Science Justification for the ALMA Correlator Upgrade Project (Phase 1)

NAASC Memo # TBD

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The long term development vision for the ALMA project is outlined in the *ALMA 2030 Roadmap* (recently approved by the ALMA Board). This document outlines three key science drivers for future ALMA development: Origins of Galaxies, Origins of Chemical Complexity, and Origins of Planets and identifies extending the receiver bandwidth by at least a factor of two as the highest priority development option. On the path to meeting these future aspirations, the Correlator Upgrade Project (CUP) was conceived that would significantly enhance the spectral capabilities of the ALMA 12-m array correlator and allow for processing of twice the instantaneous bandwidth compared to what is presently possible. The latter will be most relevant when new and / or upgraded receivers are deployed in the future, though Band 6 already produces more bandwidth than can currently be processed. These two aspects of the CUP (spectral capabilities and wider bandwidth) are separated into Phase 1 and Phase 2. Phase 1 is planned to be deployed first (with Phase 2 coming along later) and is the topic of this document. Phase 1 of the CUP will allow up to 8 times more channels per baseband than the current Base Line Correlator (BLC see Lacasse et al. 2017 compared to Escoffier et al. 2006). Phase 1 will thus allow for **both** higher spectral resolution than currently possible, and also greater bandwidth for cases where the total bandwidth must currently be sacrificed in order to obtain the required spectral resolution. There are essentially three broad types of science use cases (SCs) that will want to take advantage of the expanded capabilities of the Phase 1 CUP. In the following sections we describe these three broad use cases and then give some specific examples from current or past ALMA projects that could significantly benefit from the Phase 1 CUP.

SC-1: ULTRA HIGH SPECTRAL RESOLUTION -- Projects that require "ultra-high" spectral resolution (< 0.05 km/s) at the lower ALMA bands that cannot currently be achieved at all.

The original science requirement for the finest ALMA spectral resolution is 0.01 km/s at 100 GHz [ALMA-90.00.00.00-001-A-SPE, #30, Wootten & Wilson (2006)]. Presently, the narrowest available channel width (dual polarization) on the BL correlator is 0.0153 MHz[1], which is equivalent to 0.092 km/s at 100 GHz in terms of spectral resolution (assuming the default of online Hanning smoothing). Therefore, this requirement can only presently be met for frequencies above 450 GHz and only with single polarization (i.e. doubling the observing time from a sensitivity point of view). It is also notable that the best current spectral resolution comes at the cost of a very narrow bandwidth -- only 62.5 MHz, a situation that will also be improved by the CUP, see SC-2.

Examples of science use cases that require "ultra-high" spectral resolution include measuring infall signatures (observed in absorption) toward the cold molecular envelopes of protostars (see for example Oya et al. 2018), and measuring subtle deviations from Keplerian rotation including signatures of Keplerian sheer, vertical disk structure, and sub-Keplerian motions toward the mid-plane of protoplanetary disks. These kinematic signatures can be as small as 10 m/s (see for example Teague et al. 2016 and references therein, also see Figure 1). These types of experiments can only be done in the lower bands (< Band 7) in order to avoid significant attenuation by the high dust continuum opacity that is present at the higher frequencies, and to access molecular lines that best trace cold gas (i.e. lower J transitions). Thus, the current correlator capabilities effectively prevent this kind of science which is critical to understanding the origin of stars and planets. Although of likely high science impact, the total number of these types of projects per Cycle is likely to be relatively small.

[1] A dual polarization BL Correlator mode with two times higher spectral resolution is possible, but to date it has not been implemented because it requires the commissioning of Twice Nyquist sampling for which, heretofore, there has not been correlator software effort available, and the requisite halving of the bandwidth to only 31.25 MHz would make calibration very challenging.

