line data set like we propose here, the key metric for "largest angular structure" 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 indi-

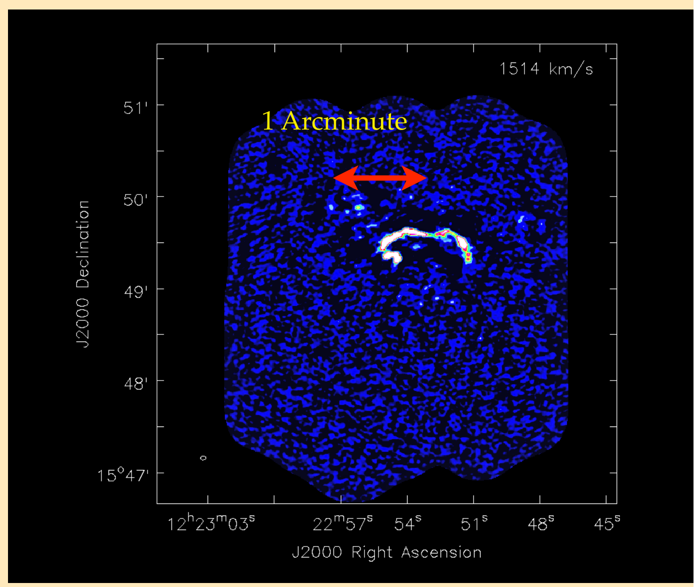


Figure 22: *Estimating the LAS of CO (1-0) emission in M100. We examine individual channels of the ALMA Science Verification data and look for the largest angular extent of emission in any direction. Within this channel we see contiguous emission extending at least an arcminute. This is larger than the maximum recoverable scale sampled by the main 12-m Array at Band 3, so ACA observations will be a necessary complement to the main array data.*

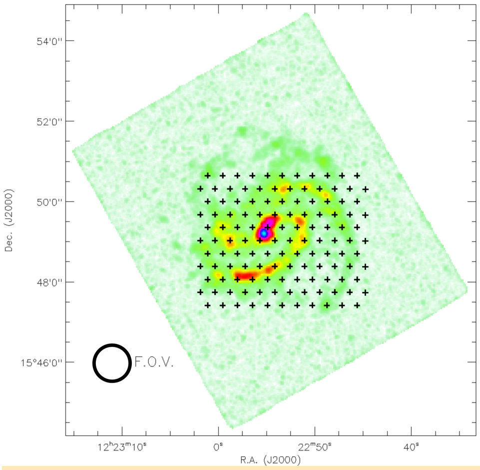


Figure 23: *Planning a large mosaic of M100. The color shows a low-resolution peak intensity map of CO (2-1) emission in M100 (HERACLES survey, Leroy et al. 2009). We plan a rectangular grid of hexagonally-packed pointings spaced by half of the ~54″ field of view (shown as a circle). With 126 pointings, shown as crosses, we cover almost all of the bright CO emission from M100.*

vidual channel often shows contiguous features up to 60″ long in their most extended direction (see the map of a single channel in Figure 22). Because 60″ exceeds the maximum recoverable scale sampled by the main 12-m Array, the project will of necessity involve complementary observations with the ACA (7-m Array). TP Array data would *not* be needed because the LAS is less than the size of the ACA primary beam (~92″).

Coverage: We know the overall extent of CO from previous observations, including wide field single dish maps (see Figure 21). 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 23. Mosaics of up to 150 pointings are allowed by the *Cycle 2* call.

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 ~2 minutes per mosaic position. With 126 fields we expect that the program will need about 5 hours on source. The OT estimates that 39 overlapping pointings will be needed for the ACA.

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 2*, 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).

Receiver(s): Bands 3, 4, 6, 7, 8 and 9: (98, 145, 233, 344, 405 and 679 GHz respectively)

Angular Resolution & LAS: 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 is resolvable during *Cycle 2* even at Band 3 (~0.4″ in the largest configuration). 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 0.4″ resolution achieved in Band 3 from the most extended configuration. Using the OT, we simply request a resolution of 0.4″ 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

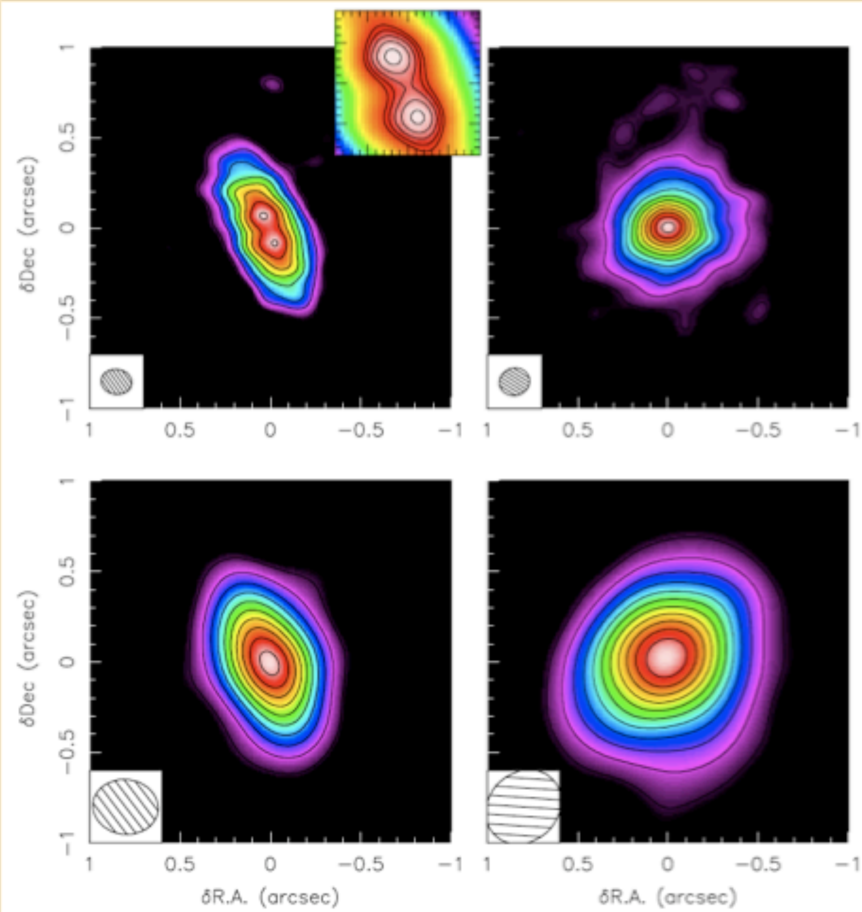


Figure 24: ***Top***: *CARMA aperture synthesis images of 1.3mm (228 GHz) continuum emission from two protostellar disks in Taurus with an inset to highlight the double structure seen in the top left panel (Isella et al. 2010, ApJ, 714, 1746).* ***Bottom***: *CARMA images of the 2.8mm (106 GHz) emission 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.*

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.

