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Enhancing ALMA's Future Observing Capabilities

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With each observing cycle at the Atacama Large Millimeter/submillimeter Array (ALMA) new features and observing modes are offered. Here we provide some background about how these new capabilities are tested and then made available to ALMA users. These activities help to drive the cutting-edge science conducted with ALMA and to maintain ALMA's position as the foremost interferometric array operating at millimetre and submillimetre wavelengths. We focus in particular on opening up high-frequency observing using ALMA's longest baselines, which offers the highest possible angular resolution.

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Extension and optimisation of new capabilities

The global effort of adding new capabilities to ALMA is referred to as Extension and Optimisation of Capabilities (EOC). EOC was the natural progression after moving away from initial tests when ALMA was commissioned. During the final years of construction and during Cycle 0 operations, almost ten years ago, the development of new modes was called Commissioning and Scientific Verification (CSV). CSV was conducted to ensure that the capabilities offered were fully operational and valid. Following this, with ALMA as a fully operational telescope, testing as part of EOC activities has continued as an ALMA-wide effort encompassing all partners[1]: the Joint ALMA Observatory (JAO) in Chile and the ALMA Regional Centres (ARCs) in East Asia, North America and Europe. In Europe there are also contributions from the ARC network (see Hatziminaoglou et al., 2015). The entire EOC effort, including all coordination, planning and the intricate steps involved, is led by the JAO (see Takahashi et al., 2021).

In this article we provide an overview of EOC, and what features might be expected in the coming cycles, with a specific focus on pushing ALMA to achieve the highest angular resolutions possible (a study involving significant input from the European ARC). We also highlight how the ALMA community benefits from each capability potentially offered.

ALMA's process for offering new capabilities

Behind the scenes, the process that makes new capabilities possible is the ObsMode process (Takahashi et al., 2021), which is led and coordinated by the JAO. The intention of the ObsMode process is to enable all observing modes that ALMA was designed to support, as well as any additional ones identified since construction began.

Unfortunately, ALMA cannot simply test a new observing mode on the telescope and thereafter open it directly to the community. This is because all parts of the observing chain involving the so-called subsystems (Control software, Observing Tool [OT], Scheduling, Quality Assurance [QA], Pipeline, and Archive, to name just a few) must be up to the task. Before opening a new capability to the community, ALMA must be able to demonstrate the entire workflow: the correct creation of the observation files; successful, error-free observations; data reduction — first using manual scripts and thereafter with the ALMA Pipeline; and finally data and product ingestion into the ALMA Archive such that it can be delivered to any Principal Investigator (PI) and used in any future Archive mining exercises.

The ObsMode process therefore follows a yearly structure and is aligned with ALMA observing cycles. For example, the majority of work in 2021 began in October 2020 and will finish in October 2021 (Figure 1). This system includes a two-year lead time, such that any capability planned for release in Cycle 9 (due to start in October 2022) must be fully tested and verified in Cycle 7[a]. Final tests during the first half of Cycle 8, before the Cycle 9 Call-for-Proposals (CfP) pre-announcement is made, mark the final date to confirm the readiness of a capability for scientific operations. The main considerations throughout the year include:

- Proposed capabilities and priorities: A list is drawn up of capabilities aimed at science operations two years later. Given the ten years of ALMA operations, there is a natural continuation from previous years. ALMA management, together with the science and operations teams, arrange and discuss the priorities with the ALMA Science Advisory Committee (ASAC), which confirms that these align with the community input[b].
- Initial capability plan: Plans are made by the expert teams leading each capability. These must provide a technical summary, identify the on-sky time requirements, and detail each team member's role. Most importantly, the plans set the criteria for declaring a particular capability as ready.
- Test Observations: EOC observations are scheduled to have a minimal impact