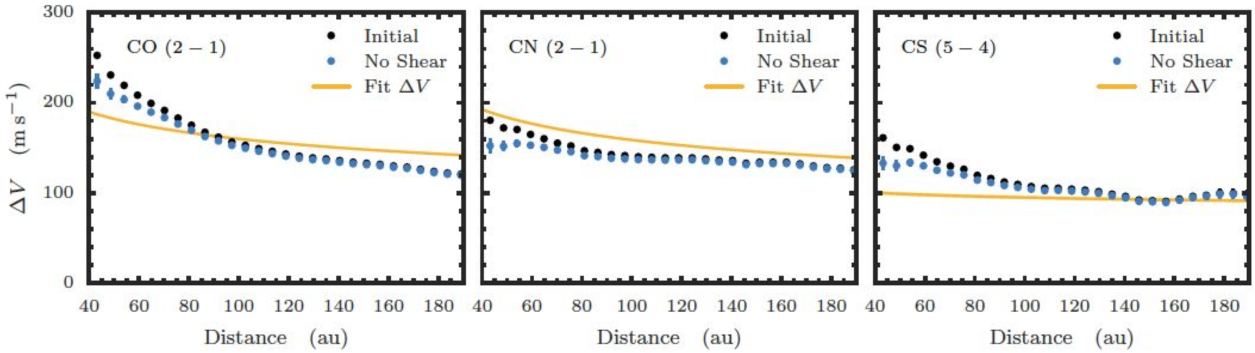

Figure 1: - ALMA observation of the TW Hydrae protoplanetary disk trying to discern subtle but dynamically important kinematic variations in the linewidth as a function of distance from the protostar -- note the vertical axis is in meters/second (2013.1.00387.S, Teague et al. 2016). These data used a spectral resolution of 0.04 km/s, while the Phase 1 CUP would be able to achieve 4x finer spectral resolution with a 12.2% improvement in spectral sensitivity (see SC-3).

SC-2: INCREASED SPECTRAL GRASP -- Projects that require moderate to high spectral resolution that can only presently be achieved by sacrificing bandwidth.

The loss of bandwidth can be detrimental in two ways:

1. The vast majority of ALMA spectral line projects also have a significant continuum component to the science goal. Indeed, in many cases, successful analysis and modeling of the spectral line emission is predicated on accurate knowledge of the continuum properties (relative morphology, brightness temperature, and optical depth to name a few). Systematic effects (relative flux scale, *uv* coverage, etc.) are minimized when the continuum and line emission are observed simultaneously. But the loss in potential continuum sensitivity scales as 1/sqrt(BW). Even for projects that in of themselves do not have a continuum component, the calibration will be improved by increased observing bandwidth.
2. Beyond the loss of continuum sensitivity that results from sacrificing bandwidth, the concurrent loss of spectral coverage is also detrimental for line-rich sources. Studies of line-rich sources depend upon detecting a wide range of transitions from a variety of molecules for successful analysis. The loss of spectral coverage also dramatically increases the time required to do spectral scans of line-rich sources. A related effect in line-rich sources is that

high spectral resolution is required to properly measure the continuum among the lines, which currently limits the total continuum sensitivity below band 7.

Projects affected by the need to sacrifice bandwidth for spectral resolution include most Galactic observations of stars and star forming regions at Band 7 and lower which typically require spectral resolution of 0.1 to 1 km/s. The number of projects that used less than the full bandwidth in Cycle 5 to achieve higher spectral resolution is relatively large: 30% (see the CUP Data Rate Impact Memo, ALMA-60.00.00.00-0148-B-MEM).

Presently for ALMA Bands 6 and below, it is impossible to achieve even moderately high (<1 km/s) spectral resolution without sacrificing continuum bandwidth. For example, at 230 GHz (CO 2--1) and 1875 GHz of bandwidth, the best spectral resolution possible is 1.23 km/s (using the native channel width of 0.488 MHz with online Hanning smoothing). If the correlator is not improved, then the new Band 1 receiver at 40 GHz will have a best spectral resolution of 7.3 km/s at full bandwidth (dual polarization), which will severely limit the study of the molecular gas in the Milky Way and even in nearby galaxies! An example of how greater spectral grasp can aid in detecting chemically important lines is shown in Figure 2.

