Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Expanded Maser Science Opportunities with the ALMA Wideband Sensitivity Upgrade

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Abstract. The ALMA Project is embarking on a partner-wide initiative to at least double, and ultimately quadruple the correlated bandwidth of ALMA by @2030. This initiative is called the ALMA Wideband Sensitivity Upgrade (WSU). In this contribution, I briefly describe the main aspects of the upgrade and status. Then I provide several examples of how the WSU will enhance (sub)millimeter maser science by affording the ability to observe more diagnostic maser transitions (and thermal lines) with a single observation.

Keywords. Radio observatories, Radio interferometers, Astrophysical masers, Interstellar molecules

1. Introduction

Consistent with the ALMA Development Roadmap (Carpenter *et al.* 2020), the ALMA Partnership has selected the ALMA 2030 Wideband Sensitivity Upgrade (WSU) as the highest priority development initiative for the coming decade. The primary goal of the WSU is to increase the system bandwidth by at least a factor of 2x, with a goal of 4x, with enhanced sensitivity. The WSU construction will involve replacing the majority of the ALMA Signal Chain, from the receivers to the correlator with new or improved technologies (Asayama *et al.* 2020). In order to ease the maintenance burden and cooling costs for a much more powerful correlator, the WSU ALMA Correlator called the "Advanced Technology ALMA Correlator" (ATAC) will be located at the Operations Support Facility (OSF) at 2,900 meters (rather than the Array Operations Site (AOS) at 5,000m). In addition to the ATAC, an upgraded Atacama Compact Array Total Power Spectrometer (ACAS), and the "receiving" portion (DRX) of the digital Data Transmission System (DTS) will also be housed in the new OSF Correlator Room.

The majority of the required hardware projects for the WSU are already underway. In November 2022, the ALMA Board approved the WSU Correlator Project, known as the Advanced Technology ALMA Correlator (ATAC). The ATAC is a collaboration between the National Research Council of Canada (NRC) and the National Radio Astronomy Observatory (NRAO). A project to prototype and demonstrate the WSU DTS was also approved at the November 2022 ALMA Board meeting; this project is a collaboration between National Astronomy Observatory of Japan (NAOJ) and NRAO. Projects are also underway to prototype and demonstrate WSU digitizers (and associated analog Back-end components) with the ability to process 4x bandwidth. The first upgraded wideband receiver bands are also under development: Band 2 (Yagoubov 2019), Band 6v2 (Navarrini *et al.* 2021), and Band 8v2 (Lee *et al.* 2021), led by the European Southern Observatory (ESO), NRAO, and NAOJ, respectively. In order to facilitate the transport of the significantly increased WSU data rate, ESO will lead a WSU infrastructure project to lay new fiber between the AOS and OSF; this project is due to begin in the next

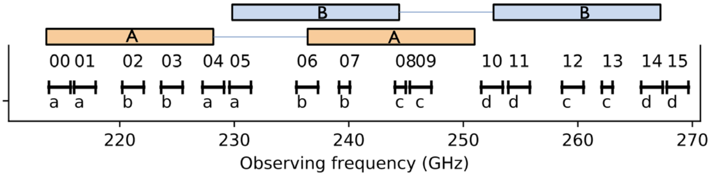

Figure 1. Demonstration of the tuning setup for the ALMA Large Program "ATOMIUM" (2018.1.00659.L, PI: Leen Decin, Decin *et al.* (2022)) that observed 17 Oxygen rich evolved stars, including a wide range of maser transitions. This program employed four spectral tunings (with spectral windows denoted by a, b, c, and d labels) in Band 6 (adapted from Gottlieb *et al.* (2022)). After the WSU, a similar spectral range can be covered by only two tunings (denoted by tunings A and B) and include additional spectral lines throughout the band. During the 2x BW era of the WSU, up to 16 GHz of the receiver's IF bandwidth (assumed to be 14 GHz per sideband for Band 6v2) can be correlated per tuning.

year. Additional efforts are underway in parallel to upgrade the downstream computing subsystems including data processing.