For this experiment, a configuration which gives an angular resolution of 0.4″ (see Figure 15 scaled to Band 3) will have recoverable angular scales of about 5″, so most likely all emission will be recovered.

Spectral Resolution: These are continuum observations, so this is not relevant.

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 peak flux densities we expect are 5.2, 12, 30, 65, 91 and 255 mJy/beam for Bands 3, 4, 6, 7, 8 and 9, respectively. We plan our observations with the consideration that the angular size of the disks is ~3 times the size of the synthesized beam at Band 3 with the edges of the disk ~10% of the peak intensity. For a 3σ detection of the disk edges, we aim for continuum sensitivities of 0.019, 0.043, 0.11, 0.24, 0.34, and 0.94 mJy/beam for Bands 3, 4, 6, 7, 8 and 9, respectively. Using the ALMA sensitivity calculator with 34 main array antennas (12-m diameter) and 7.5 GHz of bandwidth, we find that these sensitivities can be achieved in 28 minutes per disk (Band 3), 7 minutes per disk (Band 4), 1.4 minutes per disk (Band 6), 48 seconds per disk (Band 7), 1.5 minutes per disk (Band 8), and 3.2 minutes per disk (Band 9).

Figure 25: *ALMA, overlooked by the Andes. (Credit: ESO)*

Dust Polarization and Magnetic Fields in Star Forming Clouds

Science Aim: *To detect magnetic fields in a star forming core at the thermal Jeans-lengthscale through dust polarization.*
Stars form in giant molecular clouds under the influence of turbulence and large-scale magnetic (B) fields. Theoretically, the significance of the B field influences how structures are formed, such as the density contrast within structures, the star formation rate, and the suppression of fragmentation. One method to probe the B field is through observations of dust polarization. Dust grains are known to align with their shorter axes parallel to the field lines in most circumstances. The plane-of-sky projected B field integrated along the line of sight can be traced by rotating the detected polarization of the thermal dust emission by 90°. The proposed ALMA *ES* observations toward the star forming core W51 e2 will provide information on B field orientations within the core with unprecedented sensitivity and angular resolution. This will provide information of how the B field influences the formation of structures at the sizescale of the thermal Jeans-length.
Receiver(s): Band 7 (343 GHz) For this experiment the Band 7 receiver (343 GHz) provides the highest sensitivity to polarized dust emission.
Angular Resolution & LAS: 0.2″ & 0.8″ To resolve the W51 e2 dense core at the thermal Jeans length scale, we will need an angular resolution of 0.2″ (1400 AU at 7 kpc). The size of the core is 0.8″.
Continuum Sensitivity: 100μJy/beam The flux density of the W51 e2 core is 9.3 Jy over the 0.8″ core, or approximately 0.6 Jy/beam. Assuming that the polarization percentage is 1%, the expected polarization intensity will be ~6 mJy/beam. We request a sensitivity of 100 μJy/beam to achieve a 60σ detection of the polarization over the entire core.
Observing Time: It will take 4.5 minutes on-source with a 7.5 GHz bandwidth to achieve the sensitivity. However, the OT imposes a minimum time of three hours for full-polarization observations in order to get sufficient parallactic angle coverage for calibration.

