Science Verification Datasets on the ALMA Science Portal

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We summarise the ALMA Science Verification datasets released over the past year, the ALMA capabilities that were demonstrated and how the ALMA results compare with previous observations. Some new scientific results that have been produced using the public Science Verification datasets are summarised and an overview of the capabilities that will be demonstrated with future Science Verification observations is provided.

ALMA Science Verification (SV) is the process used to demonstrate that ALMA is capable of producing data of the quality required for scientific analysis. The SV process is part of the Commissioning and Science Verification (CSV) effort within ALMA and is carried out by the ALMA CSV team with data reduction support from the ALMA Regional Centres. ALMA Science Verification data are made publicly available on the ALMA Science Portal as soon as satisfactory observations and data reduction are achieved. The community is encouraged to use these datasets to familiarise themselves with the ALMA capabilities and data reduction procedures, as well as to publish interesting new science results that they may obtain from analysing the datasets. Detailed information on the ALMA SV process can be found on the Science Portal SV page[1].

About a year ago, we provided an initial account of the status of ALMA SV in Testi & Zwaan (2011). At that time, few initial datasets demonstrating single-field interferometry with a small set of antennas had been fully processed and released. Now, a broad range of datasets is available on the ALMA Science Portal[2]. The datasets cover a variety of science targets and ALMA modes, including mosaics, high frequency observing and spectral survey. All data releases are accompanied by data reduction scripts and a set of sample images or datacubes. For some of the SV data releases, detailed data reduction guides have been made available to explain the data reduction procedures for the various modes step by step. Here, we illustrate some of the released datasets and invite interested users to visit the Science Portal webpages to download the datasets in which they may be interested.

Molecular gas in galaxies

The radio-quiet quasar BR1202-0725, at a redshift z = 4.69, was one of the earliest detections of molecular gas at very high redshift (z > 2). Previous interferometric observations detected CO(5-4) emission and dust continuum in two compact sources separated by ~ 4 arcseconds (Omont, 1996). This turned out not to be due to gravitational lensing, and instead the southern component has been established to be associated with a quasar, whilst the northern component is an optically faint submillimetre galaxy (SMG). In ALMA Band 7 SV data on this field, [C II] 158 μm emission is clearly detected from both components. The brightness of [C II] makes this line ideal for tracing the kinematics of galaxies and for identifying possible outflows. The fact that ALMA SV observations detect this line at such high significance in only 25 minutes on-source integration time, using only 17 main array antennas, clearly demonstrates the power of ALMA for the study of line emission from high-redshift objects. A study using these SV data on BR1202-0725 was published by Wagg et al. (2012); see also the article on p. 56.

Centaurus A is a massive elliptical galaxy and is one of the best-studied, as well as the nearest (~ 3.8 Mpc), radio galaxies in the sky. It is characterised by a strong dust lane seen in visible light, oriented along the galaxy minor axis, which harbours ~ $4 \times 10^8 M_\odot$ of molecular gas. This feature, together with the strong radio emission, indicates that Centaurus A is the result of a collision between a giant elliptical galaxy and a smaller gas-rich spiral galaxy. High spectral resolution ALMA SV data were taken in Band 6 in order to map the extended CO(2-1) emission along the dust lane. Previously, the inner one square arcminute was mapped in the CO(2-1) line by Espada et al. (2009) using the Submillimeter Array (SMA). With ALMA, a large mosaic of pointings was used to map the three-dimensional structure of the gas disc. The CO(2-1) velocity field overlaid on a near-infrared image produced by the NTT is shown in the figure on p. 58.

Another large mosaic was taken in Band 3 to map the CO(1-0) gas in the grand-design, nearly face-on spiral galaxy M100 in the Virgo cluster, at a distance of ~ 16 Mpc. Molecular gas in this galaxy is abundant in the centre and along the spiral arms. The entire gas disc was previously mapped at 6-arcsecond resolution using the Berkeley–Illinois–Maryland Association (BIMA) millimetre interferometer (Helfer et al., 2003). The ALMA SV observations consisted of 47 pointings and cover a region of 5 by 5 arcminutes, with an angular resolution of 3 arcseconds. The CO map recovers all the structures seen by Helfer et al. (2003). Furthermore, ALMA detects continuum emission at the centre of the galaxy, which was not found in previous observations. Figure 1 shows the impressive spiral structure seen in CO by ALMA.

