First announcement of the session:

"ALMA 2030"

Chairpersons Al Wootten and Arielle Moullet (NRAO)

National Radio Science Meeting/URSI

Boulder, Colorado, 4-7 January 2018

Location: Room 265 Time: Friday, January 5 13:20-17:00

webpage: https://nrsmboulder.org/home

Scientific rationale

The Atacama Large Millimeter/submillimeter Array (ALMA)1[1] provides astronomers with transformational spectroscopic sensitivity and imaging accuracy. ALMA's immense collecting area of over 6600m^2 distributed among 66 high precision telescopes are deployable over an extent up to 16 km on the lofty Chajnantor plain at 5000m elevation in the Atacama Desert of northern Chile. High resolution, combined with its current commodious spectral grasp of 8 GHz of spectrum in dual polarizations within its current 84-950 GHz range underlies its capabilities. ALMA, an effort of 22 countries, has recently completed its fifth year of operation. Now the largest element in an even more expansive array with intercontinental baselines, an observing session expected to yield microarcsecond images was recently completed to investigate nearby Black Holes on the scales of their Event Horizons.

ALMA has delivered over 1,000 datasets that have resulted in over 800 refereed publications. ALMA's scientific output has transformed astronomy. The ALMA Development Program sustains the pace of ALMA science through community-led studies and implementation of improvements to ALMA hardware, software, and techniques. During the upcoming decade through 2030, new capabilities will expand ALMA's envelope of exploration even further. ALMA will complete its 35-950 GHz spectral grasp and increase its spectral coverage and sensitivity within that commodious spectral window.

1[1] ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

Session Schedule (Talks are 15+5 with a break at 15:00-15:20)

ALMA2030 Session

Location: Room 265 Time: Friday, January 5 13:20-17:00
Session on ALMA 2030 (Al/Arielle)

SUSTAINING ALMA SCIENCE THROUGH 2030 A NORTH AMERICAN PERSPECTIVE (Wootten)

UPGRADE TO THE 64-ANTENNA ALMA CORRELATOR (Amestica)

THE NEXT GENERATION ALMA CORRELATOR (Weintroub)

THE ALMA PHASING PROJECT PHASE 2: EXTENDING AND ENHANCING THE VLBI SCIENCE CAPABILITIES OF ALMA (Matthews)

THE ALMA BAND 1 RECEIVER: BUILDING THE LOWER FREQUENCY END OF ALMA (Morata)

SUPERCONDUCTING PARAMETRIC AMPLIFIERS: THE NEXT BIG THING IN (SUB)MILLIMETER-WAVE RECEIVERS (Noroozian)

PLANS FOR AN ALMA BAND-6 RECEIVER UPGRADE (Noroozian/Kerr)

DISCOVERY FROM HYPERSPECTRAL ALMA IMAGERY WITH NEUROSCOPE (Merenyi)

FULL-MUELLER MOSAIC IMAGING WITH ALMA (Bhatnagar)

THE SPECTRUM LANDSCAPE: PROSPECTS FOR RADIO ASTRONOMY (Liszt)

Sustaining ALMA Science Through 2030
A North American Perspective

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Abstract— **ALMA will sustain its transformational science through 2030 via an aggressive series of upgrades, for which an overview is provided.**

I. INTRODUCTION

The Atacama Large Millimeter/submillimeter Array (ALMA)[1] provides astronomers with transformational spectroscopic sensitivity and imaging accuracy. ALMA's immense collecting area of over 6600m^2 distributed among 66 high precision telescopes are deployable over an extent up to 16 km on the lofty Chajnantor plain at 5000m elevation in the Atacama Desert of northern Chile. High resolution, combined with its current commodious spectral grasp of 8 GHz of spectrum in dual polarizations within its current 84-950 GHz range underlies its capabilities [1]. ALMA, an effort of 22 countries, has recently completed its fifth year of operation. Now the largest element in an even larger array with intercontinental baselines, an observing session expected to yield microarcsecond images was recently completed to investigate nearby Black Holes on the scales of their Event Horizons. ALMA has delivered over 1,000 datasets that have resulted in over 800 refereed publications. ALMA's scientific output has transformed millimeter astronomy. The ALMA Development Program sustains the pace of ALMA science through community-led studies and implementation of improvements to ALMA hardware, software, and techniques. During the upcoming decade through 2030, new capabilities will expand ALMA's envelope of exploration even further. ALMA will complete its 35-950 GHz spectral grasp and increase its spectral coverage and sensitivity within that commodious spectral window. Here we discuss hardware alone.

II. CURRENT AND NEW INITIATIVES

Building on the successes of the initial suite of capabilities, ALMA will enhance them in several key areas in the decade leading to 2030. The ALMA Science Advisory Committee (ASAC) examined community input for potential new technical initiatives to sustain ALMA science. ASAC recommended four pathways for future development [2], distilled from the ALMA2030 summary of studies [3]. These included improving the archive, increased bandwidth (for finer resolution over a broader band and increased sensitivity and spectral coverage), higher angular resolution (longer baselines), and increased wide field imaging speed. The scientific advantages of these improvements include the ability for enhanced imaging of planetary disks, galaxy assembly, and chemical analyses of star-forming regions.