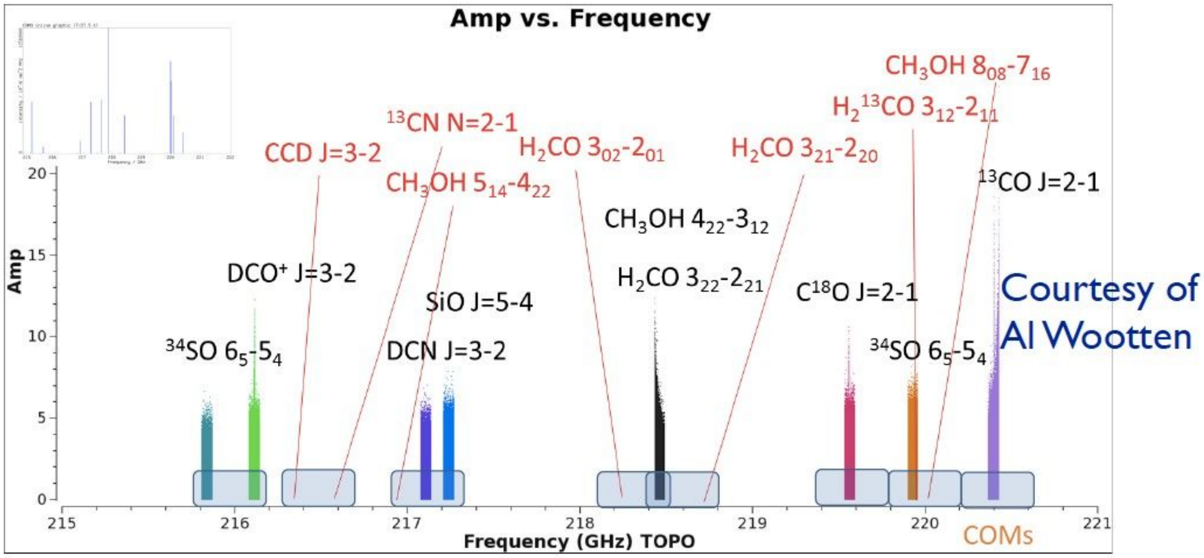

Figure 2: - Typical current Band 6 ALMA spectral setup for one sideband toward a cold starless core (Project 2015.1.00025.S Barnard 1b, Marcelino et al. 2018, submitted). The observed 62.5 MHz spectral windows are shown by colored regions with observed transitions labeled in black. The greater spectral coverage (250 MHz per spw) available with the Phase 1 CUP is shown by the light blue semi-transparent boxes (Table 3a, mode 46 of the Correlator Upgrade Specifications Document). Many more chemically important lines (red) can be covered with the upgraded correlator capabilities, the continuum sensitivity is improved by about a factor of 2, the spectral sensitivity is increased by the use of 4x4-bit sampling (see SC-3), and the spectral resolution will be better by a factor of 2.

Another example of the need for greater spectral grasp at high spectral resolution is the ALMA-PILS Survey of the IRAS 16293-2422 protostars at Band 7 from 329.15 to 362.9 GHz (2013.1.00278.S, Jørgensen et al. 2016). These data were taken with a spectral resolution of 0.244 MHz (0.2 km/s) and 4 x 468 MHz bandwidth for each of 18 spectral tunings (see Figure 3). Post-CUP this survey would have taken only ~6 tunings and only used about ⅓ the time of the original survey (not accounting for increased number of antennas since Cycle 3). This is important because protostars can differ dramatically in their dominant chemistry and the reasons for this variation are currently poorly understood (possibilities include luminosity, evolutionary state, primordial environment, etc), but spectral scans like the PILS survey are currently prohibitively expensive to carry out for a representative sample.