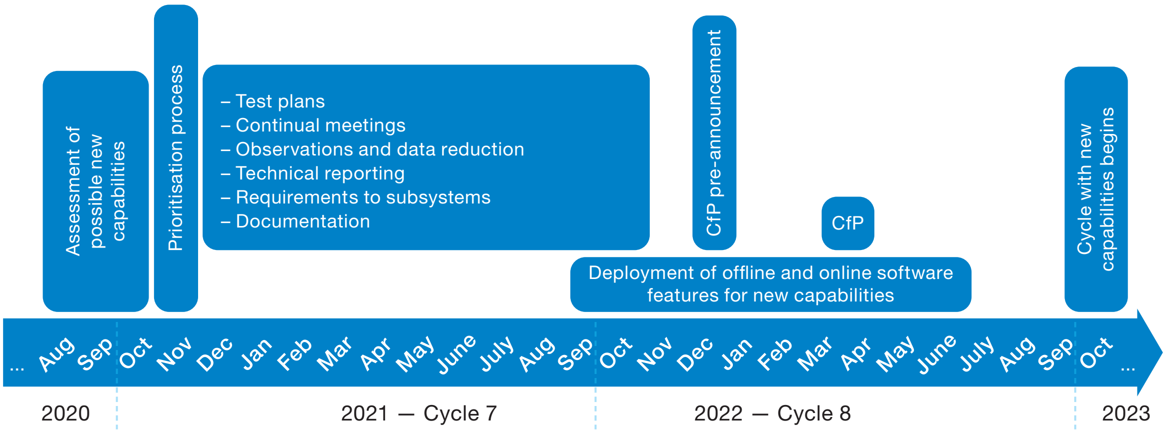


Figure 1. Simplified schematic of the general ObsMode timeline focused around the year 2021 (Cycle 7 — restarted because of the pandemic), starting from the identification of new capabilities at the end of the previous year and leading up to the point where they are planned for use in Cycle 9, two years later. In reality the EOC is a continual process as there is an intrinsic overlap of testing and development between the years.

on standard science observations, being conducted in small time windows or when science observations cannot take place. Where possible, observations use Scheduling Blocks (SBs) constructed with the OT, however some tests require custom command-line scripts to operate ALMA in a manual mode.

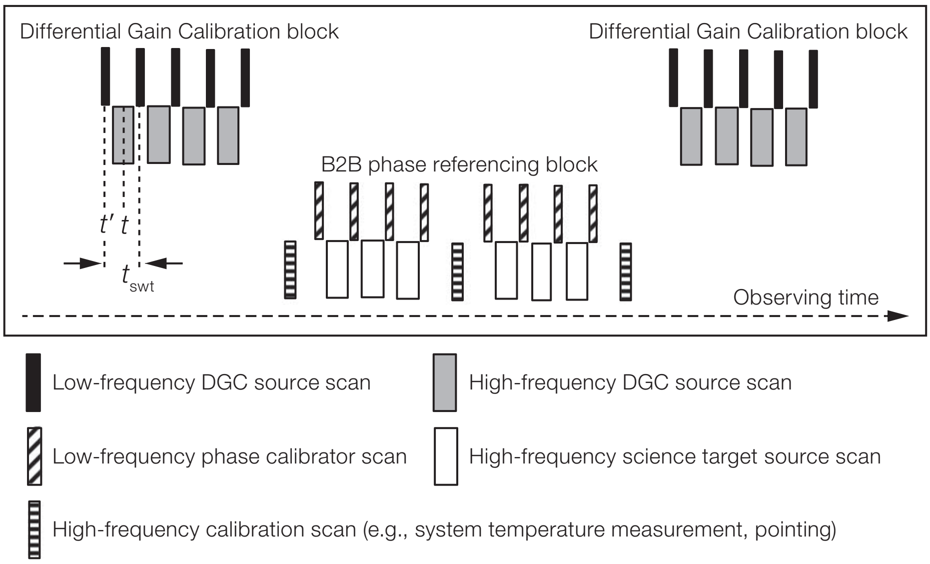
– Data reduction and problem reporting: Custom scripts are employed, using the Common Astronomy Software Applications package (CASA; McMullin, 2007) reduction software with extra analysis and heuristics. Extra system-level stability and data-validity checks are also made. EOC teams aim to provide QA-like reduction workflows to enable an easier transition to science operations.
– Technical readiness: In September and October the EOC teams report their findings and provide a technical report to specific expert reviewers. These reports are used for a readiness assessment to confirm whether the capability meets the initial readiness criteria.
– Subsystem impact: Requirements are created continually throughout the year for the subsystems involved. Although developments are continual, a capability can only be declared operational when all subsystems integrate the required modifications. Examples of subsystem changes are: (1) the addition of new OT features that allow SBs to be generated, and (2) modification of the QA2 process to provide the correct reduction path (see, for example, Petry et al., 2020).
– Documentation: Before the CfP is issued, ALMA provides users with a Proposer's Guide[2] and a Technical Handbook[3]. These documents must fully detail and explain any newly offered capabilities.