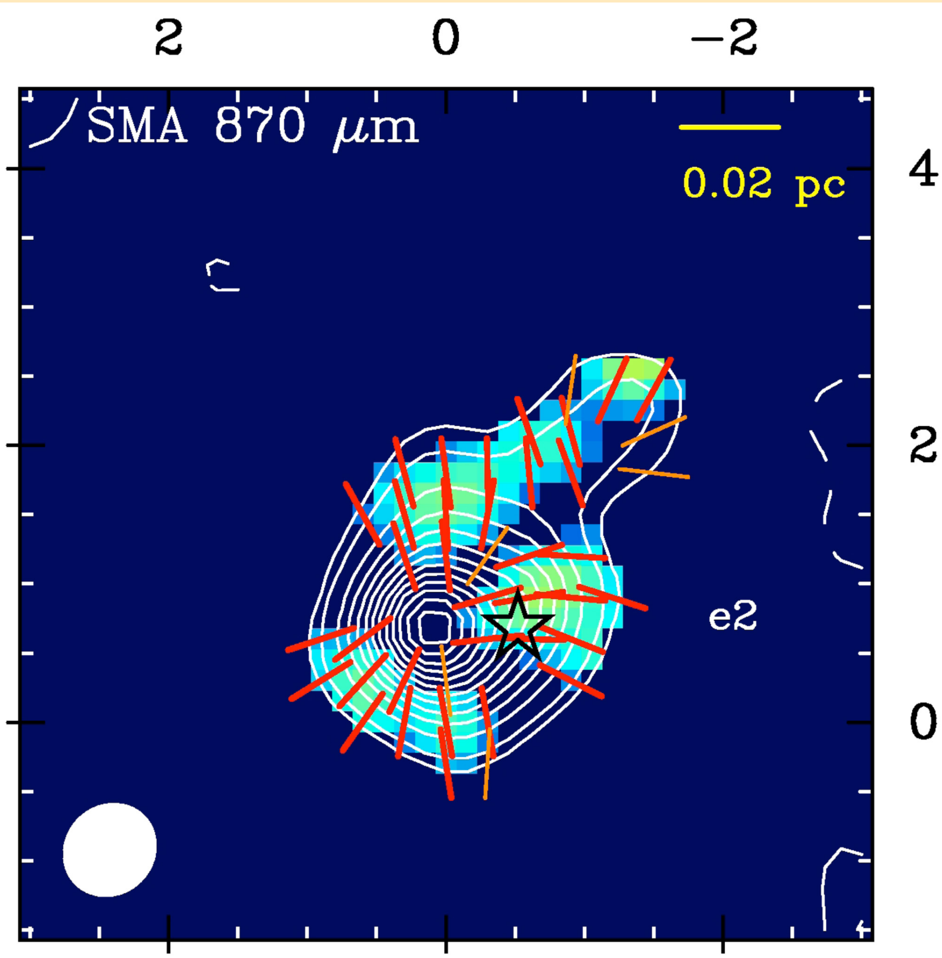


Figure 26: *Magnetic field of the W51 e2 core at 0.9 mm obtained at the Submillimeter Array. The total intensity is shown in contours. The polarization intensity is shown in color scale. The star denotes the ultracompact HII region. (Credit: Ya-Wen Tang, 2009 ApJ, 700, 251)*

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 ($n \sim 10^5$ 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).

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

Angular Resolution & LAS: 0.3" Taking the Helix Nebula results as a starting point, the angular resolution desired should be below the fragmentation scale of ~1" (which we set as the LAS). As a pilot project, we attempt to gain a factor of one hundred in angular resolution over previous observations.

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. We choose the 234 MHz bandwidth spectral mode and spectral averaging factor 2 to give a resolution of 0.183 km/s.

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 34 antennas and an effective 0.18 km/s spectral resolution predicts 3.7 hours to reach 0.5 K. The two separate pointings will require about 7.5 hours of ALMA observing time, plus overheads.

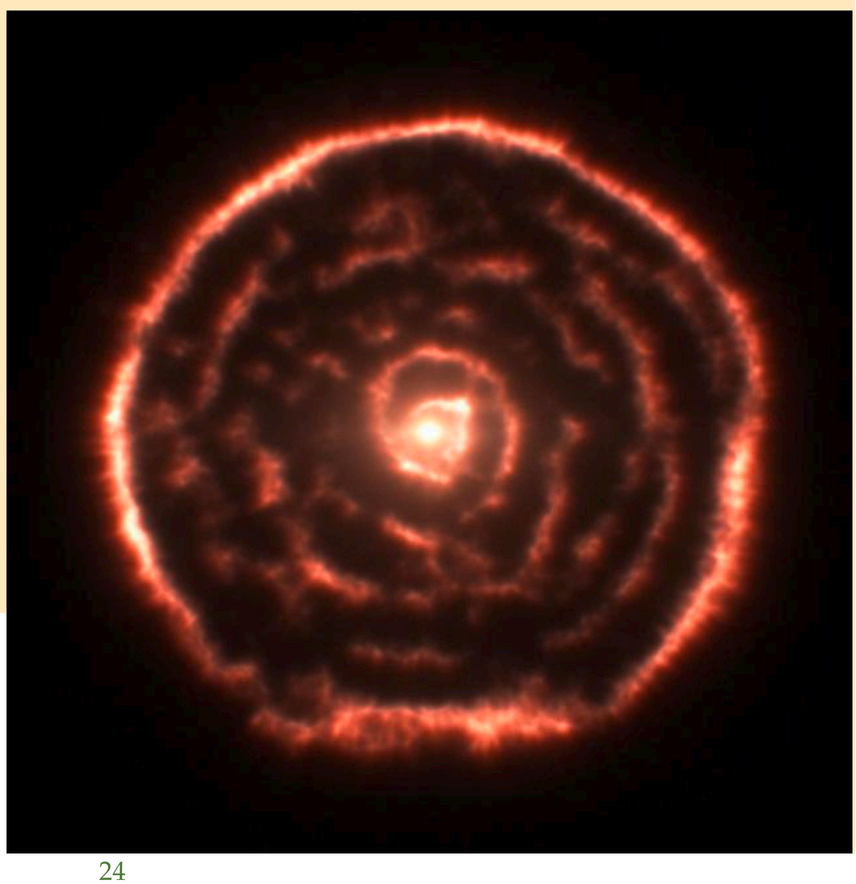


Figure 27: *Among the more spectactular images to come out of Cycle 0 Early Science is that of the expanding spherical shell and spiral wind emanating from the evolved star R Sculptoris. (Credit: ALMA (ESO/NAOJ/NRAO/Maerker et al., 2012, Nature, 490, 232, NASA Spitzer Science Center)*

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.

