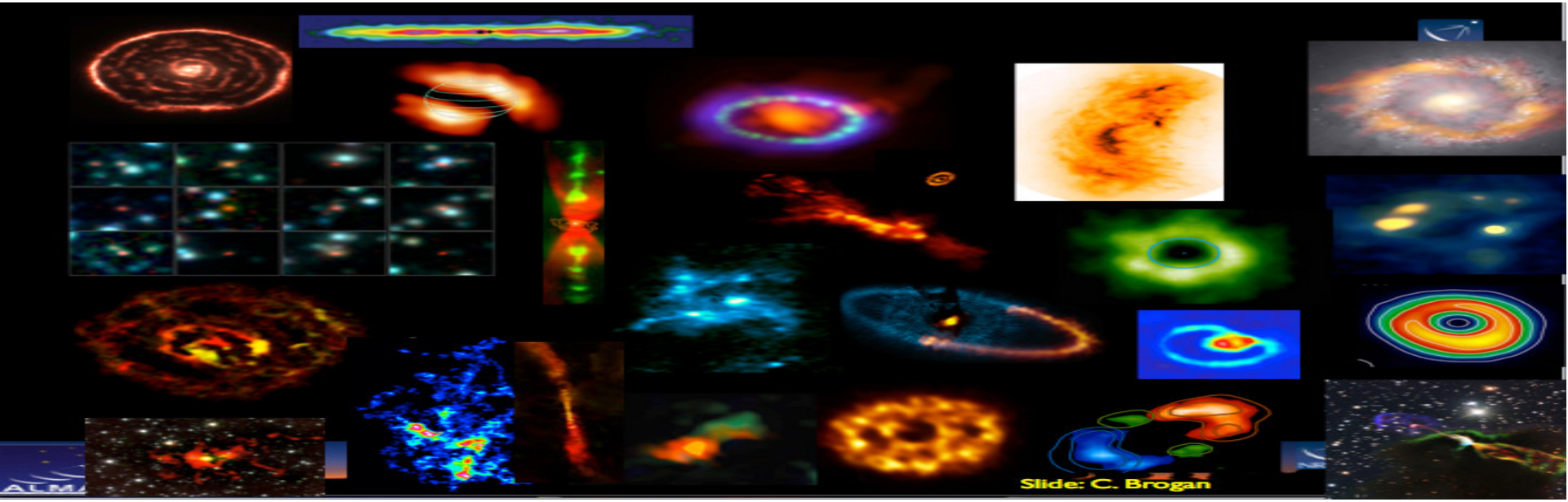
ALMA/NA Development Status

Workshop, Goteborg, May 2016



A Short Overview

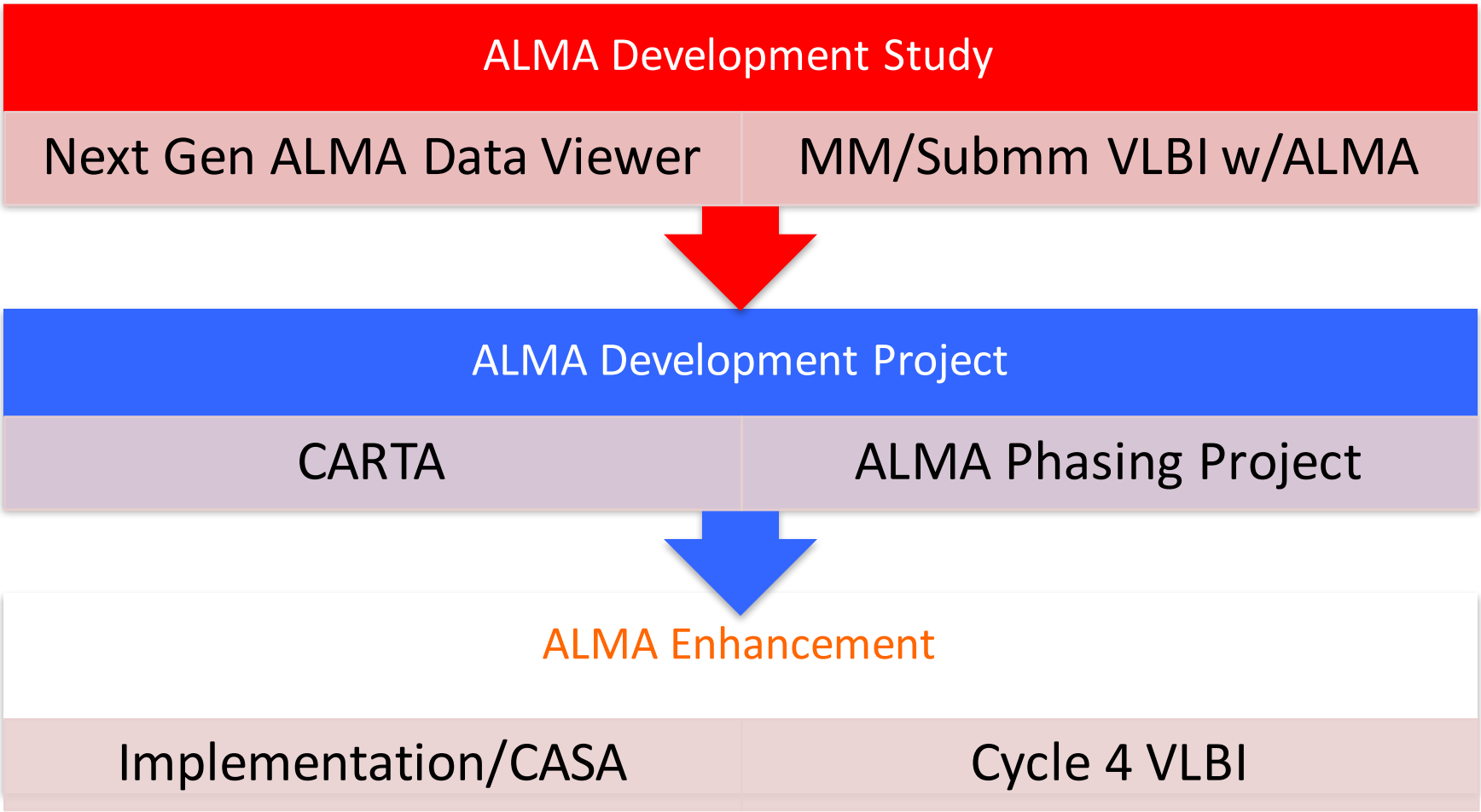
Al Wootten

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

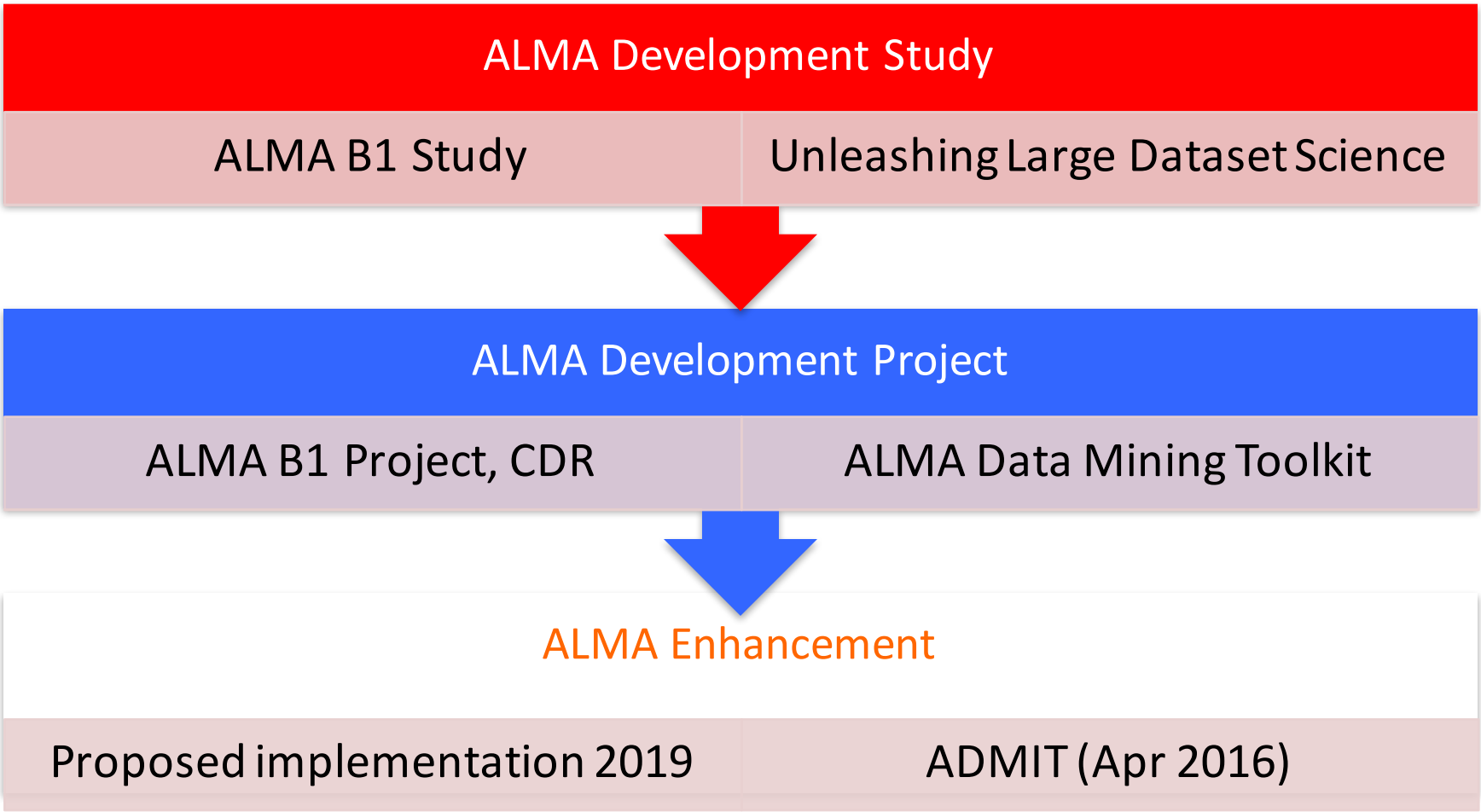
ALMA Development Jargon

- Projects are large efforts, budget >$.2M taking several years, culminating in major new capabilities or improvements
  - Begin with recommendation of ALMA Executive(s), perhaps in response to a Community Call
  - Need approval of ALMA Development Steering Committee, ASAC and recommendation of ALMA Director to ALMA Board
- Studies and small projects are shorter term, lower budget endeavors
  - Normally, Studies are initiated by a Community Call for Ideas
  - May lead to projects, singly or collectively
  - Funding at discretion of ALMA Executives
- Both are guided by a constellation of potential improvements, many listed in a document known as 'ALMA2030'

Progression of ALMA Development Components



Progression of ALMA Development Components



A ROAD MAP FOR DEVELOPING ALMA

ASAC Recommendations for ALMA 2030

- Finish the Scope of ALMA (B1 + B2 receivers, VLB capability)
  - Detailed in **ALMA Scientific Specifications and Requirements** (ALMA-90.00.00.00-001-B-SPE)
- Recommended development paths (ASAC)
  - 1. Improvements to the ALMA Archive: enabling gains in usability and impact for the observatory.
  - 2. Larger bandwidths and better receiver sensitivity: enabling gains in speed.
  - 3. Longer baselines: enabling qualitatively new science.
  - 4. Increasing wide field mapping speed: enabling efficient mapping.
- What are the NRAO/ALMA objectives?
  - Augment ALMA scientific capabilities while benefitting NRAO goals.
  - E.g. B2 has clear complementarities with ngVLA (and GBT).
  - Next Generation Correlator also has clear complementarities with ngVLA.