Focusing on high frequencies and long baselines with band-to-band (B2B)

The European ARC is particularly involved with EOC activities to offer high-frequency observations (Bands 8, 9, and 10, > 385 GHz) using the most extended array configurations (C-8, C-9 and C-10, with maximal baselines of ~ 8.5, ~ 13.9 and ~ 16.2 kilometres, respectively). Theoretically, the highest frequencies coupled with the longest-baseline array would achieve an angular resolution of 5 milliarcseconds. This translates to sub-au scales for sources within 200 parsecs and would provide the most detailed submillimetre picture of protoplanetary discs. For extragalactic targets, parsec scales could be resolved for sources within 40 Mpc, offering unprecedented details of galactic structures.

What is B2B? Band-to-Band (B2B) is a phase-referencing technique in which the phase calibrator, interleaved between the science target and used to correct for atmospheric variations (see, for example, Asaki et al., 2020a), is actually observed at a frequency lower than the observing frequency of the science target. The

Figure 2. Schematic of the main observing scheme employed for B2B test observations (Asaki et al., 2020a). The instrumental band offsets are solved using the Differential Gain Calibration (DGC) blocks, while the centre of the schematic shows the phase referencing for the calibrator and target alternating between low- and high-frequency bands. The time axis is not to scale.



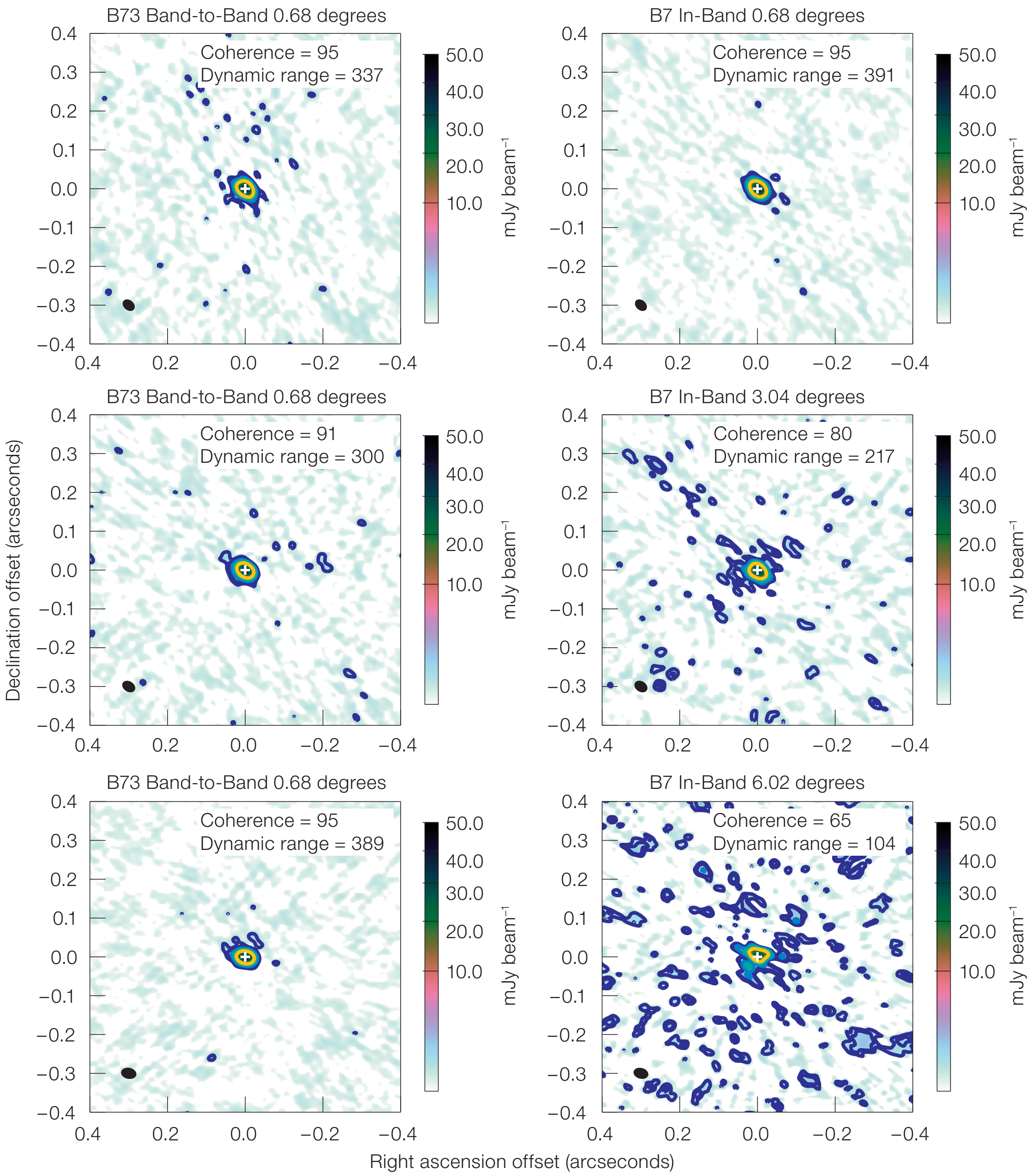


