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Observing with ALMA – A Primer
(Cycle 7)

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ALMA, an international astronomy facility, is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile.
The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

User Support:

For further information or to comment on this document, please contact your regional Helpdesk through the ALMA Science Portal at **www.almascience.org**. Helpdesk tickets will be directed to the nearest ALMA Regional Center at ESO, NAOJ or NRAO.

Revision History:

Version	Date	Editors
1	**8 Mar 2019**	**G. Schieven**

Contributors

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Purpose of this Document

This document is designed to provide basic introductory information on the Atacama Large Millimeter/submillimeter Array (ALMA) and its capabilities, 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.

Figure 1: *A panoramic view of the ALMA antennas under the Milky Way. (Credit: Y. Beletsky (LCO)/ESO)*

Some Acronyms Used in this Document

ALMA	*Atacama Large Millimeter/submillimeter Array*	**LAS**	*Largest Angular Structure*
ACA	*Atacama Compact Array (Morita 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*
FDM	*Frequency Division Mode (spectral correlator mode)*	**SV**	*Science Verification*
FOV	*Field of View (or Primary Beam)*	**TDM**	*Time Division Mode (continuum correlator mode)*
JAO	*Joint ALMA Observatory*	**TP Array**	*Total Power Array (part of the ACA)*

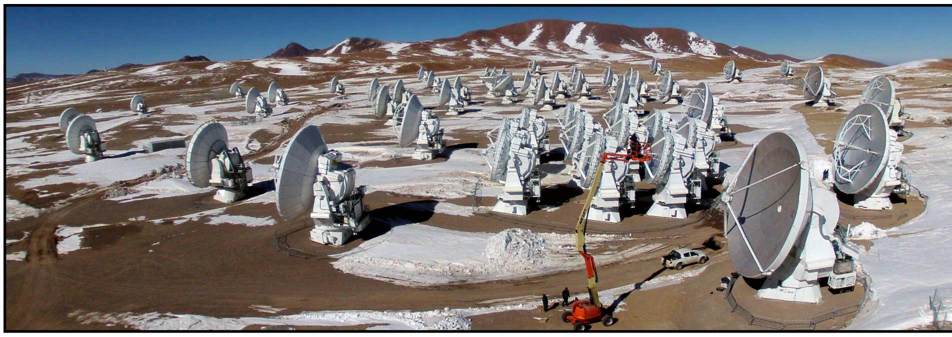


Figure 2: *An aerial photo of the ALMA array, taken with a camera mounted on a hexacopter. Note the ACA 7-m Array in the center foreground. (Credit: EFE/ Ariel Marinkovic)*

What is ALMA?

The Atacama Large Millimeter/submillimeter Array (ALMA) is one of the largest multi-national science projects to date. 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).

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 enables 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 probes the first stars and galaxies and can directly image the disks in which planets are forming.

Figure 3: *Map of Chile, showing the location of ALMA (red star).*

Unlike most radio telescopes, the ALMA antennas are located at a very high altitude on the Llano de Chajnantor in northern Chile (see Figure 3), one of the driest locations on earth. Decade-long monitoring studies of the sky above this site have shown it to have the transparency and stability at submm wavelengths essential for ALMA (Figure 4). The site is large and open, allowing easy re-positioning of the antennas over a region at least 16 km in extent (Figure 7).

Array operations are the responsibility of the Joint ALMA Observatory (JAO). The telescope array itself is located at the Array Operations Site (AOS). Due to the limited oxygen at this 5000 m elevation, the array is operated from the Operations Support Facility (OSF) at an elevation of 2900 m, with trips to the AOS only 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 global astronomical community is through the ALMA Regional Centers (ARCs; Figure 5).

Quick Links

Find a virtual tour of the ALMA site and vicinity at:
http://www.almaobservatory.org/en/multimedia-en/virtual-tour/

The current status of the ALMA observatory can be found at:
http://almascience.org/observing/alma-status-pag

Policies for using ALMA by the astronomical community are detailed at:
http://www.almascience.org/documents-and-tools/latest/alma-user-policies

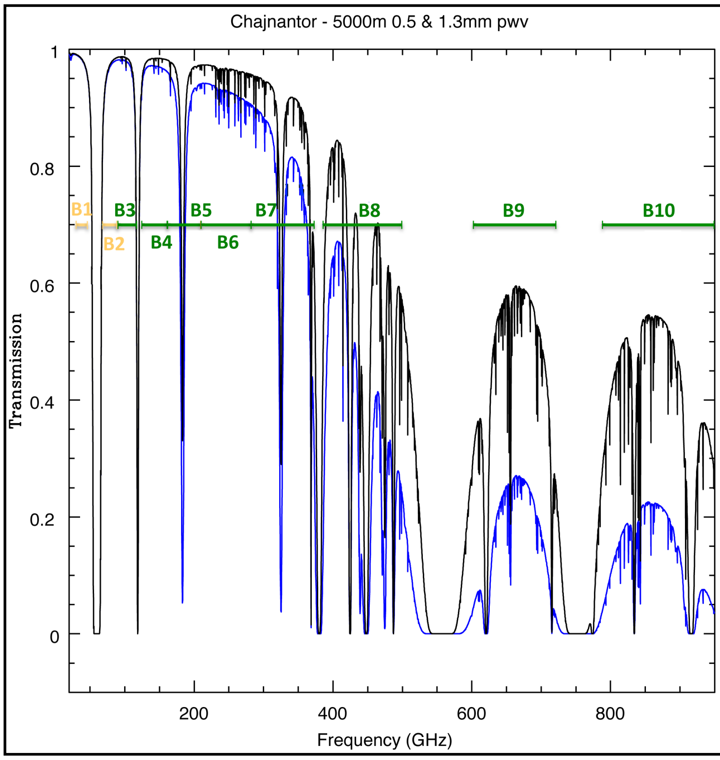


Figure 4: *Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency. Plotted in blue and black are the transparency values for the ~55th and 25th percentile conditions respectively averaged over the year. This means that ~55% of the time the sky transparency is better than shown in the blue line (corresponding to a precipitable water vapor (PWV) of 1.3 mm), and 1/4 (25%) of the time is better than the black line (corresponding to 0.5 mm of PWV). The horizontal lines represent the frequency coverage of the ALMA receiver bands. Bands 3 through 10 are available on all antennas in Cycle 7.*

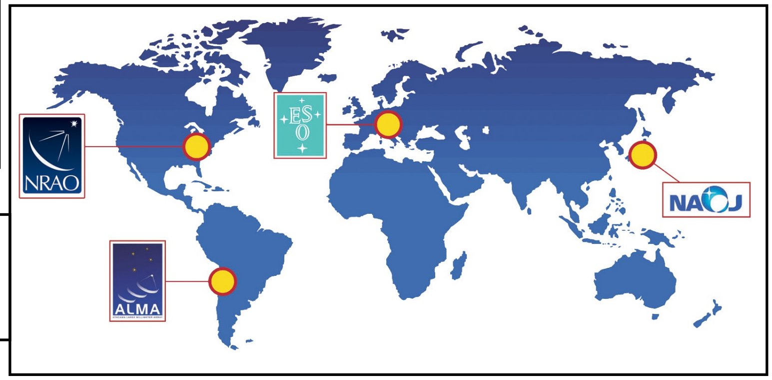


Figure 5: *ARCs are located in North America, Europe, and East Asia. The ALMA headquarters are located in Santiago, Chile. (Credit: ALMA (ESO/NAOJ/NRAO))*

ALMA Regional Centers (ARCs)

Each of the three ALMA 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. With the assistance of the National Research Council of Canada (NRC) and the Academia Sinica Institute for Astronomy and Astrophysics (ASIAA) of Taiwan, the NAASC is responsible for supporting the science use of ALMA by the North American and Taiwan astronomical communities.

Researchers within the European Southern Observatory consortium 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, Portugal, and the Czech Republic.

The East Asian ARC (EA-ARC) is based at the NAOJ headquarters in Tokyo, in collaboration with ASIAA and the Korea Astronomy and Space Science Institute (KASI), and supports the astronomy communities of Japan, Taiwan and the Republic of 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.

Quick Links

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 https://researchers.alma-telescope.jp/e/ea-arc/

What is Interferometry?

In contrast to direct imaging, e.g. with a CCD camera on an optical telescope, an interferometer samples the power spectrum of the sky brightness distribution; this is equivalent to measuring the Fourier transform of the sky. 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 (using a Fourier transform) 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 43 12 m antennas (903 baselines) available in *Cycle 7* provides good coverage. 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 baseline 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 31.

Figure 6: *An areal view of ALMA in a relatively compact configuration. The maximum distance between the 12-m Array antennas in the most compact configuration is about 150 m, and the minimum distance a mere 15 m. Indicated also are the AOS Technical Building, and the ACA 7-m Array. (Credit: C. Padilla/ALMA (ESO/NAOJ/NRAO))*

Figure 7: *In the most extended configuration of the ALMA array, antennas are scattered across the Chajnantor plateau as much as 16 km apart. Here we see the array during the November 2015 long baseline campaign, when the maximum distance between antennas was 10 km. Chajnantor means "place of departure" in the Kunza language of the Atacameño people that lived there and named this plateau. (Credit: S. Dougherty)*

Science with ALMA

Level One Science Aims for ALMA

While ALMA is revolutionizing many areas of astronomy, the technical requirements of ALMA were driven by three Level One Science Aims:

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 *Full Operations Specifications*

	Specification
Number of Antennas	***50×12 m (12-m Array), plus 12×7 m & 4×12 m (ACA)***
Maximum Baseline Lengths	***0.16 - 16.2 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)***
Frequency Coverage	***All atmospheric windows from 84 GHz - 950 GHz (with extension to ~30 GHz when Bands 1 and 2 are deployed)***
Correlator: Total Bandwidth	***16 GHz (2 polarizations × 4 basebands × 2 GHz/baseband)***
Correlator: Spectral Resolution	***As narrow as 0.008 × (300/ν GHz) km/s***
Polarimetry	***Full Stokes parameters***

ALMA's Breadth of Science

Other fields which ALMA will transform include:

• Imaging 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.

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

• Probing 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,

Figure 8: *Nighttime panorama of ALMA (Credit: ESO/B. Tafreshi (twanight.org)*

and galactic structure. The resolution of ALMA reveals 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.

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

• Uncovering 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 has 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.

• Imaging the formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae. ALMA can 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.

• Studying the 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.

• Plus countless other science goals, including unforeseen discoveries which always occur when exploring new wavelength/sensitivity/resolution regimes. Many recent exciting results are shown in figures throughout this document.

ALMA *Cycle 7 Capabilities*

Capabilities offered for *Cycle 7* include:

- At least 43 antennas in the 12-m Array; plus ten 7 m and three 12 m antennas in the ACA
- Complete spectral coverage at all frequency bands available from the ground from 84 to 950 GHz (3.6 mm to 300 μm), using receiver Bands 3 through 10 (see Figure 4)
- Baselines up to 16.2 km for Bands 3 - 7 (***new!***); and up to 3.6 km for Bands 8, 9 & 10
- Single field interferometry at all receiver bands and mosaics at Bands 3 through 9
- Full polarization capability, including circular polarization, at Bands 3 through 7 in both continuum and spectral line mode, with improved sensitivity limits compared to Cycle 6 (***new!***)
- Large programs requiring more than 50 hours of observations with the 12-m Array or more than 150 hours with the ACA in stand-alone mode. Up to 15% of the available time may go to Large Programs
- Improved efficiency of spectral scans (***new!***)
- Stand-alone ACA observations may be requested in Bands 3 through 8
- Solar observations and millimeter-wavelength VLBI at Bands 3 and 6, and solar at Band 7 (***new!***)
- An extended Band 6 IF bandwidth will allow simultaneous ^{12}CO, ^{13}CO and C^{18}O J=2-1 observations with broader spectral windows for galactic sources and nearby galaxies
- See the Proposer's Guide on the Science Portal for a full list of *Cycle 7* capabilities

Receivers and Sensitivities in *Cycle 7*

Table 1 shows the receiver bands which are available for *Cycle 7*, and various properties. The sensitivities assume an integration time of 60 seconds, a continuum bandwidth of 7.5 GHz or a spectral resolution of 0.976 MHz, the "standard" frequency for the Band (usually mid-band), and adopting the default weather conditions from the OT ALMA Sensitivity Calculator, for a source at the zenith. See pp. 25 & 27 for a discussion of resolution and maximum scales with the ACA.

