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ALMA Band 5 Science Verification

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ALMA Band 5 (163–211 GHz) was recently commissioned and Science Verification (SV) observations were obtained in the latter half of 2016. A primary scientific focus of this band is the H_2O line at 183.3 GHz, which can be observed around 15 % of the time when the precipitable water vapour is sufficiently low (< 0.5 mm). Many more lines are covered in Band 5 and can be observed for over 70 % of the time on Chajnantor, requiring similar restrictions to those for ALMA Bands 4 and 6. Examples include the $H_2{}^{18}O$ line at 203 GHz, some of the bright (3–2) lines of singly and doubly deuterated forms of formaldehyde, the (2–1) lines of HCO^+, HCN, HNC, N_2H^+ and several of their isotopologues. A young star-forming region near the centre of the Milky Way, an evolved star also in our Galaxy, and a nearby ultraluminous infrared galaxy (ULIRG) were observed as part of the SV process and the data are briefly described. The reduced data, along with imaged data products, are now public and demonstrate the power of ALMA for high-resolution studies of H_2O and other molecules in a variety of astronomical targets.

One of the bands of the Atacama Large Millimeter/submillimeter Array (ALMA) that was not initially produced during construction of the observatory and was not available when the array was officially inaugurated in 2013 was Band 5, covering the frequency range 163–211 GHz (1.9–1.4 mm). Band 5 was one of the three frequency ranges originally envisioned for ALMA, but deferred from the construction project to the development programme. The other two are: the 35–50 GHz frequency range (Band 1, currently being produced by a consortium led by Academia Sinica Institute of Astronomy and Astrophysics [ASIAA] in Taiwan); and the lower portion of the 3 mm atmospheric transparency window (below 84 GHz), for which a new-technology, high-sensitivity receiver, dubbed Band 2+3 to cover the full 67–116 GHz band, is currently being developed in Europe.

ESO and several European partners (including Chalmers University in Sweden, the Science and Technology Facilities Council [STFC] in the UK and the University of Chile) were awarded funding by the European Commission under the EU's Sixth Framework Programme (FP6) to develop prototypes of Band 5. A set of six prototype receivers was produced by the Group for Advanced Receiver Development (GARD) at Chalmers University in collaboration with the Rutherford Appleton Laboratory (United Kingdom) under an EU FP6 contract and delivered to ALMA in 2012 (Billade et al., 2012). ALMA accepted the ESO proposal to outfit all 66 antennas with Band 5 receivers in 2012.

The production of the revised and optimised full complement of 73 Band 5 cartridges started in 2013, with production shared between GARD and the Nederlandse Onderzoekschool Voor Astronomie (NOVA), who were jointly responsible for the production and the integration of the Cold Cartridge Assembly of the receiver, and the National Radio Astronomy Observatory (NRAO) in the USA, who provided the Warm Cartridge Assembly. The receivers are dual polarisation SIS (superconductor insulator superconductor) mixers used in a sideband-separating (2SB) configuration and operated with all-reflective cold (< 4 K) optics. The measured system temperature of the production receiver is < 50 K over 80 % of the band (Belitsky et al., 2017), a figure significantly better than the original ALMA specifications for this receiver band, and achieved thanks to extensive optimisation work undertaken at GARD following the production of the six prototype receivers. Figure 1 shows one of the Band 5 cartridges.

Several of the six prototype Band 5 receivers were installed in other instruments, most notably on the Atacama Pathfinder EXperiment (APEX) telescope as part of the Swedish-ESO PI receiver for APEX (SEPIA) project. The SEPIA Band 5 receiver was commissioned at APEX in 2016 and Immer et al. (2016) describe the instrument and some of the commissioning and SV observations. Other Band 5 pre-production cartridges will be installed on the Atacama Submillimeter Telescope Experiment (ASTE) on Chajnantor, and on the Large Latin American Millimeter Array (LLAMA) in Argentina. One is kept at ESO for public display. The installation of the production Band 5 receivers started at ALMA during 2015 and 2016 and the first fringes were obtained in July 2015. At the time of writing 45 Band 5 cartridges have been delivered to the ALMA project and 32 of these are integrated in ALMA Front Ends.

