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The ALMA radio telescope

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The Atacama Large Millimeter/submillimeter Array (ALMA) is an imaging radio telescope of up to 64 12-m antennas which can be moved to fixed stations across the Atacama plateau of northern Chile to form antenna configurations extending from 150 m to about 15 km. Astronomical images will thus be made with moderate spatial resolution (around 1 arc second and above) or high resolution (0.1 arcsecond or better, down to 10 milliarcseconds). ALMA will provide the highest fidelity images over small and large fields of view by combining data from the main array of 12-m antennas with the ALMA Compact Array (ACA), a set of 4 12-m antennas and 12 7-m antennas distributed over 50 m. The Atacama desert where the ALMA antennas will be deployed is at 5000 m elevation. This site was selected because of its extreme dryness in order to lower the atmospheric phase noise and attenuation and, hence, to optimize the interferometric sensitivity in all of the 10 receiving bands spanning the range 30 GHz to 1 THz. We briefly comment on the major ALMA science objectives, present some of the main elements of the telescope, outlining technical difficulties and innovations, and conclude with the expected sensitivity and the probable date for early science operation.

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1. Introduction

ALMA, the Atacama Large Millimeter/submillimeter Array[1], is the largest radio telescope ever constructed on Earth. Its construction is carried out in the Atacama desert a 5000 m high plateau of northern Chile (Figure 1) under an international agreement involving Europe, North America, Japan and the host country Chile. ALMA will explore the Universe in the millimeter (mm)/submillimeter (submm) up to 1 THz (300 micrometers) with as many as 66 moveable antennas (50 +16 antennas, see next Section) arranged in various configurations extending from 150 m to about 15 km. ALMA is designed to map with high or moderate spatial resolution the cold regions of the Universe optically invisible but bright in the mm/submm. It will be the counterpart of the present and future large optical/IR telescopes (VLT, VLT-I and future ELT and James Webb Space Telescope). ALMA, with unrivalled sensitivity, imaging quality, spatial and spectral resolutions, will become the major instrument to understand the processes leading to star formation in nearby and very distant galaxies, or leading to the formation of protoplanetary systems around young stars. Undoubtedly, it will impact a huge range of topics ranging from studies of the early Universe to studies of the Sun and other Solar System objects. At the same time, a new vision of the molecular complexity in the distant and nearby Universe is expected to emerge. ALMA will be complemented at lower frequencies by the E-VLA and the future SKA and, at higher frequencies, by the ESA Herschel satellite which will bridge the range from 1 THz to the Far Infra Red.

2. Main specifications

ALMA is the result of ambitious science objectives and of new technological possibilities to surpass all existing mm/submm telescopes in: (i) frequency coverage (up to 1 THz), (ii) collecting area (about 10 times above that used in present mm arrays), (iii) overall sensitivity (best receivers, high elevation site and broad bandwidth), (iv) spectral resolution and correlator configuration versatility, (v) spatial resolution (baseline extent up to 15 km allowing to reach around 10 milliarcseconds at the highest frequencies) and (vi) imaging quality. ALMA images will be obtained with antennas placed on fixed stations selected to provide, according to simulations, good high or low spatial resolution images at all declinations except for the unobservable North sky (the ALMA latitude is about $-23°$). ALMA is expected to surpass the best instruments available now in the mm/submm, IRAM, CARMA or the Sub-Millimeter Array, simultaneously in all of the above items (i) to (vi). In addition, ALMA will be able to accurately measure all Stokes parameters simultaneously, a unique feature compared to existing mm-wave interferometers.

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

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Figure 1: General view of the Chajnantor plateau at an altitude of 5000 m before any antenna station has been constructed. The central LO system and the correlators (see Sections 5 and 6) are installed in the technical building visible in the middle of this image. The instrument in the background is the APEX telescope. Credit: ESO.