NA Development Project Summary

ID	Study	PI	Lead Institution	Colaborating Institution(s)	Schedule	JAO Contact
P01	Band 5 Local Oscillator Production	E. Bryerton	NRAO	ESO	Complete, see Eu Project	G. Marconi
P02	Fiber JAO-AOS	J. Ibsen	JAO	NRO, ESO	Complete, awaits license	J. Ibsen, G. Siringio
P03	ALMA Phasing Project	S. Doeleman	MIT	JAO	Completion FY2016	L. Nyman
				First Call TOTAL (K)		
P04	Band 3 CC Magnet Deflux	F. Jiang	NRC-Herzberg	NRC	Completion FY2016	S. Asayama, G. Siringio
P05	ALMA Data Mining Toolkit	L. Mundy	U. Md.	NRAO+	Completion FY2016	S. Leon
P06	Next Gen ALMA Image Viewer	E. Rosolowsky	U. Calgary	NRAO+	Completion FY2016	
P07	Band 2 Proto Cartridge	K. Saini	NRAO	CalTech	Completion FY2016	
P08	Central LO Expansion	C. Jacques	NRAO		Installation Dec 2015	B. Lopez

NA Development Study Summary: Cycle 1

The first call for ALMA Development Studies (Cycle 1) was reported in eNews https://science.nrao.edu/enews/5.6/index.shtml#almadev.
77 investigators associated with 26 institutions responded to the Call with a total of 21 Study Proposals, of which the following 8 were funded.

Cycle 1 Study Title *(hover for linked reports)*	PI	Notes
Second Generation Receiver for ALMA Band 6 (*Study continues into Cycle 2*)	Anthony R. Kerr (NRAO)	
Ultra-wideband quantum limited amplifiers for receiver frontends	D. Woody (Caltech)	
Design Study for Production of the Band 2 Cartridges	Eric Bryerton (NRAO)	Study has become a Cycle 2 ALMA Development Project: *Design and Testing of a Prototype Band-2 Cartridge* (PI: K. S. Saini)
A Visualization Portal for ALMA Data	E. Rosolowski (UBC-Okanagan)	Study has become a Cycle 2 ALMA Development Project: *The Next Generation ALMA Viewer* (PI: E, Rosolowsky)
Millimeter/Submillimeter VLBI with ALMA	Jeff Kern (NRAO)	Study was associated with an ALMA Development Project now reaching realization: *The ALMA Phasing Project* (PI: S. Doeleman, MIT)
Unleashing Large Dataset Science	Lee Mundy (Univ. Maryland)	Study has become a Cycle 2 Development Project: *ALMA Data Mining Toolkit: ADMIT* (PI: Lee Mundy)
Increasing the ALMA Data Rate	B. Glendenning (NRAO)	NOTE: Study proposal was withdrawn
ALMA Band 1 Receiver Development Study	P.T.P. Ho (ASIAA)	Study has become an ALMA Development Project led by East Asia, in collaboration with North America and Universidad de Chile

NA Development Study Summary: Cycle 2

The second call for ALMA Development Studies (Cycle 2) was reported in eNews Feb 2014: https://science.nrao.edu/enews/7.3/index.shtml
9 submissions were received from 8 PIs with teams totaling 41 investigators from 17 institutions; 6 were funded.

Cycle 2 Study Title	PI	Notes
Advanced Solar Observing	T. Bastian, NRAO	Study has resulted in ALMA offering solar observations in Cycle 4 Observations
2nd Generation Band 10 Receiver	A. Kerr, NRAO	
Community Science Tool Development	A. Leroy, NRAO	
2nd Generation Band 6 Receiver	A. Kerr, NRAO	
Millimeter Camera	S. Claude, NRC-Herzberg	
Calibration Refinements for ALMA Imaging	T. Wilson, NRL	

NA Development Study Summary: Cycle 3

Results from the third call for ALMA Development Studies (Cycle 3) were reported in eNews Dec 2015:
https://science.nrao.edu/enews/8.11/index.shtml
15 submissions were received from 15 PIs with teams totaling 53 investigators from 19 institutions; 7 were funded.