Band 5 will be offered as a “standard mode” in all available array configurations (including the ALMA Compact Array, ACA) in ALMA Cycle 5. Current plans are for Band 5 to be available for science observations starting in the second half of the cycle (March 2018), following commissioning of all the receivers.

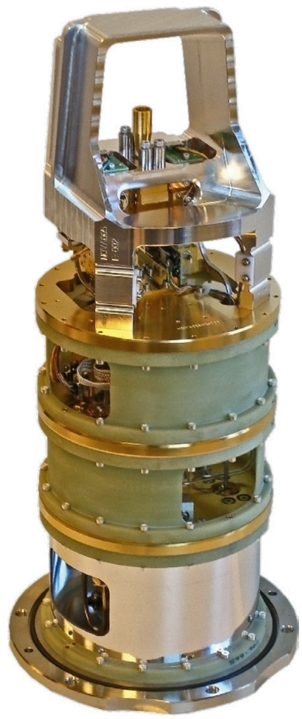


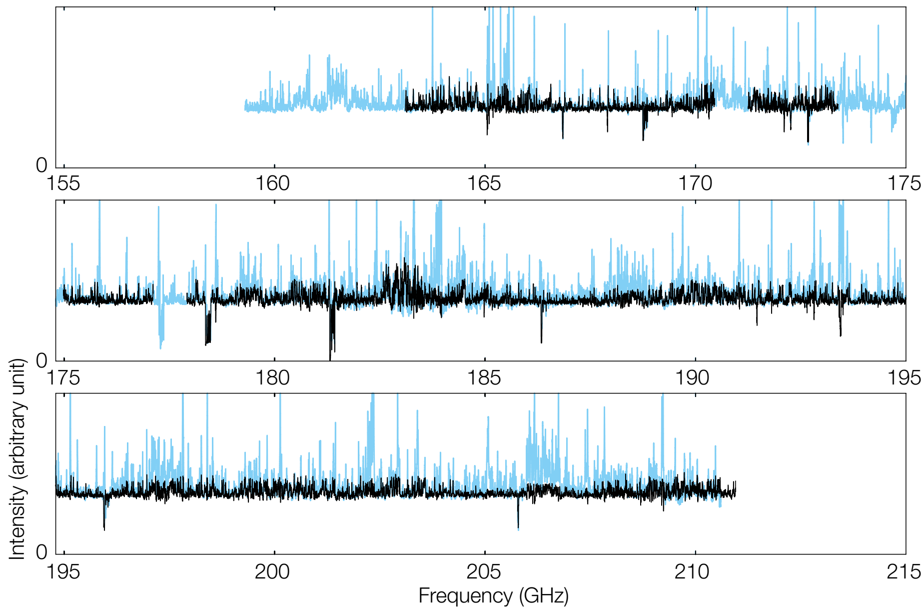
Figure 1. An assembled ALMA Band 5 receiver cartridge, shown courtesy of NOVA/GARD.

Band 5 Science Verification

ALMA Band 5 Science Verification (SV) observations took place from May to October 2016. In contrast to SV with Very Large Telescope (VLT) instruments, where proposals are solicited from the community, a set of targets are selected by an SV team composed of ALMA staff and scientists with the goal of providing a full end-to-end test and scientific validation of the new capability under operational conditions. The selection of targets and modes for SV focuses on testing challenging or novel calibration schemes to ensure smooth science operations. As per ALMA policy, the intention was to select targets with previous H_2O observations in order to enable a careful comparison with the ALMA results; in all cases the targets were also common to APEX SEPIA Band 5 observations. In the case of ALMA Band 5 SV, one extragalactic target with previously detected H_2O emission was selected — Arp 220, a prototypical luminous infrared galaxy — along with two Galactic targets: the molecular cloud complex near the Galactic Centre, Sagittarius B2, selected for a full-band spectral scan; and the evolved supergiant star VY CMa, chosen to demonstrate the line and continuum polarisation performance.