Table 1: *Receiver Bands and Selected Properties*

Cycle 7 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.24)	Spectral Sens. ΔT_{line} (K)	Angular Resolution (mas)	Approx. Max. Scale (") (see P.24)	Spectral Sens. ΔT_{line} (K)
3	84-116	3.6-2.6	73-53	0.088	4.0-2.9	34-25	0.16	50-36	0.59-0.43	1075
4	125-163	2.4-1.8	49-38	0.12	2.7-2.1	23-18	0.18	34-26	0.40-0.30	1104
5	158-211	1.9-1.4	37-29	0.12	2.1-1.6	18-13.5	0.15	26-20	0.30-0.24	962
6	211-275	1.4-1.1	29-22	0.12	1.6-1.2	14-10	0.14	20-15	0.24-0.18	947
7	275-373	1.1-0.8	22-16	0.22	1.23-0.91	10.4-7.6	0.2	15-11	0.18-0.13	1307
8	385-500	0.78-0.6	16-12	0.42	0.88-0.68	7.4-5.7	0.35	55-42	0.67-0.52	91
9	602-720	0.5-0.42	10-8.5	2.0	0.56-0.47	4.7-4.0	1.2	35-29	0.43-0.36	312
10	787-950	0.38-0.32	7.8-6.5	4.6	0.43-0.36	3.6-3.0	2.5	27-22	0.33-0.27	662

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 pages 28 & 36. Quoted angular resolutions are for sources which transit at the zenith.

ALMA Correlators in *Cycle 7*

The ALMA Correlators combine the signals of the individual antennas and are immensely powerful and flexible instruments.

Each receiver outputs four 2 GHz-wide *basebands* in each *polarization*, which are fed into the correlator. (See the *Glossary* starting on page 31 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

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

Mode	Polarization✣	Band width (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: 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.
†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.

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 (large channel spacing).

Each baseband is sampled by the correlator according to a given correlator mode, defining the total bandwidth, number of channels, and spectral resolution. Currently a subset of the correlator modes is available for use. See Table 2 (previous page) for the modes available in *Cycle 7*.

The channels within each baseband may be set up as one contiguous *spectral window*, or split up into two to 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 (see Figure 36).

Another feature of the correlators is the ability to apply *spectral averaging* prior to writing the data. *Spectral averaging* allows one to reduce the number of channels in order to improve the S/N per channel, to lower the data rate, and to reduce the sheer volume of data to manage. It is worth noting that, because the correlator channels are Hanning smoothed before averaging, there is only a marginal decrease in spectral resolution when an averaging factor of 2 is chosen, but with a factor of 2 decrease in the data rate and volume.

Did You Know? In *Cycle 7* ALMA can…

…resolve molecular structures in M83:	
create an HCN(J=1-0) mosaic of the full M83 bar with 30 pc resolution	***in 2.14 hours***
…detect the ISM in high-redshift galaxies:	
dust emission in a "normal" 10^{11} L⊙ galaxy between z=1 and z=6	***in 4.3 hours***
…reveal the behavior of solar system objects:	
trace the atmospheric water content of Venus using HDO lines	***in 7.7 minutes***
measure Kuiper Belt Object sizes from their thermal emission	***in 48 minutes***
…survey Galactic Clouds and star forming regions:	
measure the polarization of dust in 30 protostars in a single star-forming region	***in 3 hours***
…reveal the nature of planetary disks around nearby stars:	
measure dense gas flows across gaps in protoplanetary disks	***in 14 minutes***
…measure stellar activity from low-mass to high-mass stars:	
investigate heating mechanisms of red giant stars	***in 5 minutes***
…study black holes and their environments, near and far:	
infer gas properties in the host galaxy of an obscured z=2.8 quasar	***in 12 minutes***
…trace the formation of galaxy clusters, cosmic structure:	
survey clustering in a sample of 23 Lyman-α Blobs (LABs) at z=3.1	***in <1 hour***

Quick Links

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

Science During *Cycle 7*

From the start of science observing in late-September 2011 (*Cycle 0*), ALMA was already a powerful millimeter/submillimeter interferometer, and is now essentially in full operation mode. By early 2019, over 1300 papers featuring ALMA data had already appeared in refereed journals. Some exciting recent results are shown in figures throughout this document. A few example projects suitable for *Cycle 7* have been compiled by the world-wide ALMA science staff and can be found on the previous page, or worked out in more detail on pages 12 to 21.

Quick Links

Find a list of published ALMA papers at http://telbib.eso.org

Before You Propose

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 an ALMA proposal using the OT, you should have at hand:

- **The "Proposing Guidance" page.** This page (at http://almascience.org/proposing/learn-more/) 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.** ALMA's wavelength coverage is excellent, and you can often get several molecular lines of interest in a single setup. However, setups targeting several specific lines can sometimes be challenging to create, requiring careful positioning of the spectral windows in more than one Science Goal, which strongly affects the time required.
- **Required angular resolution and largest angular structure (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. 31). Note that if you want very high angular resolution, you may end up resolving out larger structures of interest unless you use a combination of array configurations, which can be costly of time. See page 23-24 for a discussion of *angular resolution* and *maximum recoverable scale*. The OT automatically determines the configurations you will need, as shown in Figure 28. The schedule of array configurations for *Cycle 7* can be found in the Proposer's Guide, available from the Science Portal.
- **Required mapping area.** The field of view (FOV or *primary beam*; see Table 1 and page 33) is the area of the sky that the array maps at a single pointing. Maps larger than the primary beam will require a mosaic, where the field centers are spaced by approximately half the primary beam size. Note that the sensitivity of the primary beam decreases with distance from the field center. It is strongly recommended that if the map area of interest is larger than about 1/3 the primary beam, that you consider making a small (3 point) mosaic instead of a single pointing.
- **Required sensitivity.** Care must be taken when

Figure 9: *(above) 360 degree panorama of the room containing the ALMA correlators. The correlators are housed in the ALMA AOS Technical Building (below). In the background, Chajnantor Volcano looms over the plateau bearing its name. (Credit: ALMA (ESO/NAOJ/NRAO))*

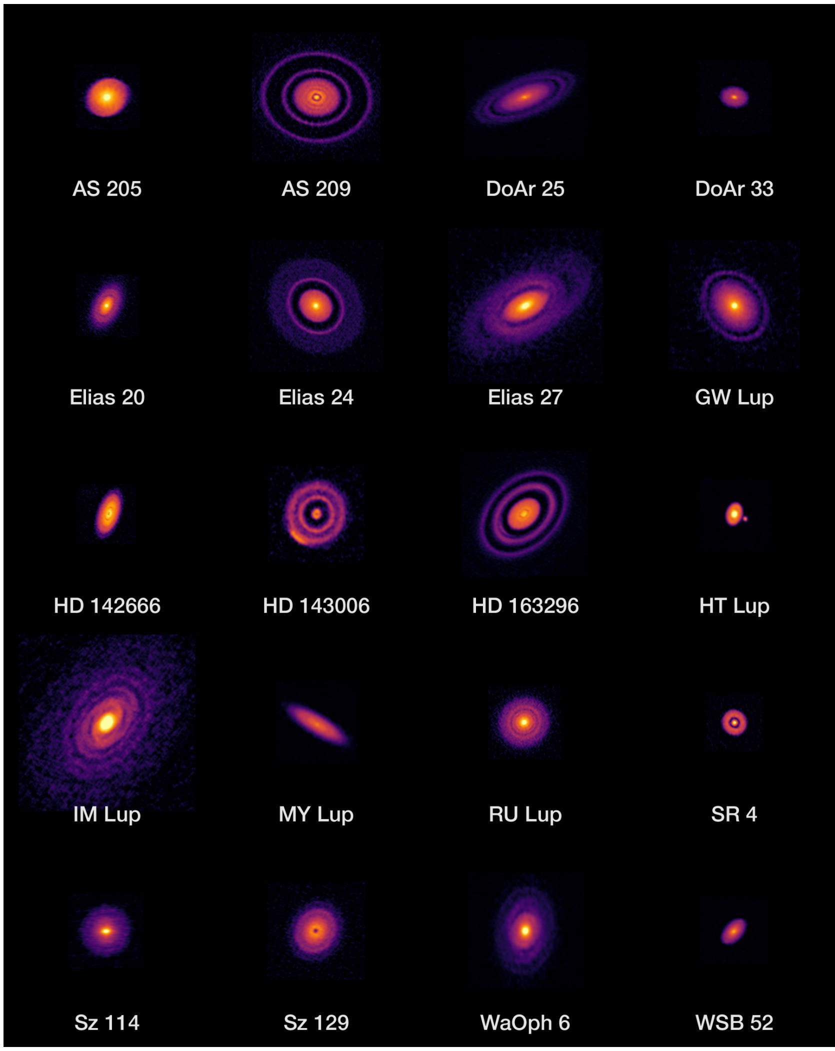


Figure 10: *The release of the spectacular ALMA image of rings in the protoplanetary disk around HL Tau in 2014 was a game changer in the study of planet formation. Now an international team led by S. Andrews of the CfA has reported that this kind of structure is the rule rather than the exception. Their Cycle 4 ALMA Large program, DSHARP (Disk Substructures at High Angular Resolution Project) mapped 20 nearby protoplanetary disks (left) and released their results in a series of ten papers published in volume 869 of the Astrophysical Joural. (Credits: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; N. Lira)*

estimating the sensitivity needed per synthesized beam, particularly if estimating the source brightness from single-dish millimeter/submillimeter 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.) See p. 28 for a discussion on using single-dish data to estimate required ALMA sensitivities.

• **Dynamic range needed.** The dynamic range (ratio of brightest to the faintest emission) in an image (or ratio of strongest to weakest detectable features in a spectral line image (spectral dynamic range)) 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 OMC1) will require great care, and may not achieve the theoretical noise level. (See p. 26.)

During *Cycle 7* with at least 43 antennas, ALMA will have 903 or more baselines. Thus the array should be able to image most “simple” fields with good fidelity. Imaging dynamic ranges are typically expected to reach up to around 50-100 depending on band and configuration (extended configurations, or Bands 9 and 10 are likely to be closer to 50). In many cases it may be possible to achieve higher dynamic ranges using special calibration techniques or *self-calibration*. However, if your science aim involves imaging a complex field or one with a nearby bright source, then the *uv*-coverage can be 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* or the *Observation Support Tool* can do, see page 27.

Quick Links

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

http://almascience.org/proposing/

• **Calibration and overhead.** ALMA’s sensitivity is exquisite compared to earlier submm/mm instruments. However it is important to keep in mind that calibration and overhead can take up a significant amount of time, so that surveys of objects scattered across the sky are much less efficient than surveys of objects nearby in the sky which can share calibration. The Time Estimate button in the ALMA OT can tell you the overhead time for your project.

Examples of *Cycle 7* Observing With ALMA

In the following sections we provide a few examples of observations that could be done with ALMA during *Cycle 7*. **Note that these examples use the sensitivities and capabilities of ALMA as they were known at the time of the *Cycle 7* Announcement. Any astronomer proposing observations with ALMA 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 8). In addition, the *continuum* or *channel sensitivity* is quantified so the on-source *observing time* can be calculated. Note that the examples may not 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 31.

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 12-m 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, for example, 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″ is needed so that the two lensed components of the quasar can be separated. In the OT, we will select a range of angular resolutions, from 0.3″ to 1″, and LAS of 0.5″, corresponding to array configurations C43-4/5/6.

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 spectral (FDM; see Table 2) correlator mode gives a spectral resolution of ~3 km/s, but to decrease the data rate (and data volume), we will use a *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.

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: Using the spectral scan mode, setting up such spectral surveys is very simple. In the OT in the *Spectral Setup* frame, we request a start and end sky frequency of 86.0 and 115 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 15 minutes (plus overheads of approximately 48 minutes) will be required to cover this frequency range.

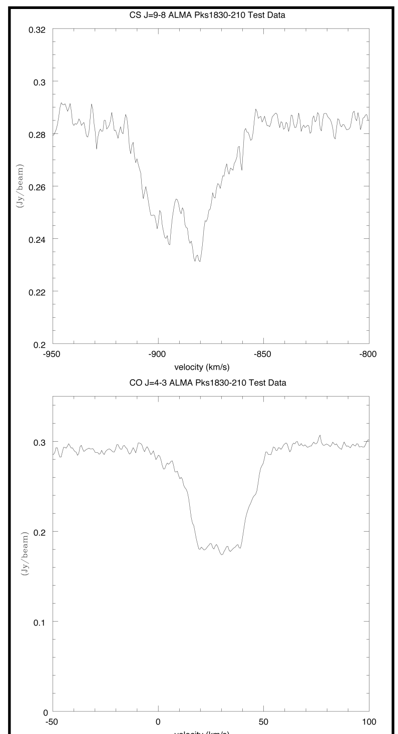


Figure 11*: Examples of molecular absorption lines detected toward PKS1830-211. These observations were made by ALMA in late 2010 when there were only a few antennas.*

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 12) that have a combined extent of ~5". Each image has been resolved into at least four components (Figure 12a) and large amounts of molecular gas have been detected (Figure 12b). Although resolved, the source is small and dominated by relatively compact structures and therefore well-suited to ALMA. As an example project, we will attempt to map both the continuum and the molecular gas at high angular resolution where the ALMA array may be able to resolve the source structure.

