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ALMACAL: Surveying the Universe with ALMA Calibrator Observations

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The Atacama Large Millimeter/submillimeter Array (ALMA) has accumulated thousands of hours of observing time on calibrator sources, which are typically bright quasars. These calibration scans are usually observed with the same instrumental setup as the science targets and have enormous potential for conducting science. ALMACAL is a survey that is exploiting these data which are accumulating “for free” with every scheduled ALMA observing project. Here, we present a brief survey status update and summarise the science that can be achieved. For instance, if data acquired during multiple visits to many ALMA calibrators are combined, low continuum noise levels can be reached, allowing the detection of faint dusty star-forming galaxies in a number of bands. Also, redshifted CO and other emission and absorption lines are detected in the ALMACAL data. The total on-source integration time for all ALMACAL scans to date amounts to approximately 2500 hours, more than all ALMA Large Programmes to date combined.

The ALMACAL pipeline

Every ALMA dataset delivered to a principal investigator contains observations of several calibrator sources. These calibrator observations are used to set the flux density scale, correct for the bandpass response, and solve for the complex gains as a function of time, which are all standard operations executed by the ALMA quality assurance procedure. According to the ALMA operations plan, these calibrator data are not protected with proprietary time and are accessible to any user immediately after the parent science dataset has passed quality assurance. At ESO, an ALMACAL[1] pipeline was developed that runs automatically on all delivered datasets. This pipeline executes the so-called scripForPI.py script, which comes with each data delivery, and produces fully calibrated calibrator data. The pipeline then solves again for the complex amplitude and phase solutions, this time using the highest possible time resolution allowed by the data. After applying these solutions, a point source model is fitted to the data and subtracted in visibility space, which leaves us with optimally calibrated and continuum-free data. Finally, in order to reduce the total data volume, the individual measurement sets are averaged in time and rebinned spectrally to a common channel separation of 15.6 MHz.

ALMACAL in numbers

Since Cycle 1, the ALMACAL pipeline has been run on more than 11 000 delivered datasets. As every dataset contains several calibrator scans, this implies that the total ALMACAL dataset comprises over 33 000 individual observations of calibrators. The contribution of different frequency bands to this total number is distributed very unevenly, with some 39% of the scans taken in Band 6. This reflects the popularity of this frequency band which, as it lies roughly in the middle of the ALMA frequency range, gives a good trade-off between atmospheric absorption and the brightness of dusty continuum sources. Band 3 follows, with about 31% of the scans, then Band 7 with 19%. The other bands together make up the remaining 11%. Altogether, ALMACAL has collected data for over 1000 calibrator fields so far. Of these calibrators, which are usually quasars, roughly 70% have spectroscopic redshifts and more will be obtained in an upcoming X-shooter programme in P109. After eight observing cycles, the total on-source integration time for all ALMACAL scans amounts to approximately 2500 hours and continues to grow (see Figure 1 for the integration time per field). For comparison, ALMA Large Programmes are typically awarded 50 to 150 hours of telescope time.

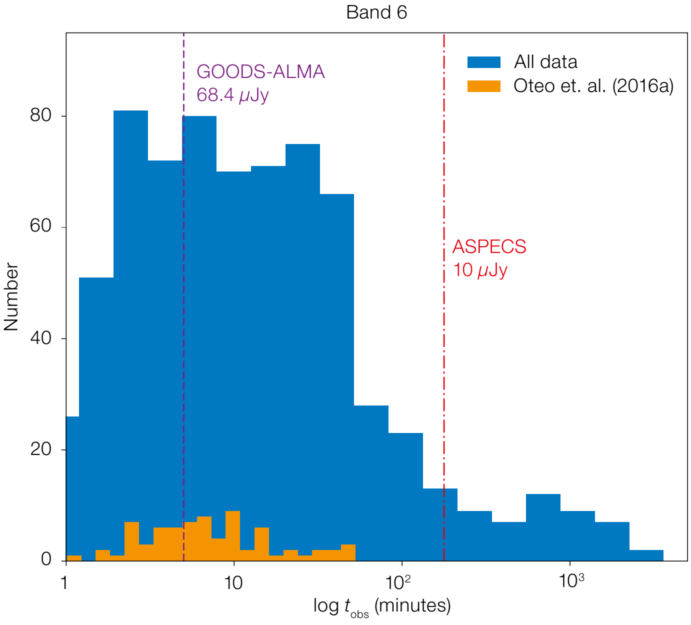

Figure 1. Number of ALMACAL fields as a function of accumulated integration time for data taken in Band 6. The blue histogram shows the current status, while the orange histogram represents the database in 2016. The two vertical lines show the rms noise level in the GOODS-ALMA and the ASPECS Band 6 continuum maps.