The Galactic Centre

The Galactic Centre, Sagittarius A* (Sgr A*), is a very interesting ALMA target for the purpose of studying the interaction between a supermassive black hole and its surrounding environment. ALMA SV data were taken towards Sgr A* both in Band 3 and Band 6 with the aim of imaging the hydrogen recombination line emission. The Band 6 data were taken in a seven-point mosaic, while the Band 3 observations consisted of a single pointing. The mini-spiral structure is clearly visible in both recombination line maps (Figure 2), and these maps agree very well with the Combined Array for Research in Millimeter-wave Astronomy (CARMA; H41α; Shukla et al., 2004) and SMA (H30α; Zhao et al., 2011) observations.

Star-forming regions

The study of protoplanetary discs is one of the main science goals of ALMA and

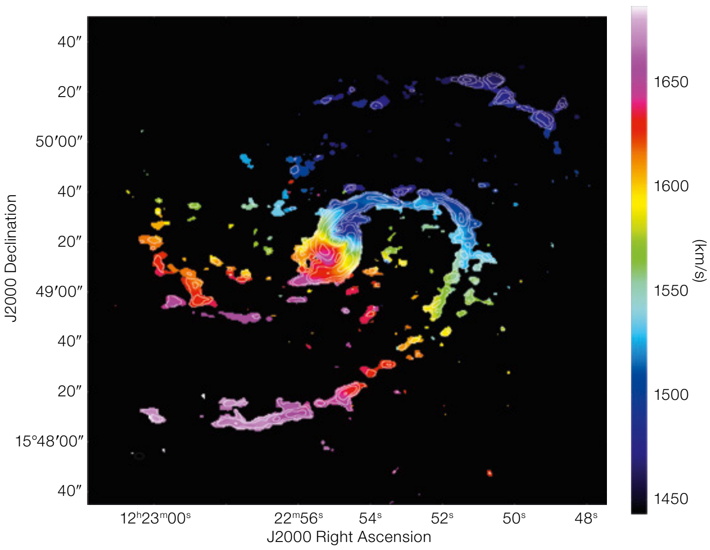

Figure 1. Intensity-weighted CO(1-0) velocity field of the grand-design spiral galaxy M100, with total intensity contours overlaid.

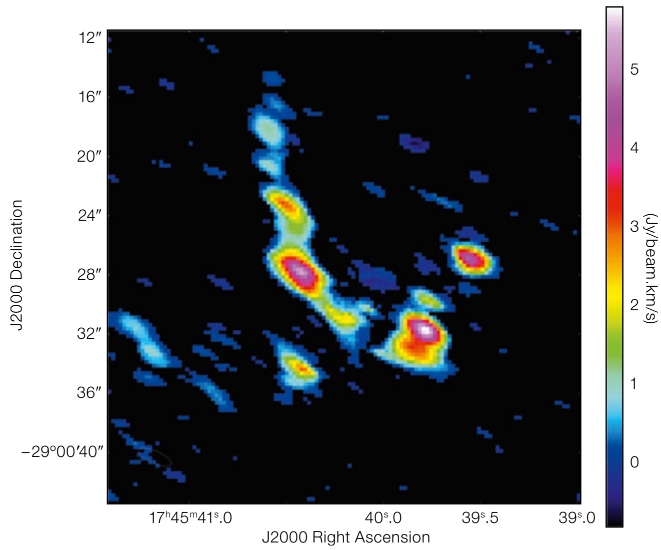

Figure 2. Hydrogen recombination line emission toward SgrA*. The map shows the integrated emission map of the H30α line seen in the inner 30 square arcsecond region of the Galactic Centre.

we had foreseen from the beginning a large number of external users wishing to obtain data on these objects. SV data on two very well-known protoplanetary discs — TW Hya and HD163296 — have been released. TW Hya datasets have already been presented in Testi & Zwaan (2011). HD163296 is a young intermediate-mass star known to host a protoplanetary disc and has been extensively studied at millimetre wavelengths (Mannings & Sargent, 1997; Isella et al., 2007; Qi et al., 2011). SV observations demonstrated one of the basic multi-spectral resolution ALMA capabilities, where lines and continuum can be observed using a combination of four separate spectral windows with different bandwidth and spectral resolution. The released ALMA Band 6 and Band 7 observations cover the continuum at 1.3 and 0.85 mm as well as several emission lines from the isotopes of CO and HCO^+. A few examples are shown in Figure 3.