Various science requirements have been identified to define the ALMA technical requirements later used for the engineering implementation. As an example, the ability to detect line emission from CO or ionized carbon in a normal galaxy at a redshift of z = 3 in less than 24 hours was used to define the total collecting area. For several engineering reasons and because of the imaging constraints which require to reconfigure the antennas, the preferred solution was to fabricate several tens of 12-m antennas. ALMA is primarily designed as an imaging radio telescope. With nearly 200 antenna stations distributed across the ALMA Operations Site (AOS) at 5000 m the array can be expanded and contracted as required by the science programs with the help of a specific antenna transporter (Figure 2). Optimum (u,v) coverage and reliable images with high or moderate spatial resolution (from 0.1 arcsecond or better to 1 arcsecond or above) are obtained by combining the 12-m array configurations with the twelve 7-m antennas of the ALMA Compact Array (ACA). The spatial information in sources more extended than the primary beam is lost. However, it can be recovered by observing in total power mode more time than in the interferometric mode; this is performed with the four 12-m antennas of the ACA.

High quality imaging up to the highest frequencies requires the design of a highly phase stable array. This is achieved by preserving the phase information within and above the instrument with: (i) a special transport and control system of the Local Oscillator used in the heterodyne receivers installed behind each antenna, and (ii) a dedicated water vapour radiometer installed at each antenna to compensate for the pathlength changes due to the residual atmosphere. In fact the incoherent effects of the atmospheric phase fluctuations are compensated, either by by combining the water vapor content measured above each antenna with an atmospheric model, or by fast switching to a nearby calibrator in order to freeze the properties of the residual atmosphere. An accurate amplitude calibration is also required to obtain the highest quality images; the ALMA goal is around 1 to a

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Figure 2: The ALMA antenna transporter moving one of the first assembled antennas at the 3000 m high site (OSF). Each antenna weighs more than 100 tons. A second transporter has been built and will be operated at the 5000 m high site (AOS) to relocate the antennas on the AOS stations so that the astronomical imaging requirements are met. When all integration and verification tasks will be completed at the OSF these two transporters will be used to move antennas from the OSF to the AOS. Credit: E. DuVall

Table 1: ALMA 12-m array specifications

Array parameter	Specification
Antennas	50 (up to 64)
Diameter	12 m
Surface precision	$<$ 25 micrometers
Pointing accuracy	$< 0.6''$
Collecting area	up to 7240 m^2 (+ 910 m^2 with ACA)
Configurations	150 m to 15 km
Angular resolution	arcsec to a few milliarcsec
Processed bandwidth	16 GHz per baseline
Spectral channels	up to 8192 per 2 GHz bandwidth

few percents which might be difficult to reach despite the consistent bandpass properties among antennas of the array.

A summary of the ALMA specifications for the 12-m main array is given in Table 1. The number of antennas is 50 with an option for 14 more. The ACA specifications are identical to those of the main array except that the twelve 7-m antennas have a surface precision better than 20 micrometers and that there are only four 12-m antennas.

3. ALMA science

ALMA will cover a broad range of topics (see e.g. Science with ALMA, 2008); we briefly mention below, somewhat arbitrarily, a few of them. A summary of the science requirements leading to the main ALMA technical requirements is given in Table 2.

The main targets for ALMA are the cold regions of the Universe with temperatures ranging from a few K to about 100 K, namely the cold molecular and dust clouds in which stars and protoplanetary systems are being formed. The discovery of complex molecules and giant molecular clouds in the interstellar medium dates back to the seventies and eighties but the most sensitive mm-wave instruments available now, even though they still bring new results, are limited in terms of sensitivity, spectral and spatial resolutions or imaging capabilities. ALMA will provide new images of the star-forming regions and of the disks associated with the newly born, low-mass or massive stars. Modeling of protoplanets embedded in circumstellar disks and orbiting at a few AU around solar mass objects shows that at the highest ALMA frequencies a proto-Jupiter located 50 to 100 pc away from us will be detectable. Thanks to its superb spatial resolution and sensitivity ALMA will also be able to survey the distant regions in which massive stars are being formed thus allowing us to understand the mechanisms leading to massive star formation, a topic of major interest to predict the evolution from molecular clouds to young stellar clusters.

ALMA will provide images of the most distant objects in the Universe in the continuum (dust) as well as in the lines of CO or ionized carbon. The latter species was detected (but could not be imaged) with the IRAM interferometer toward $J1148+5251$ at the record z = 6.42 distance. More generally, distant galaxies will be detected up to z = 7 to 12 because the FIR peaks of these objects are red-shifted to the mm/submm part of the spectrum. Many distant objects should thus be detectable in the 1 mm broad band window of ALMA where we expect a sensitivity of about 10 microJy in one hour.