ALMA deliveries processed		11 138
Measurement sets (MOUSs) processed		33 038
Independent fields observed		1001
	Sky coverage	Number of observations
Band 3 (3 mm)	567 arcmin^2	~ 10 000
Band 4 (2 mm)	106 arcmin^2	~ 2000
Band 5 (1.6 mm)	28 arcmin^2	~ 500
Band 6 (1.2 mm)	93 arcmin^2	~ 13 000
Band 7 (870 μm)	32 arcmin	~ 6000
Band 8 (650 μm)	5 arcmin^2	~ 700
Band 9 (450 μm)	1 arcmin^2	~ 200
Band 10 (350 μm)	0.1 arcmin^2	~ 100
Imaging noise level		down to 10 μJy beam^{-1}
Total integration time		~ 2500 hours

Table 1. A summary of ALMACAL survey statistics. This is the status of the survey at the end of Cycle 7, i.e., 1 October 2021.

ALMACAL compared to targeted ALMA surveys

Clearly, the total amount of observing time accumulated in the ALMACAL database cannot be easily surpassed by PI programmes and the sheer volume of data offers a number of advantages. Firstly, the total sky coverage in Band 3 (~ 100 GHz) amounts to approximately 567 arcmin^2, where we count the area of the primary beams out to the half-power point. In Band 6, this drops to about 93 arcmin^2 and in Band 8 to 5 arcmin^2. For comparison, the ALMA Spectroscopic Survey in the Hubble Ultra Deep Field (ASPECS) is currently the deepest ALMA untargeted or "blind" survey, covering 2.9 arcmin^2 at a sensitivity of 9 μJy beam^{-1} in Band 6 (González-López et al., 2020). GOODS-ALMA[a] covers 72 arcmin^2, but with a significantly lower sensitivity of around 68 μJy beam^{-1} (Gomez-Guijarro et al., 2021).

Since ALMA calibrators lie quasi-randomly across the southern sky, ALMACAL's survey area is also very distributed. In essence, the survey areas listed in Table 1 are spread over ~ 30 000 degrees^2. For science based on serendipitous line and continuum detections and which aims to derive statistical properties of the Universe (for example, cosmic gas density or source counts), this distribution implies that the results are nearly immune to the effects of cosmic variance that hamper most deep-field surveys.

Along with these obvious strong points, there are a number of challenges associated with ALMACAL data, both in terms of data reduction and scientific interpretation. Of the latter, an obvious one is that because ALMACAL consists of pointed observations of bright calibrators, it is not a truly blind survey, in contrast to, for example, ASPECS. For science that requires a random sampling of the Universe, it must be assessed whether the bright calibrator source in the field implies that the field is tracing a cosmic over-density. Submillimetre galaxies, for example, are known to cluster around bright quasars and radio galaxies (see, for example, Stevens et al., 2003, 2004). However, there are two arguments in favour of the premise that ALMACAL is not biased in that sense. Firstly, the calibrators are predominantly blazars (97%; Bonato et al., 2018) and are thus bright submillimetre sources as a consequence of the fact that their jets point towards the observer (Urry & Padovani, 1995) rather than because they are particularly massive — clustering around most of these sources is therefore likely to be minimal, and their gravitational lensing potential is similarly reduced. Secondly, the redshifts over which continuum- or line-detected galaxies are found are typically unrelated to the redshifts of the calibrators themselves (see, for example, Hamanowicz et al., 2022, submitted to MNRAS).

Blazar jets or dust emission

Further challenges emerge when we search for continuum emission from dusty galaxies in ALMACAL fields. Single-band detections of the dust continuum of background galaxies can in principle be easily confused by jet emission from the calibrator sources (see, for example, Klitsch et al., 2020). Radio maps that are often available from the literature can help identify jet emission, and in some cases symmetric continuum emission around the central source is indicative of jet emission. However, multiband ALMACAL observations are often available which help to establish with high certainty the origin of the emission. Jet emission should have a synchrotron spectrum which increases with decreasing wavelength, whereas dust emission is modified black-body radiation, the intensity of which increases in the opposite wavelength direction.