- Note: the due date for Reports for Cycle 3 Studies has not yet occurred.

Cycle 3 Study Title	PI	Notes
Extensions & Enhancements to the ALMA Phasing System	L. Matthews, MIT	
Spectral Resolution and Bandwidth Upgrade of the ALMA Correlator	R. Lacasse, NRAO	
Improving the Calibration of Atmospheric Spectral Features	T. Hunter, NRAO	
Pulsars, Magnetars, and Transients with Phased ALMA	J. Cordes, Cornell	
Feature Extraction and Data Cube Visualization through Topology	P. Rosen, U of Utah	
Advanced Materials and On-wafer Chip Evaluation: 2nd Generation	A. Lichtenberger, UVA	
Digital Correlation and Phased Array Architectures	J. Weintroub, SAO	

NA ALMA Development – QSU2

Current Studies (Cycle 3)

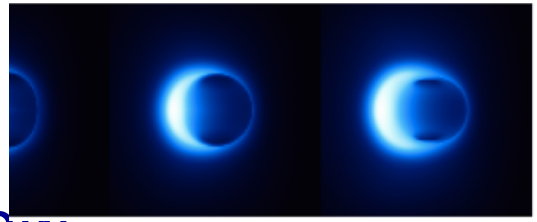
PMD ID	Status	NRAO Study	PI	Lead Institution	Collaborating Institution(s)	Budget ($)
365	**Active**	Spectral Resolution & Bandwidth Upgrade of the ALMA Correlator	R. Lacasse	NRAO	JAO, UVA, U. Bordeaux	196,770.00
385	**Active**	Improving the Calibration of Atmospheric Spectral Features in ALMA Data	T. Hunter	NRAO	JAO, IRAM	68,411.00
					SubTotal	**265,181.00**
PMD ID	**Status**	**External Study**	**PI**	**Lead Institution**	**Collaborating Institution(s)**	**Budget ($)**
N/A	**Active**	Extensions and Enhancements to the ALMA Phasing System	L. Mathews	MIT Haystack	N/A	199,800
N/A-SSR	**Active**	Pulsars, Magnetars, and Transients with Phased ALMA	J. Cordes	Cornell University	MIT, MPIfR, NRAO	185,267
N/A-SSR	**Active**	Feature Extraction and Visualization of ALMA Data Cubes through Topological Data	P. Rosen	University of Utah	NRAO	185,133
N/A	**Active**	Advanced Materials and On-wafer Chip Evaluation for Second Generation ALMA	A. Lichtenberger	UVA	N/A	183,504
384	**Active**	Digital Correlator and Phased Array Architectures for Upgrading ALMA	J. Weintroub	SAO	U. Bordeaux, NRC, NRAO	147,915
					SubTotal	**901,619.00**
					Total Cycle 3 Studies Award	**1,166,800.00**

All Cycle 3 Studies are underway.