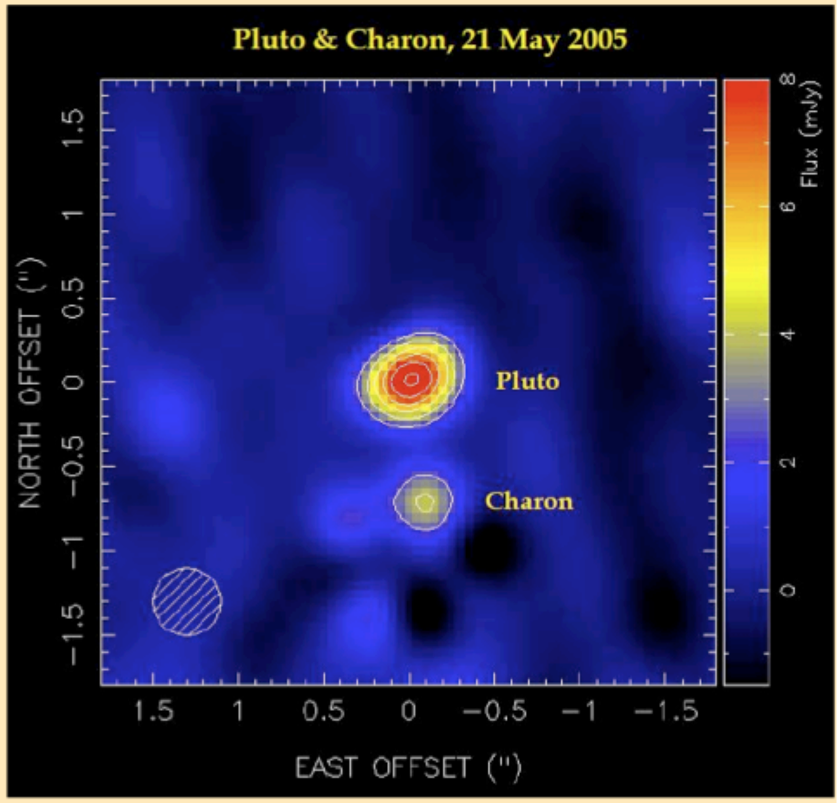


Figure 28: *Submillimeter Array (SMA) aperture synthesis images of 1.4 mm (220 GHz) continuum emission of Pluto and Charon (Gurwell & Butler. 2005 BAAS 37, 743). These observations were made with the most extended SMA configuration during an 8 hour track, achieving a synthesized beam of ~ 0.4″ FWHM.*

Receiver(s): Bands 7 and 9: (345 GHz and 690 GHz)

Angular Resolution & LAS: 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 2, 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 2* configuration. Extended emission is irrelevant, so ACA observations are not needed.

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 234 MHz bandwidth and a spectral averaging factor of 4 (to reduce the data rate), which yields 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 at Bands 7 & 9 respectively.

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.

Observing Time: Using the ALMA sensitivity calculator with thirty-four 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 16 minutes of observing time. The remaining 5.625 GHz of continuum will yield a continuum sensitivity of 0.063 mJy/beam (i.e. a S/N > 100). To reach the continuum sensitivities with 7.5 GHz of bandwidth and dual polarization at Band 9 will require 5 minutes of on-source integration during of exceptional weather.

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 cycle.

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. If you wish to receive these notifications automatically, you can subscribe to the email distribution list of your ARC by submitting a request through the Helpdesk.

Registering as an ALMA User: All users who wish to be part of any ALMA proposal (either as Principal Investigator or Co-Investigator), submit tickets to the ALMA Helpdesk, track a project, or retrieve proprietary 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 archived data, 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 Chile or from non-ALMA member regions may select any of the three ARCs for support.

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

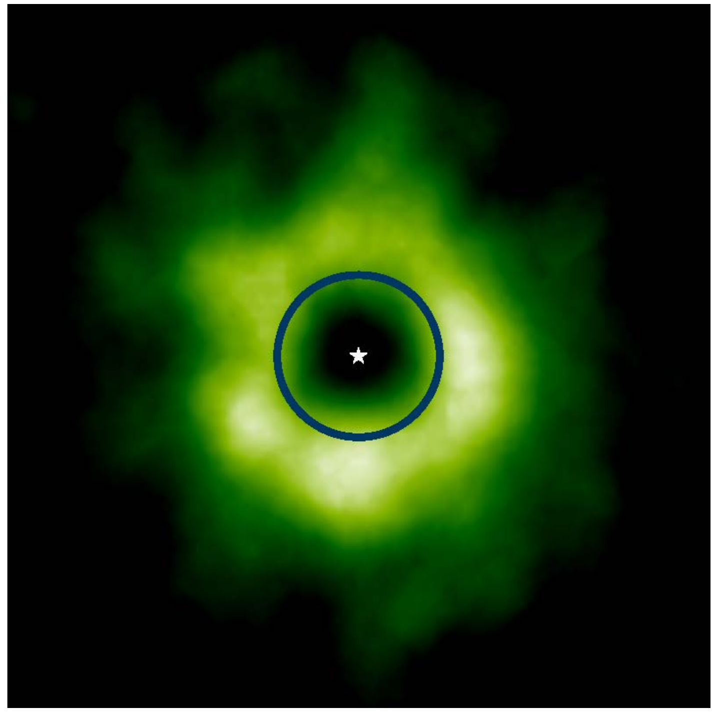
Proposal Preparation & Submission (Phase 1): After the CfP is issued, users will have some period (1-2 months) to prepare their Phase 1 materials using the ALMA OT. Phase 1 consists of a detailed observing proposal with a scientific and technical justification submitted to the Observatory through the OT. The OT includes a sensitivity calculator and viewers for assisting with correlator setups and mapping parameters while preparing 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 1 Support).

If desired, one can simulate ALMA observations using the *simalma* 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. (See page 39 for links to these tools.)

Proposal Review Process: Phase 1 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 proposal's 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 associated with the North American, Europe, East Asian, and Chilean partners, respectively. Time

For the non-expert reading this section, a list of Interferometry Concepts is included, starting on page 33.

Figure 29: *This Band 7 image shows the first convincing evidence for a CO "snow line" in the planet-forming disk around a young star. The image shows emission from the N_2H+ molecule toward the young star TW Hya. This fragile molecule is easily destroyed in the presence of CO gas, so would only appear in detectable amounts in regions where CO had frozen out, and is hence a proxy for CO ice. The circle indicates the size of Neptune's orbit. (Credit: Qi et al., 2013, Science, 341. 630)*



will also be available to projects from non-ALMA regions through the Open Skies policy. Users should consult the Science Portal and CfP for details. Users will receive notification of the proposal review process via email.

Scheduling Block Preparation (Phase 2): During Phase 2, successful proposers will use the OT to convert their Phase 1 Science Goals into Scheduling Blocks (SBs), a series of blocks of observing commands corresponding to a certain observation length. During *Early Science*, ARC and DSO staff will carry out SB generation, in consultation with the proposer. SBs are then 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 goal have been successfully observed, the data will be calibrated, reduced and quality assured by ALMA/ARC 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 and calibrated 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 2, to guide in planning the execution of the project. Depending on the nature of a given project, the observational parameters may be interrelated. In the following, we describe the basis for choosing these parameters.