A. *ALMA Correlator Upgrade*

A staged upgrade to the ALMA 64-antenna has been proposed that will enlarge the number of channels and increase resolution by 8x, while improving spectral sensitivity by employing higher accuracy correlation. Scientifically, this will enable broader spectral windows to be deployed at a given resolution instantaneously, offering scientists nearly an order of magnitude broader suite of lines with which to investigate protoplanetary disks and protostellar clouds. The sensitivity enhancement is equivalent to the addition of eight additional antennas. When complemented with an upgraded digitization and frequency distribution system and receivers, the correlation capacity will be doubled to 8 GHz per polarization and sideband. This would double the current continuum sensitivity of the array enabling deeper images in less time, better calibration and access to a much broader swath of spectrum for line surveys or deep redshift searches. Adiitionally, an improved special use correlator for the four Total Power antennas is under construction by East Asia at KASI in Korea.

B. *ALMA Receivers*

ALMA Band 1 covers 35-50 GHz and is the lowest frequency on ALMA, with the largest beamsize. Science goals for this band include evolution of dust in protoplanetary

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disks; masers; molecular gas at high-redshift; grain growth and spinning dust; molecular lines; the Sunyaev-Zel'dovich effect; Zeeman effect and polarization. Band 1 construction is under way as an East Asia project led by ASIAA in collaboration with NAOJ, U of Chile, NRAO, and HIA. The Critical Design Review and Project Review were held Jan 19-20, 2016 at ASIAA in Taiwan, and the Band 1 LO Critical Design and Manufacture Review (CDMR) was held and passed on December 12th 2016. The Manufacturing Readiness Review is upcoming; first units have been manufactured and tested. They provide $T_{rx} < 28.0$ K for 35.5 – 48.5 GHz (80% bandwidth) and <30K for the full band, well within specifications. It is expected that Band 1 will be available by 2022.

AMA Band 2 (nominally 67-90 GHz) offers new frequency coverage with singular importance for the study of cold and icy deuterium-enhanced regions and redshifted CO. The highest level science goal, detection of CO at z~3 from a galaxy like the Milky Way, the J=3-2 line at 86 GHz, falls within this band. A project to build a prototype was approved by the ALMA Board in its March 2014 meeting. A single cartridge was built. The budget, project plan, and science vs. cost have been evaluated; the Preliminary Design Review was held on 30-31 May 2017. An independent project to combine ALMA Bands 2+3 has yet to be reviewed; published measurements of the performance of the LNA to be used suggest implementing the wider bandwidth will compromise sensitivity over that used for Band 2 NA by about 16%, jeopardizing the highest level science goal.

The **ALMA Band 5** receiver (covering 163-211 GHz) has been installed on ALMA, offered for science use in Cycle 5, and observations are expected to begin in March 2018. It was developed by the Group for Advanced Receiver Development (GARD) at Onsala Space Observatory, Chalmers University of Technology, Sweden, and was tested at the APEX telescope in the SEPIA instrument. The first production receivers were built and delivered to ALMA in the first half of 2015 by a consortium consisting of the Netherlands Research School for Astronomy (NOVA) and GARD in partnership with the NRAO, which contributed the local oscillator to the project. The performance of the receiver is considerably better than 50 K over the band.

C. *Phased ALMA Upgrades*

ALMA Phasing Project Phase 2 is intended to further enhance and expand the capabilities of the ALMA Phasing System through new software development and commissioning, furthering the goal of achieving the highest sensitivity possible on the longest possible baselines on earth.The Project will provide enhanced sensitivity through improved delay management, will enable spectral line VLBI and an extended frequency range for VLBI Band 1 through ALMA Band 7, introduction of a "passive" phasing mode to enable VLBI on weak sources such as pulsars (recently detected with ALMA) and ALMA 'total-power' VLBI capability (compatible with subarrays)

D. *Increased Collecting Area*

Additional antennas would restore ALMA to its originally planned complement of 64 or more, benefitting all science programs by increasing sensitivity, decreasing integration times and improving imaging fidelity. As a result of construction to these initial plans, much of the infrastructure for a 64 element array exists. Broadening the bandwidth increases sensitivity, but additional collecting area increases sensitivity over the narrow bandwidths of most spectral line emission. This is a critical need for the characterization of targets from protoplanetary disks, in which planets are shaped, to extremely distant galaxies, where the first heavy elements are forged in the first stars.

E. *Longer Baselines*

ALMA can currently image nearby (<200pc) terrestrial planet-forming zones on its longest baselines at its highest frequencies. Often, however, the disks at those frequencies are opaque and their interior structure hidden. Dust optical depth is less at lower frequencies, allowing better characterization of interior structure. Developing an imaging capability matching the resolution of that at the highest frequencies requires longer baselines. However, the number of antennas, their placement and achievable baseline lengths require study, driven by the science required at higher low-frequency resolution. There are a number of logistical issues that also require thought for baselines more extensive than a few dozen km.

F. *Focal Plane Arrays*

Focal plane arrays increase the field of view and are important for objects too extended for imaging in a single ALMA beam. Currently, many ALMA fields require multiple pointings for achieving their science goals, whether within the Solar System, molecular clouds, nearby galaxies or cosmologically distant groups or clusters of galaxies. While focal plane area is limited on ALMA, initial studies have suggested modest-sized arrays could be accommodated [4]. The science demands need to be studied to develop requirements on the preferred frequencies, the number of pixels and the necessary bandwidth. Arrays might be implemented on a subset of antennas, for instance the four in the Total Power array, for initial investigation, as interferometry with Focal Plane Arrays is a challenging instrumental goal.