Thanks to its broad bandwidth, very high spectral resolution and zooming capability (see Section 6) ALMA will discover several new molecules and isotopic species in a variety of objects ranging from the galactic star-forming regions or evolved stars to the nearby or distant galaxies. We thus expect a renewed picture, or a least a new inventory of the molecular complexity observed in nearby or distant star-forming regions and in the expanding outer layers of evolved stars. Spectral confusion may complicate the analysis, but the ALMA imaging capability will help in the spatial differentiation and thus in the identification of the various molecular species. Finally, we expect that the main chemical tracers of many protostars and protoplanetary systems will be identified and that ALMA will reveal the complex kinematics of these young systems.

The magnetic field is an important but still largely unknown ingredient of the insterstellar medium and of the protostellar environment. Its geometry and intensity, and thus its importance in several star-forming regions should be accessible to ALMA which has the ability to measure the polarization parameters of the observed sources.

Finally, we mention that many objects of the Solar system will also be observed with ALMA. The photosphere/chromosphere transition region of the Sun will be imaged with high time resolution. Images of comets will be performed in various molecules and cometary nuclei will be detected and imaged in the continuum. We also expect that many new studies of asteroids and of planetary atmospheres with their moons will be undertaken.

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Table 2: ALMA science requirements

Science parameter	Specification
Frequency coverage	30 to 950 GHz
Angular resolution	1.4 to 0.015 arcsec at 300 GHz
Spectral resolution	0.01 km/s at least at 100 GHz
Maximum bandwidth	8 GHz per polarization
Polarization	all Stokes parameters
Flux density sensitivity	a few microJy per hour at 1 mm (continuum mode)
Imaging dynamic range	50000
Spectral dynamic range	10000 (weak lines against stronger ones)

4. Main technical features and innovations

The ALMA telescope is built as a 'classical' imaging radio interferometer. The antennas are moveable and collect the signals for further processing in cooled front-ends followed by intermediate frequency down-conversion and amplification stages. Once all signals from all antennas are digitized they are ultimately processed in a digital correlator. What makes ALMA so special is the simultaneous implementation of several difficult technical requirements in order to meet the ambitious science objectives. In addition, many ALMA modules have to be produced in large quantities with high technical performance requiring early industrial involvement. State-of-the-art technology or innovative designs are present in most systems or sub-systems of the ALMA project. This is especially true for the: antennas (e.g. advanced materials, high surface precision, fast switching); dual-polarization front-ends (e.g. SIS tunnel-junction mixers providing receiver temperatures close to the quantum limit, see Table 3); Local Oscillator distribution (photonic laser distribution with photomixers at antennas); digitizers at the antennas (broad bandwidth and several comparison levels); correlator (digital filtering of a broad bandwidth and new ASIC to process many antennas); ALMA software (e.g. development of a new data reduction package, CASA).

In the following two Sections we limit ourselves to a few details on the receiving system, including the LO oscillator distribution sub-system, the digitizers and the correlator.

5. Receivers and Local Oscillator system

Table 3 gives the receiver noise temperature for the ten ALMA bands; up to 10 receivers can be assembled in a common cryostat. The noise temperature specified here corresponds to the maximum value over 80% of the receiving band. The superconductor-insulator-superconductor (SIS) mixers provide single sideband separation (SSB) for bands 3 to 8 (see e.g. Kerr et al. 2004 for band 6), while bands 9 and 10 will be operated in the double sideband (DSB) mode. The upper and lower sideband signals are provided as two intermediate frequency outputs (2 sideband mixers) for each of the two polarizations in bands 3 to 8. For these bands the 8 GHz maximum bandwidth available per polarization can be arranged either as 4 GHz from each sideband (upper and lower sidebands) or as 8 GHz in a single sideband (but with best performance guaranteed across 4 GHz only). Bands 3, 6, 7 and 9 are the four priority bands. They are produced by North America (bands 3 and 6) and Europe (bands 7 and 9). Receivers for bands 4, 8 and 10 are under development in