> **Learn More**
>
> A fuller description of ALMA observing considerations can be found in the Technical Handbook
>
> http://almascience.org/proposing/call-for-proposals/technical-handbook

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 angular scales (i.e., spatial frequencies), as measured by the antenna pairs making up an array (see “*uv*-coverage”, page 37). Since the number of angular scales measured is finite, the resulting image is spatially "filtered" and only reflects the emission on the observed angular 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 Recoverable Scale (MRS) is the largest angular scale structure that can be recoverable from observations by an interferometer, and is 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). MRS is a guideline for the largest angular structure on which some 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 configurations (such as compact configurations of the 12-m Array and/or the 7-m Array) or large single-dish telescopes (e.g. the TP Array). One can explore with CASA *simalma* or the Observation Support Tool whether the ACA will be required for a particular project. The OT shows the MRS for the most compact and most extended 12-m Array configurations in the *Control and Performance* tab, and based on the requested *angular resolution* and *largest angular structure* (LAS), may recommend the use of multiple 12-m Array configurations and/or the ACA (see Figure 15).

> **Learn More**
>
> A video explaining Maximum Recoverable Scale can be viewed at
>
> https://science.nrao.edu/science/videos

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.

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 Recoverable 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 Table 2 page 9.) 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 (though see *Data Rate* on page 34 for a caveat). The width of these channels can be defined from 3.8 kHz to 25 MHz. (In *Cycle 2*, the smallest available channel spacing is 7.6 kHz (in single polarization), with a spectral resolution of 15.3 kHz due to Hanning smoothing.) For continuum observations or for observations of very broad spectral lines (e.g. high-redshift galaxies), wide bandwidths and low spectral resolution channels are used to achieve high sensitivity; the total bandwidth of all correlator settings used cannot exceed 7.5 GHz. For observations of spectral lines, narrower bandwidths with higher spectral resolution channels may be required. There is, however, a cost to sensitivity in using small bandwidth channels. Sensitivity can be improved 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. Channel averaging can be set up during Phase 1 in the OT, which has the added benefit of reducing the *data rate*, or later during data reduction. The ALMA correlators are highly complex and extremely flexible and can be configured to observe simultaneously several spectral lines within

Learn More

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

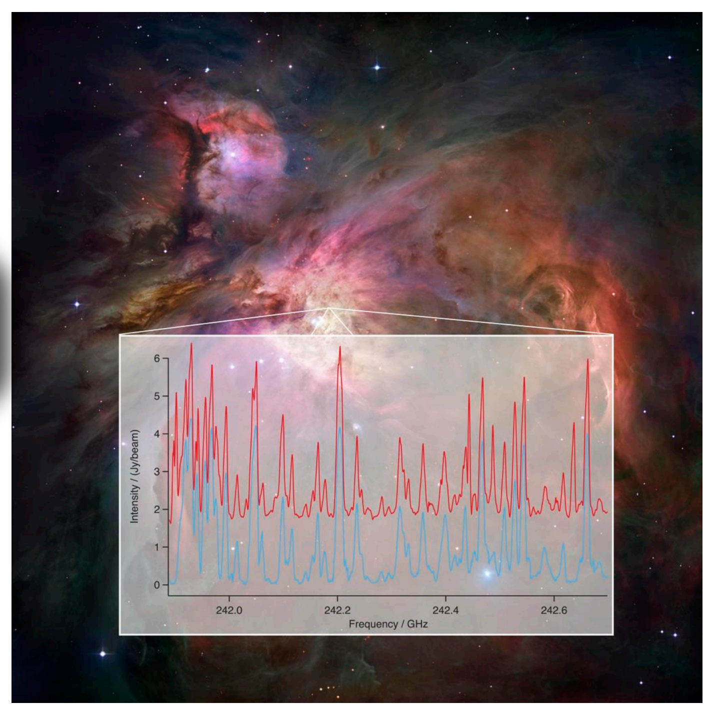


Figure 30: *Plot of Band 7 emission from the molecule ethyl cyanide (CH3CH2CN). Blue is the plot from terrestrial laboratory measurement; red is the plot from ALMA observation of a star-forming region in Orion. Plots are superimposed on Hubble Space Telescope image of the Orion Nebula; small box indicates location of area observed with ALMA. Credit: Fortman, et al., NRAO/AUI/NSF, NASA*

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. (See *Baseband* and *Spectral Windows*, pp. 33 and 36.) Such "mixed" spectral modes will be available during *Cycle 2*.

Sensitivity is usually defined as the 1 sigma RMS variation of noise in the data (ΔS) and so serves as a threshold for the detection of emission. For ALMA, basic sensitivity depends 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 (see *Useful Equations*, page 38). 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 strongly 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 sometimes 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. 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. (See page 38.) How data are weighted during imaging also affects sensitivity. 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), also built into the OT.

Creating Images From Your Data

Once the data are taken, ALMA data will be reduced by staff from the JAO and ARCs using a pipeline employing the Common Astronomy Software Applications (CASA) package. After the data have been reduced and quality assured, the reduced data are ingested into the JAO archive and transferred to the ARC archives, where they are made available to the project teams. The project teams are

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> Casaguides
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> http://casaguides.nrao.edu/
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> are step-by-step guides for learning data reduction and imaging with CASA
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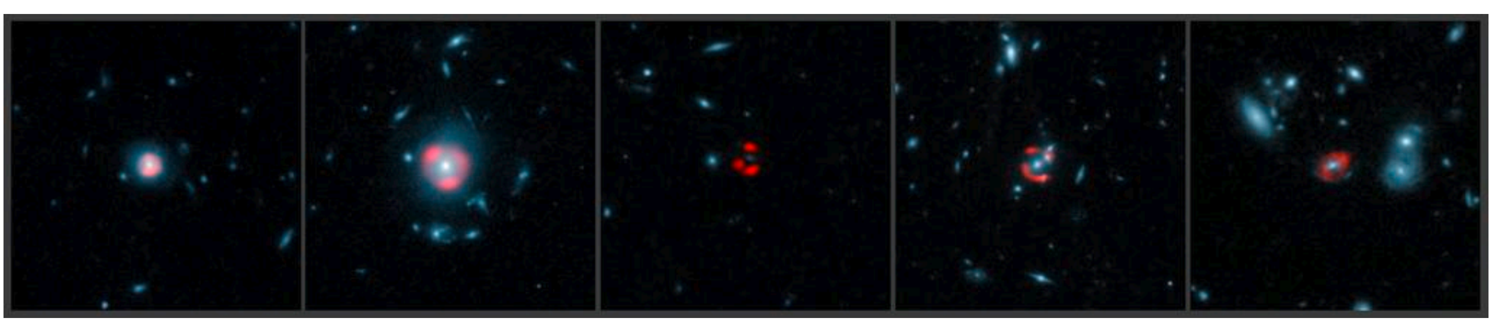
provided with the calibrated data, the reference images (i.e. the pipeline-reduced calibrated data cube), and the scripts used by the pipeline.

