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Report on the ESO workshop

The Promises and Challenges of the ALMA Wideband Sensitivity Upgrade

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The Atacama Large Millimeter/submillimeter Array (ALMA) is undergoing the most ambitious project since its inauguration: the Wideband Sensitivity Upgrade (WSU). The WSU will increase the instantaneous bandwidth by as much as a factor of four while retaining full spectral resolution over the entire bandwidth, thus resulting in increases of the spectral scan speed of up to a factor of 50 for the highest spectral resolution. In addition, an upgrade of the full signal chain of ALMA — from the receivers and digitisers all the way through to the correlated data — will result in increases in sensitivity for all observations. However, the increased bandwidth and throughput bring several technical challenges. In June 2024, we organised the first conference at ESO in Garching to inform the ALMA community about all the details of this upgrade. Here we report on the outcome of this meeting.

Motivation

In its first decade, the Atacama Large Millimeter/submillimeter Array (ALMA) has revolutionised our view of the Universe, both near and far (see Díaz Trigo et al., 2024). Serving a very broad range of science topics has been one of the main successes of ALMA, leading to a sustained high demand from the scientific community. Being the most powerful (sub)mm observatory in the world also comes with the responsibility to continuously fulfill the high expectations of the community. While ALMA set new standards in (sub)mm technology during construction, other observatories such as the Northern Extended Millimetre Array (NOEMA) and the Submillimeter Array (SMA) now offer an instantaneous bandwidth coverage wider than ALMA's. Indeed, expanding that bandwidth was set as the top priority of the ALMA2030 roadmap (Carpenter et al., 2020), and the Wideband Sensitivity Upgrade (WSU) is the response to that goal. The WSU2024 conference was the first time the entire ALMA user community was informed in detail of the broad scope of the WSU. While many of the technical upgrades within the WSU are intrinsically linked to each other (for example, digitisers, digital signal transport and correlator), others are relatively independent (for example, receiver upgrades, data reduction software). Therefore, having scientific input from the community to help set the priorities within the WSU project was a second goal of the meeting.

The conference brought together the scientific and technical user communities, while also covering a broad range within these communities. For example, the science topics covered the Sun, the Solar System, protoplanetary discs, stars, astrochemistry, the interstellar medium, nearby and distant galaxies, galaxy clusters, cosmology and special observing modes such as time domain, polarisation and very long baseline interferometry. The technical topics covered the whole ALMA signal chain from receivers and their components, digitisers and correlator, to the impact of the WSU on ALMA operational aspects such as user support, quality control, data processing software tools and the archive. The presentations are available on Zenodo[1].

Interaction between science and technology

Fostering interaction between science and technology during a conference is a challenging task, and has been attempted at several previous meetings, when these different topics were often clearly separated in the programme. Unfortunately, this leads to many participants attending only the session(s) in their own field, which does not stimulate interaction between the groups. We therefore attempted a new structure in the programme[2], mixing technical and scientific talks within the same session. To retain coherence, we did keep a focused technical and scientific topic within each session. Each half-day was then concluded with a one-hour discussion on a topic relevant to both the preceding scientific and technical talks. To further stimulate engagement of the participants, we organised quick online polls using Mentimeter, which also allows online participants to be actively involved. While these polls obviously do not pretend to offer a representative opinion of the whole ALMA user community, they did help to streamline the discussion and to provide some guidance about community priorities for the WSU (see below).

One positive outcome of these interactions between technical and scientific groups was a lively discussion of how ALMA users can help increase the visibility of instrument builders. For example, encouraging astronomers to cite the relevant instrument papers in their scientific papers can help obtain funding for new receiver development. Facilitating access to instrument papers in the SAO Astrophysics Data System, making accessible to users a list of relevant technical papers[3] or updating the ALMA citation policy were discussed in this context.