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UPGRADE TO THE 64-ANTENNA ALMA CORRELATOR

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An upgrade to the 64-antenna ALMA correlator is described here which will double the instantaneous bandwidth and increase the number of spectral points by a factor of 8, making ALMA a significantly more efficient instrument at all bands.

The strategy behind this upgrade is to provide the enhancements above with a minimum of cost, effort, disruption, risk, and software rework. The idea is to retain the correlator system infrastructure (racks, cables, power supplies, microprocessor control system, etc.) and swap out old logic cards with newly designed cards using modern technology.

Doubling the bandwidth of the system requires doubling the operating clock frequency from the current 125 MHz to 250 MHz. Also, existing motherboard and signal cable data paths will be required to operate at twice the current data rate.

A study project (PMD-365), funded by the North American ALMA Development Program, was conducted largely in 2016 to investigate the feasibility of such an upgrade. Cost and schedule estimates were made and some of the critical features, such as using existing motherboard and cable interfaces at the new data rate, were tested to demonstrate adequate capability for use in the upgrade. The study project also produced detailed designs of almost all of the new logic cards and the custom ASIC necessary for the upgrade, thus reducing the time required to bring the new system to operation if funding is approved.

An additional advantage of the increased frequency resolution is that observations not requiring the highest frequency resolution will have the option to trade frequency resolution for sensitivity by, for example, selecting 4-bit correlation or twice Nyquist sampling modes with lower but still high resolution.

A prime objective of the upgrade will be to keep system software modifications to a minimum. This is accomplished by retaining the same control system with minor modification to control protocols, and by upgrading the existing modes to similar ones with wider bandwidth and greater resolution. Still, the software effort is significant. In particular, the correlator data processor backend will process 8 times more data than today.

In order to take advantage of the new correlator capacity, changes to other parts of the ALMA system must be implemented. The principal modification required is new digitizers, some rework of the optical data transmission system from the antennas and the design of new flexible digital filters. A group at the Observatoire de Bordeaux is currently working on an upgrade to these systems.

Existing ancillary operating support of the correlator, such as for VLBI support, will be retained and support for a future high time resolution system to observe transient phenomena will be incorporated into the upgraded system.

The ALMA Phasing Project Phase 2: Extending and Enhancing the VLBI Science Capabilities of ALMA

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The ALMA Phasing Project (APP) recently developed the hardware and software necessary to coherently sum the signals from individual ALMA antennas and record the aggregate signal in standard Very Long Baseline Interferometry (VLBI) format. These capabilities now allow the ALMA array to operate as the equivalent of a single large aperture antenna and participate in global VLBI networks operating at millimeter (mm) wavelengths. VLBI observations at these wavelengths are capable of yielding angular resolution as fine as a few tens of microarcseconds—the highest presently achievable for observations of astronomical sources. Given ALMA's extraordinary sensitivity, the addition of phased ALMA to existing mm VLBI networks provides an order of magnitude boost in sensitivity, along with significant enhancements in the ability to reconstruct images of sources.

The first VLBI science observations with phased ALMA were conducted in April 2017 at wavelengths of 3 mm and 1 mm. These observations are expected to probe in unprecedented detail the launch and collimation of astrophysical jets and the physics of black holes on event horizon scales. In parallel, our team has been laying the groundwork for an "APP Phase 2" that will introduce a suite of extensions and enhancements to the existing ALMA Phasing System in order to expand and diversify its scientific capabilities. Major components of this work will include the introduction of a spectral line VLBI mode, the extension of VLBI into the sub-mm (0.7 mm) regime, and the ability to perform ALMA VLBI on sources considerably weaker than current thresholds. This talk will briefly describe the scientific motivation for an APP Phase 2 and review the steps necessary for its implementation at ALMA.

The Next Generation ALMA Correlator USNC-URSI National Radio Science Meeting

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On behalf of an International
ALMA Development Consortium
See Closeout Report for list of collaborators:
`http://library.nrao.edu/alma.shtml`

***Abstract*—A Cycle 3 ALMA Development Study entitled *Digital Correlator and Phased Array Architectures for Upgrading ALMA* was completed in 2017. SAO led a consortium staffed with an international group of domain experts. The team developed science-driven architectures that greatly enhance bandwidth and continuum sensitivity; and are flexible, to facilitate modes providing extremely fine spectral resolution and native phased array VLBI recording, among others. Increased reliability, as well as reduced size, power consumption and life-cycle costs, are important natural benefits of these architectures which use state-of-the-art computing platforms and interconnect. A variety of technologies and algorithms were studied balancing costs and timelines against benefits. A detailed and practical system design is documented and justified in a comprehensive report to be submitted as an ALMA memo. This summary paper gives an outline of the proposed next generation ALMA digital system.**

I. INTRODUCTION

Recent developments at the Submillimeter Array (SMA) [1] demonstrate the feasibility and potential of ultra-wide band digital processing with fine uniform spectral resolution and VLBI capability. Figure 1 shows what the upgraded SMA can do. The extrapolation to ALMA is an exciting prospect indeed.

A system-wide specification of the next generation ALMA system (see table I) was developed for the Cycle 3 Study. Published findings from the ALMA Science Advisory Committee (ASAC) [2], as well as consultations with scientists and other experts across the International ALMA community, guided the requirements. While the requirements of next generation ALMA are outside the Study's purview, they were absolutely necessary at the outset to focus the work. The intent is to stimulate community-wide conversation leading to consensus.