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. *Casaguides* (see link page 39) are available which will guide you step-by-step in reducing real ALMA Science Verification data.

Calibration: ALMA observing is heavily constrained by weather conditions on the Llano de Chajnantor. Therefore, ALMA projects are 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 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 require calibration of their amplitudes and phases as a function of frequency and time. Flux calibration requires the observation 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, bright Solar System objects (planets, moons, asteroids) which are unresolved or only partially resolved for the required array configuration, and which have accurate models, are used as flux standards. The observed data from these objects can be used to scale accurately the intensities recorded from the target. Bandpass (or passband) calibration, sometimes called frequency calibration, also requires observations of bright sources with the same correlator setup as the target. This is used to correct for frequency-dependent variations in amplitude and phase. Gain (or phase) calibration corrects for phase errors due to differential atmospheric changes above each antenna on timescales of seconds to minutes, and for amplitude fluctuations as well. Atmospheric water vapor can cause very rapid fluctuations over timescales of seconds. Water vapor radiometers (WVRs) are installed on all antennas on the 12-m Array to monitor these variations, which are routinely applied to the data during pipeline processing. Longer timescale phase drifts are monitored using periodic observations of a moderately bright, very compact source at relatively small angular distance from the target. The best sources for gain 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

Figure 31: *This montage combines Band 3 data from ALMA with images from the NASA/ESA Hubble Space Telescope, for five distant galaxies. The ALMA images, represented in red, show the distant, background galaxies, being distorted by the gravitational lens effect produced by the galaxies in the foreground, depicted in the Hubble data in blue. The background galaxies appear warped into rings of light known as Einstein rings, which encircle the foreground galaxies. (Credit: ALMA (ESO/NRAO/NAOJ), J. Vieira et al., 2013, Nature, 495, 344)*



cadence at which the gain 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 gain calibrators from every few minutes to every few seconds (depending on frequency and baseline length) to capture these variations.

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 by members of the DSO and the ARCs using a combination of the pipeline and by hand using CASA and other specially designed software.) There are many approaches to reducing and imaging interferometer data but here 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 flagged and removed from the ensemble before the FT, and finally, the image is made from the inverse FT. Flagging is used to remove poor quality data, which might affect image quality, or atmospheric spectral lines in calibrator data which may skew the calibration solutions. Flagged data can be ignored by the reduction software and are then effectively removed from the data ensemble.

Data that have gone through flagging and calibration 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 angular resolution of the data can be accurately represented. Various angular 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 angular scales observed in the ensemble, typically provides the highest sensitivity (but at a slightly reduced resolution). 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, the *uv*-coverage, and the amount and quality of data obtained; such images are sometimes called "dirty images". Since interferometers cannot measure all angular 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.

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 angular frequency components to lower angular 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 Frequency See *Spatial Frequency.*

Angular Resolution (or Synthesized Beam) The effective angular resolving power (equivalent to a point spread function) provided by the ensemble of transformed visibilities given its range of spatial frequency coverage. Essentially this is roughly proportional to λ/L_{max}, where λ is the observed wavelength and L_{max} is the size of the array's largest baselines projected in the plane of the sky. (Note that this means that an observation at low elevation has a larger synthesized beams than an observation at high elevation.) The angular resolution can also be adjusted through the choice of an imaging weighting function (see *Imaging* page 31). 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.

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 the ALMA 12-m Array. A heterogeneous array consists of antennas of different diameters, like the ALMA 12-m Array plus 7-m Array.

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 Table 3 on page 10 for the full list of receiver bands that ALMA will have in Full Operations.

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 correlators (see Figure 32). For the dual polarization receivers (e.g. Bands 3-8), 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 same 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.).

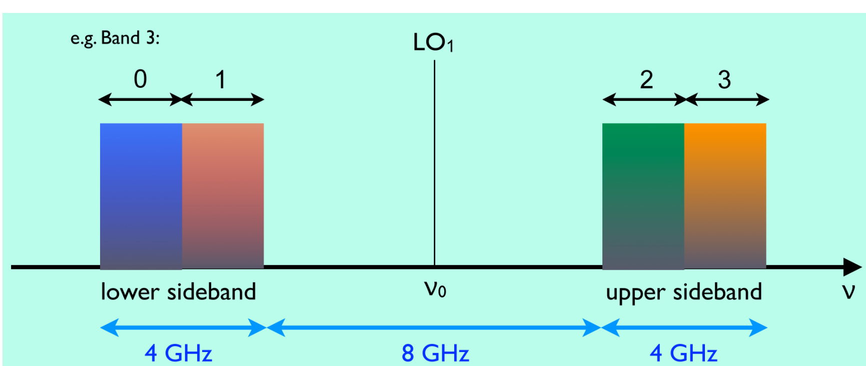


Figure 32: *A graphical view of basebands and sidebands. Basebands may be tuned to overlap if the user wishes, or may be located so as to maximize the total bandwidth (as shown). Each baseband may be further subdivided into as many as 8 spectral windows. Up to four spectral windows per baseband will be available during Cycle 2.*

Baseline A pair of any two antennas in the array. The angular frequency that a given baseline measures is related to the instantaneous foreshortened distance between the two antennas relative to the source and to 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 2, 34 antennas provide 561 baselines in the 12-m Array, nearly half the number of baselines (1225) when all 50 12-m Array antennas are in operation.

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 2 page 9 for the available modes in Cycle 2) defines the bandwidth and resolution of the spectral window.

