Cycle 7 NRAO ALMA Development Study Proposal – Technology Development of Quantum-Limited, Ultra-Wideband RF Amplifiers for ALMA: A 65-150 GHz Amplifier Test Case

PI: Omid Noroozian (now GSFC) with Cyberey, Hinton, Farrahi, Lichtenberger, Weikle, Day, Klimovich, Zmuidzinas, Kooi, Mangum

Institutions: GSFC, NRAO, UVa, JPL, CIT

ABSTRACT
The ALMA 2030 roadmap recommends the development of receivers with larger bandwidth and better sensitivity for improving observation speed. In this 1 year study, we propose to continue the development of a breakthrough amplifier technology called the Traveling-Wave Kinetic Inductance Parametric (TKIP) amplifier that was invented by our collaborators at Caltech/JPL. These “paramps” are a new type of cryogenic power amplifier applicable in the microwave to THz range (0.001 – 1 THz) that exhibit ultralow noise reaching the fundamental quantum limits set by Heisenberg’s uncertainty principle, along with very wide instantaneous bandwidth (an octave or more).

The study of these amplifiers is considered strategic for NRAO’s long-term technology program, and their successful development could have a huge impact on the performance of ALMA and other future radio telescopes. In this study, we intend to build upon our progress in developing both microwave (post-downconversion, or IF) and millimeter-wave (pre-downconversion, or RF) paramps during our on-going study from ALMA cycle 5. We designed and fabricated several versions of our IF paramps with improvements in gain, bandwidth, noise, dynamic range, gain ripple, pump power level, and chip footprint. We tested these in our JPL and NRAO/UVA shared testbeds and demonstrated that they can operate at 4 Kelvin while maintaining high gain (~ 15 dB) and wide bandwidth (>6 GHz), although noise has not been tested at 4 K yet. When operated at <1 K, we consistently measured noise within a factor of two of the fundamental quantum limit for our IF paramps. At higher frequencies, we designed and fabricated several RF paramps with a simulated gain of >15 dB over the 65-150 GHz band, and made significant improvements in the fabrication methods. These chips have been mounted and are ready for testing in our W-band testbeds. In cycle 5, significant work was placed in building entirely new laboratory infrastructure at NRAO/UVA for testing both IF and RF paramps in a new testbed that can continuously operate the paramps at temperatures between 10 mK and 5 K. The results from our combined efforts at NRAO/UVA and Caltech/JPL and our new testbed infrastructure have put our team in an excellent position to continue this promising work, which is clearly synergistic with ALMA’s roadmap.

The enhanced imaging capabilities that would be enabled by our proposed RF TKIP amplifiers would benefit a wide range of ALMA observations. For example, the Band-3 improved receiver noise performance from a front-end RF TKIP amplifier would increase the array efficiency (speed) by a factor of ~4 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 the IF amplifier and should allow the instantaneous bandwidth to be expanded from 16 GHz to ~ 40 GHz. For continuum observations, this provides a factor of 2.5 increase in imaging efficiency (speed), which combined with the increased RF efficiency would result in a factor of 10 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.

In this 1-year study, we will concentrate our efforts on two fronts: 1) Careful characterization of noise, gain, and dynamic range of our already-fabricated and packaged RF paramps in our W-band testbeds using cryogenic blackbody noise sources, and 2) Developing new materials growth and fabrication techniques at UVML that will allow our team at UVA to fabricate paramp circuits.

Cycle 7 NRAO ALMA Development Study Proposal – ALMA Band 6 Local Oscillator Modifications

PI: K. Saini, with D. Vaselaar

Institutions: NRAO

ABSTRACT
The receiver noise temperature of the present ALMA Band 6 receiver increases substantially outside of 6 – 10 GHz IF band. Currently, only 4.5 – 10 GHz is accessible to observers due to this IF band-edge noise degradation.

Of foremost importance is reducing the noise temperature at the edges of the 4 – 12 GHz IF band, particularly on the low frequency side. This will allow the 13CO and 12CO lines at 220.4 GHz and 230.5 GHz to be observed simultaneously with improved sensitivity. It is proposed to study ways to reduce the AM noise present on the sidebands of the Band 6 Front-end local oscillator in order to improve the overall receiver noise and line sensitivity when using low IF frequencies to observe certain spectral lines.