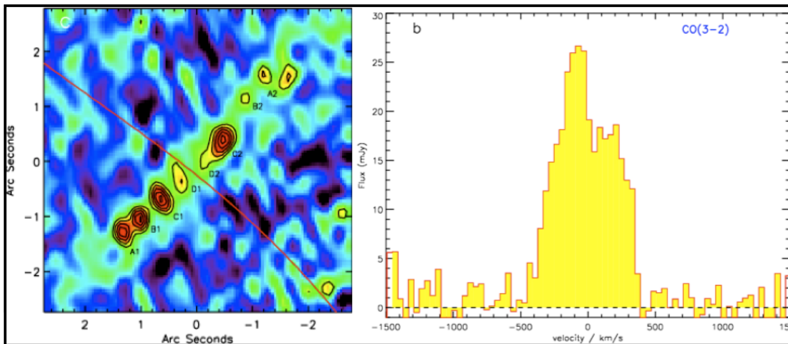


Figure 12: *(a) SMA (very extended configuration) 870 μm image of the Cosmic Eyelash. The red line marks the division between the two images of the background source. (b) Spectrum of CO(3-2) taken with the Plateau de Bure interferometer. Both figures are from Swinbank et al. (2010, Nature, 464, 733).*

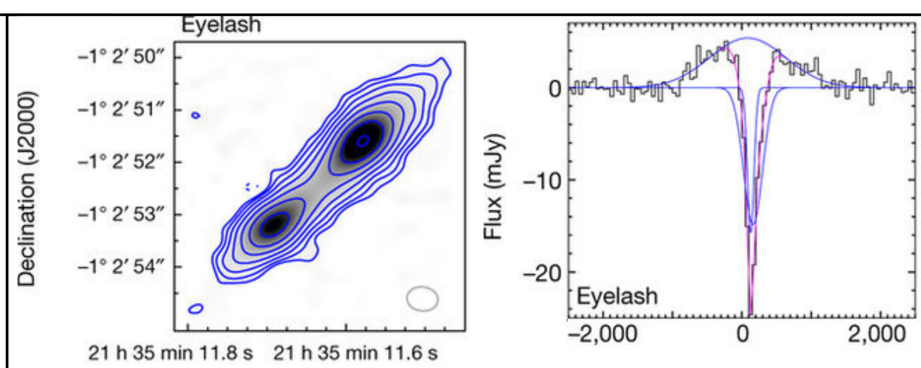
Receiver(s): Band 7 (spectral line and continuum, 312 GHz).

Angular Resolution and LAS: 0.1" (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), and perhaps resolve individual lenses. Though the total extent of emission is ~5", only structures of order 1" are of interest so the LAS selected is 1". Hence, only one 12-m Array configuration and no ACA observations will be required.

Spectral Resolution: For Band 7, we use the continuum (TDM; see Table 2) correlator mode to provide 14 km/s channels (i.e., 30 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.

Spectral (Band 7) Sensitivity: The peak flux density of the redshifted CO J=9-8 line is expected to be ~10 mJy. Assuming the clumps are 0.2" in extent, the expected flux density at 0.1" resolution would be 10 mJy * $(0.1''/0.2'')^2$ = 2.5 mJy/beam. To detect the line at a sufficient S/N across the entire width of the line, we aim to achieve a S/N~10 at the peak in a 100 km/s channel. This requires a 1 σ noise level of 0.25 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 43 12 m antennas predicts 42 minutes of integration to reach 1 σ = 0.25 mJy/beam plus another 36 minutes for calibration/overheads. This amount of time will also produce a sensitivity of 34 μJy/beam in a map of the remaining 5.625 GHz of line-free continuum providing a S/N ~29 for the continuum signal (~1 mJy).

Figure 13: *(left) ALMA Band 6 continuum image of the Cosmic Eyelash showing showing the main lensed components of the z=2.3 galaxy. (right) Continuum subtracted emission/absorption spectrum of CH+ (1-0) at a rest frequency of 835 GHz. These observations confirmed the existence of huge reservoirs of highly turbulent gas in this and other high-redshift galaxies. (Credit: Falgarone et al., 2017, Nature, 548, 430)*



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 submillimeter galaxies (SMGs). SMGs are typically detected with single-dish telescopes at 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 and LAS: ~0.2″ at Band 7. A good rule of thumb is that 1″ corresponds to ~ 8 kpc for z ~ 1, so spatially resolved observations can be made with ALMA. The ACA and more compact 12-m Array configurations are not needed for these observations since the sources are small. An LAS of 1″ is selected.

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

Continuum (Band 7) Sensitivity: In *Cycle 7*, up to 150 sources (see Proposers Guide for restrictions) may be observed in each science goal. As an example, there are ~150 sources in the COSMOS-AzTEC catalogue (Aretxaga et al. 2011) with (de-boosted) flux densities > 3.3 mJy. Furthermore the sources are all within a few degrees of each other, making the observations highly efficient since the calibration can be shared among many sources. Given the exceptional atmospheric conditions at ALMA, we choose to pinpoint these sources at a higher frequency (344 GHz or 0.8 mm) where they are significantly brighter ($S \propto \nu^{\beta}$, typically $\beta \sim 2$ at $z \sim 2$). 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). We thus request a sensitivity of 0.125 mJy/beam.

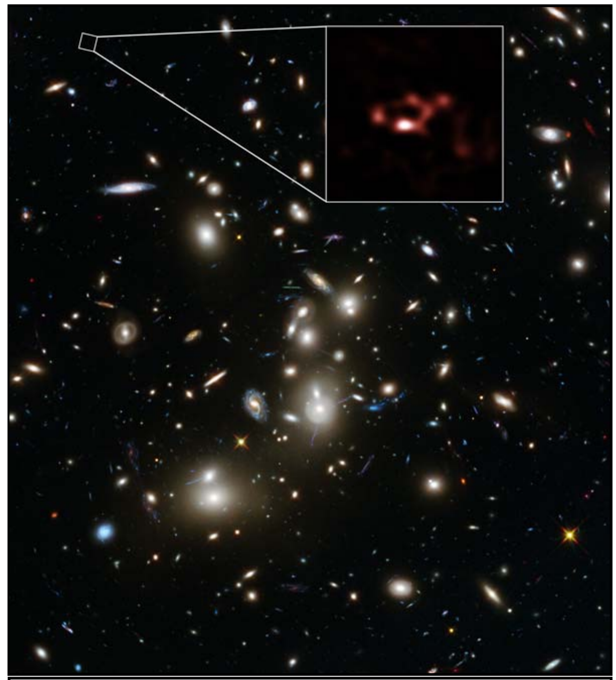


Figure 14: The inset of this HST *image galaxy cluster Abell 2744 shows an ALMA image of the z=8.38 gravitationally-lensed galaxy A2744_YD4. At this distance, the universe was a mere 600 million years old, and yet the ALMA observations show that the galaxy is rich in dust. (Credit: ALMA (ESO/NAOJ/NRAO); NASA; ESA; ESO; D. Coe (STScI)/J. Merten (Heidelberg/Bologna); Laporte et al., 2017, ApJ, 837, L21)*

Band 7 Observing Time: For Band 7, the ALMA sensitivity calculator, assuming 43 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 6.75 hours of on-source integration, for a total of 12.7 hours including overheads and calibration.

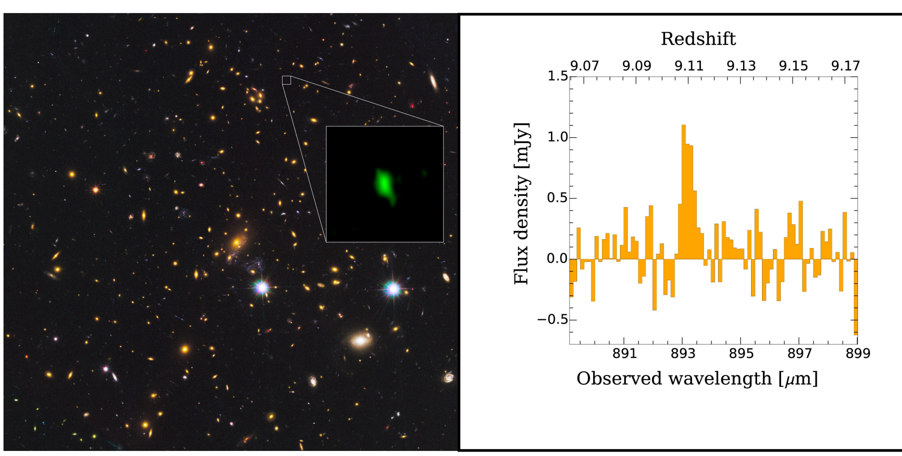
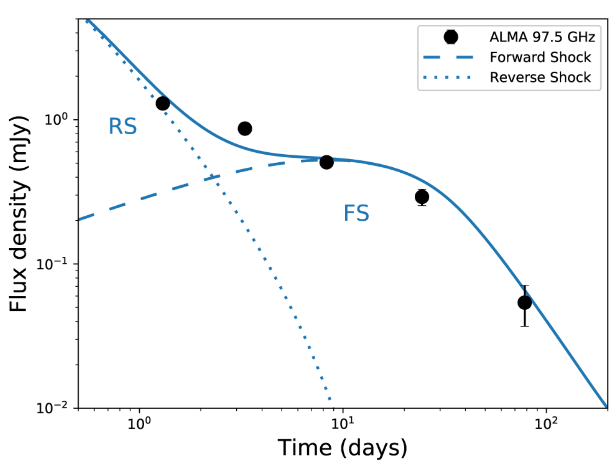


Figure 15: *ALMA has detected [OIII] emission from a z=9.11 galaxy, MACS1149-JD1, shown in green on the far left. Also shown in that figure is an HST image of the galaxy cluster MACS J1149.5+2223. The spectrum shows the detected 88μm line redshifted to Band 7. (Credits: ALMA (ESO/NAOJ/NRAO); NASA/ESA Hubble Space Telescope; T. Hashimoto et al., 2018, Nature, 557, 392)*

Observing a GRB Afterglow (A Target of Opportunity)

Science Aim: ***Detect & monitor the mm/submm afterglow of a GRB from its burst to one month later***
Long-duration gamma-ray bursts (GRBs) are among 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 submm wavelengths, we can observe the synchrotron emission directly, where it is free from interstellar scintillation. Continuum monitoring at mm and submm 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 submm 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 submm 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 and LAS: The sources will be unresolved, since they are about the size of a star. We select an angular resolution of "Any" using the OT so that any configuration can be used.
Spectral Resolution: N/A. Each measurement will use the largest bandwidth possible in dual polarization.
Sensitivity and Observing Time: With 43 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. These can be specified in the OT by selecting "Yes" for time constraints in the Control and Performance window, and specifying the required time constraints.
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 7*, there is no limit on the size of the time window, but whether such observations are technically feasible will be judged on a case-by-case basis. See the Proposer's Guide, Appendix A.10, for details. Once the proposal is approved, full details on how to trigger the ToO observations will be sent to the PI.



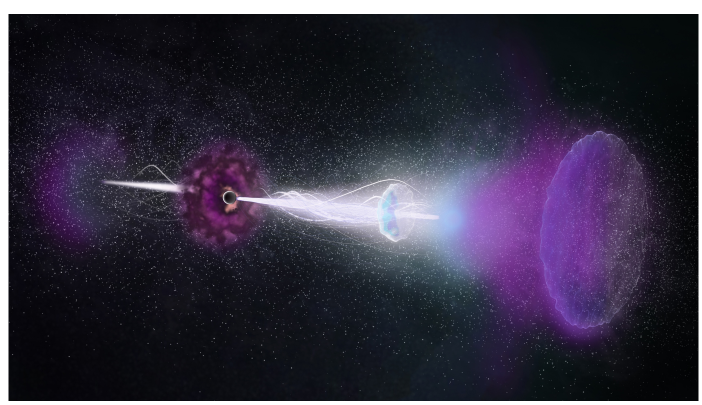


Figure 16: *GRB161219B was observed by ALMA at Band 3 over five epochs ranging from 1.3 days to 78 days after the burst. On the left above, the Band 3 flux density is plotted as a function of time. The rebound, or reverse shock, triggered by the GRB's powerful jets slamming into surrounding debris, lasted thousands of times longer than expected. On the right is an artist's impression of the "reverse shock" echoing back through the jets of the GRB. (Credits: Laskar et al., 2018, ApJ, 862, 94L; NRAO/AUI/NSF, S. Dagnello)*

Mosaicing the Nearby Spiral Galaxy M100

Science Aim: ***Map the distribution and kinematics of molecular gas in a nearby spiral galaxy***
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) fuelling 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. ALMA *casaguides* provide a tutorial on combining data from the 12-m Array, the 7-m Array, and the TP Array (see https://casaguides.nrao.edu/index.php/M100_Band3).

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 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 multi-wavelength 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: M100 exhibits structure over a large range of angular scales. We set the LAS to the extent of the map (270") to recover structure at all scales down to the resolution of the observations. All three arrays (12-m Array, 7-m Array, and TP Array) will be required.