We hope to start science observing with the WSU, with at least 2x the current system bandwidth (16 GHz per polarization) and three wideband receivers (Bands 2, 6v2, and 8v2), before the end of this decade. Additional receiver bands will be upgraded to wideband designs over time (next in line are likely to be Bands 7, 9, and 10), and the correlated bandwidth will eventually be expanded to 4x the current bandwidth (32 GHz per polarization).

The science case and expanded capabilities for the WSU is described in detail in ALMA Memo 621 (Carpenter *et al.* 2023). In this proceeding we focus on a few examples of how the WSU will expand the ability to observe multiple diagnostic maser species simultaneously, or with many fewer tunings than previously. For demonstration purposes, we assume that upgraded WSU receivers will all have an IF bandwidth $= 4 - 18$ GHz in a 2 Sideband configuration (dual polarization); and that the maximum correlated bandwidth is 16 GHz per polarization (consistent with the start of WSU Science Operations). These assumptions are consistent with the WSU goals but the final receiver designs may be somewhat different.

2. Wider Bandwidth = More Maser Science with Less Observing Time

A significant limitation of the current Baseline Correlator used for 12 m-array observations (Escoffier *et al.* 2007) and the ACA spectro-correlator system, used for 7 m-array and total power array observations (Kamazaki *et al.* 2012) is that when high spectral resolution is required, one must give up significant bandwidth, especially in the lower ALMA bands. A key science goal of the WSU is to enable the ability to observe with a spectral resolution as fine as 0.1 km s^{-1} at full correlated bandwidth at any ALMA frequency from 35 to 950 GHz (a requirement that cannot presently be achieved at any ALMA band). This new capability will dramatically affect maser science, since high spectral resolution, especially for star formation masers, is essential.

2.1. *Band 6v2 Example for evolved stars*

The ALMA Cycle 6 Large Program: ATOMIUM (2018.1.00659.L, PI: Leen Decin) observed 17 Oxygen rich evolved stars using 4 distinct Band 6 tunings that spanned from 213.8 to 269.7 GHz with a total bandwidth of 27.19 GHz (see Figure 1). The key science goals were to study both thermal and maser emission lines from a wide range of diagnostic chemical tracers with a spectral resolution of 1.3 km s^{-1} (Gottlieb *et al.*

2022; Baudry *et al.* 2023). With the WSU, during the 2x BW era, a similar frequency range, including almost all the originally targeted maser transitions, can be covered with only two tunings, together covering a total of 32 GHz of correlated bandwidth. Taking into account the sensitivity improvements and fewer tunings, the same survey sensitivity could be accomplished with only 25% of the original observing time, or including 4x more targets. Alternatively, such a survey with same number of targets could be 2x deeper for the same observing time. This example demonstrates that after the WSU spectral scans will be much more efficient. Although it wasn't necessary for the evolved star science of the ATOMIUM survey, the same total bandwidth with two tunings (32 GHz in total) could be achieved for a spectral resolution as fine as 0.1 km s^{-1}.

2.2. *Band 6v2 Example for massive star formation*

A significant limitation of the current Baseline Correlator used for 12 m-array observations (Escoffier *et al.* 2007) and the ACA spectro-correlator system, used for 7 m-array and total power array observations (Kamazaki *et al.* 2012) is that when high spectral resolution is required, one must give up significant bandwidth, especially in the lower ALMA bands. A key science goal of the WSU is to enable the ability to observe with a spectral resolution as fine as 0.1 km s^{-1} at full correlated bandwidth at any ALMA frequency from 35 to 950 GHz (a requirement that cannot presently be achieved at any ALMA band). This new capability will dramatically affect maser science, since high spectral resolution, especially for star formation masers, is essential.