Observations of the H_2O ($3_{1,3}$–$2_{2,0}$) 183.3 GHz line are challenging even from the very high site on Chajnantor, since the precipitable water vapour (PWV) is only below 0.5 mm about 15 % of the time (~ 50 days per year). Figure 2 of Immer et al. (2016) shows the atmospheric transmission through the 183.3 GHz H_2O line as a function of PWV; a PWV < 0.5 mm ensures a transmission in the line peak of > 35 %, with PWV of 0.3 mm required for transmission > 50 %. There are a number of other molecular lines of interest in Band 5, including HCN(2–1) at 177.3 GHz, HNC(2–1) at 181.3 GHz, CS(4–3) at 196.0 GHz, CH_3OH(4–3) at 193.5 GHz and several SiO (J = 4–3) lines between 171.3 and 173.7 GHz, but none of these is seriously affected by the H_2O transmission unless the PWV is large (≳ 2 mm). See Table 1 and Figure 2 of Immer et al. (2016) for an extended list of molecular lines in the band.

An additional aspect of the SV observations was to test the compatibility of the standard ALMA observing software with Band 5 observations, and to determine the best calibration parameters to be used in Band 5 Cycle 5 observations. As Band 5 had never been used with the ALMA Observing Tool (OT) before, it was important to check that Scheduling Block (SB) generation worked as expected and that the SBs could be submitted to the archive and successfully executed. All SV observations were carried out with SBs created using an SV version of the OT, and observations were performed in a pre-release version of the Cycle 5 ALMA control system.



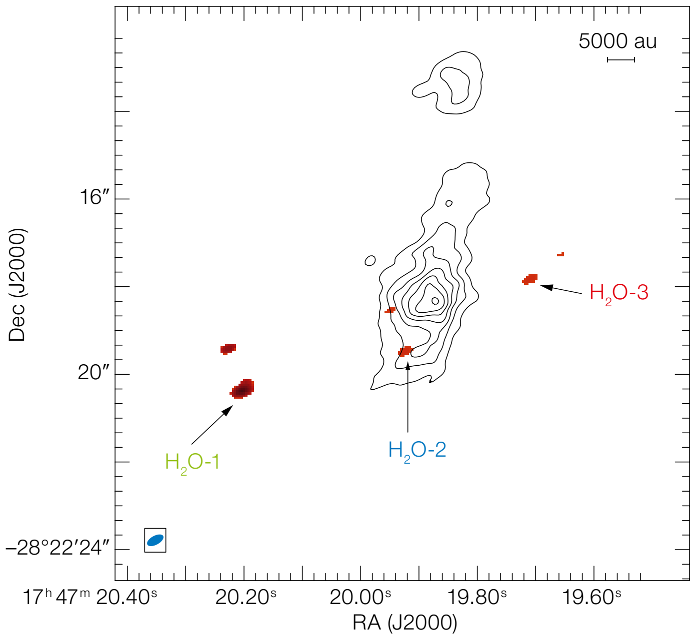


Figure 2. Superposition of ALMA (black) and APEX (blue) spectra from part of the Band 5 full spectral scan of the Sgr B2 star-forming region (from Baobab Lu, Katharina Immer, Anita Richards, Ana Lopez-Sepulcre, Lydia Moser and Daniel Tafoya). Spatially extended emission from bright lines is suppressed in the interferometric spectrum, while the absorption features against the compact continuum sources and the H_2O maser lines are well matched in the two spectra. In the lower panel, the estimated continuum emission image is shown overlaid with some of the H_2O maser spot emission and spectra.

SV observations

Sgr B2

Sagittarius (Sgr) B2 is a massive and dense high-mass star-forming complex situated at a projected distance of ~ 120 pc from the Galactic Centre. The cloud is well known for its rich chemistry and has been extensively studied with submillimetre telescopes, including APEX and ALMA, with the goal of detecting complex organic molecules and understanding the chemical processes in the dense interstellar medium (for example, Belloche et al., 2013). Sgr B2 had already been observed in Band 5 with APEX SEPIA (Immer et al., 2016) so could provide an ideal comparison with the ALMA data.