Figure 3. Images of a test-target source, the quasar J2228-0753, observed repeatedly at Band 7 using the long-baseline array for B2B studies in September 2017 (Maud et al., 2020). The left panels show the images from three different observations, all using B2B, for which the target was calibrated using another quasar only 0.68 degrees away on the sky observed at Band 3. These indicate the repeatability of accurate B2B imaging. The right panels show images from the corresponding standard In-Band observations where the calibrator and target are observed at Band 7. The calibrator-to-target separation angles are 0.68, 3.04 and 6.02 degrees (top to bottom). For these In-Band data, all using sufficiently strong calibrators, the images visibly degrade when calibrators are farther from the target, indicating the need to limit the separation.

technique also involves special calibrations, using Differential Gain Calibration to measure instrumental differences between the low- and high-frequency bands (Figure 2).

Why do we need B2B? At high frequencies, quasars used as phase calibrators are weaker, making it is rather difficult to find a sufficiently strong one close to every science target. Strong and close calibrators are paramount for providing accurate phase calibration for high-frequency and long-baseline observations where atmospheric instabilities have a larger impact and where antenna position uncertainties are amplified (Figure 3). During high-frequency observations, visits to the phase calibrators must be more frequent, while each visit must be as short as possible before shifting back to observe the science target. Quasars are generally much stronger at lower frequencies (< 373 GHz), and therefore there are many more that can act as calibrators. B2B therefore enables the use of stronger and closer calibrators for each target and will provide an accurate phase calibration of the science data for high-frequency and long-baseline observations (Figure 4).