We view the Study as Phase I of three phases of development. A Phase II bench prototype has been proposed, the implementation of which would retire substantially all development technical risk, and serve to pin down the timeline and costs of Phase III installation, verification, and commissioning.

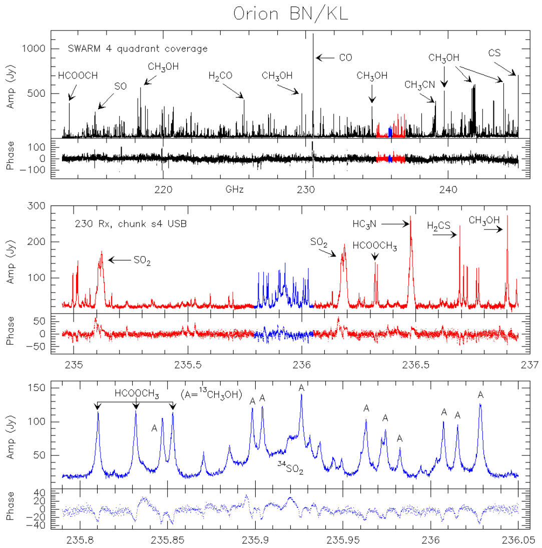

Fig. 1. The spectrum of Orion BN/KL covering an instantaneous 32 GHz on the sky with 140 kHz resolution across the full bandwidth. The data were taken on 26 January 2017 UTC with the SMA Wideband Astronomical ROACH2 Machine (SWARM), a FPGA based FX packetized back end. From the top the three panels show: the full 32 GHz, a single 2.0 GHz 'chunk' from one of 16 IF-ADC channels; and a detail of just over 200 MHz span, revealing the fine structure available in *all the data*—the 200 MHz blue fragment could be placed anywhere to reveal similar detail.

II. ENABLING NEW FRONTIERS IN ALMA SCIENCE

Unsurpassed instantaneous bandwidth for spectral line surveys will provide truly unbiased connections between chemistry and the planet formation process in protoplanetary disks. An order of magnitude increase in coverage of spectrally surveyed star forming regions and extragalactic sources will provide entirely new approaches to chemical evolution across a range of exciting sources. Proportional increase in the cosmic volumes accessible via intensity mapping allows complete inventories of galactic gas at high-redshifts and new views of the physics of galactic evolution across cosmic time. Simultaneous line detection facilitates rapid high-z redshift surveys, demystifying the accumulation of galactic stellar mass.

In the time domain, new evolutionary studies of transients in the millimeter and submillimeter are enabled, providing insight into mechanisms for variability in γ-ray bursts, which peak in the ALMA bands. Cometary studies rely on rapid cadence observations to disentangle coma versus jet emission: the key to solving the puzzle of their origin. VLBI features [3] allow ALMA to form multiple beams, becoming the anchor station of the Event Horizon Telescope (EHT). With earth-size apertures, and EHT evolving to band 7, our direct views of black hole event horizons sharpen, addressing the most fundamental questions in astronomy, physics and mathematics.

III. Assumed ALMA-wide requirements

The Development Study was broken down into eight work packages, each researched in depth by a focused team. An abbreviated listing included specifications, platform and architecture for F-engine, corner-turn, and X-engine, VLBI phased array mode [3], and staging for installation. Table I gives a highly abbreviated summary of the key *assumptive specifications* developed in the first work package, and used by the others.

TABLE I

Abbreviated assumed specifications for study.

Parameter	Specification	Remarks
# antennas	72	configuration
Max. baseline length	300 km	Sets max delay
Instantaneous BW	64 GHz	16 GHz/SB/Pol
Baseband (BBC) BW	8 GHz	single ADC block
Finest spectral resolution	0.01 km/s:1 kHz	band 1, cold cores
Effective bits	4	99% digital efficiency
Spec. dynamic range	10,000:1	weak lines near strong
Spec. dynamic range	1,000:1	lines on continuum
readout interval	16 ms	for x-correlations
reconfiguration time	1.5 seconds	agile mode change
VLBI mode	phased sum out	two subarrays

IV. An outline next generation system design

The proposed digital system is an optimized supercomputer that receives antenna data over a packetized network interface, and delivers full Stokes cross-correlation fringe visibilities, auto-correlations, and coherently phased antenna sums at its output. An 8 GHz *BaseBand Converter* (BBC) band in two polarizations readily scales by replication to the 64 GHz instantaneous sky coverage our Study requirements target. An ultra-fine spectral resolution setting of 1 kHz is available, useful to resolve lines in cold starless cores using ALMA Band 1. This astonishing resolution aggressively drives the output data rate, so modes to throttle the output are provided.

Historically in radio interferometry, *XF* correlators—cross-correlation first, with Fourier transform in software on the integrated lags—have been favored because expensive wide multipliers are not needed since the bit-width in the X-stage remains at the width of the sampled data. The advent of wide multipliers in digital signal processing hardware such as field programmable gate arrays (FPGAs) has effectively reduced the penalty for bit growth in the butterflies of the Fast Fourier Transform (FFT). The well known economy of the Cooley-Tukey algorithm, and correlation collapsing to bin-wise cross-multiplication in the Fourier domain, yields computational savings. So the number of instantiated multipliers for a given array size and spectral resolution is substantially reduced. Thus FX architecture allows for great economy in systems with fine spectral resolution and large numbers of antennas. *Packetized* FX correlators are now widely employed in radio astronomy [4], and are a clear choice for next generation ALMA.