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Table 3: ALMA bands and receiver noise temperatures

ALMA Band	Frequency (GHz)	Maximum noise temperature (K)	Technology
1	31 - 45	17 SSB	HEMT
2	67 - 90	30 SSB	HEMT
3	84 - 116	37 SSB	SIS
4	125 - 163	51 SSB	SIS
5	163 - 211	65 SSB	SIS
6	211 - 275	83 SSB	SIS
7	275 - 373	147 SSB	SIS
8	385 - 500	196 SSB	SIS
9	602 - 720	175 DSB	SIS
10	787 - 950	230 DSB	SIS

Japan for the full array. Receivers for band 5, containing the water vapour transition at 183 GHz, are being developed with European funds for a subset of 6 antennas in the array.

The Local Oscillator (LO) signal consists of a YIG oscillator followed by warm and cold multiplication stages providing the desired frequency at each receiver. The first multiplication stage providing an intermediate frequency around 100 GHz is compared to a centrally generated frequency resulting from the beat of two laser frequencies. The two lasers are sent on a single fiber to each antenna. The optical length of each fiber is controlled with a specific design comprising a servo loop and a line stretcher to compensate for any thermal expansion or instrumental motions. This active system loop allows to maintain a good synchronization of the LOs throughout the array thus achieving good instrumental phase coherence (see e.g. Shilue et al. 2004). ALMA requires that the LO reference remains stable over 300 seconds to within $\approx$ 20 fsec between all antennas and that the total instrumental delay error per antenna remains around $\approx$ 75 fsec. The latter temporal delay error corresponds to a phase noise of 26 degrees per antenna at the highest frequency of 950 GHz for an integration interval of one second.

6. ALMA Digitizer and Correlator

In order to obtain an image of the observed astronomical source one must first derive the cross- and auto-correlation coefficients for all of the independent antenna pairs in the array. This is performed in a large synchronous machine processing up to 64 antennas. Prior to correlation the 2 GHz analog baseband signals are converted to digital samples in a digitizer module specifically designed for ALMA. The most critical component in this module is the fast sampler accepting input signals up to 4 GHz and providing 8 levels of comparison corresponding to a theoretical 96% 3-bit digitizing efficiency. The ALMA correlator cannot process the data at a rate as high as 4 Gsamples/sec; therefore, the digitizer module includes a time demultiplexing stage to lower the data rate. The sampling and demultiplexing chips have all beeen specifically designed for ALMA and several thousands of pieces produced with industrial support.

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The ALMA correlator is a complex hybrid digital XF architecture system described in Escoffier et al. (2007) and, in more general terms, in Baudry (2009). First, the 2 GHz input baseband is digitally split into 32 subbands in order to enhance the spectral resolution. This is followed by station electronics cards providing the digital delays required before correlation. The baseline based electronics comprise many custom chips performing at 125 MHz clock rate the cross-correlation products for all antenna pairs; this is the X-part of the correlator system where the multiplications are made in the time -or 'lag'- domain. The spectral properties of the correlated signals are later obtained by Fourier transforming the correlation products (F-part of the system). The hybrid digital architecture provides much flexibility. Each subband is independently processed, assigned to one of the 32 correlator planes and the spectra stitched together to form a composite spectrum with 32 times more spectral channels across the 2 GHz input baseband. One correlator plane is a 64x64 matrix with many specific integrated circuits to derive the cross- as well as the auto-correlation coefficients. There are 32 correlator planes in total to process all 64 antennas. One can distribute the correlator plane resources to less than 32 digital filters, thus narrowing the input bandwidth and increasing the spectral resolution; up to 3.8 kHz resolution is supported. Many observing modes are available. Depending on the sensitivity options, one can perform 2- or 4-bit correlation and twice-Nyquist sampling or not. Full Stokes parameter analysis is also supported, or, if more spectral channels are desired, single or double polarization observations may be selected. The correlator system is organized by quadrants. All four quadrants process the four baseband pairs from each antenna in the array. The first quadrant (Figure 3) is in operation at the AOS and all other three will be delivered in the period 2009 to 2011. All quadrants are identical and each quadrant can be split into independent subunits. The latter property combined with the fact that the spectral subbands can be moved anywhere within the 2 GHz input baseband increases the flexibility. For instance, it is possible to select a multi-spectral resolution mode and zoom on specific spectral features. The potential science impact in the mm/submm and the technical challenges met during the construction phase of the ALMA correlator are discussed in Baudry (2009). There is also an ACA correlator (FX architecture where the multiplication is performed in the frequencey domain) processing the 16 antennas of the ACA. The 64-antenna and the ACA correlators are both located at the AOS in two contiguous rooms.