Wideband and sensitivity upgrades

The overarching goal of the meeting was to present in detail the improvements the WSU will bring to ALMA users. To enable the wider bandwidth and increase the digitisation efficiency, ALMA will first need a completely new signal chain. The signal chain will include new digitisers in all the ALMA antennas, which will allow any intermediate frequency (IF) in the range 2–20 GHz to be covered, providing a flexible system to serve the upgraded receivers. A new digital signal transport system will carry the signal to the Operations Support Facility (OSF), where the Advanced Technology ALMA Correlator (ATAC) will be installed to offer spectral resolutions of 0.1 km s^{-1} or better over the entire correlated bandwidth, so that ALMA users no longer have to sacrifice bandwidth for spectral resolution. Even before upgrading the receivers, the new digitisers and the ATAC will already offer an increase of spectral grasp and a sensitivity improvement of more than 10%.

When combined with ALMA's high spatial resolution, the WSU will allow much more powerful studies of astrochemistry in a wide variety of targets including comets, protoplanetary discs, prestellar cores and (high-mass) protostars, star-forming regions, and nearby galaxies. Several speakers highlighted the formidable

Figure 1. Conference photo.

challenge that awaits them in modelling WSU datasets containing thousands of molecular lines. Results from several ALMA Large Programmes presented at the meeting already gave a first glimpse of what to expect from WSU datasets, showing that we are already at the limit of what astronomers can handle with the current analysis tools. With the WSU, these datasets will increase by at least an order of magnitude. Significant upgrades of the spectral fitting and chemical analysis tools are already starting, and will require the incorporation of machine learning techniques.

The promise of the WSU is to increase the instantaneous bandwidth by at least a factor of two, the goal being a factor of four (i.e., 16 GHz per sideband and per polarisation). Reaching this goal of a factor of four came out as a clear priority from the quick poll of the participants (see Figure 2). The benefits of the broadest possible bandwidth are obvious for spectral line surveys (both Galactic and extragalactic, such as redshift surveys), where broader bandwidth provides not only a commensurate gain in observing time, but also more uniform data over a wide spectral range, thereby increasing their archival value. For sources with a lower density of spectral lines, a broader bandwidth also increases the flexibility in the spectral setup. Several speakers highlighted the importance of such more efficient spectral setups, for example for time-critical or time-intensive observations of variable sources or polarisation measurements, for which the use of subarrays was also suggested as a way to further increase the simultaneous broad bandwidth. The factor of four increase in bandwidth will result in an improvement of the sensitivity and calibration accuracy, which is important for, for example, accurate spectral slope determinations.

While the ATAC ingest has been designed to record up to four times the current bandwidth, reaching this full capacity will require additional hardware investments. Reaching bandwidths of 16 GHz is also a challenge for the receivers being upgraded. Some receiver components such as the optics, corrugated horns and lenses or cryostat entrance windows may not need upgrades, while others such as the cryogenic low-noise amplifiers already have prototypes covering IF bandwidths from 4 to 20 GHz which would meet the WSU requirements. Improving in areas such as the polarisation accuracy may come with a penalty on sensitivity, which could be alleviated by reducing waveguide losses using new fabrication technologies.

The receiver upgrades presented for Bands 6, 7, 8, 9 and 10 are all planning to use silicon-insulator-silicon technology, where the most challenging part is to combine a bandwidth four times broader with tighter requirements on the receiver temperature and sideband rejection. The new Band 2 receiver (extending over the existing Band 3 range) instead uses a low-noise amplifier as the first active component (see Figure 3). Band 2 is both the last of the originally planned ALMA receivers, and also the first receiver that

Figure 2. Results from a quick poll of the conference participants to gauge their main priority for the WSU.

is compatible with the new WSU requirements. As the ongoing installation of the Band 2 production receivers should be completed by the time the ATAC, digitisers and digital signal chain are being installed, Band 2 will be a critical band for the WSU commissioning.