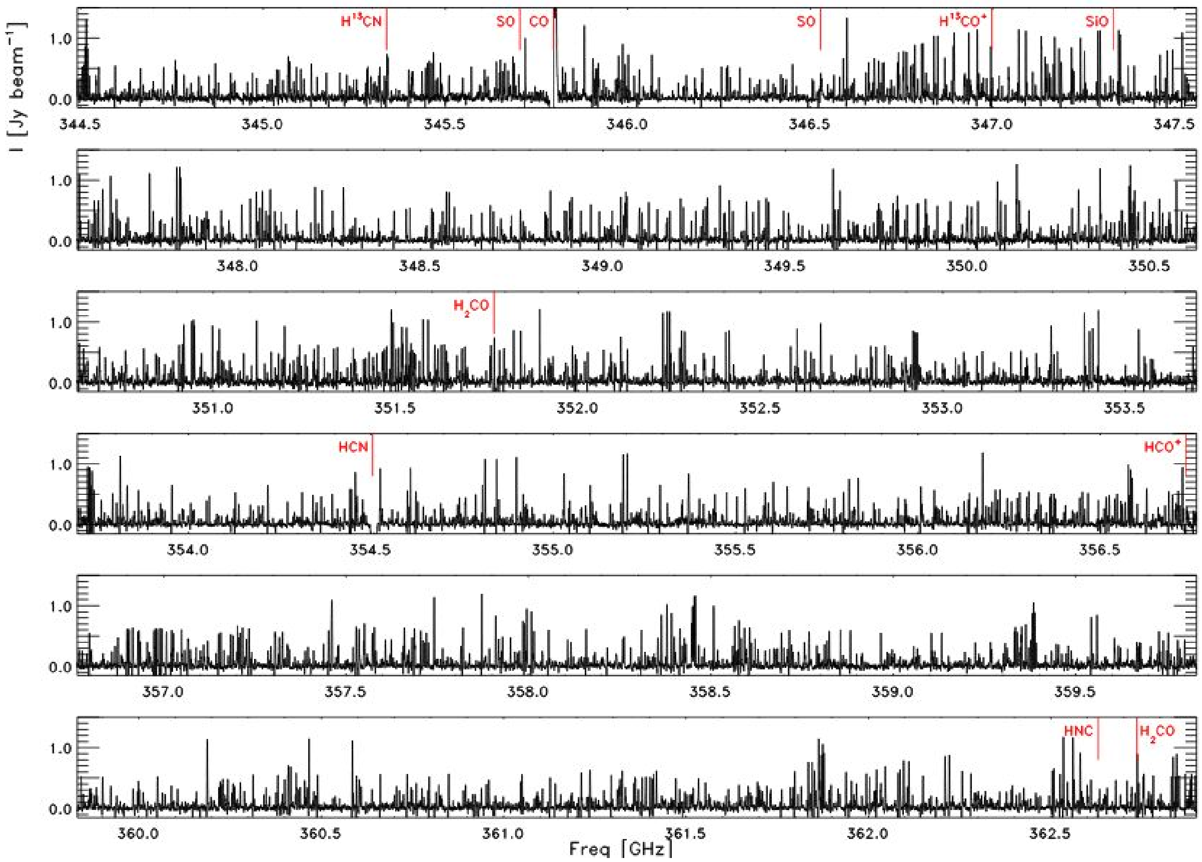

Figure 3: -- Spectra from about ½ the spectral region covered by the ALMA-PILS survey toward the protostars in IRAS 16293-2422 (Jørgensen et al. 2016). Due to the high spectral resolution requirements of this project (0.2 km/s) only 1875 MHz of bandwidth could be used per tuning with the Baseline Correlator. After the phase 1 CUP, which will allow this spectral resolution with 4x higher bandwidth, this survey could be done in less than 1/3 the time.

SC-3: IMPROVED SPECTRAL SENSITIVITY -- Projects that require high spectral line sensitivity at moderate to high spectral resolution that can afford to sacrifice continuum sensitivity and spectral coverage (i.e. bandwidth).

The Phase 1 CUP can offer increased spectral sensitivity by 12.2% (0.9881 vs. 0.8810) by using 4-bit x 4-bit correlation instead of the BL correlator default of 2-bit x 2-bit (see rows 2 and 4 of Table 2 in Ojeda 2017). *This improvement would be equivalent to adding 6 antennas to a 48-antenna array*[2]. The current BL correlator is

[2] Sensitivity improvement scales as the square root of the number of correlated baselines, so adding 6 antennas yields: (54*53/2.)**0.5 / (48*47/2.)**0.5 = 1.126 (Eq. 7-64 of Crane and Napier 1989)

also capable of this mode, but to date it has not been implemented (ICT-155 and ICT-11225), in large part because the resulting loss in bandwidth (a factor of 2) and spectral resolution (another factor of 2) is unlikely to be a very popular mode with the current correlator's limited spectral resolution capabilities (see Escoffier et al. 2006). With the Phase 1 CUP, the 4-bit x 4-bit correlation option is significantly more appealing because one can still have up to 8x better spectral resolution than the BL correlator operating with 4-bit x 4-bit correlation, and 4x better than the BL correlator can do with 2-bit x 2-bit correlation, along with a gain of 12.2% in spectral sensitivity (the factor of 2 loss in bandwidth is common to both correlators, for a 30% decrease in continuum sensitivity).