Coverage: We know the overall extent of CO from previous observations, including wide field single dish maps. A single ALMA beam covers only a small part of the galaxy, but a rectangular grid of 137 pointings spaced by ~half of the primary beam does manage to encompass most CO emission. Mosaics of up to 150 pointings per Science Goal (SG) are allowed by the *Cycle 7* call.

Sensitivity and Mosaicing: Entering the mosaicing parameters and a required sensitivity of 3 mJy/beam directly into the OT, the integration time calculator (which takes into account the overlapping of the mosaic fields) estimates an observing time of ~2.1 minutes per mosaic position. With 137 fields we expect that the program will need about 4.8 hours on source, or just over 7.6 hours with overheads. The OT estimates that 52 overlapping pointings will be needed for the 7-m Array requiring about 40 hours total, and about 78 hours for the total power observations.

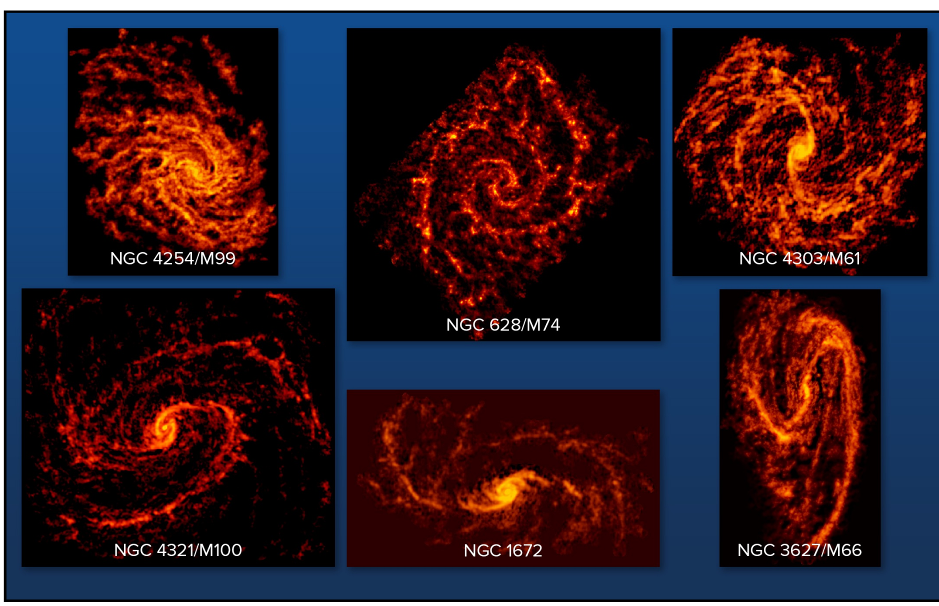


Figure 17: *Six of the galaxies imaged using mosaics of 12-m, 7-m, and TP Arrays in the 2017 Large project to image 100,000 giant molecular clouds in 74 nearby galaxies. These results are being presented in a series of papers in the Astrophysical Journal and Astrophysical Journal Letters.(Credit: ALMA (ESO/NAOJ/NRAO); NRAO/AUI/NSF, B. Saxton; J. Sun et al., 2018, ApJ, 860, 172)*

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. Although in *Cycle 7* ALMA will be able to resolve nearby protostellar disks in exquisite detail (see the images in Figure 10), for this survey we will only measure global properties but at great sensitivity in relatively short integrations. 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).

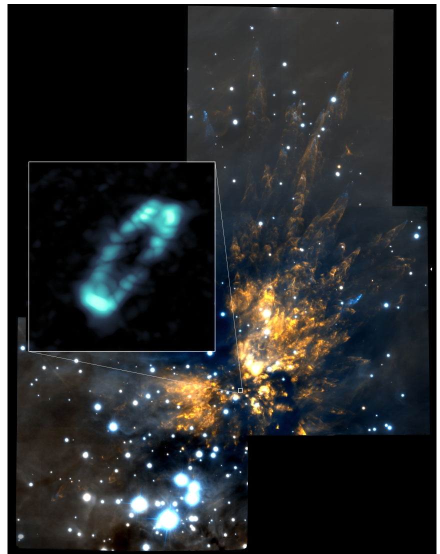


Figure 18: *ALMA Band 6 observations have detected table salt, NaCl, along with KCl and their isotopologues in the dusty disk around the Orion proplyd SrcI. This is the first time these molecules have been discovered in the ISM outside of evolved stellar envelopes. Here the NaCl emission is shown as an inset on a Gemini image. (Credits: ALMA (NRAO/ESO/NAOJ); NRAO/AUI/NSF; Gemini Observatory/AURA; Ginsburg et al., 2019, ApJ, 872, 54)*

Receiver(s): Bands 3, 5, 7, & 9: (98, 203, 344, & 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″. In this experiment we aim to measure global properties of the disks, including the SED. We therefore seek observations at each frequency at 0.4″. 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 a more extended configuration. If necessary, we can fine-tune the angular resolution achieved in each band by applying a *uv* taper during the data analysis. It should be noted however that such a taper suppresses the contribution from the longest baselines and changes the sensitivity. For this experiment, a configuration which gives an angular resolution of 0.4″ (see Technical Handbook Chapter 7) will have recoverable angular scales of about 3″, 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 flux densities we expect are 5.2, 20, 65, and 255 mJy for Bands 3, 5, 7, & 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 (and thus the average flux density per beam is 1/9 the values quoted above) and that the edges of the disk are ~10% of the average flux density. For a 3σ detection of the disk edges, we aim for continuum sensitivities of 0.019, 0.074, 0.24, and 0.94 mJy/beam for the seven bands respectively. Using the ALMA sensitivity calculator with 43 main array antennas (12 m diameter) and 7.5 GHz of bandwidth, we find that these sensitivities can be achieved in 21 minutes per disk (Band 3), 2.4 minutes per disk (Band 5), 40 seconds per disk (Band 7), and 2.6 minutes (Band 9) for each science target, or 3.4h/30m/21m/39m respectively including calibrations and overheads.

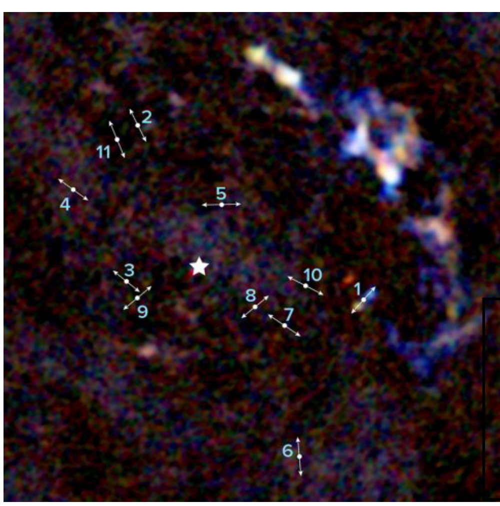


Figure 19: *An ALMA image of the center of the Milky Way galaxy revealing 11 young protostars within about 3 light-years of our galaxy's supermassive black hole. The lines indicate the direction of the bipolar lobes created by high-velocity jets from the protostars. The star indicates the location of Sagittarius A*, the 4 million solar mass supermassive black hole at the center of our galaxy. (Credit: ALMA (ESO/NAOJ/NRAO), Yusef-Zadeh et al. 2017, ApJ, 850, L30; B. Saxton (NRAO/AUI/NSF))*

Dust Polarization and Magnetic Fields in Star Forming Clouds

Science Aim: ***To detect magnetic fields in a star forming core at the thermal Jeans length scale 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°. ALMA observations toward the star forming core W51 e2 can 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 size-scale of the thermal Jeans length.

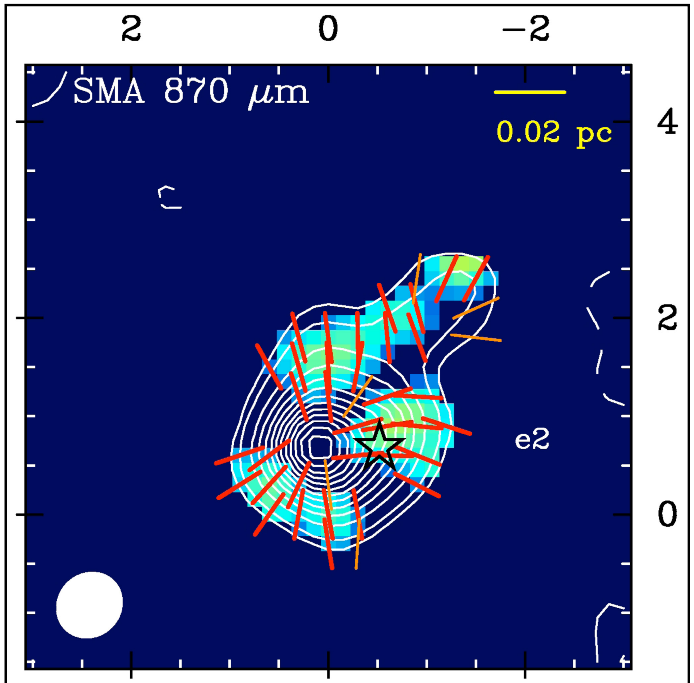


Figure 20: *Magnetic field of the W51 e2 core at 0.9 mm obtained at the Submillimeter Array. The total intensity is shown in contours. The polarization intensity is shown in color scale. The star denotes the ultracompact HII region. (Credit: Ya-Wen Tang, 2009 ApJ, 700, 251)*

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. At 0.2″ resolution, the flux would be spread over $(0.8''/0.2'')^2$=16 beams. Hence the estimated ALMA flux density is 9.3/16=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 5.0 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.

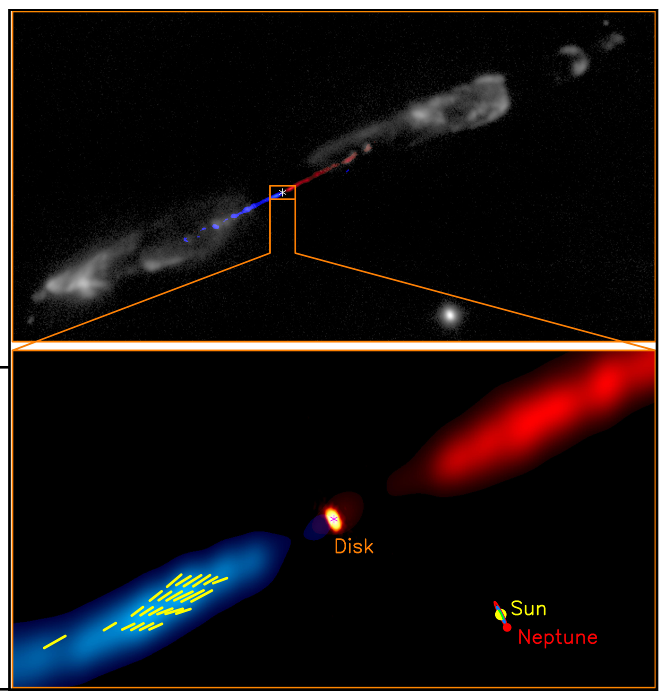


Figure 21: *ALMA was used to detect the magnetic field in the jet from a protostar, using polarized SiO line emission. The top image (right) shows an optical H_2 image of the HH 211 jet (from Hirano et al. 2006). The blue and red image shows the blue- and red-shifted SiO J=8-7 emission. The inset image shows the inner jet, with the recently detected disk (Lee et al. 2018), the solar system scale for comparison, and yellow bars showing the SiO line polarization vectors. The vector orientations are consistent with a model of a helical magnetic field threading the jet. (Credit: ALMA (ESO/NAOJ/NRAO); Lee et al., 2018, NatCo, 9.4636)*

Observing Molecular Gas in a Planetary Nebula

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

In Planetary Nebulae (PNe) molecular gas is often observed in a torus surrounding a core of ionized gas. The detailed structure of molecular gas in PNe, however, is of great interest since it contains information on the physical processes that created the nebulae. High resolution observations of a few PNe show that this molecular gas is characterized by a high degree of fragmentation. For example, the Helix Nebula has been found to be made of thousands of small (Diameter < 1"), dense (n ~ 10^5 cm^{-3}), quiescent (ΔV < 1 km/s FWHM), and faint (peak 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 until ALMA began science observing the highest angular resolution millimeter molecular line observations had beam sizes greater than 3" (see Huggins et al. 2002, ApJ, 573, L55).