Central bright sources

Having bright sources at the centre of the field may raise questions about the dynamic range achievable in ALMACAL continuum imaging. We find that in general the central point source subtracts very well, leaving no significant artifacts in the image. Having a bright point source at the centre of the field means that atmospheric and electronic antenna-based temporal amplitude and phase variations can be solved with high accuracy and image dynamic ranges of up to 10^5 can be achieved in this way. However, in some cases residual structure is present after point source subtraction. This often manifests itself as prominent "ears" around the central source, symmetric patterns whose origin lies in small amplitude calibration errors that are not yet well understood. When combining many ALMACAL observations to produce deep images, we take care to omit these individually affected data sets by inspecting individual images.

Random frequency settings

The frequency settings of ALMACAL datasets are defined by the science goals of the observations from which the calibrator data are extracted and as a result each calibrator has a different frequency coverage. Some calibrators are covered by only a few GHz in a single band, while others are observed in all ALMA bands with full coverage in selected regions. For the purpose of conducting spectral surveys, the redshift coverage is therefore fairly random and inhomogeneous. For an individual calibrator, the achieved noise level in an ALMACAL image cube can vary by a factor of a few as a function of frequency.

Incomplete ancillary data

ALMA cosmological surveys target mostly well-studied fields for which a multitude of multi-wavelength ancillary data are available to help establish the redshifts of new detections and provide measurements of stellar mass, star formation rates, etc. Given the non-contiguous sky coverage of ALMACAL, similar data are rarely available and obtaining them is an unrealistic goal given the extensive number of follow-up observations that would be required. However, as the ALMA calibrators are also used by other interferometers operating over the full radio, millimetre and submillimetre spectrum, ancillary data are readily available in these regimes, and there is the promise that some of the quasars will be useful as beacons for adaptive optics at shorter wavelengths.

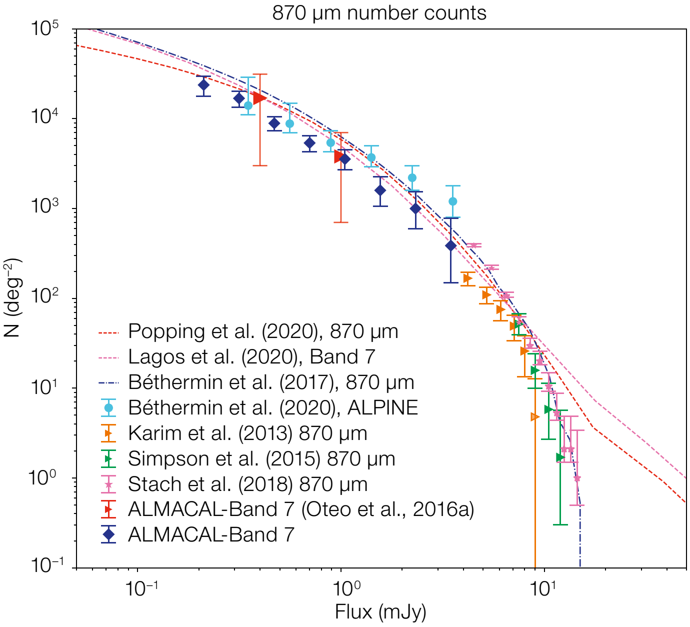

Figure 2. Cumulative Band 7 (870 μm) number counts of dusty star-forming galaxies derived from ALMACAL (Chen et al., in preparation), along with previous results and models from Popping et al. (2020) and Lagos et al. (2020). Previous ALMACAL results from Oteo et al. (2016a) are shown in red.

ALMACAL Science

Since the start of the project in 2016, ALMACAL has produced science results focusing primarily on four main areas: the properties of dusty star-forming galaxies, the evolution of molecular gas, extragalactic absorption lines, and active galactic nucleus (AGN) physics. Given the richness of the dataset, many other science questions can be addressed and we invite the community to get in touch for possible collaborations. Here we provide a brief overview of some of the ALMACAL science highlights so far.