A prime example of the impact that this new WSU capability could have can be demonstrated by considering the follow-up of the recent accretion outburst event discovered toward the massive protostar G359.93-0.03-MM1 (Sugiyama *et al.* 2019; Burns *et al.* 2020; Stecklum *et al.* 2021). In (sub)millimeter follow-up aimed at constraining the expected rise in dust continuum emission, 14 never-before-seen methanol masers, primarily from $v_t = 1$ transitions, were discovered with initial peak emission in the thousands of Jy, declining in one month by factors of 4–7, and by 9 months later declining to near-thermal levels (See Figure 2, Brogan *et al.* 2019a). While a single low angular resolution but wideband observation with the SubMillimeter Array (SMA) detected 14 bright maser transitions from 198 to 360 GHz, higher angular resolution observations with ALMA required substantial observing time, including a total of four tunings (and three bands) to examine only nine of them. Moreover, very high angular resolution (30 mas) observations could only be arranged for one Band 6 tuning that could include only two of the masers (see Brogan 2019b), which revealed that the emission arose from a remarkable ring-structure surrounding the continuum emission and encompassing the 6.7 GHz masers which trace out a spiral arm structure (Burns *et al.* 2023). This lack of spatial coincidence could only be probed for two of the (sub)millimeter $v_t = 1$ maser transitions that are A-type pairs with $E_{upper} = 374$ K. Unfortunately, we will never know if other transitions, including $v_t = 0$ and $v_t = 2$ transitions, and E_{upper} as high as 877 K showed a similar morphology. After the WSU, many more maser transitions (and diagnostic thermal lines) can be included in a single observation – especially critical for time-variable phenomena (see Figure 3). Moreover, even for other kinds of science, the ability to include maser lines in more observations will enable more serendipitous detections, and even improved self-calibration (Brogan *et al.* 2018) in cases where the line signal-to-noise ratio is higher than the continuum.

2.3. *Band 7v2 Example*

(Sub)millimeter water masers and SiO masers (including other isotopologues of these species) are important tracers of a wide range of phenomena from star forming regions

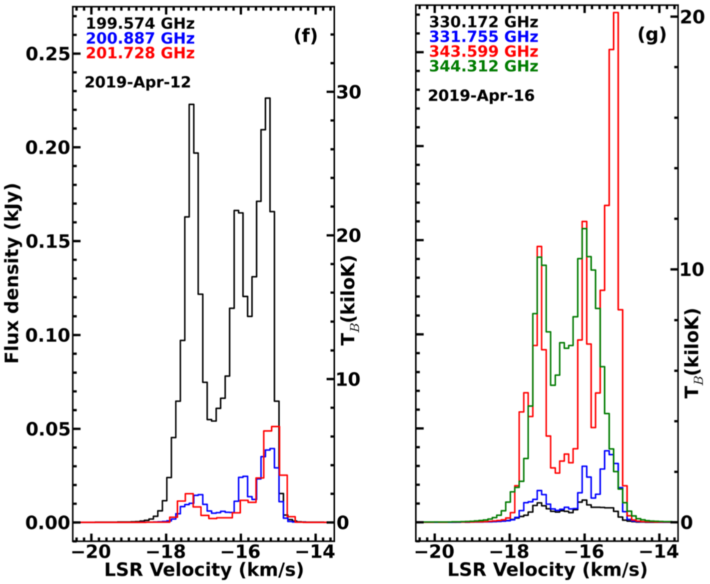

Figure 2. Spectra extracted from cubes obtained by ALMA observations in April 2019 of several newly-discovered torsionally-excited methanol maser transitions toward G358.93-0.03-MM1 (adapted from Brogan *et al.* 2019a). The 330.172 GHz line is the first detection of a maser from the $v_t = 2$ state.