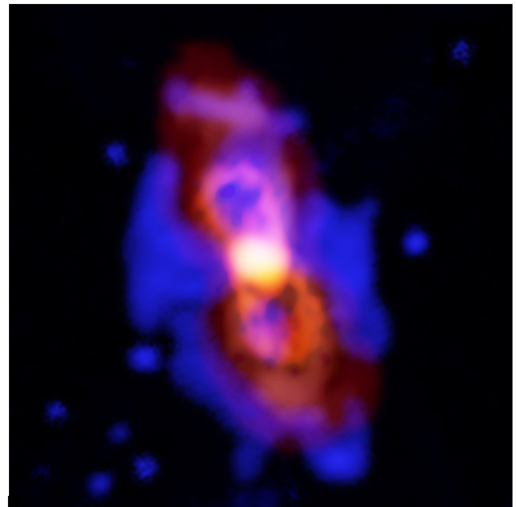


Figure 22: *The first unambiguous detection of a radioactive molecule was made using ALMA at Band 6. Shown is a composite image of CY Vulpeculae, a star which is suspected, based on ALMA observations (Eyres et al., 2018, MNRAS, 481, 4931), of undergoing a collision between a white dwarf and a brown dwarf. In this image, orange represents the emission of radioactive ^{26}AlF detected by ALMA, red is dust emission (also from ALMA), and blue is optical hydrogen emission. (Credit: ALMA (ESO/NAOJ/NRAO); Kamiński et al., 2018, NatAs, 2, 778; Gemini, NOAO/AURA/NSF; NRAO/AUI/NSF, B. Saxton)*

Receiver(s): Band 6 (230.538 GHz) For this 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). 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 (~0.8 km/s FWHM) within the Helix Nebula. We choose the 117 MHz bandwidth spectral mode and spectral averaging factor 4 to give a resolution of 0.158 km/s.

Channel (Line) Sensitivity: 0.5K. The fragments observed in the Helix Nebula are quite faint, with peak < 5 K. In this scenario, a moderate sensitivity is desired (S/N ~ 5), which would detect the brighter Helix Nebula fragments.

Observing Time: For Band 6, the ALMA sensitivity calculator, assuming 43 antennas, 0.3″ angular resolution, and an effective 0.16 km/s spectral resolution predicts 3.6 hours to reach 0.5 K (or 6.6h including calibration and overheads). The two separate pointings will require about 13 hours of ALMA observing time.

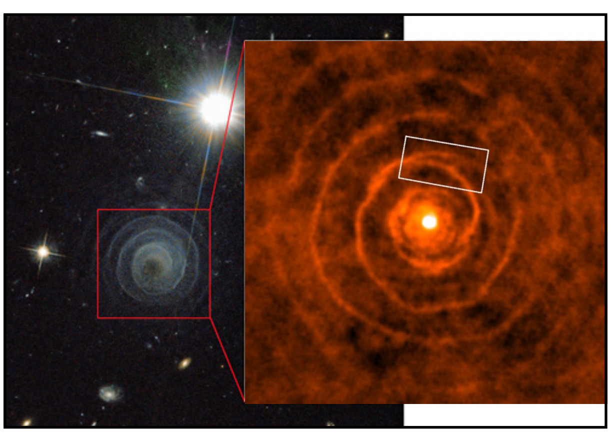


Figure 23: (left) HST image and (right) ALMA image of *an expanding spherical shell and spiral wind emanating from the evolved star R Sculptoris. Recent modelling suggests that the bifurcation of the spiral-shell pattern (indicated by a white box) results from a highly elliptical binary system. (Credit: ESA/NASA & R. Sahai. (Right) ALMA image of LL Pegasi. Credit: ALMA (ESO/NAOJ/NRAO) / Kim et al., 2016, NatAs, 1, 60)*

Continuum High Resolution Imaging of the Asteroid 3 Juno

Science Aim: ***To observe the 1.3 mm continuum emission on the Asteroid 3 Juno:***
Submillimeter wavelengths are well-matched as probes of the thermal response of asteroid surfaces. ALMA can resolve thermal emission from an asteroid's surface to measure the temperature distribution across the surface and estimate the regolith thickness and composition. Tracking the asteroid over time will reveal its rotational period and 3D shape.

Receiver(s): Bands 6: (233 GHz or 1.3 mm)

Angular Resolution & LAS: Near-infrared adaptive optics imaging combined with modelling puts the size of Juno at ~240 km. To obtain at least eight resolution elements across the asteroid, a resolution of ~29 km is required which translates to 20 mas at the distance to Juno of 1.97 AU. Multiple resolution elements will reveal variations in brightness temperature over the surface of the asteroid. With an angular size of ~0.17″, Juno is smaller than the Maximum Recoverable Scale of 0.21″ with the most extended configuration available in *Cycle 7* (see ALMA Technical Handbook, Chapter 7), and so all relevant size-scales will be recovered.

Continuum Sensitivity: Juno has a single-dish flux density of 240 mJy at 250 GHz. At a resolution of 20 mas, there are ~64 synthesized ALMA beams across the 240 km (i.e. 168 mas) wide asteroid. Thus the flux density per beam will be 240 mJy / 64 beams = 3.8 mJy/beam. The sensitivity required to reach a signal-to-noise ratio of 100 is then 3.8 mJy/beam /100 ~ 38 μJy/beam. With a bandwidth of 7.5 GHz, dual polarization, and 43 antennas, this can be achieved in 11 minutes of on-source integration time (but with approximately 37 minutes of overhead).

Observing Time: Juno's known rotation period is approximately 7.2 hours. Sampling at least 10 epochs of the orbital period should allow a detailed model of the 3D shape of the asteroid. These 10 epochs do not necessarily need to be observed contiguously, and indeed contiguous observations longer than 2-3 hours are not permitted in *Cycle 7* (see the Proposer's Guide Appendix A.10), and can be scheduled over several days using the Time Constraint feature in the OT.

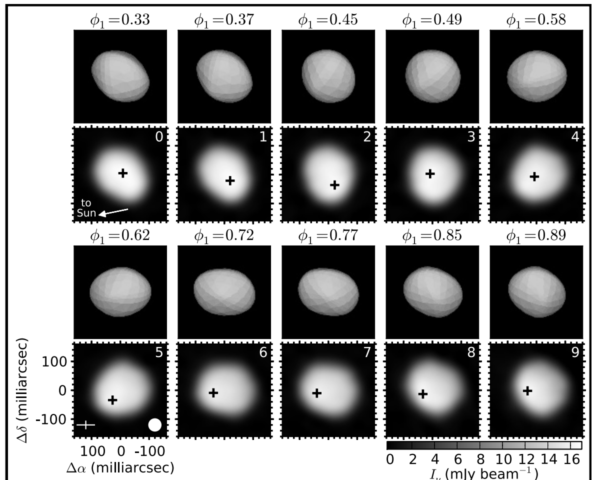
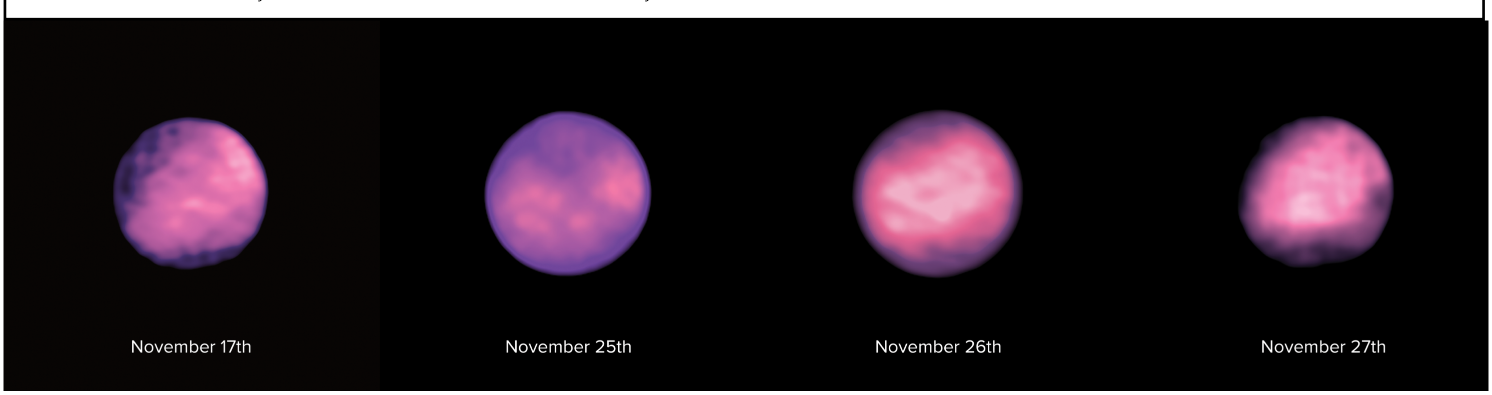


Figure 24: *Asteroid 3 Juno was observed in October 2014 during the commissioning period of the ALMA long baseline campaign. Over the course of the observations, the achieved resolution varied from 32 x 24 mas to 42 x 36 mas, differing mostly due to changes in phase stability as the observations spanned the transition from night through dawn and into daytime. The baselines used to achieve this resolution ranged from 26 m to 13 km. The observations spanned 10 epochs, covering 60% of the 7.2h rotation period. (Credit: ALMA Partnership et al., 2015, ApJ, 808, L2)*

Figure 25: *These Band 6 images of Jupiter's moon, Europa, reveal the first spatially resolved thermal data set with complete coverage of Europa's surface, with a typical linear resolution of about 200 km. The temperature range is roughly 50-90 K. (Credit: ALMA (ESO/NAOJ/NRAO), S. Trumbo et al., 2018, AJ, 156, 161)*



Continuum Mapping of the Sun at Millimeter Wavelengths

Science Aim: ***To map the brightness distribution of the solar chromosphere at millimeter wavelengths:*** Radiation from the Sun at millimeter and submillimeter wavelengths probes a fascinating and dynamic layer of the solar atmosphere where non-radiative heating becomes manifest. Since the source function is Planckian and these wavelengths are in the Rayleigh-Jeans regime, observations in these wavelengths offer a convenient linear thermometer with which to probe the thermal, spatial, and dynamical structure of the chromosphere in a variety of physical regimes: the quiet Sun, coronal holes, active regions and sunspots, prominences and filaments.

Receiver(s): Bands 3 and Band 6: (100 and 239 GHz)

Angular Resolution & LAS: The ALMA primary beam is much less than the angular size of the Sun (e.g., 24″ vs ~1920″ in Band 6). The Sun therefore fills the ALMA primary beam and its sidelobes with complex emission. Dense snapshot *uv*-coverage is essential and, for accurate recovery of "absolute" brightness, total power mapping observations are also needed. To this end, Cycle 7 offers observations of the Sun that use a hybrid array comprised of both the fixed-station ACA 7 m antennas and the 12-m Array in configurations corresponding to angular resolutions of approximately 3.4″, 1.8″, 1.2″ and 0.92″ in Band 3 (corresponding to configurations C43-1, -2, -3, & -4), approximately 1.5″, 0.8″, and 0.5″ in Band 6 (configurations C43-1, -2, & -3), and approximately 1″ & 0.7″ at Band 7 (configurations C43-1 & -2). An angular resolution of 1″ corresponds to ~730 km on the Sun. Fields of several arcminutes are typically mapped through mosaicking techniques, with up to 150 offset pointings relative to a PI-specified solar ephemeris that provides offset pointing coordinates and optionally corrects for differential solar rotation. The largest angular scales are recovered using fast-scan mapping techniques with the total power (TP) antennas to map the entire Sun with a total field of view of 2400″.

Spectral Resolution: These are continuum observations and so the observations were made in TDM mode and default channelization is used.

Sensitivity and Observing Time: The source dominates the system temperature although, for solar mode observing in the "active Sun mode", the receiver temperature is ~1000 K. For imaging programs requiring "large" fields, mosaicking is required with each pointing receiving a few seconds integration time on source. The sensitivity is limited by various systematic effects: time variability of the source, details of the *uv*-sampling, as well as integration time and bandwidth. However, test data using 30 antennas yielded an rms of approximately 26 K (GHz-s)$^{-1/2}$ for Band 3 and 68 K (GHz-s)$^{-1/2}$ for Band 6. With *Cycle 7* data, for which 43 antennas in the 12-m Array and 10 antennas in the 7-m Array are offered, the sensitivity is significantly better.