Dusty star-forming galaxies

Embarking on this project, our original aim was to use the ALMA calibrator data to search for dusty star-forming galaxies, to establish their space density and their contribution to the cosmic far-infrared background. The first ALMACAL publication (Oteo et al., 2016a) addressed exactly this topic and presented number counts of 870-μm and 1.2-mm detections, demonstrating the feasibility of ALMACAL for this purpose. Klitsch et al. (2020) extended this technique to Band 8 (650 μm), using data from 81 ALMA calibrator fields, together covering a total area of 5.5 arcmin^2 and reaching noise levels as low as σ = 47 μJy beam^{-1}, such that the sky density of 650-μm sources was established. The full cosmic infrared background was recovered, which means that the contribution from objects below our detection limit of 0.7 mJy must be very small. Since these initial publications, the ALMACAL data volume has grown substantially and improved multi-band number counts are currently being evaluated. For example, Figure 2 presents the latest Band 7 (870 μm) ALMACAL number counts along with previous results and models that will be presented soon (Chen et al., in preparation).

A striking example of a high-resolution case study is provided by the ALMACAL

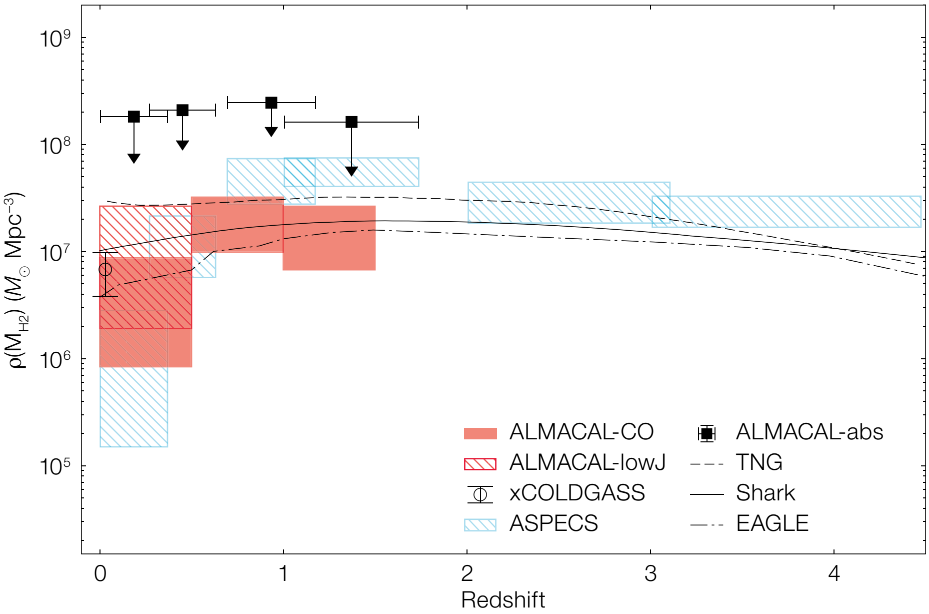

Figure 3. The evolution of molecular gas mass density with redshift as measured from an ALMACAL pilot survey (Hamanowicz et al., 2022, submitted to MNRAS; red boxes). The filled boxes represent the results of a simulation-based source classification, while the red dashed box corresponds to assuming all CO detections are the lowest-J transitions. The black points show the ALMACAL absorption-line constraints (Klitsch et al., 2019b). The results of ASPECS (Decarli et al., 2020, in blue) are also shown, along with the z = 0 reference from xCOLD GASS (Fletcher et al., 2021), and the TNG, Shark and EAGLE simulation results.

analysis of the J1058+0133 field, which is one of the brightest blazars close to a Cosmic Evolution Survey (COSMOS) field. Oteo et al. (2017) found two bright submillimetre galaxies, achieved 20-milliarcsecond spatial resolution for these two galaxies, and identified nearly 20 emission lines.