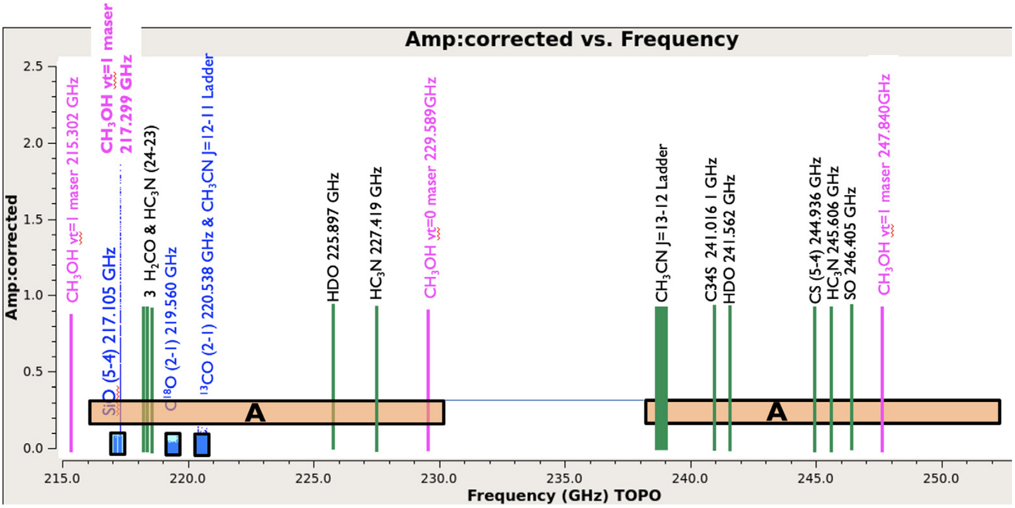

Figure 3. Example of an ALMA Band 6v2 setup (denoted tuning "A") that will be enabled by the WSU that could be used to follow-up future massive protostellar accretion outbursts for both methanol masers and diagnostic thermal transitions. Actual data from the narrow spectral regions shown along the bottom left side of the plot indicate the very limited amount of bandwidth (distributed within 217–221 GHz) that could be employed using the current ALMA system for the high angular and spectral resolution ($\sim 0.1\,\mathrm{km\,s^{-1}}$) follow-up of G358.93-0.03.

and evolved stars in our Milky Way to the nuclear disks of luminous galaxies (see for example Hirota *et al.* 2014; Wittkowski & Paladini 2014; Kameno *et al.* 2023). Band 7 covers two particularly diagnostic water maser transitions at 321 and 325 GHz with E_{lower} of 1846 K and 453 K, respectively (Neufeld & Melnick 1990; Menten *et al.* 1990). Unfortunately, as demonstrated in Figure 4, both of these transitions cannot presently

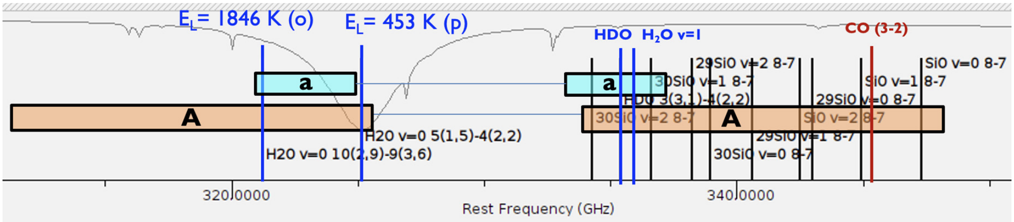

Figure 4. Example of a maser-focused current Band 7 tuning (denoted with "a") and a potential WSU tuning using an upgraded Band 7v2 tuning (denoted with "A"). During the 2x BW era of the WSU, up to 16 GHz of the receiver's IF bandwidth (assumed to be 14 GHz per sideband for Band 7v2) can be correlated per tuning.

Rest Freq (GHz)	Elower (K)	$S_{ij}\,\mu^2$	Target
437.347 (p)	1045	0.32	SF, Star
439.152 (o)	742	1.10	SF, Star
443.018 (o)	1045	0.98	thermal
470.889 (p)	742	0.36	SF, Star
474.689 (p)	488	0.41	Star

Figure 5. Previously detected water maser transitions in Band 8, where (o) or (p) denote whether it is an ortho or para transition. For the Target environment column, SF=Star Formation.

be observed simultaneously with ALMA, as a result there are few spatial comparisons between the two. Similarly, only a few SiO transitions can currently be observed with the same tuning at Band 7, though comparison between them can be used to study different envelope scale heights around evolved stars, as well as, isotopic abundances (see for example, Peng *et al.* 2013). With the 2x BW WSU, both water maser transitions can be observed in a single tuning, as well as a number of additional transitions with diagnostic value. For example, the ^{28}SiO, ^{29}SiO, and ^{30}SiO J=8–7 transitions, from the ν=0, 1, 2, vibrational states along with thermal emission from CO (3-2) and HDO 3(3,1)–4(2,2) can also be included in the same tuning. The ability to observe more diagnostic lines in a single observation will significantly improve the science "throughput" afforded by a single ALMA observation.