ALMA presently samples 3-bit data; while 2-, 3- and 4-bit arithmetic are available, the high resolution modes are limited to 2-bit and 88%. Wide multipliers facilitate processing of wider bit-widths, thereby improving the digital efficiency of the correlator from 88%, for a two bit machine, to 99% for 4-bits. An 11% increment equates to 22% less integration time for a given SNR, yielding an effective 80 extra nights per year.

Communication between F-processing nodes, which operate on full-bandwidth data from a subset of antennas, and X-processing nodes, which operate on a fraction of the bandwidth from all antennas, requires at least three duplex ports per antenna on a 100 Gbps Ethernet switch. Since different ALMA BBCs handling independent band fractions may be handled by entirely separate and independent systems, the implementation quantum is a system for 72 antennas, capable of dealing with 8 GHz BBC bandwidth, two polarizations, one sideband, and 4-bit samples, or 16 GHz in total. This amounts to 256 Gb/s per dual-polarization antenna. Quadrupling this system covers the full 64 GHz bandwidth of the upgraded ALMA. A *dual band* mode can be supported by further parallelization.

V. Conclusion and future work

Increasing ALMA's bandwidth is the least expensive approach to improving its sensitivity. Reduction of power, magnified by concomitant lower cooling requirements reduces life-cycle costs and improves robustness against power disruptions. *Using current and conservatively projected technologies one can build a system that enables all ALMA Development priorities, with improvements in reliability, power and size.*

The next-generation correlator and phased array is the central component of a system-wide enhancement of ALMA. This includes wideband receivers, analog-to-digital converters [5], Digital Transmission System (DTS) and a data pipeline with commensurate capacity and speed. The context is an overall system-engineering plan for ALMA Development. Consensus on system-wide next generation ALMA requirements is a prerequisite. The next step is to comprehensively validate a bench prototype of this radically new correlator and phased array for ALMA, substantially retiring technical risk of full deployment.

ACKNOWLEDGEMENT

A North America Cycle 3 ALMA Development Study funded many of these developments.

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The ALMA Band 1 receiver: building the lower frequency end of ALMA

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The ALMA Band 1 receiver development project is the East Asia contribution to ALMA development. The project is led by ASIAA (Academia Sinica Institute of Astronomy & Astrophysics) in Taiwan, in collaboration with NAOJ (Japan) and the University of Chile, and with contribution from HIA (Canada) and NRAO (USA). The development of the ALMA Band 1 receiver will allow ALMA to use the 35–50 GHz frequency range, and will open up access to a wide range of compelling scientific cases, as shown in the ALMA Band 1 Science case. The two main scientific goals of ALMA Band 1 are also two Level One ALMA goals: the study of dust around protoplanetary disks, and the follow-up of dust grain growth to cm-sizes; and the observation of molecular gas in galaxies at high redshift, up to the era of reionization, through the observation of several transitions of CO. The ALMA Band 1 receiver is expected to provide similar or improved sensitivity and substantially better imaging and mosaicking capabilities compared to the JVLA. Currently, we are entering the production phase of the Band 1 receiver: the three initial pre-production cartridges and several production cartridges are already assembled and tested in Taiwan. We are expecting to start deploying the cartridges in Chile during 2018. In my talk, I will show the latest status of the production phase and the plans for the upcoming Band 1 Science Verification observations.

Plans for an ALMA Band-6 Receiver Upgrade

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We propose to upgrade the current ALMA Band 6 receivers to achieve more uniform sensitivity across the full 211-275 GHz band while increasing the IF bandwidth from the current 16 GHz (4 GHz per sideband per polarization) to 32 GHz. The increased IF bandwidth will allow full advantage to be taken of the planned second-generation ALMA correlator. Additional improvements will be made to reduce the sidelobe level and the cross-polarization.

The current Band-6 SIS mixers will be replaced with a new design using Nb/AlN/Nb SIS junctions. This will allow the use of smaller SIS junctions with higher critical current density and smaller capacitance, hence wider RF bandwidth. To improve reliability and ease of assembly, the mixer substrates will be silicon membranes with beamleads.

The IF amplifiers will be replaced with balanced 4-12 GHz amplifiers, thus reducing the variation of receiver noise across the IF band caused by interaction between the mixers and the present amplifiers. The balanced amplifiers will use a pair of superconducting quadrature hybrid on 3 x 1 mm quartz chips, and will incorporate a circuit to provide bias to an SIS mixer connected to the amplifier.

To reduce the contribution of LO sideband noise present in some of the Band-6 LO modules, the feasibility of using balanced sideband-separating mixers will be investigated. This requires four elemental SIS mixers per balanced sideband-separating mixer.

The original Band-6 feed horn and orthomode transducer can have a trapped mode resonance near the middle of the band. This will be eliminated in a new horn and OMT design. A new OMT without a septum will be developed, which will be less difficult to assemble and more reproducible.