The almost complete range of Band 5 was observed with 13 receiver tunings and a hybrid array, consisting of 8–12 12-metre antennas with baselines of up to 1.6 km, with four 7-metre antennas included for some observations. Given the complexity of the source morphology, the limited number of antennas used and the sparse coverage of the (*u*,*v*) plane with the limited set of available baselines, the imaging of this dataset is challenging, and the image fidelity is relatively low compared to typical ALMA observations. The importance of this SV observation was to provide a complete spectral scan of the whole of Band 5 to test the ability to calibrate across the full band in varying atmospheric absorption conditions.

Figure 2 (upper) shows the ALMA and SEPIA spectra overlaid. A wealth of molecular lines is revealed at a velocity resolution of ~1 km s^{-1}, many of which remain to be identified. For part of the observing time the H_2O transmission was low enough to map some water maser emission clumps associated with the massive star formation (Figure 2, lower). The comparison between the APEX and ALMA spectra shows that the brightest lines, associated with more extended emission, are not fully recovered in the interferometric spectrum, because of the aforementioned limitations in the (*u*,*v*) coverage. The compact structures, including all absorption lines against the bright and compact continuum emission, are well matched.

VY CMa

VY Canis Majoris is a red supergiant star of spectral type M5 in a phase of strong mass loss (< 10^{-4} $M_{\odot}$ yr^{-1}). The star is very extended and of high luminosity (~ 3 × 10^5 $L_{\odot}$, for a distance of 1.2 kpc) and the 25–32 $M_{\odot}$ progenitor star is now evolving blueward in the Hertzsprung-Russell diagram (Wittkowski et al., 2012).

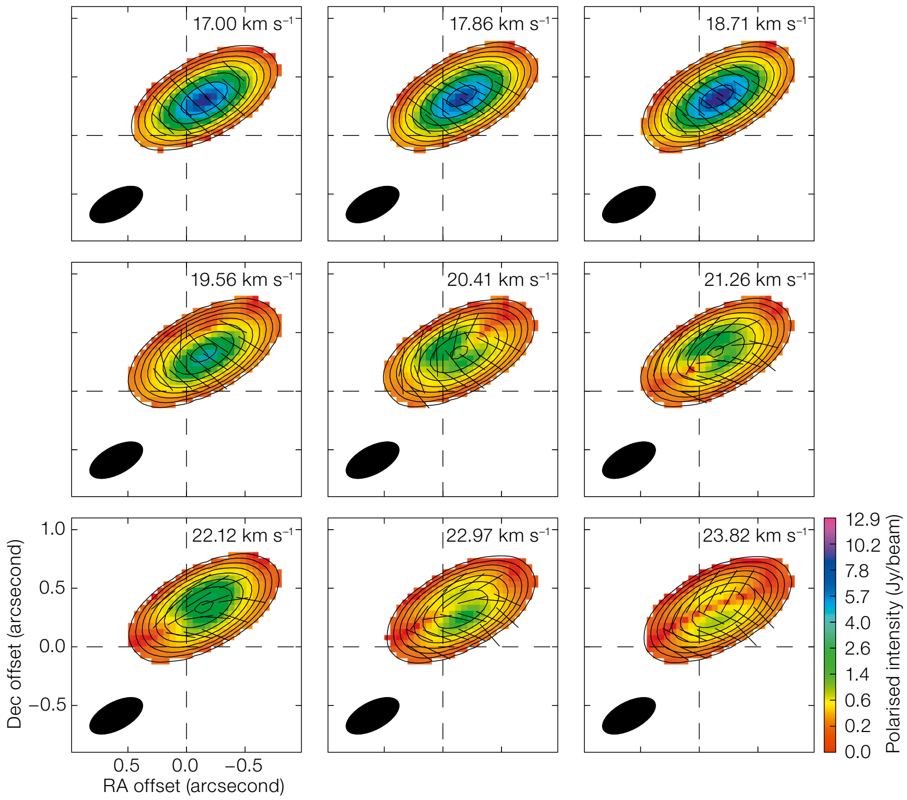


Figure 3. Spatially resolved velocity slices of the polarisation vectors in VY CMa superimposed on the polarised intensity image for the SiO maser line around 172.5GHz (from a report released with the ALMA data by Iván Martí-Vidal, Wouter Vlemmings and Tobia Carozzi[2]).