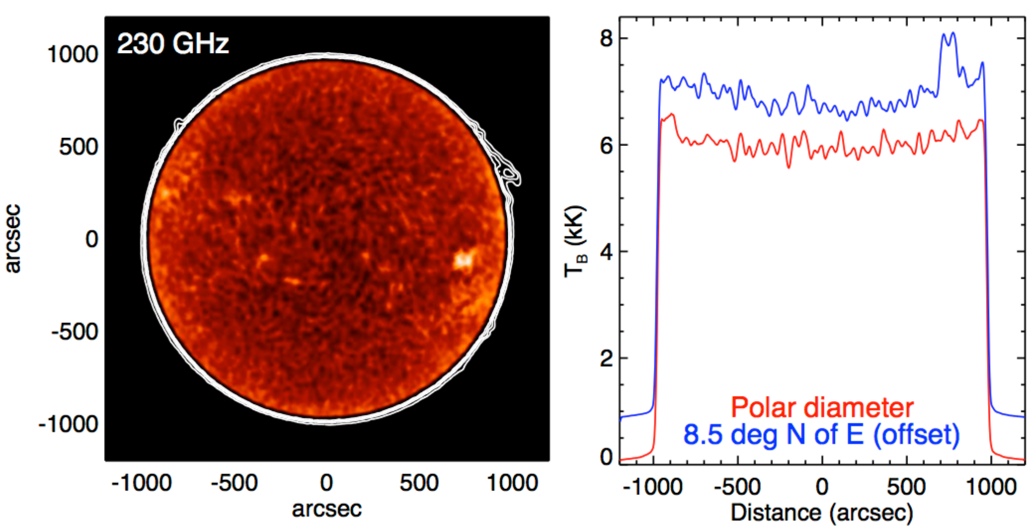


Figure 26: *The left panel shows a 230 GHz (band 6) image of the Sun on 7 December 2016. In order to emphasize structure on the disk, the 230 GHz image color display ranges from 5300 to 7400 K. Low-level contours are plotted at 300, 600, 1200, and 2400 K in order to show features above the limb. The right panel shows disk profiles through the Poles and on a diameter through the active region in the southwest quadrant, but with the blue curve offset by 800 K in order to show structure in both. (Credit: ALMA (ESO/NAOJ/NRAO; S. White et al., 2017, SoPh, 292, 88)*

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 is broadcast to the regional and worldwide communities by the ARCs using standard broadcasting means (e.g. society and observatory newsletters and mailing lists), and is 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, or register as an ALMA user on the Science Portal.

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 37). 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 to which users will be directed for data retrieval and helpdesk support. Users from Chile or from non-ALMA member regions may select any of the three ARCs for support.

Proposal Preparation & Submission (Phase 1): After the CfP is issued, users 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 (SGs). 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). Users should be very careful to input the correct information (source coordinates, frequencies, bandwidths, etc.) into the OT at Phase 1. Only very minor changes are permitted during scheduling block preparation (Phase 2), and significant changes require a major change request which can cause delay or may not be granted.

> **Quick Links**
>
> The Observing Tool (OT) is accessible from
> https://almascience.org/proposing/observing-tool
> Instructional videos on using the OT can be found at
> http://almascience.org/proposing/observing-tool/video-tutorials

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 are peer-reviewed by a single international committee that is divided into a number of science-themed review panels (Scientific Review). Priority status is 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%, and 10% made available to projects associated with the North American, Europe, East Asian, and Chilean partners, respectively. (Large programs, i.e. those requesting more than 50 hours of 12-m Array time or 150 hours of ACA time (see Proposer's Guide section 4.3) will have their time split among the partner regions of the co-PIs.) Time will also be available to projects from non-ALMA regions through the Open Skies policy. Users should consult

> **Quick Links**
>
> The spectral line catalogue tool *Splatalogue* is available at http://www.splatalogue.net/
>
> Information on observing with ALMA, including the Project Tracker (SnooPI) and allocated projects, can be found at:
> http://almascience.org/observing/

For the non-expert, a list of Interferometry Concepts is included, starting on page 31.

the Proposer's Guide available from the Science Portal for details. Users will receive notification of the proposal review process via email. (See details on the proposal review process at http://almascience.org/documents-and-tools/latest/alma-proposal-review-process.)

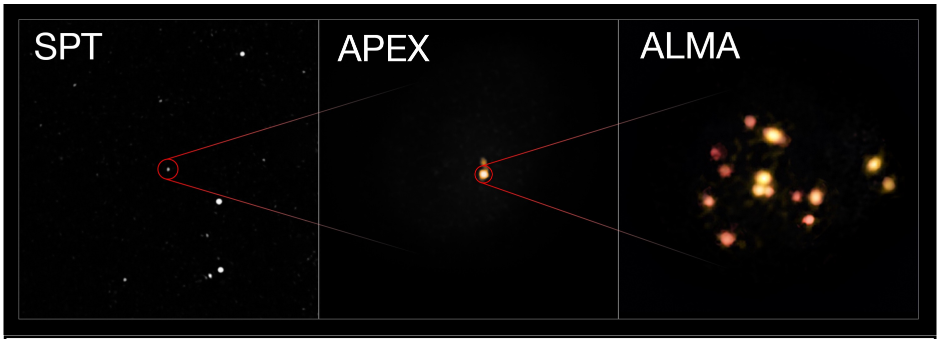


Figure 27: *This montage shows three views of a distant group of interacting and merging galaxies in the early Universe. The left image is a wide view from the South Pole Telescope that reveals just a bright spot. The central view is from Atacama Pathfinder Experiment (APEX) that reveals more details. The right picture is from the Atacama Large Millimeter/submillimeter Array (ALMA) and reveals that the object is actually a group of 14 merging galaxies in the process of forming a galaxy cluster. (Credit: ESO/ALMA (ESO/NAOJ/NRAO); Miller et al., 2018, Nature, 556, 469)*

Scheduling Block Preparation (Phase 2): The highest-ranked projects (Grades A and B, and some Grade C as required) then proceed to Scheduling Block Preparation, also called Phase 2. During Phase 2, successful proposers will have the opportunity to review their SGs and make minor changes if necessary (but see below). After this their Phase 1 Science Goals will be converted into Scheduling Blocks (SBs), which contain all the instructions necessary to carry out the observations specified in the SG, including calibrations, etc. 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 can track the status of their project through the ALMA Project Tracker (SnooPI), a user application available from the Science Portal (https://almascience.org/observing/snoopi). Note that only very minor changes (e.g. source position change less than half the primary beam size) to the SBs are permitted during Phase 2. Any significant change requires a major change request through the Helpdesk, and may result in delays to implementing the SBs and/or may not be granted. See the Proposer's Guide section 7.2 for details.

Archive & Data Delivery: After each SB has been successfully observed, the data will be calibrated, reduced and quality assured by ALMA/ARC staff and deposited into the ALMA Science Archive, available from the Science Portal, 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.

> **Quick Links**
>
> A fuller description of ALMA observing considerations can be found in the Technical Handbook
> http://almascience.org/documents-and-tools/latest/alma-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 the observing 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 35). 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 28).

> **Quick Links**
>
> A video explaining Maximum Recoverable Scales can be viewed at
> https://science.nrao.edu/opportunities/courses/alma-instructional-videos

Note that if you are only interested in small details, faint extended emission of no interest can be ignored if it is of too low surface brightness (a few times the rms) at the expected resolution. However, emission which is so bright that it would be strongly detected were it not smooth can cause artefacts in high resolution images if low-resolution data are not also used.

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. 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. 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. For this reason, if the map region of interest extends beyond about 1/3 of the primary beam from the field center, it is strongly recommended that a small mosaic is made instead of a single pointing.

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.)

Spectral resolution is the minimum separation in frequency whereby adjacent independent features can be distinguished. The digitized data from ALMA allows for a remarkable range in spectral resolution. (See Table 2 page 8.) 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 32 for a caveat). The width of these channels can be defined from 3.8 kHz to 31.25 MHz. (In *Cycle 7*, 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 obser-

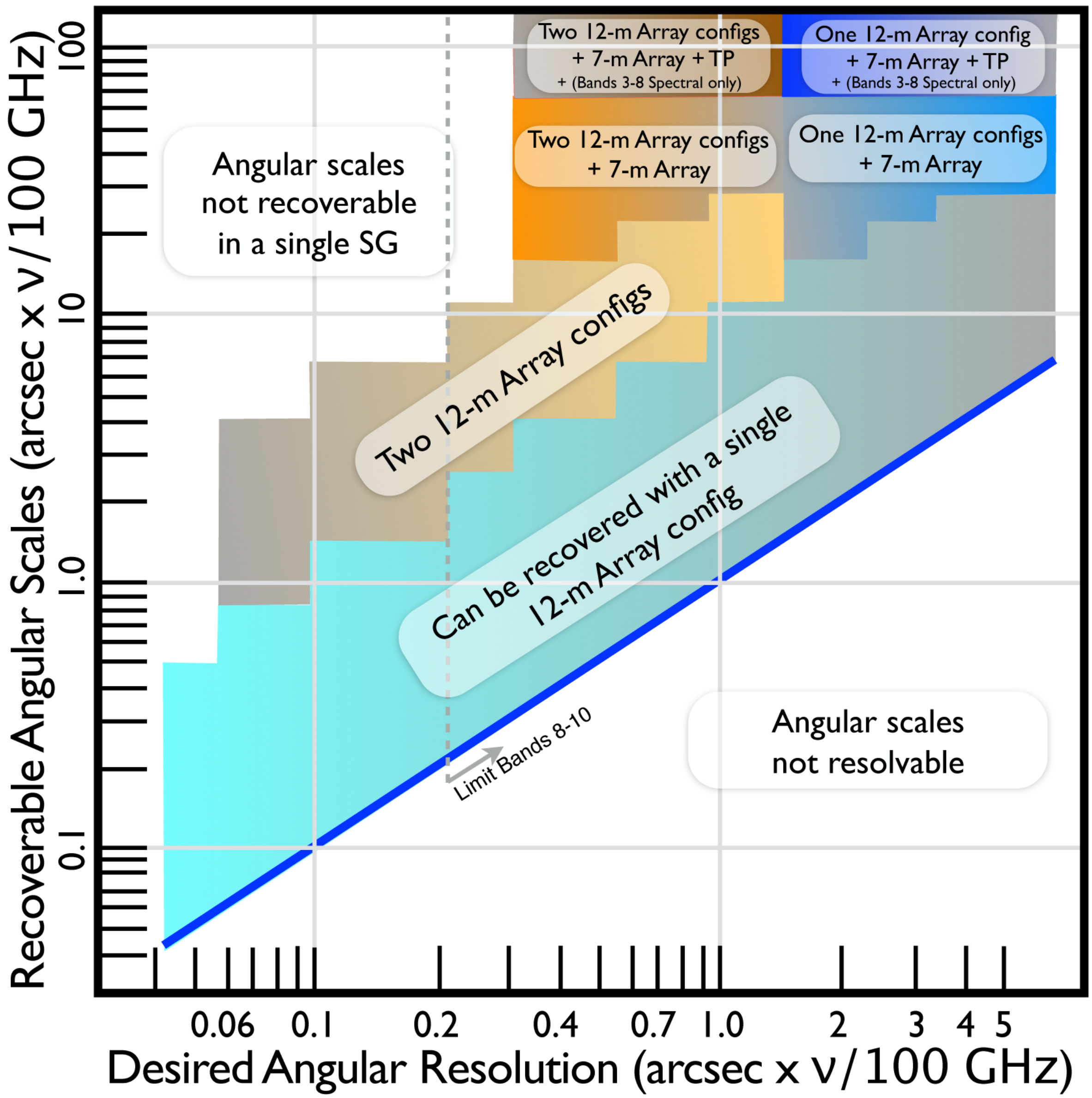


Figure 28: *This figure links Desired Angular Resolution to the Maximum Recoverable Scale (MRS). The desired angular resolution determines the largest baselines (and hence the configuration) of the 12-m Array. The observations from that configuration can recover structure over a range of angular scales; for example, an observation at 1″ resolution at 100 GHz can recover structure over size-scales from ~1″ to ~11″ (cyan region). Structures larger than the "Maximum Recoverable Scale" (MRS; see p. 24) 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, by adding observations using the 7-m Array, or by adding both another configuration and the 7-m Array. Still larger scale structure may be recovered for Bands 3-8 spectral observations by adding data from the Total Power (TP) array. To use this figure, you first need to scale your desired angular resolution and LAS by the factor (ν/100GHz), where ν is your desired frequency in GHz. For example, suppose you wanted to observe at 300 GHz (Band 7) with angular resolution 0.4″ and LAS of 10″. These become 1.2″ and 30″ respectively when scaled to 100 GHz. Reading from the figure above, two 12-m Array configurations plus the ACA 7-m Array would be needed to recover all angular scales. (The OT will automatically determine the required combination of arrays/configurations to achieve the resolution/LAS you require.) Note that adding configurations or the ACA will significantly increase the required observing time. See Chapter 7 of the* Technical Handbook *and the* Proposer's Guide *in the Call for Proposals for details and restrictions. Note that angular resolutions finer than (0.21″ x 100 GHz/*ν*) are not permitted for Bands 8-10 (Limit Bands 8-10 on figure above).*

vations 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*, and later reducing the sheer volume of data during reduction (see *spectral resolution*, page 24). (It should be noted that, because the correlator channels are Hanning smoothed before averaging, there is only a marginal (~14%) decrease in spectral resolution when an averaging factor of 2 is chosen, but with a factor of 2 decrease in the data rate and volume. In *Cycle 7*, the OT will select a spectral averaging factor of 2 by default.) The ALMA correlators are highly complex and extremely flexible and can be configured to observe simultaneously several spectral lines within the 7.5 GHz band at high spectral resolution while additional correlator channels can be simultaneously used to observe continuum emission at low spectral resolution. In addition, a combination of high and low resolution correlator windows can be chosen over the same bandwidth to determine how emission from lines at these frequencies is contributing to the emission observed at low spectral resolution. (See *Baseband* and *Spectral Windows*, pp. 31 and 34.)