Science Use Cases that would employ this mode include projects with a few key spectral lines (so that spectral coverage is not a priority) that require moderate to high spectral resolution for which the best possible continuum sensitivity is not needed. Examples include low mass protoplanetary disks for which the continuum is bright but spectral line detection, including organic and prebiotic molecules is challenging, high fidelity imaging of molecular gas in nearby galaxies, and the detection of molecular gas from the first galaxies at high redshift (when the redshift is already known such that full bandwidth is not required). All three of the preceding examples would gain 12.2% in spectral sensitivity from using the 4-bit x 4-bit mode (assuming same observing time, number of antennas etc).

An additional area where the 4-bit x 4-bit mode can make an important impact is to use less observing time for a given sensitivity requirement. An example of such a use case is the Cycle 5 Large program 2017.1.00886.L (PI: E. Schinnerer) which seeks to observe the molecular gas in 80 massive star-forming galaxies within 17 Mpc with 1" resolution (see example galaxies in Figure 4). The 12m-array portion of this study requires 75 hours of observing time. Using Phase 1 of the CUP, provided that a ~25% reduction in continuum sensitivity is acceptable, the 12m-array portion of this project could be executed in 66 hours -- opening time for more science throughput on the telescope.

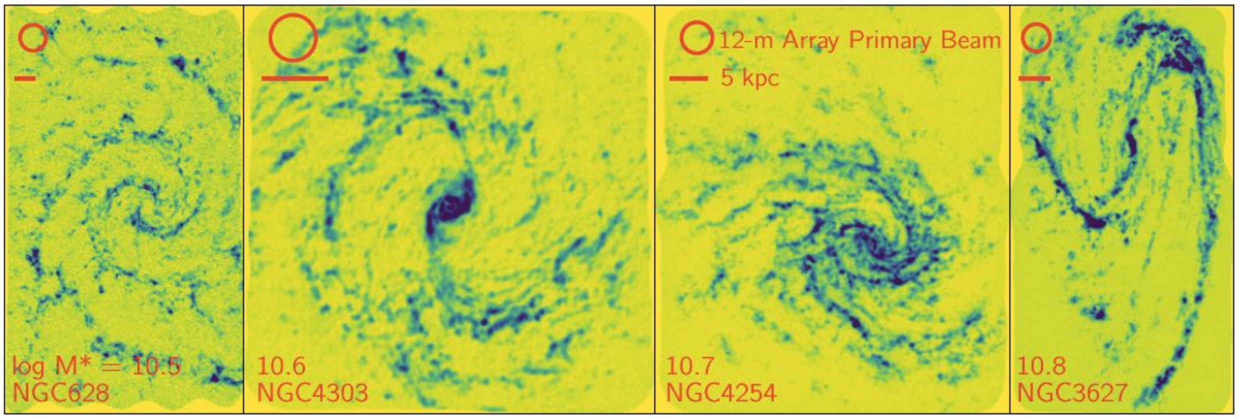

Figure 4: -- Examples of the kind of high fidelity CO(2-1) molecular gas images of galaxies in the local universe that will be forthcoming from the Cycle 5 Large program 2017.1.00886.L (PI: E. Schinnerer) and could benefit from the improved spectral sensitivity afforded by 4 bit x 4 bit sampling.

In summary, the Phase 1 CUP will bring about science benefits for many different kinds of projects including access to unprecedented "ultra high" spectral resolution, access to full bandwidth for moderate to high spectral resolution needs -- increasing the spectral grasp and continuum sensitivity, and providing access to improved spectral sensitivity (or reduced observing time) when bandwidth is not a priority. In the Correlator Data Rate Implications Memo (ALMA-60.00.00.00-0148-B-MEM), we estimated from the spectral properties of approved Cycle 5 projects that up to 49% of SBs (54% by observing time) might want to use some upgraded aspect of the Phase 1 CUP, with 36% of SBs being quite likely to use upgraded capabilities. Thus, we expect the Phase 1 CUP to yield new/improved science opportunities to a significant fraction of the ALMA user community.

References

Jørgensen, J. K., van der Wiel, M. H. D., Coutens, A., et al. 2016, A&A, 595, A117
Oya, Y., Moriwaki, K., Onishi, S., et al. 2018, arXiv:1801.04174
Teague, R., Guilloteau, S., Semenov, D., et al. 2016, A&A, 592, A49