The road to offering B2B observations at ALMA has been a long one. The major

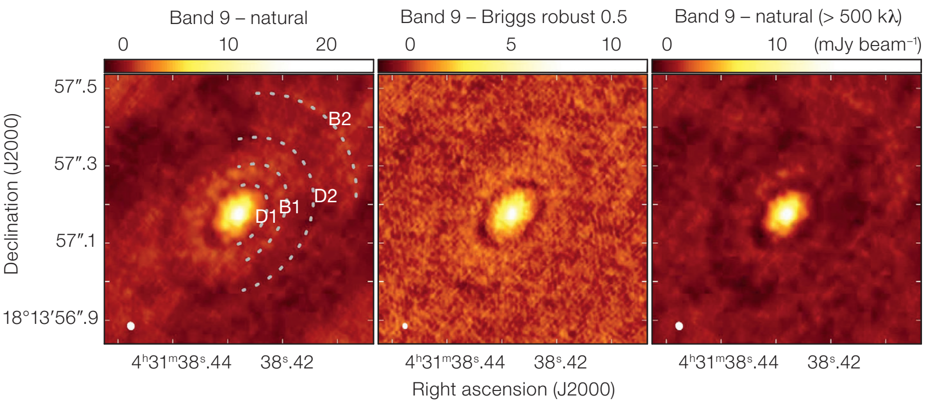


Figure 4. Band 9 images of the inner ~1 arcsecond of the well-known protoplanetary disc source HL Tau observed using B2B (Asaki et al., 2020a). The test observations are short, only 45 minutes on source, compared to the first long-baseline observations that produced the famous original image (~5 hours; ALMA partnership et al., 2015), yet still the inner dark and bright structures are clear. The spatial resolutions are 20 × 18, 14 × 11 and 20 × 18 milliarcseconds for the left, middle and right images, respectively. These tests used Band 4 for calibration, and again highlight that B2B can yield accurate, high-resolution images.

challenge was to understand the system stability and how to calibrate instrumental offsets. Significant software and hardware updates were also required to make fast frequency changes possible. It now takes only 2–3 seconds to swap certain frequency combinations, compared to the 20-second delay previously incurred. Tests over the last five years (involving all ALMA partners) required custom observing scripts and even custom Python tasks for data reduction, before CASA could handle B2B phase transfer. The JAO and European ARC efforts over the past three years have led to the use of science-like SBs for observations, while QA2-like reduction is entirely performed with CASA. The QA2 process has also been finalised, led by the European ARC, and all ARCs will now be able to calibrate B2B observations. B2B will be in use for some Cycle 7, Band 7 long-baseline observations.

The first successful Band 10 (860 GHz) B2B long-baseline observations were made in mid-2019, along with a number of Band 9 tests. These have formed the basis for the forthcoming observations, in which the final observing parameters, calibrator and weather conditions requirements will be specified with a view to acceptance for Cycle 9. A number of studies have also recently been published that highlight the progress of the B2B technique (Asaki et al., 2020a; Asaki et al., 2020b; Maud et al., 2020).

Testing new capabilities in the coming years

Below we list some of the focus areas of the work that is needed to offer new capabilities to ALMA users. From the outset it must be made clear that none of the capabilities listed below is guaranteed to be offered, and also that this list is not exhaustive. Rather, it serves as an illustration of where the activity is focused over the next few years. The final decision to offer the new modes will depend on the progress of each capability through the ObsMode process.