Data Rate The rate (in Mb/sec) that data are fed from the correlator into the archive. With the large number of baselines and the huge number of channels (up to 3840 in each of four basebands), the data rate can reach unsustainable levels. Unless the science requires such high data rates, proposers should look for ways to lower the rates, for example by using Spectral Averaging.

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 (FOV) See Primary Beam.

Fringes See Visibilities.

Largest Angular Structure (LAS) The largest scale structure of interest in the source to be observed. If the LAS is larger than the maximum recoverable scale which the array can recover, then a more compact array configuration, e.g.

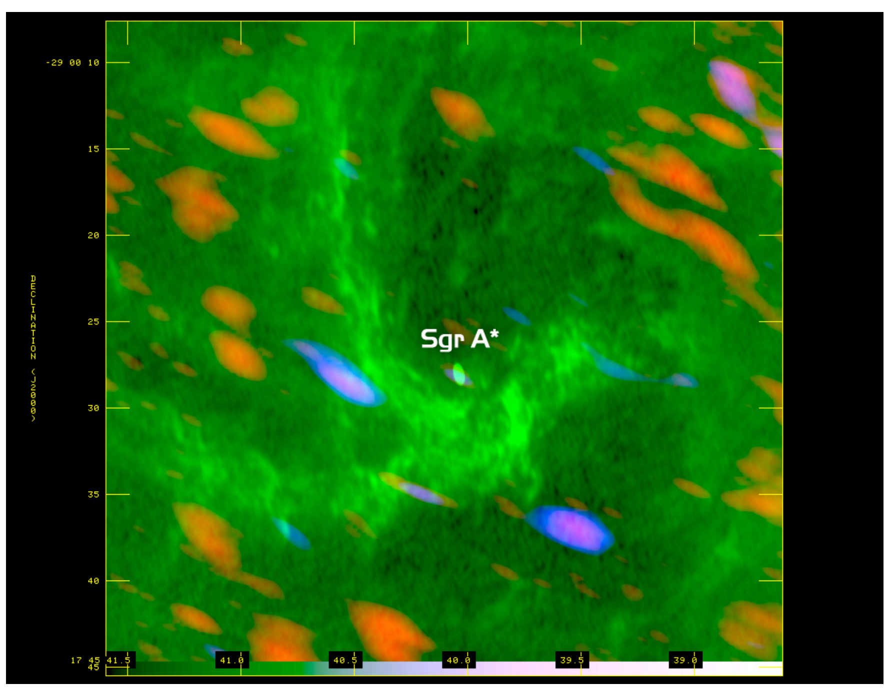


Figure 33: *A combined ALMA Band 6 and VLA image of the galactic center. The supermassive black hole is marked by its traditional symbol Sgr A*. The red and blue areas, taken with ALMA, map the presence of SiO, an indicator of star formation. The blue areas have the highest velocities, blasting out at 150-200kilometers per second. The green region, imaged with the VLA, traces hot gas around the black hole and corresponds to an area 3.5 by 4.5 light-years. (Credit: ALMA (ESO/NAOJ/NRAO), Yusef-Zadeh & Wardle, 2013, ApJ, 770, L21)*

with the ACA, may be required. A 4-minute video explaining LAS can be viewed at https://science.nrao.edu/science/videos.

Maximum Recoverable Scale (MRS) The maximum angular scale structure that may be recoverable from observations with an interferometer, and is dependent on the minimum separation between antennas; MRS~0.6 λ/D_{min}. Larger structure are "resolved out" and cannot be recovered. See Total Power, the discussion on page 28, and Figures 15 & 16.

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). Alternatively, one polarization may be discarded in order to double the number of channels over the requested bandwidth, yielding much greater spectral resolution. A third option is to use the polarization information to obtain the full Stokes parameters in order to measure the polarization of the source. A limited full Stokes capability will be available in Cycle 2.

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(λ/D), where λ is the observational wavelength and D is the antenna diameter. Parabolic radio antennas can have significant secondary angular sensitivities called sidelobes or the error beam, but these can be minimized by careful design and construction. The primary beam sets the FOV for an observation with the array, unless a larger mosaic is made.

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 angular frequencies.

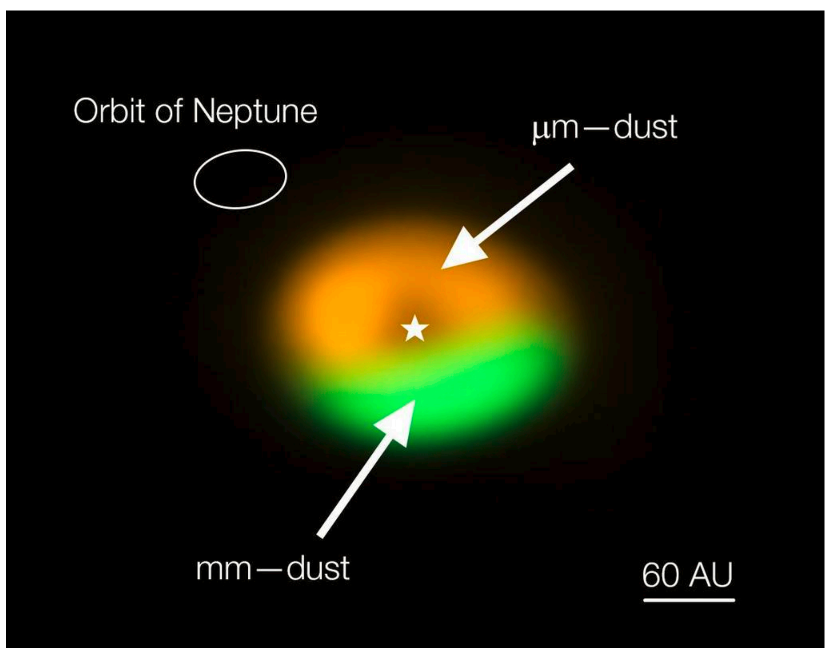


Figure 34: *This image shows ALMA Band 9 data in green tracing mm-sized dust, and in orange the location of micron-sized dust (from the VISIR instrument on the VLT), surrounding the protostar Oph-IRS 48. The larger grains may be constrained in a "dust trap", allowing them to clump together and grow to sizes that allow them to survive on their own. (Credit: ALMA (ESO/NAOJ/NRAO), van der Marel et al., 2013, Science, 340, 1199)*

Sideband At any given tuning, each receiver is sensitive to two separate ranges of sky frequency of equal width called sidebands (see Figure 32). 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 2.) This technique can also be used in lower frequency bands to obtain even greater sideband separation than that provided by the receiver.