7. First results, schedule and expected sensitivity

At the time of the second MCCT-SKADS school (August 2008) much hardware and software testing had been completed with the two prototype antennas of the ALMA Test Facility (at the VLA site in New Mexico). As early as January 2008 a 2 GHz spectrum had been obtained with 7.8 MHz resolution in the direction of the Orion hot molecular core (see Laing, 2008). As of this writing (April 2009), the AOS and OSF buildings are ready, the two antenna transporters are currently being used at the OSF, the ACA correlator and the first quadrant of the 64-antenna correlator have been installed at the AOS and operated, much hardware is being delivered at the OSF for assembly, integration and verification, and around 10 to 20 antennas have been either delivered or parts are being assembled. In April 2009 first astronomical fringes were obtained at 104 GHz in the direction of Mars at the OSF with two commissioned antennas and full front-end systems together with production back-end and correlator hardware. By the end of 2009 we expect to bring from the

Figure 3: The 8 racks of the first quadrant of the 64-antenna correlator installed in a dedicated room at the AOS central building (5000 m). The 4 central racks contain the correlator cards while the 4 outer racks on each side of the central racks contain the digital filter cards and other station electronics cards. Heat dissipation from thousands of cards in the system is a difficult task at 5000 m because the air density is nearly twice less than at sea level.

OSF to the AOS three antennas outfitted with production hardware to perform the first 3-antenna interferometric observations. Astronomical validation will start with these first 3 antennas and we expect to open the 'Early Science' phase in 2011 with 16 antennas at the high site. Full science operations will require a total of 66 antennas from the full main array and the ACA.

The expected sensitivity cannot be specified accurately because many commissioning tasks are not completed yet. However, we may give the sensitivity goals for 64 12-m antennas of the main array in the four priority bands. In the continuum, with 2 x 8 GHz bandwidth, we expect to reach for one minute integration an r.m.s. flux density of 0.045, 0.1, 0.2 and 1 mJy in bands 3, 6, 7 and 9, respectively. Around 110 and 230 GHz (bands 3 and 6) and for two polarizations and 1 km/s spectral resolution the flux density will go up to 7 and 10 mJy which is still remarkable for just 1 minute integration. The brightness temperature sensitivity, which is the relevant concept for extended molecular emission sources, depends on the maximum baseline used in the array. At 230 GHz (the J = 2-1 transition of the widespread CO molecule) we expect for a 200 m baseline, an integration time of one minute and with 1km/s resolution a temperature sensitivity of about 0.1 K. These estimates indicate that ALMA will undoubtedly surpass all existing mm/submm arrays in sensitivity.

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References

[1] A. Baudry, *The ALMA correlator: performance and science impact in the mm/submm* , *The Messenger* **135** (p. 5), 2009

[2] R. Escoffier, G. Comoretto, J.C. Webber, A. Baudry, et al., *The ALMA Correlator*, *A&A* **462** (p. 801), 2007

[3] A.R. Kerr, S.K. Pan, E.F Lauria, A.W Lichtenberger, et al., *The ALMA Band 6 sideband-separating SIS mixer-preamplifier*, *ALMA Memo Series* **No 498**, 2004

[4] R. Laing, *Recent progress at the ALMA test facility* , *The Messenger* **132** (p. 28), 2008

[5] Science with the Atacama Large Millimeter Array: A new era for astrophysics, *Astrophys. and Space Science* **313** (Nos 1-3), 2008

[6] B. Shillue, S. AlBanna, L. d'Addario, *The ALMA first Local Oscillator reference*, *ALMA Memo Series* **No 483**, 2004