- High-frequency interferometric capabilities include opening the longest baselines while also optimising the currently offered modes on the 12-metre main array and the Atacama Compact Array (ACA). These studies are linked by the B2B calibration technique described above.
- Polarisation testing encompasses further ACA modes and also adds a spectral-line mode to the continuum mosaicking already offered with the 12-metre array. With the ACA, users could conduct polarisation studies that probe larger spatial scales, while spectral-line polarisation with mosaicking would provide a means to map the line polarisation of extended targets (see, for example, Hull et al., 2020).
- Solar work covers two main components. First, fast regional scanning would allow users to obtain total-power maps of solar targets in a reduced time, which is important for imaging short-lived solar features. Secondly, offering polarisation, initially in band 3, would facilitate the investigation of magnetic fields, possibly originating from thermal free-free emission above sunspots, or from gyro-synchrotron emission in solar flares (see Bastian et al., 2018 for more details of future solar capabilities).
- Very-Long-Baseline Interferometry (VLBI). Incorporating ALMA's huge collecting area in VLBI arrays has boosted millimetre sensitivity enormously (for example, Tilanus et al., 2014). VLBI with ALMA is currently offered in Bands 3 and 6 in continuum mode. Testing aims to extend the VLBI capabilities in two obvious areas: including higher frequencies, which will provide unprecedented angular resolutions, and offering the spectral-line mode[4].
- Correlator software studies aim at offering users improved sensitivity for the same observing time, as well as 12-metre main-array system temperature calibration using full spectral resolution (see, for example, Escoffier et al., 2007).
- Astrometry tests aim to investigate how special phase calibrations, with multiple phase calibrators, could offer an increased position accuracy (see the ALMA Technical Handbook[3] for the current limitations).
- Total-power observations are arranged to investigate spectral-line imaging at the highest frequencies (for example, Meyer et al., 2015). Users would then have single-dish maps to merge with corresponding high-frequency ACA and 12-metre main-array data. Another opportunity is offering the total-power spectral scan mode in certain bands.
- Band 1 testing encompasses the whole process of introducing the new receiver band that would offer observations in the frequency range ~ 35–50 GHz (for more details, see Huang et al., 2016).
- ACA Total Power Spectrometer[5] is new hardware to replace the ACA correlator for total power observations.

The 2030 ALMA Development Roadmap

The 2030 ALMA Development Roadmap[6] is not directly part of the EOC process and should instead be regarded as a preceding, or overarching, stage. In short, the Development Roadmap comes from investigations by the ASAC, who examined potential technical developments for ALMA leading up to 2030 that would significantly expand ALMA's capabilities and be able to address new fundamental science drivers. More details will be presented in a future Messenger article.

Conclusions and forward look

New capabilities continually push the forefront of science with ALMA. Each time milestones are met, the boundaries will be pushed even further. ALMA will therefore continue EOC efforts for the foreseeable future. With every new mode, when operational for at least one cycle, there are also inevitably improvements that can be made to optimise observations or efficiency — just as most new capabilities take a cautious approach during their first use. Continuous improvements will therefore be made, ultimately resulting in improved data that are taken more efficiently and thus increasing the overall number of accepted projects, benefitting the entire ALMA user community.

Acknowledgements

Prior to Cycle 0, during CSV times up to current ALMA science operations and EOC testing, the contributions have been extensive. Considerable effort comes not only from the staff of the ALMA partners, but also from external research institutes and university faculties. We extend a particular thanks to the hundreds of people involved with EOC over the last decade. In addition, we thank all staff who ensure the smooth daily running of ALMA and the Operations Support Facility. To everyone involved, for all levels of contribution, we extend our sincerest gratitude.

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Links

[1] ALMA Organization: https://almascience.eso.org/about-alma/alma-organization
[2] ALMA Proposers Guide: https://almascience.eso.org/documents-and-tools/cycle7/alma-proposers-guide
[3] ALMA Technical Handbook: https://almascience.eso.org/documents-and-tools/cycle7/alma-technical-handbook
[4] The ALMA phasing system: https://zenodo.org/record/3585360
[5] ALMA new spectrometer: https://www.almaobservatory.org/en/announcements/alma-board-approved-development-of-new-spectrometer-for-morita-array
[6] ALMA Development roadmap: https://www.almaobservatory.org/en/publications/the-alma-development-roadmap

Notes

[a] Uniquely, Cycle 7 continues through 2021 because of the COVID-19 pandemic.
[b] ALMA users are encouraged to contact their ASAC members, the Users Committee, their local ARC node or the ALMA helpdesk to engage with future ALMA capabilities.

Sangku Kim/ESO

ALMA, located in the Chilean Atacama desert, is the most powerful telescope for observing the cool Universe — molecular gas and dust. ALMA studies the building blocks of stars, planetary systems, galaxies and life itself. By providing scientists with detailed images of stars and planets being born in gas clouds near our Solar System, and detecting distant galaxies forming at the edge of the observable Universe, which we see as they were roughly ten billion years ago, it allows astronomers to address some of the deepest questions of our cosmic origins. ALMA can also be used to study Solar System objects.