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 36). 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 4), 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, particularly from single-dish telescopes, are sometimes given in units of Kelvin (K). (See *Using Single-Dish Data to Estimate Sensitivity Requirements*, p. 28, or watch a 6-minute video available at https://science.nrao.edu/opportunities/courses/alma-instructional-videos.) Converting from one unit to another requires knowledge about the angular resolution of the data, where the sensitivity in K (ΔK) is proportional to the sensitivity in Jy (ΔS) 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 36.) 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 online sensitivity calculator available (see tools p. 37), also built into the OT.

Dynamic range is the ratio between the peak flux in an image and the required rms. When making an image from interferometric data, the incomplete *uv*-coverage causes every source to be convolved with the array's point-spread function (dirty beam). This spreads sidelobes throughout the map and thus makes detecting faint sources challenging. The dirty beam must therefore be deconvolved from each source (usually using the "clean" algorithm) but this is difficult for very bright sources, depending on the *uv*-coverage and the accuracy of the calibration. Imperfectly deconvolved sources leave residual sidelobe patterns in the cleaned image and prevent the theoretical image rms being reached and faint sources being detected. The ratio of the peak source flux in the field to the image rms is referred to as the imaging dynamic range and large values can be difficult to achieve. In *Cycle 7* imaging dynamic ranges are typically expected to reach up to around 50-100 depending on band and configuration (extended configurations, or Bands 9 and 10 are likely to be closer to 50). In some cases it may be possible to achieve higher dynamic ranges using special calibration techniques or *self-calibration*.

Similarly, spectral dynamic range is the ratio of the brightnesses of the strongest and weakest detectable features in one channel in a spectral line image, with obvious generalizations to smoothed or integrated data. Since the weakest detectable feature is some multiple of the single-channel rms, the spectral dynamic range is often quoted as the ratio of the strongest signal to the channel-to-channel rms, much like the continuum case. In some cases the brightest signals will actually be continuum and the presence of very strong continuum emission limits the detectability of weak line signals for the same reasons that are discussed in the case of the imaging dynamic range, though bright continuum also means that *self-calibration* can improve the S/N. The spectral dynamic range is ultimately limited by the quality of the bandpass calibration, whose own fractional noise (rms/continuum) is added in quadrature with that of the imaging data. Most spectral line emission experiments have low S/N (5:1) and the spectral dynamic range is not limited by the bandpass calibration, but when the continuum is strong the fractional noise in the bandpass calibrator can produce noise in a spectrum which overwhelms weak line signals. To reduce the fractional noise of the bandpass calibration it is often possible to smooth the bandpass calibrator spectrum.

Calibration and overhead are important considerations when observing. Interferometric observations at submm/mm wavelengths are extraordinarily sensitive to atmospheric conditions which can vary over timescales of minutes to seconds depending on frequency and other factors. Each execution of a scheduling block (see page 23 for a discussion of calibration and scheduling blocks) requires a significant amount of time, at least several minutes up to several tens of minutes, for calibration alone. This can make surveys of bright objects, which may only require very short integration times, much less efficient than surveys of objects nearby in the sky which can share calibration.

Simulating ALMA Data

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 task *simalma* (the online ALMA *Observation Support Tool* (*OST*) is also available). The largest angular structure (LAS) is shown by the arrows in the model image (top left image in Figures 29(a) and (b).

Quick Links

The CASA *simulator* and
ALMA *Observation Support Tool*
can be used to simulate ALMA data
and are available at
http://almascience.org/tools/

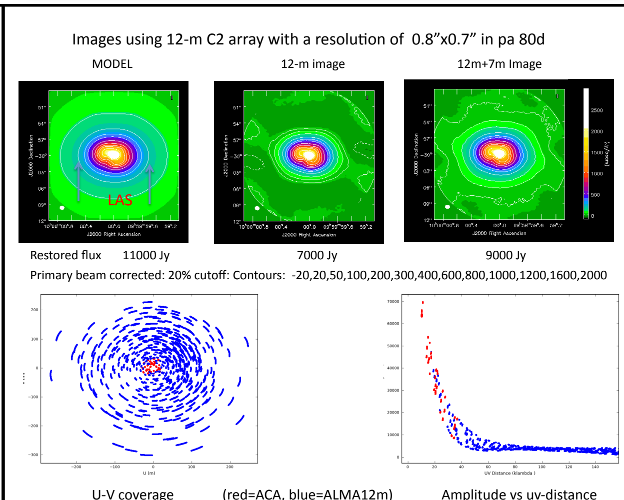


Figure 29(a) [above]: *Demonstrated here is a simulated observation of a source with structure on very large angular scales. This theoretical model of a protostellar disk has a power-law envelope, so in principle has power on all spatial scales (top left). In this case, for a high-sensitivity observation, the LAS is clearly as large as the field of view.*

When observed at 345GHz with a desired resolution of 0.75", the 12-m Array-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 Array 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.

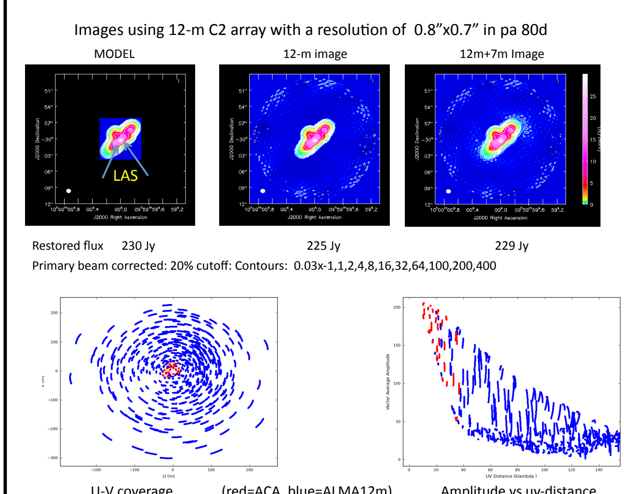


Figure 29(b) [below]: *Here we show simulated observations of a source which has structure only on small spatial scales, such as a cluster of compact galaxies or protostars (top left). The LAS is well within the range of the shorter 12-m Array baselines.*

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.

Using Single-Dish Data to Estimate ALMA Sensitivity Requirements

Results from single-dish telescopes like Herschel, the JCMT, Nobeyama, IRAM, and so on, can greatly strengthen an ALMA proposal, but converting those observations into a sensitivity estimation for ALMA is not always straightforward. Fortunately, if we just need to use these single-dish results to estimate ALMA sensitivities, we can use some simple approximations.

Suppose your observation was presented in Jy/beam, which is the flux density of the source measured within the telescope's beam. To estimate the flux density within ALMA's usually much smaller beam, you'll need an estimate of the angular size of the source. If the source is small compared to the ALMA beam, for example, then all of the flux will fit into the beam. You now know the expected flux density for an ALMA observation, and you just need to decide on the signal to noise ratio (SNR) you need.

If you know, or have reason to believe, that the source is bigger than the ALMA synthesized beam, then you will need to correct the measured flux by the ratio of the area of the source to the area of the ALMA beam. For example, suppose you have a JCMT observation of a submm galaxy, and have measured a flux density of 32 mJy within the JCMT beam. From other evidence you believe that the angular size of the galaxy is about 2″, and you would like to observe it with ALMA at an angular resolution of 0.5″. That 2″ wide galaxy would be spread over $(2''/0.5'')^2$=16 ALMA beams in area. The expected flux density in the ALMA beam would thus be only 32 mJy/16 = 2 mJy/beam. If you wanted a 10 sigma detection, you'd need a sensitivity of 0.2 mJy/beam.

Observations from single-dish telescopes, particularly spectral data, are often quoted in units of Kelvins or K km/s, which is the integrated intensity over a spectral line. The simplest, if not most rigorous, way to use an antenna temperature to estimate an ALMA observation is first to convert the antenna temperature into a flux density using the point source approximation, usually written as:

$$2kT_A = S_\nu A_e$$

where T_A is the intensity in Kelvins, $S\nu$ is the flux density, k is the Boltzmann constant, and A_e is the effective area of the antenna surface of the single dish telescope, equal to the area of the antenna times the overall aperture efficiency (η_A), which is usually available from on-line documentation for the single dish telescope in question.

Armed with this approximation, we're now ready to convert our integrated intensity into a flux density. Plugging in the appropriate values and constants, the conversion factor simplifies to:

$$S_\nu = \frac{3614}{\eta_A D^2}\ T_A\ Jy/K$$

where D is the diameter of the single-dish telescope in meters, and η_A is the aperture efficiency.

Let's try an example. Suppose we had an IRAM observation of a nearby galaxy, and detected a 200 km/s wide CO J=2-1 line with an integrated intensity of 22 K km/s. IRAM has an antenna diameter of 30m and an aperture efficiency η_A~ 0.45 (from the IRAM website) at 230 GHz. Plugging these values into the equation above, we find the measured flute density is 191 Jy km/s per beam. Dividing by the line width, the average intensity of the line is about 0.9 Jy/beam. We want to observe it with ALMA at an angular resolution of 1″. What flux do we expect in a 1″ beam? As before, that depends on how large the source is. In the worst case, the emission is spread evenly over the 11″ IRAM beam, or over 121 ALMA beams. In this case the expected flux density would be about 7 mJy/beam. A 10-sigma detection per spectral channel would require a sensitivity of 0.7 mJy/beam. Conversely, if the source were only 1″ or smaller in angular size, the expected flux density would be the full 0.9 Jy/beam. A 10-sigma detection of the line emission per channel would require a sensitivity of 90 mJy/beam.

As you can see, some *a priori* knowledge of source size can be quite important when estimating the required sensitivity. In some cases you simply will not know this before getting ALMA data. In absence of other data or a solid physical argument that leads you to expect a particular size, the most conservative estimate, that the source fills the single-dish beam, may be the best. In any case, be sure to explain in your technical justification how you estimated the required sensitivity.

Quick Links

A video about estimating ALMA sensitivities can be viewed at
https://science.nrao.edu/opportunities/courses/alma-instructional-videos

Creating Images From Your Data

Once the data are taken, ALMA data will be reduced by staff from the JAO and ARCs using the ALMA Data Reduction 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 provided with the calibrated data, the reference images (i.e. the ALMA Pipeline-reduced calibrated data cube), and the scripts used by the ALMA Pipeline.

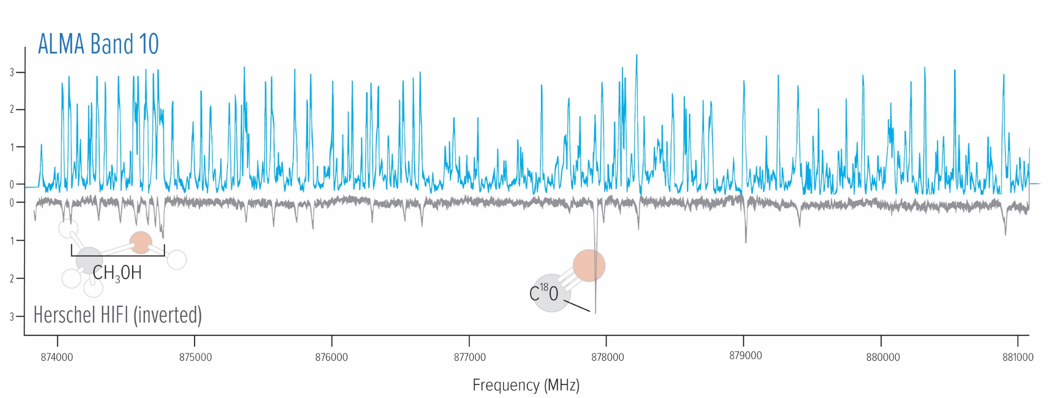
Once the ALMA Pipeline-reduced data are released, the PI may still want to optimize the reduction and imaging to get the best possible data for the project, most likely using CASA. In the following, we describe the basic concepts of reducing interferometer data. This process can be distilled down to two stages, calibration and imaging, and we discuss these below in turn. *Casaguides* are available which will guide you step-by-step in reducing real ALMA Science Verification data.

> **Quick Links**
>
> The CASA homepage
> with links to documentation, downloads and tools is available at
> http://casa.nrao.edu/
>
> Casaguides
> are step-by-step guides for learning data reduction and imaging with CASA
> http://casaguides.nrao.edu/

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) before, during and after the target source observations are made. The calibrator data are 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 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 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. Typically flux calibrators are also used as bandpass calibrators. Phase (or gain) 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 ALMA Pipeline processing. Longer timescale phase drifts are monitored using periodic observations of a moderately bright, very compact source at relatively

Figure 30: *The upper blue portion of this graph shows the spectral lines ALMA detected in the NGC6334I star-forming regionThe lower black portion shows the lines detected by the European Space Agency's Herschel Space Observatory. The ALMA observations detected more than ten times as many spectral lines. Note that the Herschel data have been inverted for comparison. Two molecular lines are labeled for reference. (Credit: NRAO/AUI/NSF, B. McGuire et al., 2018, ApJ, 863, L35)*



small angular distance from the target. The best sources for phase calibration are unresolved at the angular scales probed by the array; since such objects are point sources, their data have intrinsically zero phase (no emission at any angular offsets), and any phase changes recorded in the data are due only to changes in the system and/or atmosphere. The cadence at which the phase calibrator will be observed will depend on the stability of the atmosphere, the observational frequency, and the maximum baseline length. Atmospheric phase varies more rapidly at longer baselines, while at higher frequencies the variations have larger magnitude. The ALMA antennas "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.