ALMA Development Program

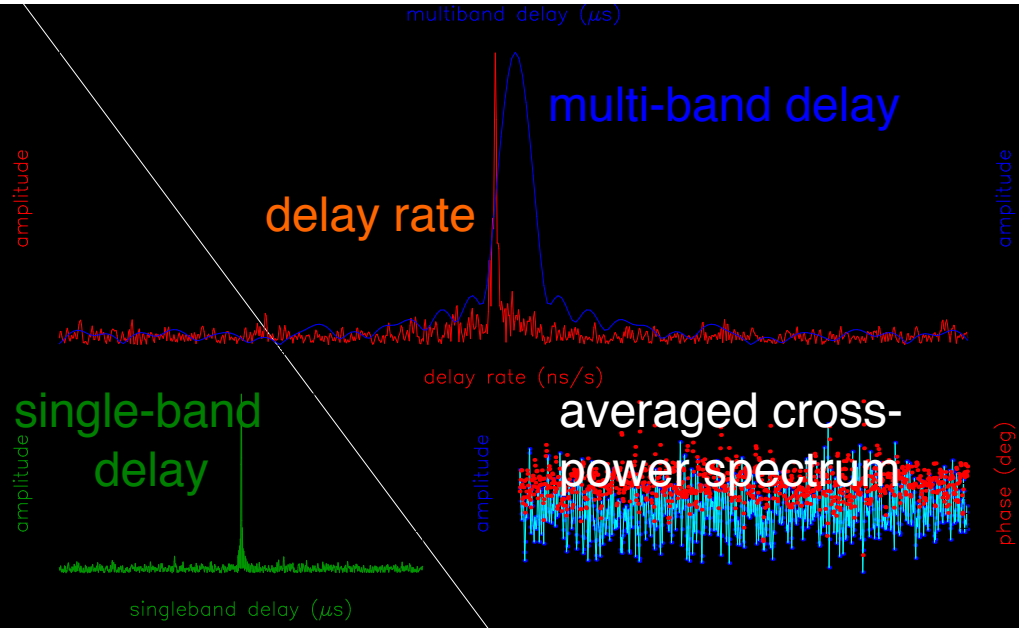
- The last *Call for Study Proposals* was released 01 March 2016
- A Proposal Webinar was held on 15 March 2016
- The Proposal deadline was COB 02 May 2016
- Proposal categories were:
  - Advanced techniques
  - Advanced hardware
  - Advanced software
- The Call does not emphasize any particular category
  - There were 12 ALMA Development Study submissions. Along the with 12 Principal Investigators, there were 34 co-Investigators, from nine institutions. Funding requests totaled $2.2M.

Existing Projects Status



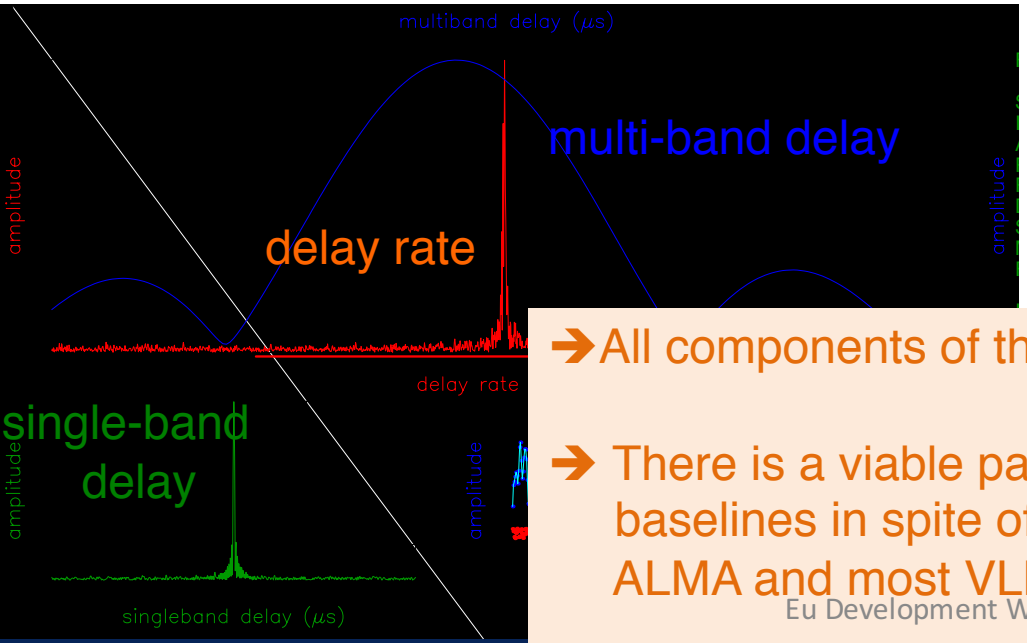
- ALMA Phasing Project (NA)
  - Key science: Test GR using BH Shadow
- ALMA Band 5 Project (EU/NA)
  - Key science: [C II] at z~8-10; Water
- JAO-AOS Fiber Link Project (JAO, NA, Eu)
  - 150km fiber connects AOS to Chilean internet (RE[illegible]d to the world
  - Operational, in testing. Awaiting permits.