Various modifications to several local oscillator modules, as described in this proposal, will be carried out and evaluated. We will also prototype new LO architectures and evaluate them for their AM noise performance. All of the results will be summarized in the final report. Additionally, for feasible solutions/approaches that are identified during this study, the cost and effort of upgrading the Band 6 LO system on the ALMA telescope will be worked out and presented in the final study report.

This investigation is a follow-up to the Band 6v2 Conceptual Design Review panel recommendation to improve the LO sideband noise which will enable simplification of the proposed new receiver architecture. Specifically, the Band 6v2 Conceptual Design Review final panel report [RD1] suggests, ". . . investigate the options of using a single-ended mixer (with improvement of the local oscillator noise level) and using a single-ended LNA with isolator. The panel recommends that those investigations are executed to sufficient depth to accurately predict performance and thus provide robust information for the architecture down-selection."

It should be noted that even if the LO upgrade is implemented in isolation, it holds the promise to improve the noise performance of the existing Band 6 receiver.

Cycle 7 NRAO ALMA Development Study Proposal – ALMA Band 6v2 SIS Mixer-Preamp Development

PI: A. Kerr with A. Lichtenberger

Institutions: NRAO, U. Va.

ABSTRACT
This proposal will continue the development of an SIS mixer-preamplifier combination for a future ALMA Band 6 receiver upgrade – referred to here as the B6v2 upgrade. A number of options will be explored and a best design chosen for the upgrade. The options include the use of SIS junctions with an aluminum nitride tunnel barrier (Nb/Al-AlN/Nb) instead of the usual aluminum oxide barrier (Nb/Al-AlOx/Nb), single-ended versus balanced sideband-separating (2SB) mixers to reduce LO sideband noise, IF amplifiers with and without ferrite isolators, balanced IF amplifiers (which require no isolator), a substantially expanded IF bandwidth, and a modestly expanded RF bandwidth (beyond 211-275 GHz) to cover additional spectral lines.

Because the physical constraints of the ALMA cartridge govern the configuration of the mixer-preamplifiers, magnets, and orthomode transducer (OMT), all of which must be located near the output of the feed horn but must not protrude into the optical path which twice traverses the 4-K section of the cartridge, it is important that these components be developed in close collaboration with the optics development.

Parallel interdependent proposals are being submitted with this one to cover simultaneous development of an improved LO source with low sideband noise, an improved OMT with a compatible geometry, and improved optics.

The essential work on superconducting and silicon membrane circuits will be done in collaboration with the University of Virginia Microfabrication Laboratory (UVML) and supported by separate funding.

Cycle 7 NRAO ALMA Development Study Proposal – NRC TALON FSA CBF for ALMA

PI: S. Vrcic with Pleasance, Carlson, Rupen, Gunaratne

Institutions: NRC Herzberg

ABSTRACT
The National Research Council of Canada (NRC) Herzberg Astronomy and Astrophysics Research Center (HAA) has designed a Frequency Slice Architecture (FSA) Correlator/Beamformer (CBF) based on the NRC's TALON technology for the Square Kilometer Array (SKA) Mid Frequency Correlator/Beamformer (Mid.CBF) [1]. The TALON FSA CBF design is flexible in nature and easily adapted to other radio interferometers. This has been demonstrated with the inclusion of a TALON FSA CBF in the ngVLA reference design [2] for the 2020 decadal review.

This proposal describes a Cycle 7 ALMA Development Study that would investigate the potential of integrating a TALON FSA CBF into the ALMA observatory. The scope of the study includes two main activities:

1. Document a detailed design for a suitable TALON FSA CBF. This includes detailing the capabilities, rack space, and power estimates for a CBF that handles the existing bandwidth and number of antennas and potential expansion of such a CBF for additional bandwidth and antennas. It will also include first order estimates of the cost and schedule required to develop and deploy the CBF, although an additional study would likely be required to develop a more detailed cost and schedule.

2. Investigate the existing ALMA interfaces to the CBF and document how a TALON FSA CBF could be integrated with minimal impact to the surrounding ALMA systems. This will require access to ALMA interface documentation and a limited amount of support from an ALMA system expert.