Superconducting Parametric Amplifiers: the Next Big Thing in (Sub)Millimeter-wave Receivers

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Abstract—**Please include a brief abstract here. The abstract should be limited to 50-200 words and should concisely state what was done, how it was done, principal results, and their significance.**

I. INTRODUCTION

A recent breakthrough at Caltech/JPL in amplifier technology called the Travelling-Wave Kinetic Inductance Parametric (TKIP) amplifier has resulted in near quantum-limited performance over more than an octave instantaneous bandwidth in the microwave range [1]. Until now the quantum computing community has been the main driver for developing these amplifiers for qubit readout, but their devices have narrow bandwidths, low dynamic range, and operate at sub-Kelvin temperatures. Our collaborators at JPL recently demonstrated a microwave TKIP amplifier with several GHz of bandwidth, and orders of magnitude higher saturation power that maintains quantum-limited noise performance up to an operating temperature of 3K. Similar amplifiers but at higher frequencies up to 1 THz could be designed since the operation principle and physics remain largely unchanged. These qualities make TKIPs suitable candidates for ground-based astronomy with instruments such as ALMA.

II. TKIP AMPLIFIER DEVELOPMENT AT NRAO

In a 2-year study we are planning to build a high-frequency TKIP demonstration prototype as a front-end replacement for the ALMA band-3 SIS mixer receivers. Our collaborator has designed and fabricated a TKIP chip that covers a very wide bandwidth of 55-175 GHz, and we are preparing to test this device at NRAO-CDL. Ultimately we envision similar TKIP amplifiers for higher frequency ALMA bands if this device is successful. We also plan to explore TKIP amplifiers as quantum-limited microwave IF amplifiers, which could be applied as a one size fits all replacement for all ALMA IF amplifiers, and would reduce SIS receiver noise typically by 2x. The main challenge in this work is in further optimizing the superconducting thin-film materials to retain their sub-Kelvin properties such as ultra-low loss at temperatures close to 4K.

III. INCREASED OBSERVATION EFFICIENCY WITH TKIP AMPLIFIERS ON ALMA

The enhanced observational capabilities that would be enabled by these front-end amplifiers would benefit ALMA science across all bands. For example the Band-3 improved signal-to-noise from a front-end RF TKIP amplifier would be a factor of 5 measured at the receiver input. Including the loss of atmosphere this translates to a doubling of system sensitivity and a factor of 4 increase in array efficiency (speed) enabling the detection of weaker spectral lines and continuum sources and mapping larger fields. The increased sensitivity from the RF front-end relaxes the requirements on IF amplifiers and allows for tradeoff with bandwidth to increase the instantaneous IF bandwidth from the current 4 GHz per sideband per polarization to 10 GHz. For continuum observations, this provides a greater than factor of two increase in efficiency (speed), which combined with the increased RF efficiency would result in a factor of 8 increase in observation efficiency (speed). For spectral observations such a wide bandwidth also enables the detection of various spectral lines simultaneously, removing the need of multiple observations at different LO frequencies to cover the whole band. This is also ideal for obtaining spectral index information on sources in much shorter integration times than is currently possible. In addition, as quoted from the ALMA 2030 roadmap document, Bandwidth expansions will, simultaneously, enormously increase the legacy value of the archive while increasing the likelihood of serendipitous discoveries [2]. The ALMA 2030 roadmap recommends that Long-term sustained research in better devices or new technologies (such as TKIP amplifiers) has the potential to yield significant breakthroughs that are equivalent to doubling or tripling the collecting area of the array with its present instrumentation. Therefore, because of the potential game changing improvements that might be achieved it is important to further study these amplifiers with a long-term view of what will be possible in 5 to 10 years.

IV. ENHANCED SCIENCE STUDIES WITH ALMA

The potential science return from these amplifiers is significant. Studies of regions undergoing star and planet formation, molecular gas surveys, afterglows of Gamma-Ray

Bursts (GRB), and objects in the high-redshift Universe are but a few of the current ALMA capabilities which will be vastly improved by these amplifiers. The increased continuum bandwidth will also allow for studies of clusters of galaxies, thought to be tracers of dark energy in the universe.

V. OTHER APPLICATION AREAS FOR TKIPS

These amplifiers are not only interesting for the NRAO and ALMA community, but are also sought after in the direct detection astronomy community (e.g. MKID detectors, TES detectors etc.) for amplifying or multiplexing signals from large focal-plane arrays of photon detectors for space telescopes such as NASAs Origins Space Telescope and X-ray telescopes. Finally, they are also a powerful general tool for exploring quantum physics and have many experimental applications in research labs (quantum optics, quantum cryptography, nanomechanical sensors, dark matter detectors).

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Discovery From Hyperspectral ALMA Imagery With NeuroScope

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***Abstract*—We aim to add significant ALMA analysis capabilities for finding source regions with distinct kinematic and compositional properties. The NeuroScope approach is based on clustering with artificial neural maps and advanced knowledge extraction tools. It affords simultaneous use of multiple spectral lines and all velocity channels for discovery of complex structure and discrimination of subtle pattern variations.**

I. MOTIVATION AND OBJECTIVES

The Atacama Large Millimeter and sub-millimeter Array (ALMA) collects images at hundreds-to-thousands of frequencies with high spectral and spatial resolution. The resulting data cubes provide unprecedented opportunities for discovery of structure in protoplanetary disks, molecular clouds and other astronomical sources. However, these data also exhibit unprecedented complexity in addition to enormous volume, requiring new approaches to extracting relevant information. Traditional techniques (e.g., analyzing images at selected frequencies, moment maps) and even newer methods may become intractable or they can no longer fully exploit and visualize the rich information [1]. To address this problem, we develop tools — collectively called NeuroScope — to analyze ALMA data, and, in general, complex multi-dimensional data. These tools are rooted in state-of-the-art neural machine learning techniques. We show the effectiveness of NeuroScope on ALMA data of the protoplanetary disk HD142527 [2]. In the near future, we aim at automating our clustering for fast distillation of large data cubes in autonomous pipelines or on-board scenarios, and test it on more complex dataset, such those resulting from large field of view spectroscopic observations of molecular clouds.