It is expected to eventually explode as a core collapse supernova. It has a complex, extended and outflowing dusty and molecular envelope with H_2O and SiO maser emission detected. The SV observations concentrated on measuring the polarisation in continuum and in the H_2O and SiO maser lines (at 183.3 and around 172.5 GHz, respectively). Fifteen ALMA 12-metre antennas and baselines up to 0.48 km were employed and again there were previous APEX observations with which to compare.

This is the first ALMA SV line polarisation dataset obtained and it was used to check the observation and data reduction procedures for this important observing mode, expected to be used for a variety of science cases and astronomical targets. For supergiant stars like VY CMa, it is anticipated that ALMA line polarisation observations will make transformational advances in understanding stellar magnetic field strength and morphology. This may be important for understanding the mass-loss process from these stars, and the structures observable in the circumstellar envelopes. For lower mass stars, such as those on the Asymptotic Giant Branch, ALMA polarisation observations may additionally provide information on the processes leading to planetary nebulae. In the SV dataset, one of the results is that both the continuum and the SiO and H_2O maser emission towards VY CMa are confirmed to be polarised. Maps of the polarisarisation vectors in SiO maser emission are shown in Figure 3.

Arp220

Arp 220 is the closest (at ~ 78 Mpc) ultraluminous infrared galaxy (~ 4 × 10^{12} $L_{\odot}$) representing an ongoing merger. The core has a very high star formation rate and is a rich source of molecular emission. It has been extensively observed at mm and radio wavelengths and displays H_2O maser emission (at 22, 183 and 325 GHz). The 183 GHz water emission was previously observed using the Institut de Radioastronomie Millimétrique (IRAM) 30-metre telescope and APEX.

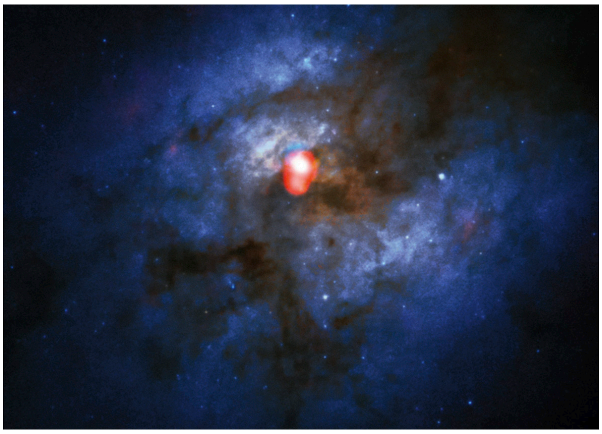


Figure 4. Composite sub-mm/optical image of Arp 220 showing the Band 5 emission including HCN, CS, SiO and H_2O from the SV observation of the nuclear star forming region (in red) on top of an image from the NASA/ESA Hubble Space Telescope (blue/green). West is up and north left in this composite. The ALMA image was provided by Sebastien Muller and Sabine König. See Release eso1645 for details.