> **Quick Links**
>
> Learn the principles of interferometry.
> Lectures and tutorials from the 2014 Synthesis Imaging Workshop (NRAO) are found at:
> https://science.nrao.edu/science/meetings/2014/14th-synthesis-imaging-workshop/

If a science observation has a relatively bright and reasonably compact source in it, it may be possible to apply self-calibration to the data, correcting for phase and amplitude variations during the observations. This powerful technique must be applied carefully, but can result in an increase in effective sensitivity by large factors. It works because the large number of baselines provides redundancies in the solutions which can be used to improve the temporal gain calibration, leading to better source images. (For more information, see the *casaguides*.)

Imaging: ALMA datasets will be processed through the ALMA Pipeline so that project teams will be able to see preliminary results quickly. Non-standard and more complex projects may have their data calibrated by members of the JAO and the ARCs using a combination of the ALMA Pipeline and by hand using CASA. 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; ”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 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 under-sampled (*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 beam than an observation at high elevation.) The angular resolution can also be adjusted through the choice of an imaging weighting function (see *Imaging* page 29). 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 1 on page 8 for the full list of receiver bands that ALMA will have in Cycle 7.

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 31). 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 Bands 9 and 10 have the same basebands in both sidebands simultaneously, though in *Cycle 7* it is possible to separate out the signal from the unwanted image sideband. (See Sideband)) 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; Sideband)

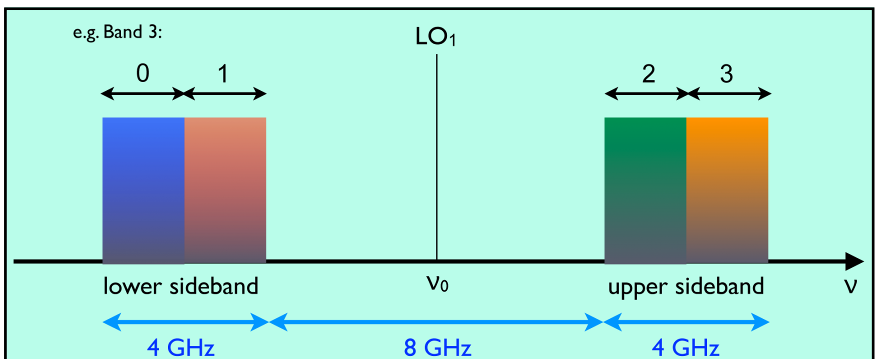


Figure 31: *A graphical view of basebands and sidebands. Basebands may be tuned to overlap if the user wishes, or may be located so as to maximize the total bandwidth (as shown). Each baseband may be further subdivided into as many as 8 spectral windows. Up to four spectral windows per baseband will be available during Cycle 7.*

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 Array will have 1225 baselines. In *Cycle 7*, at least 43 antennas provide 903 or more baselines in the 12-m Array.

Clean Image or Cube A deconvolved image (or cube of images), where the emission in each has been modelled in some manner so that distortions induced by secondary features to the synthesized beam are minimized. The

Figure 32: *The ALMA transporter carrying one of the 7-m Array antennas to the OSF for servicing. (Credit G. Schieven)*

optimal method of deconvolution depends on the science goals of the observation.

Configurations There are 192 antenna foundations (pads) distributed over the Chajnantor plateau. The pattern of the antennas on a subset of these pads is called a *configuration*, and is designed to provide as uniform a *uv*-coverage as possible for a given angular resolution. An extended configuration provides a very small synthesized beam though at the expense of larger scale structure, and vice versa (see Figure 28). See the Proposer's Guide for the configuration schedule for *Cycle 7*.

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 8 for the available modes in *Cycle 7*) 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.

Dynamic Range This is the ratio between the brightest emission in an image and the rms noise of the image. (Spectral dynamic range is the ratio between the brightest flux density and the rms noise within a spectral channel.) Large dynamic ranges (≳100 for Bands 3-8, ≳50 for Bands 9 & 10 in *Cycle 7* can be difficult to achieve because of limitations of interferometry (see p. 26), but may be enhanced in some cases using *self-calibration*.

Field of View (FOV) See Primary Beam.

Fringes See Visibilities.

Image Sideband See Sideband.

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

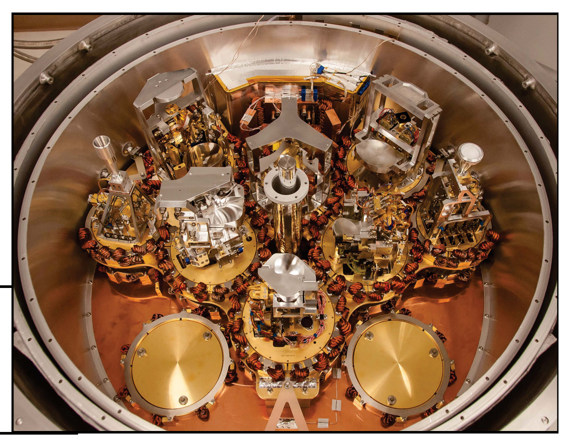


Figure 33: *An open cryostat fitted with receivers covering Bands 3 through 10. The two "empty" slots will eventually be occupied by Bands 1 and 2 receivers, giving ALMA complete spectral coverage from ~30 GHz to nearly 1 THz. (Credit: ALMA (ESO/NAOJ/NRAO)*

Figure 34: *Some of the residents of the OSF and environs. (top row) Vicuña; gecko; mother and young burro; Andean condor; flamingos; (bottom row) culpeo (Andean fox); viscacha (member of the chinchilla family); viscacha. (Credit: G. Schieven)*

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 structures are "resolved out" and cannot be recovered. See *Total Power*, the discussion on page 23-24, and Figures 28 & 29.

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, including circular polarization, will be available in *Cycle 7*; see the Proposer's Guide in the *Call for Proposals* for details (link p. 37).

Point Source Sources which are much smaller than the synthesized beam are often called *point sources*. Because the source is not resolved, the *visibilities* will be the same whether the antennas are close together or far apart; hence *point sources* can be observed with any *configuration* of the antennas.

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 field of view (FOV) for an observation with the array, unless a larger mosaic is made.

Figure 35: *This spectacular and unusual image shows part of the Orion Nebula. It combines a mosaic of emission from N_2H^+ from ALMA and the IRAM 30-metre telescope, shown in red, with the infrared view from the HAWK-I instrument on ESO's Very Large Telescope, shown in blue. The group of bright blue-white stars at the left is the Trapezium Cluster. (Credit: ESO/H. Drass/ALMA (ESO/NAOJ/NRAO)/A. Hacar)*

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 (e.g. a bright compact source).

Sideband At any given tuning, each receiver is sensitive to two separate ranges of sky frequency of equal width called sidebands (see Figure 31). 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. By default for Bands 9 and 10, the signal from one sideband is rejected by a technique called LO offsetting. Alternatively, the signals from both sidebands can be separated and recorded using a technique called *90° Walsh switching*, which will be available in some restricted cases in Cycle 7. (see Proposer's Guide).

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 and affecting the *uv*-coverage.

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. Note that, because the correlator applies a Hanning filter to the data before averaging, choosing a spectral averaging factor of 2 only marginally changes the spectral resolution, while halving the data rate and subsequent volume of data during calibration and imaging. The OT default is to use an averaging factor of 2.

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 8). 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 band-

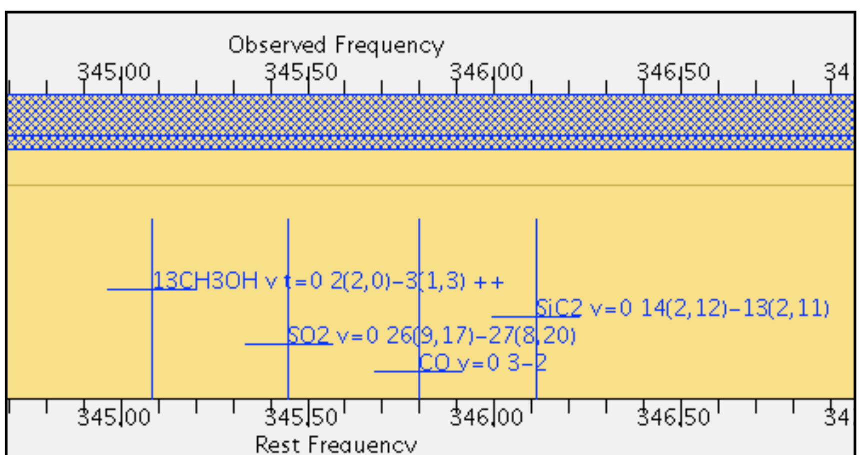
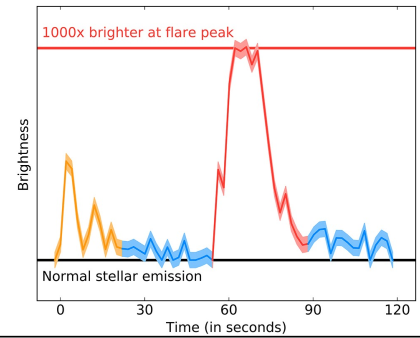


Figure 36: *Four spectral windows were set up to observe these four lines simultaneously in one baseband using the OT. The windows are each 234 MHz wide (with 0.43 km/s channels), and are centered at 345.80, 345.45, 346.11 and 345.09 GHz. The spectral windows must fit within the 2 GHz wide baseband.*

Figure 37: *New analysis of ALMA observations reveal that Proxima Centauri emitted a powerful flare that would have created inhospitable conditions for planets in that system. Here is shown the brightness of Proxima Centauri as observed by ALMA over the two minutes of the event on March 24, 2017. The massive stellar flare is shown in red, with the smaller earlier flare in orange, and the enhanced emission surrounding the flare that could mimic a disk in blue. At its peak, the flare increased Proxima Centauri's brightness by 1,000 times. (Credit: M. MacGregor et al., 2018, ApJL, 855, 2)*



width per spectral window and/or larger channel spacings. Spectral windows can be placed anywhere within the ~2 GHz wide baseband. In Cycle 7, 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 (Fig. 28).

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 of a given frequency channel is the number of integrations times N(N-1), where N is the number of antennas.

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.

Walsh Switching See Sideband.

Zero Spacings See Total Power.

Figure 38: *This view shows several of the ALMA antennas and the central regions of the Milky Way above. The image was taken during the ESO Ultra HD (UHD) Expedition. (Credit: ESO/B. Tafreshi (twanight.org))*

A Few Useful Equations

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

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

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

To achieve a particular 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 8) 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

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

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:

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

As described on p. 28, in simple cases one can estimate a flux density from an antenna temperature measurement from a single-dish telescope with the following:

$$S_\nu = \frac{3614}{\eta_A D^2}\ T_A\ Jy/K$$

where T_A *is the source intensity in K*, D is the diameter of the single-dish telescope in meters, and η_A is the aperture efficiency.

A Summary of “Quick Links”

ALMA Science Portal	http://almascience.org/
Call for Proposals	http://almascience.org/proposing/call-for-proposals/
Proposer’s Guide	http://almascience.org/documents-and-tools/latest/alma-proposers-guide
Technical Handbook	http://almascience.org/documents-and-tools/latest/alma-technical-handbook
Cycle 7 Science & Software Tools	http://almascience.org/tools/
Proposing Guidance quick links	http://almascience.org/proposing/learn-more/
Current ALMA Status	http://almascience.org/observing/alma-status-pag
ALMA Archive and Data	http://almascience.org/alma-data/
JAO Public Web	http://almaobservatory.org
ALMA Users’ Policies	http://www.almascience.org/documents-and-tools/latest/alma-user-policies
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	https://researchers.alma-telescope.jp/e/ea-arc/
Intro to Interferometry	https://science.nrao.edu/science/meetings/2014/14th-synthesis-imaging-workshop
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://almaost.jb.man.ac.uk/
Splatalogue	http://www.splatalogue.net/
ALMA Publications	http://telbib.eso.org
Press Releases	http://www.almaobservatory.org/en/press-room
ALMA Instructional Videos	https://science.nrao.edu/opportunities/courses/alma-instructional-videos
*Cycle 7** Quick Facts	http://science.nrao.edu/facilities/alma/didyouknow
ALMA Web Site for Children	http://kids.alma.cl/?lang=en

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