II. METHODS

The NeuroScope approach uses artificial neural map-based machine learning combined with advanced knowledge extraction methods. It identifies spectrally homogeneous spatial regions by clustering the spectral signatures in a 2-step process: a) intelligent summarization with advanced variants of Self-Organizing Maps (SOMs), which shrinks the data to a sparse representation with a small number of prototype spectra while reducing noise and retaining the salient pattern variations; b) grouping the prototypes using a “connectivity” measure that captures pattern affinities and topological relations from the SOM ([3] and references therein).

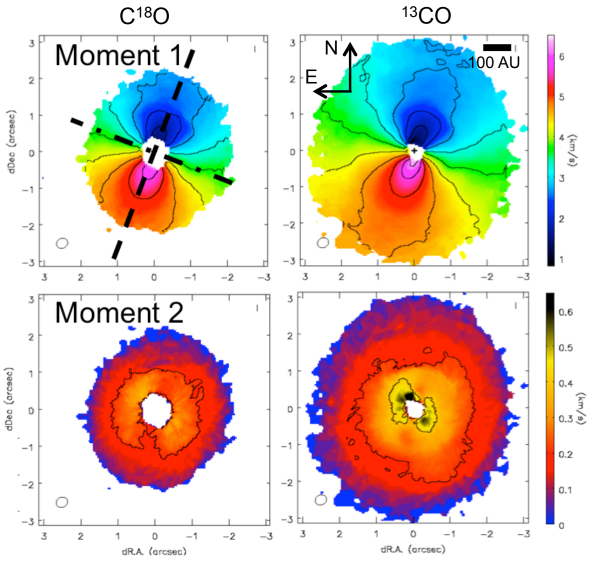

Fig. 1. Moment maps generated separately from molecular lines C^{18}O J=3–2 and ^{13}CO J=3–2, from high-resolution observations of the protoplanetary disk HD142527 [2]. The dot-dashed and dashed lines, respectively, indicate the rotation axis and the apparent major axis of the disk. The moment 1 map shows the spatial distribution of the velocity of the emitting gas relative to the observer. The moment 2 map indicates the width of the line emission.

This process is capable of handing multiple spectral lines and all spectral channels simultaneously, sensing subtle but consistent pattern differences, and capturing clusters of widely varying statistical properties without requiring a predetermined number of clusters. This allows effective exploitation of the rich information though utilization of the full depth of these data, for discovery of complex structure. The intelligent sparse data summarization lends efficiency for large data.

III. DATA AND PRELIMINARY RESULTS

We test NeuroScope on ALMA data of the protoplanetary disks surrounding the young binary star HD 142527 [2]. The observation consists of two data cubes containing the J=3-2 rotational line emission of C^{18}O and ^{13}CO molecules,

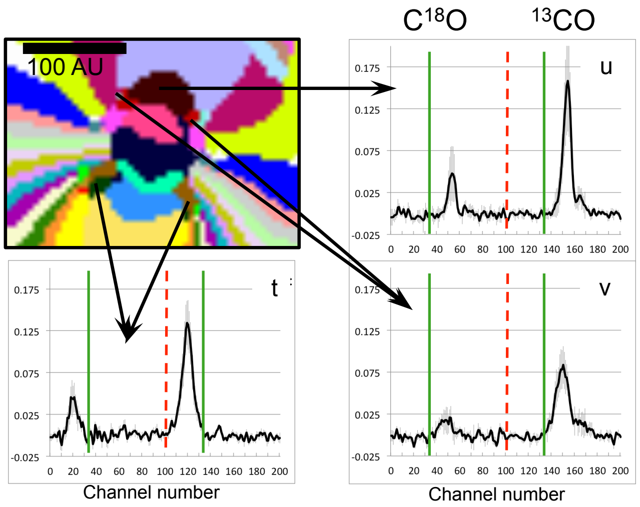

Fig. 2. Magnified center of the disk with clusters (regions highlighted by different colors) discovered from the 200-channel spectra combined from the $C^{18}O$ and ^{13}CO lines., and plots of mean spectra of three clusters. The dashed vertical red line in each plot indicates where the two spectral lines were concatenated. The vertical green line is drawn at the rest frequency within each of the spectral lines. Colors were chosen to contrast regions (not to provide a heat map). The mean spectra of the three clusters each exhibit widening of the spectral lines, or a double peak in the case of the cluster labeled "t" (very small, dark green downward pointing pair of spatial areas). These may suggest departure from the Keplerian rotation.

respectively. Each data cube comprises 100 velocity channels. Despite the fact that protoplanetary disks have a rather simple kinematics consistent with Keplerian rotation, NeuroScope analysis revealed regions with subtle but consistent discriminating patterns, which are missed by moment maps (Figs 1 and 2).