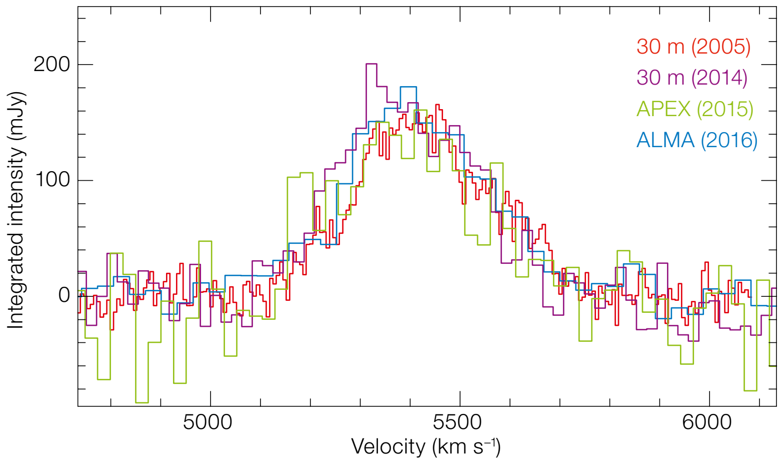


Figure 5. The H_2O 183.3 GHz line as observed with the IRAM 30-metre telescope in 2005 (Cernicharo et al., 2005) and 2014, with SEPIA on APEX in 2015 (Galametz et al., 2016) and with ALMA in 2016 (König et al., 2017), displaying the relative constancy of the line profile. From König et al. (2017).

Arp 220 has a double nucleus with the peaks of molecular emission separated by 1.1 arcseconds and the Band 5 observations (beam size 0.7 arcseconds) resolved the H_2O emission into the east and west nuclei (see Figure 4). The western component is brighter while the eastern one has a steep velocity gradient. König et al. (2017) compared the H_2O 183.3 GHz line profile with previous observations using the IRAM 30-metre telescope (Cernicharo et al., 2006) and the SEPIA Band 5 receiver on APEX (Galametz et al., 2016). The line profiles are remarkably similar over a period of > 10 years (see Figure 5). This is perhaps unexpected for maser lines, which characteristically change in strength on timescales of months to years. It is therefore suggested that the H_2O profile represents the emission of many unresolved maser spots within the star-forming complex, so that, while individual masers vary, the aggregate profile does not (König et al., 2017).

Data Release

After the initial data collection and assessment, an intensive workshop was held at Chalmers University, Sweden in October 2016 where participants from across the European ALMA Regional Centre (ARC) worked to solve the calibration problems and finalise the calibration and data release products. On 7 December 2016, the Band 5 raw data, calibrated data and reference images, as well as the calibration scripts and detailed documentation explaining the imaging and calibration procedures, were publicly released on the ALMA SV page[1]. At the Band 5 Workshop in February 2017 (see the following article by de Breuck et al., p. 11), analysis and results from these SV observations were presented and discussed.

These SV observations allowed us to validate and release the science operations procedures to obtain successful ALMA Band 5 observations and resulted in the inclusion of Band 5 as a standard mode in the Cycle 5 call for proposals. The datasets are now being used by astronomers in the community to perform scientific analysis and to prepare for their own observing proposals in the forthcoming ALMA Cycle.

Acknowledgements

Obtaining, validating and releasing the ALMA Band 5 SV data was a team effort involving a large number of people at ESO, the EU ARC Network and the Joint ALMA Observatory (JAO). We thank for their key contributions Tobia Carozzi, Simon Casey, Sabine König, Ana Lopez-Sepulcre, Matthias Maercker, Iván Martí-Vidal, Lydia Moser, Sebastien Muller, Anita Richards, Daniel Tafoya, Wouter Vlemmings, Allison Man, John Carpenter, Paulo Cortes, Diego Garcia, Itziar de Gregorio, Antonio Hales, Violette Impellizzeri, Andres Felipe Perez Sanchez, Neil Phillips, Adele Plunkett, Giorgio Siringo, Satoko Takahashi, the JAO Extension and Optimisation of Capabilities (EOC) Team and the JAO Department of Science Operations (DSO) team members who performed the observations. The fantastic Band 5 receivers we have on ALMA would have not been possible without the preproduction effort funded by the EU FP6 at GARD and RAL, and without the cartridge optimisation and production effort at GARD, NOVA, and NRAO, and the Integration and Verification team on site in Chile supported by ESO, with contributions from the National Astronomical Observatory of Japan (NAOJ). We thank Jeremy Walsh for his work on this article.

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Links

[1] ALMA SV Band 5 data release: targets: https://almascience.eso.org/alma-data/science-verification
[2] Band 5 Polarisation Calibration Information: https://almascience.eso.org/almadata/sciver/VYCMaBand5/VYCMa_Band5_PolCalibrationInformation.pdf