There are many potential benefits of integrating an NRC TALON FSA CBF into the ALMA observatory which include:

- Standard channel bandwidth of ~13 kHz for close to 600,000 channels across 8 GHz / polarization of correlator bandwidth.
- Additional zoom channels with channel bandwidth as low as 210 Hz.
- Near perfect correlation efficiency with 6-bit correlation and up to 18-bits carried through signal processing prior to correlation.
- Flexible allocation of processing resources between correlation and tied-array beamforming for VLBI.
- Seamless expansion to add correlator or beamformer bandwidth.
- Cost and power advantages of using the latest generation FPGA technology.
- FPGA based platform provides ability for a "living instrument" through functionality upgrades in the future within the same hardware and system architecture.
- The NRC is actively developing the TALON FSA CBF with several possible deployment timelines in mind:
    - Next two years: TALON Demonstration Correlator
    - Next five years: SKA1 Mid.CBF
    - Next ten years: ngVLA (using future generation technology)

Cycle 7 NRAO ALMA Development Study Proposal – ALMA CLOA Improvements and Upgrades

PI: C. Jacques with Shillue

Institution: NRAO

ABSTRACT
As delivered, the ALMA Photonic LO currently operates within its original specifications. However, as we anticipate future directions for ALMA science, such as the longer baselines articulated in the ALMA ASAC 2030 Roadmap and ALMA Development Roadmap reports, enhanced capabilities are envisioned that the existing specifications were not designed to support (for example, the current maximum AOS-to-antenna pad distance where all specifications are met is 15 km). The analysis and testing conducted under this study will help provide a roadmap for ALMA scientists to proactively plan and budget for technical enhancements that will be required to support future science goals. This longer term groundwork will be carried out by the lead experts that designed, built, tested, and delivered both versions of the current ALMA Central LO Article, and who are therefore fully versed in the ALMA requirements and interfaces.

The areas that we have targeted for enhanced performance in this study are motivated by the following goals:

- To provide a clear roadmap towards the scientific goals made possible by extending ALMA to longer baselines, by pro-actively investigating the changes necessary to the Central LO, in order for it to support longer distances to the antennas with adequate phase stability, to allow for higher resolution imaging.
- To improve array visibility and coherence, especially for Bands 8-10 to get maximum value from the limited observing hours in these bands.
- To improve antenna-to-antenna phase stability by improvement to the Central LO photonic line length correction, providing better visibility which will also have higher impact on the shorter wavelength bands.
- To increase the dynamic range and resolution of the ALMA active phase correction, thereby lengthening the amount of time that ALMA can maintain exceptional phase stability before recalibrating.
- To present budgetary figures linked to the various options, as well as the timelines that will be required to implement and deploy the upgrades.

The study would ultimately provide a pathway for the ALMA Photonic LO to evolve.

Link CASA to the Astropy ecosystem

PI: A. Ginsburg (now U. Florida) with Rosolowsky, Robitaille, Koch

Institutions: U. Florida, U. Alberta

ABSTRACT
We propose to make ALMA data more accessible to the broader astronomical community by establishing a rich suite of analysis tools that extend the existing CASA toolkit. In doing so, we will also provide a framework demonstrating how open source tools can be used within CASA. We will make the Astropy ecosystem accessible from within CASA and produce tools for interoperability with CASA. This project will demonstrate a testing framework to ensure compatibility between CASA and community-provided tools. It will develop compatibility tools to convert files of different formats to and from CASA formats. The study will define the standards (application program interfaces, APIs) for interoperation between CASA and community packages and implement tools that meet these standards.

The study will require the effort of an experience software developer over 1 year to implement new functionality and incorporate existing tools into CASA compatible python packages.

Development will include:

1. A robust pipeline to reproject 3D data from one coordinate grid to another, allowing ALMA data to be compared to 3D data sets from other facilities.
2. A framework for using bright spectral lines to identify the signal containing regions in other parts of the data cube.
3. A unified interface to signal identification tools and workflows.
4. Tools and documentation for conversion between CASA and community formats for images, spectra, and regions.
5. Infrastructure for remote data access via cube subsets.
6. Integration of community-developed tools (pyspeckit, xclass, gausspy, multicube) into a common framework.
7. Parallelization of analysis tasks within spectral cube.
8. A curated repository for user-submitted workflows, i.e., Jupyter notebooks analogous to CASA guides for the reduction and analysis of ALMA projects.

Cycle 7 NRAO ALMA Development Study Proposal – ALMA Archive Science Mining

PI: P. Teuben with M. Pound

Institutions: U. Md.