The combined (concatenated) 200-channel spectra are input to our clustering to produce a cluster map. For reasons of space constraints, we show in the top-left panel of Fig. 2 only the magnified center of the cluster map. Each cluster (a differently colored spatial region) signifies a spectrally homogeneous region, with spectral characteristics different from regions depicted by other colors. Thus the variations of the compositional and kinematic behavior are portrayed in a 2-dimensional map which is easy to inspect visually and to notice possible irregularities. The kinematical and compositional properties of cluster regions can be examined from their average signatures, which can be automatically generated. In Fig. 2, the standard deviations are also plotted for each channel to indicate the within-cluster variations, which is also a measure of the reliability of the clusters. The sample plots of three interesting clusters, pointed at by arrows in Fig. 2, exhibit double or widened velocity peaks. (Notice that two of those clusters, "t" and "v" consist of two symmetric parts.) Cluster "t", in particular, has two ^{13}CO peaks at opposite sides of the rest frequency (green line), which may be caused by two gas components traveling in opposite directions. The larger regions adjacent to cluster "t" (such as the arcuate medium blue and several yellow-hued clusters) have abruptly different spectral properties (not shown here). In a protoplanetary disk, clusters like the ones highlighted in Fig. 2 could indicate the presence of non-Keplerian motion, such as, for example, inflow motion of gas toward the star or onto forming planets. The moment 2 map of the ^{13}CO line shows widening at two of the locations indicated by arrows in the cluster map but misses the most prominent "t" region. Whereas an in-depth analysis and physical interpretation of these (and other) kinematic features in HD142527 is ongoing, it is clear that NeuroScope is capable of expanding the space of discovery provided by ALMA observations.

A. *Conclusion and Outlook*

We show here an example of finding well-defined parts of the protoplanetry disk HD142527 with spectral properties that have potential physical relevance for understanding the kinematical structure of this system. Finding the small spatial areas that exhibit unusual behavior hinges on "precision mining" the high-dimensional ALMA cube and accurately delineating them from other areas. NeuroScope is tool in development. Future work will include exploration of visualization schemes where colors can be used to express some relationships across regions; or interactive visualization where the spectral plots of regions pop-up on demand. Future work will also be aimed at perfecting the automation of the (partially interactive) clustering process [4], so that NeuroScope could be used in pipeline processing at high speed without compromising quality. To complete the analysis of the HD142527 system, NeuroScope will be tested on ALMA mock-up observations of disks characterized by kinematical signatures deviating from the Keplerian motion. Finally, we will exploit NeuroScope capabilities by analyzing more complex astronomical data, such as the multidimensional spectral cubes resulting from wide field of view mapping of nearby molecular cloud.

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Full-Mueller Mosaic Imaging with ALMA

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Due to small field of view (FoV) of ALMA antennas (100 – 10 arcsec), mosaic imaging is a popular mode among ALMA users. Full-polarization mosaic imaging is significantly affected by the (a) differences in the shapes of the primary beam (PB) of the different antenna types in the array, and (b) the off-axis instrumental polarization effects of the PB. Error due to these effects increase with distance from the center of the PB preventing full-FoV imaging in full Stokes, even for single-pointing observations. In mosaic imaging, outer parts of the PB corrupts the inner parts of the PB (where off-axis effects may be smaller) of all the neighboring pointings, thus spreading these corruption throughout the mosaic image. As a result, no part of a mosaic image is free of these corruptions. This has limited the ALMA imaging performance in terms of achievable dynamic range and prevents wide-field imaging beyond the inner 1/3 of the PB for full Stokes imaging for single pointing observations and entirely prevents full-Stokes mosaic imaging. Imaging performance is also limited due to the significant antenna-to-antenna differences in the measured aperture illumination patterns and antenna pointing errors, both of which affect the PB projected on the sky.

In this talk, we present the characterization of the effects of antenna PB on full-polarization mosaic imaging. We then briefly also describe the full-Mueller imaging approach which we plan to use to correct for these PB effects using the full-polarization direction dependent Mueller matrix, which encodes the precise mixing of the incoming polarized flux vector across the FoV.

The spectrum landscape: prospects for radio astronomy

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Radio astronomers work within broad constraints imposed by commercial and other non-astronomical uses of the radio spectrum, somewhat modified to accommodate astronomy's particular needs through the provision of radio quiet zones, radio frequency allocations and other devices of spectrum management. As astronomers increase the instantaneous bandwidth, frequency coverage and sensitivity of their instruments, these external constraints, and not the limitations of its own instruments, will increasingly be the greatest obstacles to radio astronomy's ability to observe the cosmos from the surface of the Earth.

Therefore, prospects for future radio astronomy operations are contingent on planning for non-astronomical uses of the radio frequency spectrum. New radio astronomy instruments will have to incorporate a variety of adaptive reactions to external developments and radio astronomers should be encouraged to think in untraditional ways. Even about spectrum management, for instance.

In this talk I'll summarize present trends for non-astronomical radio spectrum use that will be coming to fruition in the next decade or so, categorized into terrestrial fixed and mobile, airborne and space-borne uses, sub-divided by waveband from the cm to the sub-mm. I'll discuss how they will impact terrestrial radio astronomy and the various ways in which radio astronomy should be prepared to react. Protective developments must occur both within its own domain – designing, siting and constructing its instruments and mitigating RFI – and facing outward: engagement with spectrum management is also an important means by which radio astronomy can take an active role in shaping its future environment.