The low-mass multiple protostar and hot corino IRAS16293 (Ceccarelli et al., 1998; Jorgensen et al., 2011) was observed as part of the SV process of demonstrating very high spectral resolution in a near-line confusion condition in Band 6 and to demonstrate high-frequency observations at Band 9. A small mosaic was performed at Band 9 to properly cover the two main components of the multiple system. This was the first ALMA Band 9 dataset to be publicly released and is accompanied by an extensive data reduction guide. The data have been used by separate groups to study the gas kinematics around the protostars (Pineda et al., 2012) and to detect, for the first time, in a solar-mass protostellar system, a simple form of sugar, glycolaldehyde. This is a key pre-biotic molecule which is found to be present in the disc surrounding the young protostars and infalling onto the planet formation regions of the disc (see Figure 4, Jorgensen et al., 2012 and ESO release eso1234).

The Orion KL hot core was observed in Band 6 as a spectral survey. This region, extensively studied at all wavelengths, including the millimetre and submillimetre, was the obvious choice for such an SV observation, due to the bright and numerous lines and plenty of comparison data to check against (see Zapata et al. [2011] for a recent study). The ALMA SV data surveys the lower two thirds of Band 6, from 214 through 246 GHz, at a spectral resolution of approximately 0.7 km/s. In spite of this being one of the best-studied regions of the sky, the ALMA SV data, even with only the 16 antennas available at the time of the observations, is of such a high quality that five separate studies based on these data have already been published (Fortman et al., 2012; Galvan-Madrid et al., 2012; Hirota et al., 2012; Niederhofer et al., 2012; and Zapata et al., 2012). The results span the range of topics from comparison with laboratory spectra, to the study of water masers, SiO isotopologues in the outflow and radio hydrogen recombination line emission.

Future SV observations

At the time of writing, ALMA SV is now moving into demonstrating the capabilities for Cycle 1 and beyond. The details of the planning and the targets for SV are discussed in detail on the Science Portal SV page[2]. Here, we provide a summary of the areas that will be the subject of SV in the near future and for which external users may expect release of SV data in the coming months.

High angular resolution

The longest baselines for Cycle 1 will be ~ 1 kilometre compared with ~ 400 metres in Cycle 0. It is necessary to verify that coherence is maintained and that the calibration techniques, particularly phase correction, are working properly on these longer baselines. Bright compact sources will be used for this purpose. It is