ABSTRACT
We propose a study to create a prototype Science Query Database that enables broad science-driven queries of ALMA projects. Our goal is to enable science discovery with ALMA archival data by enhancing users' ability to identify, access, and examine relevant data sets through database access to scientific and observational metadata. This study proposes a design and prototype implementation as a pathfinder for a full ALMA implementation.

We will design and construct a Science Query Database on an Amazon Web Services (AWS) testbed using selected public Cycle 5 data. We will image, as necessary, and run the ALMA Data Mining Toolkit (ADMIT) on full projects to create a standard set of science products, and ingest the ADMIT science metadata (e.g., line identifications, line characteristics, source intensities, image statistics, source coordinates) into the Science Query Database. We will merge these metadata with metadata harvested from the ALMA Science Archive system and the u,v and image data files. Combining these with the existing archive interface capability of searching project abstracts and science keywords will allow investigators to make queries that dig through the data rich archive to facilitate new science and explore new ideas.

We will create a new AstroQueryLite Python package to showcase how this implementation can be integrated into many user environments. We will use remote Jupyter notebooks for our study, which are familiar to many astronomers. The outcomes of this study will be: the design framework for including science metadata in future ALMA archive upgrades, a prototype implementation of a Science Query Database and associated access tools, and a test of the viability of AWS as an archival database server for public use.

Cycle 7 NRAO ALMA Development Study Proposal – ARCADE: ALMA Reduction in the CANFAR Data Environment

PI: Helen Kirk with Wilson, Brown, Bemiss

Institutions: NRC Herzberg, McMaster University

ABSTRACT
ALMA is among the most exciting operating telescopes, thanks to its unique combination of wavelength coverage, sensitivity, and imaging capability. ALMA is so far beyond the previous state-of-the-art that every observation represents a major step forward, and has the potential for important (and often startling!) results well beyond what the original observer may have intended. This makes the ALMA archive an incredible resource – if it could be used to its full potential. Unfortunately, the size of the data sets is a major barrier. Here, we propose to unleash the potential of the ALMA archive by providing a dedicated interactive processing system with sufficient computational resources and all versions of CASA pre-loaded. This system will address one of the main points of the ALMA Development Roadmap, namely improving "the functionality needed for the community to mine the ALMA archive efficiently".

Our proposed platform is called ARCADE, ALMA Reduction in the CANFAR Data Environment. ARCADE builds off the computing infrastructure and interfaces developed by the highly successful CANFAR (Canadian Advanced Network for Astronomical Research) science platform. CANFAR uses resources provided by Compute Canada to provide an accessible interface for astronomers to securely, reliably and permanently store and share large datasets (VOSpace) and access significant computational resources through semi-interactive (Open Stack) and non-interactive (Batch Processing) modes.

ARCADE will be a web-accessible, fully interactive computing environment tailored to ALMA users. We already have a prototype with significant computing resources that comes pre-loaded with several versions of CASA. Our goal is to improve the functionality of this prototype system and to determine the feasibility of rolling out a fully-developed version of ARCADE to the wider astronomical community. Specifically, we seek to:

- Fully test the performance and usability of the prototype and determine what changes are necessary to enable larger-scale use.
- Increase the functionality of the prototype. We will integrate and fully test all versions of CASA within ARCADE (back to version 3.4.0, as recommended for reprocessing Cycle 0 data). We will also explore adding other ALMA tools to the software suite offered, including ADMIT and CARTA.
- Fully test the backend technology, including a containerized environment, cloud desktop environment, and cloud storage with remote data access.
- Determine the additional steps needed to scale out the deployment of ARCADE to multiple simultaneous users, each with independent computing resources.

Our study includes an external science team to test the usability of our system. Co-I Wilson and her group are mining the ALMA archive for large samples of spectra of nearby galaxies to analyze the relationships between dense and total molecular gas content and star formation rate in a wide range of galactic environments. Running this project successfully on ARCADE will require the team to download, re-calibrate, and image a number of spectral datasets using multiple versions of CASA. As such, the

external science team will be testing the capabilities of ARCADE under similar conditions to a science driver use-case emphasized by the ALMA Development Roadmap, i.e., mining archival spectra. Finally, we note that while our emphasis is on enabling ALMA archival science, these capabilities will also serve to enable PI science.