The evolution of the cosmic molecular gas mass density

The random sampling of the Universe in frequency and sky position makes ALMACAL ideally suited for an untargeted survey for CO emission lines, enabling a measurement of the cosmic molecular mass density as a function of redshift. Molecular gas provides the fuel for the formation of stars and many of the properties of galaxies are determined by the amount of gas they contain, more specifically how efficient they are at converting their innate gas into stars. It is therefore essential to probe the evolution of cold gas over cosmic time. The first steps towards using ALMACAL for this purpose were made by Hamanowicz et al. (2022, submitted to MNRAS), who restricted the search to a small subsample of deep observations (see Figure 3). Based on this analysis it was possible to set limits on the molecular mass density. The ALMACAL team is now embarking on a new analysis using the full dataset and thus increasing the probed volume by a factor of 50.

Absorption lines.

Another way of studying the evolution of the gas mass density of the Universe is to use intervening absorption lines seen in the spectra of background quasars. For neutral hydrogen, this method has been shown to be very productive and surveys for damped Lyman-alpha systems have provided accurate measurements of Omega(HI). Radio surveys for intervening 21-cm absorption are now becoming productive (ASKAP-FLASH, etc.) and it therefore seems logical to use ALMA observations of calibrators to search for the absorption signal of CO caused by galaxies along the line of sight to the calibrator. An initial study has been carried out by Klitsch et al. (2019b) who, despite a cumulative redshift pathlength (summed over all calibrators) of approximately Δz = 180, found no new extragalactic absorbers. This demonstrates the extremely small cross-section of high-density molecular gas. However, the study did put new constraints on the evolution of Omega(H_2) and many Galactic absorption lines were identified.

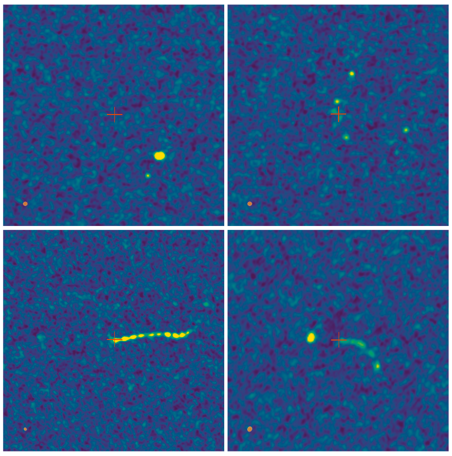

Figure 4. Examples of ALMACAL continuum fields. Each of the fields is centred on a bright (~ 1 Jy) continuum source, which has been subtracted in uv-space. The top two fields show examples of multiple detections of dusty star-forming galaxies. Detection of the same sources in other ALMA bands allows the confirmation of their being dust SEDs. In contrast, the bottom two examples show jet emission, emanating from the central quasar. The bottom-right panel is based on Band 3, the others on Band 7.

In addition, ALMACAL has been used to identify CO emission lines from galaxies associated with strong Lyman-alpha absorption systems, occasionally identifying multiple CO transitions and indicating a more excited interstellar medium in these types of galaxies (Klitsch et al., 2019a).

AGN physics

As stated above, some images of ALMA calibrator sources show powerful jets emanating from the central AGN. The standard ALMA calibration procedure, which assumes the calibrator to be a point source, is usually not affected by these jets as their flux is negligible (<< 1%) compared to that of the point source. Figure 4 shows two examples of jets seen in ALMACAL data.

On the topic of AGN, ALMACAL data offer many other avenues for research, including long-term multi-band flux monitoring and line absorption and emission from the AGN host galaxies. A beautiful example of a study of the morphology and kinematics of the gas surrounding 3C273 based on calibrator data was presented by Husemann et al. (2019). The CO (1-0) emission shows an arc-like structure around the AGN, which is a 12.9-Jy continuum source in ALMA Band 3.

Concluding remarks

We first presented the ALMACAL survey in the Messenger in 2016 (Oteo et al., 2016b). At that time, we showed our first 1.2-mm continuum number counts, based on observations of 240 individual calibrators. Since then, the number of observed calibrators and their individual on-source integration times have grown by an order of magnitude, and new data are still coming in almost every day. In this short article, we have provided some examples of the science that ALMACAL has produced and which is currently being worked on. There are undoubtedly other applications of these data and we welcome collaborations with the community to enable this science.

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Links

[1] ALMACAL website: https://almacal.wordpress.com

Notes

[a] GOODS-ALMA is an ALMA survey at 1.1 mm of the southern field of the Great Observatories Origins Deep Survey (GOODS), itself centred on the Chandra Deep Field South.