2.4. *Band 8v2 Example*

The WSU will also afford new simultaneous water maser tuning opportunities in Band 8. First discovered by Melnick *et al.* (1993), Figure 5 provides the rest frequencies, the energies above ground of the lower state (E_{lower}), the line strengths multiplied by the square dipole moment ($S_{ij}\mu^2$), and the typical environment(s) in which these water masers have been found to date (either "Star Forming" or AGB stars). As shown in Figure 6, presently, only the two lower frequency transitions can be observed simultaneously with ALMA. After the 2x BW WSU, four water transitions, including two ortho- and para- "pairs", can be observed simultaneously. These maser lines are of particular interest because there is evidence that they have a radiative component to their pumping in contrast to, for example 22 GHz water masers, which are thought to be pumped by collisions alone. The diagnostic value of surveying multiple of these water maser transitions was demonstrated using the 12 m telescope of the Atacama Pathfinder Experiment

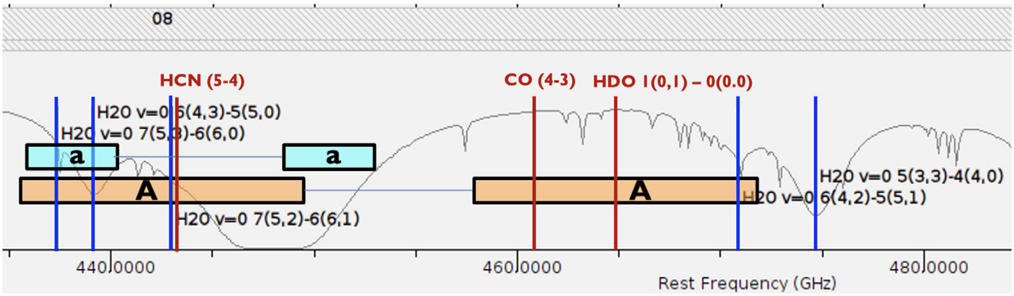

Figure 6. Example of a maser-focused current Band 8 tuning (with sidebands denoted with “a”) and a potential WSU tuning using an upgraded Band 8v2 tuning (width sidebands denoted with “A”). During the 2x BW era of the WSU, up to 16 GHz of the receiver’s IF bandwidth (assumed to be 14 GHz per sideband for Band 8v2) can be correlated per tuning.

(APEX) by Bergman & Humphreys (2020) toward a sample of evolved stars. At the same time, the thermal lines of CO (4-3), HCN (5-4), and HDO 1(0,1)–0(0,0) in Band 8 can also be observed to provide a more complete picture of the physical conditions that masers can provide alone. As demonstrated in NGC 6334 I by McGuire *et al.* (2018), HDO can be a powerful tracer of the thermal water reservoir associated with water masers.

3. Summary

The vision of the ALMA2030 Development Roadmap will begin to be realized with the increase in bandwidth, sensitivity, and spectral grasp that will be provided by the WSU. The new digital signal chain will raise the observing efficiency for all projects, while the increase in instantaneous receiver bandwidth and correlator capacity at high spectral resolution will increase the scientific yield in a variety of ways for many use cases. For maser science in particular, the ability to image multiple maser lines and thermal lines *simultaneously* coupled with more sensitive continuum should revolutionize our view of the formation mechanism of massive protostars. By the end of the decade, the WSU will become operational, including multiple receiver bands with expanded capability. Upgrades of the rest of the receiver bands will follow.

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