During the discussion sessions of the WSU2024 conference, there was constructive input from ALMA users on the timeline of the upgraded receivers. With the upgrade projects for Bands 6 and 8 already started, the participants expressed a clear preference for Band 7 to be the next priority, consistent with the priorities originally set in the ALMA2030 roadmap. Interestingly, the conference participants appeared to be willing to compromise on the schedule or even forego the last GHz of bandwidth to see this important band upgraded. After band 7, most participants preferred to upgrade band 9 before bands 1, 4+5 and 10.

Impact on ALMA users

As previously mentioned, the increased spectral grasp and bandwidth of ALMA in the WSU era will lead to substantially increased data volumes. While the median increase in the product size is expected to be less than an order of magnitude, some products will be more than three orders of magnitude larger. This will require the replacement of the current ALMA data reduction software, the Common Analysis Software Applications (CASA), by a new suite named the Radio Astronomy Data Processing System (RADPS). The WSU2024 conference also had a session dedicated to collecting new ideas and user requirements for the ALMA archive in the WSU era. It became clear that there is a strong desire to execute more of the processing steps on servers hosting the data, especially for ALMA users who do not have access to powerful computing facilities. In addition, machine learning techniques may help to alleviate the formidable challenges of the WSU data volumes.

A major upgrade like the WSU will not come without some sacrifices by the ALMA users. A mitigation plan to reduce the operational downtime during the upgrade was presented during the meeting. For example, during the commissioning of the initial WSU, the new signal chain will operate in parallel to the existing one. With the diversity of the ALMA user community represented during the WSU2024 conference, it became clear that it is impossible to find a strategy that will satisfy all users. For example, during the most intense WSU commissioning phase, a reduced number of antennas and time will be available for science observations, and some observing modes or configurations may not be offered. The alternative of a prolonged shutdown period, or even skipping a full Cycle, was not considered as attractive by most of the conference participants.

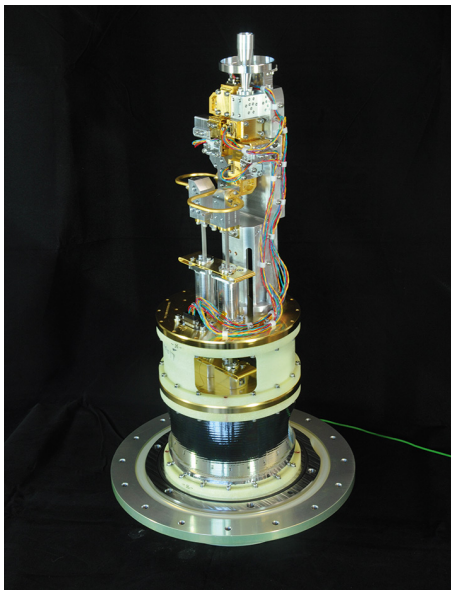

Figure 3. The ESO-led Band 2 receiver will be the first ALMA receiver compatible with the WSU requirements, covering an IF bandwidth from 2 to 18 GHz.

Demographics

The Scientific Organising Committee (SOC) included representatives from all the ALMA Regional Centre nodes as well as ESO ALMA staff and the ALMA observatory scientist. To ensure a representation from a wide range of scientific and technical fields, the SOC invited 27 speakers. Both the SOC and invited speakers had a 44% female participation. The total number of registered participants was 152, of whom 110 attended in person and 42 remotely. The overall female participation percentage was 39%, which could reflect the lower female fraction in technical staff positions. Although the SOC tried to attract more early-career scientists by offering a reduced registration fee, only 28% were students or postdocs. While the meeting primarily targeted European users, 30 participants from North America, East Asia and Chile also participated.

Acknowledgements

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References

Carpenter, J. et al. 2020, arXiv:2001.11076
Díaz Trigo, M. et al. 2024, The Messenger, 193, 57

Links

[1] Zenodo link to the presentations: https://zenodo.org/communities/alma-wsu-2024
[2] Link to workshop page: https://www.eso.org/sci/meetings/2024/wsu.html
[3] ALMA technical handbook: https://almascience.eso.org/proposing/technical-handbook