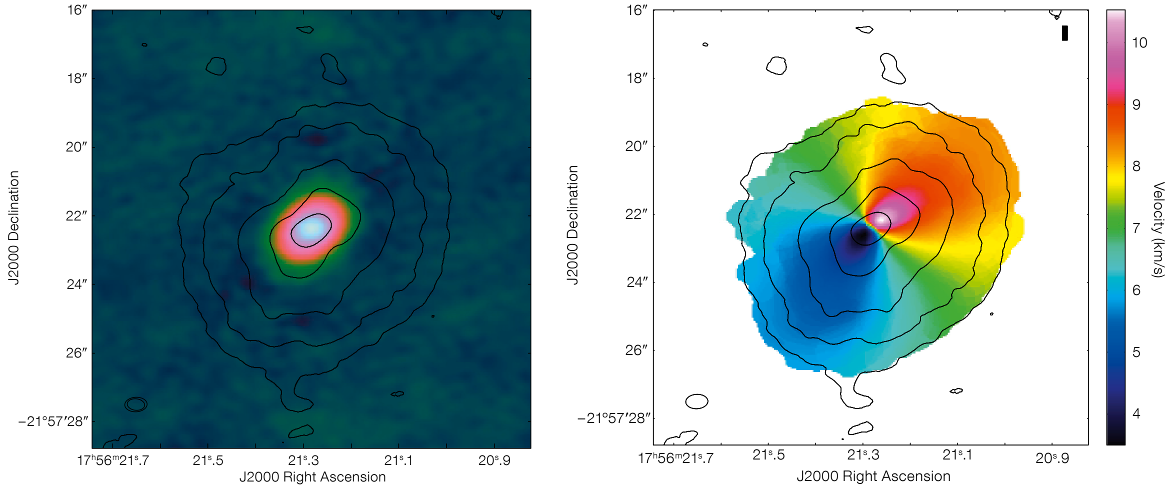

Figure 3. ALMA SV Band 7 data on the protoplanetary disc HD 163296. Left: contours of the CO(3-2) integrated line emission are shown on top of the continuum image. Right: The same CO(3-2) integrated intensity contours are overplotted on the mean velocity map for the same line. In both plots the ellipse in the bottom left corner shows the angular resolution.

expected that ALMA will be in a position to start these observations at the end of 2012.

Ephemeris

One critical goal is also to demonstrate that the special steps required to observe and reduce the data on objects that move in right ascension, declination and radial velocity (Doppler tracking) work correctly in all cases, including both those objects that use the built-in ephemeris, e.g., planets and major moons, and those for which a special ephemeris has to be uploaded, e.g., comets. Dynamical selection of phase calibrators is also required since the objects move on the sky during the possible scheduling period, so this is an additional observatory mode (normally transparent to the users) that an SV project in this area will verify.

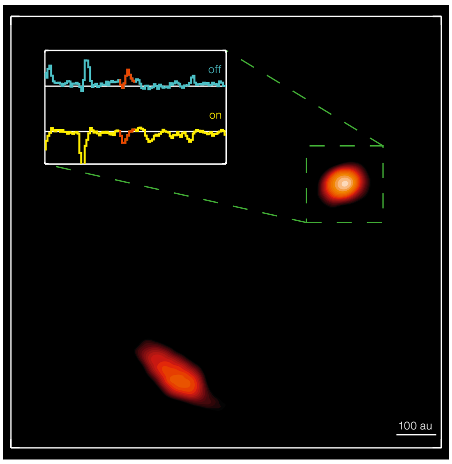

Figure 4. ALMA SV Band 9 690 GHz continuum image of IRAS 16293-2422. Jorgensen et al. (2012) have identified 13 transitions of the simplest sugar, glycolaldehyde, a basic building block of biological molecules, along with many other complex organic molecules, toward the two components of this binary system. The green box around one of the sources in the image measures 270 au on the side; the spatial resolution of the ALMA observations are 0.2 arcseconds (25 au at the distance of the Ophiuchus cloud). The insert shows spectra toward the continuum peak of the source ("on"), where the lines typically are seen as redshifted absorption lines indicative of infall, and toward a position offset from this by about 25 au ("off"), where the lines are seen in emission. One of the 13 identified glycolaldehyde lines is indicated in red.

Spectral modes

Cycle 1 capabilities include cases where the different basebands are used with different spectral modes (time/frequency domain mode; TDM/FDM) or different resolutions. The end-to-end process is more complicated than in Cycle 0, involving changes to the Observing Tool, the control of observations and the data reduction. An important additional capability is the use of spectral averaging, which will make the data volume much smaller in many cases, but again introduces many additional steps in the end-to-end observing process, which need to be verified.

Imaging extended structure

This is the most critical and complicated of the new capabilities for Cycle 1. ALMA has to take well-matched data with the Atacama Compact Array (ACA) and the 12-metre array and then combine these with the correct scaling and weighting into a single cube. When single-dish measurements are made with total power antennas, data have to be taken and reduced in a different way compared to the interferometric data. The three datasets, 12-metre array, ACA and total power, then need to be combined together. Band 9 will be particularly challenging because, in addition to the usual problems of getting good quality data at such high frequencies, the single-dish data requires a special observing technique to separate the signals from the two sidebands.

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Links

[1] ALMA Science Portal SV page: http://wikis.alma.cl/bin/view/ScienceVerification/ScienceVerificationNoticeboard?cover=print
[2] ALMA Science Portal: http://almascience.eso.org/alma-data/science-verification