Shadowing Partial eclipsing of one antenna by another. When observations are made of sources at very low elevation, there is a potential for antennas which are close together to "shadow" one another, i.e. one antenna is attempting to look partially through another. This is particularly a problem for the ACA when observing at high north or south declinations (low elevations). Visibilities involving the shadowed antenna may need to be flagged as bad when reducing the data, resulting in a lower sensitivity than expected.

Snapshot A short-duration set of integrations of an astronomical source using all baselines. Since only a limited number of angular 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. 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 Averaging Averaging of spectral channels in order to reduce the number of channels, to improve the S/N per channel, and to lower the data rate. Within the OT's Spectral Setup frame, one can choose a spectral averaging factor of 1 (no averaging), 2, 4, 8, or 16, which reduces the number of channels by averaging that number of channels together.

Spectral Window A spectral window is a frequency subrange of a baseband. Each baseband may be divided into one or more spectral windows by allocating a fraction of the correlator resources to each window (see Table 2 page 9). The properties of the spectral window depend on the fraction of the correlator resources allocated to it. A single window will have the maximum bandwidth and minimum channel spacing, while multiple spectral windows provide reduced bandwidth per spectral window and/or larger chan-

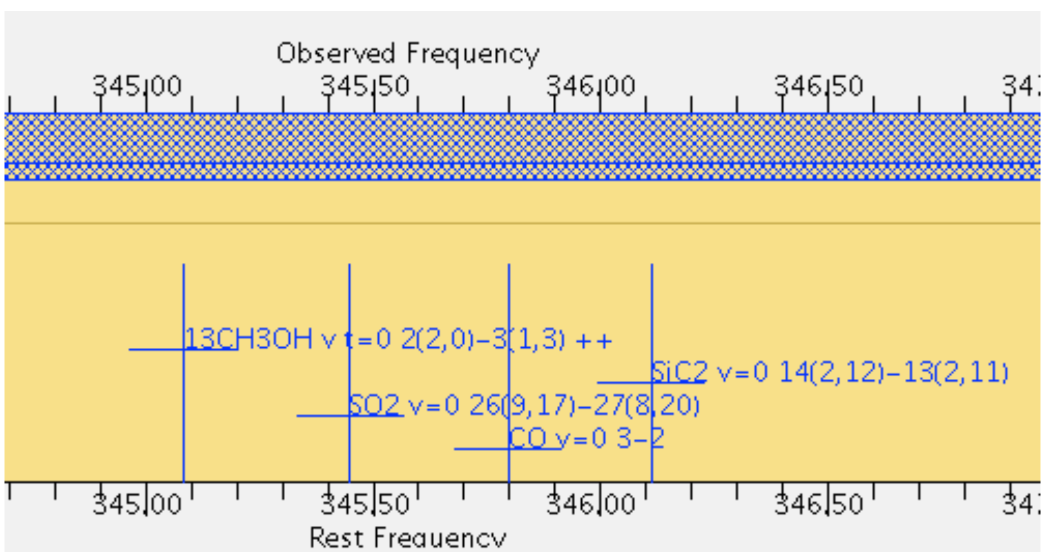


Figure 35: *Four spectral windows were set up to observe these four lines simultaneously in one baseband using the OT. The windows are each 234 MHz wide (with 0.43 km/s channels), and are centered at 345.80, 345.45, 346.11 and 345.09 GHz. The spectral windows must fit within the 2 GHz wide baseband.*

nel spacings. Spectral windows can be placed anywhere within the baseband. In Cycle 2, each baseband may contain up to four spectral windows (with the same correlator mode in each window within a baseband).

Synthesized Beam See *Angular Resolution*

Total Power, or Zero-Spacing Flux The large-scale emission which the array cannot detect (see *Maximum Recoverable Scale*). A pair of antennas cannot be physically separated by a distance less than the antenna diameter. Hence in any observation there is a range of low spatial frequencies (from 0 to the lowest spatial frequency sampled by the array) 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 and/or a more compact configuration of antennas. For example, data from an extended 12-m Array configuration can be combined with data from smaller 12-m Array configurations, and/or with the ACA 7-m Array and/or the 4-antenna TP Array (see Figure 15 for how to recover larger-scale structure during *Cycle 2*).

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.

Figure 36: *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. (Credit: W. Garnier, ALMA (ESO/NAOJ/NRAO), General Dynamics C4 Systems)*

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),

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

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

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

For example, a 1 km/s resolution at 300 GHz would require a resolution of 1 MHz. Similarly a resolution of 0.0153 MHz (see Table 2 page 9) would correspond to a resolution of 0.0153 km/s at 300 GHz, or 0.0051 km/s at 900 GHz.

For a gaussian source, the conversion from Rayleigh-Jeans 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

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

Finally, the noise ΔS_ν, in an integration time Δt, varies with system temperature T_{sys}, spectral 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 2 Call for Proposals	http://almascience.org/proposing/
Science & Software Tools	http://almascience.org/documents-and-tools/
JAO Public Web	http://almaobservatory.org
ALMA Virtual Tour	http://almaobservatory.org/en/visuals/alma-virtual-tour/
Common ALMA acronyms	http://www.almaobservatory.org/en/about-alma/acronyms
North American ARC	http://science.nrao.edu/facilities/alma/
European ARC	http://www.eso.org/sci/facilities/alma/arc.html
East Asian 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=Guide_To_Simulating_ALMA_Data
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/
ALMA Primer Videos	https://science.nrao.edu/science/videos
Cycle 2 Quick Facts	http://science.nrao.edu/facilities/alma/didyouknow

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