APP Project: First Intercontinental VLBI Fringes with ALMA



Phased ALMA – IRAM 30m:
March 30, 2015

- Band 6 (1.3 mm); Source 3C273
- 9770 km baseline



Phased ALMA – VLBA (MK)
(plus 5 other VLBA stations):
August 1, 2015

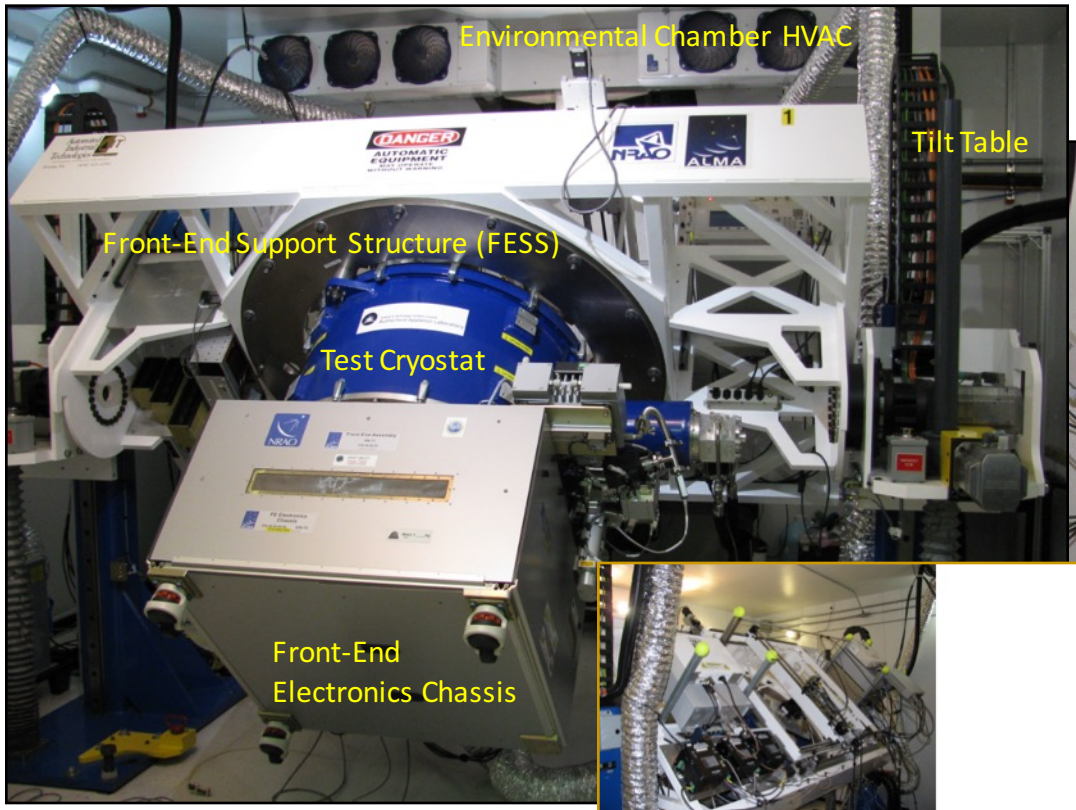
- Band 3 (3 mm); Source 3C454.3

➔All components of the APS hardware are working to spec

➔ There is a viable path to correlation of VLBI data on ALMA baselines in spite of the different sampling rate used by ALMA and most VLBI sites

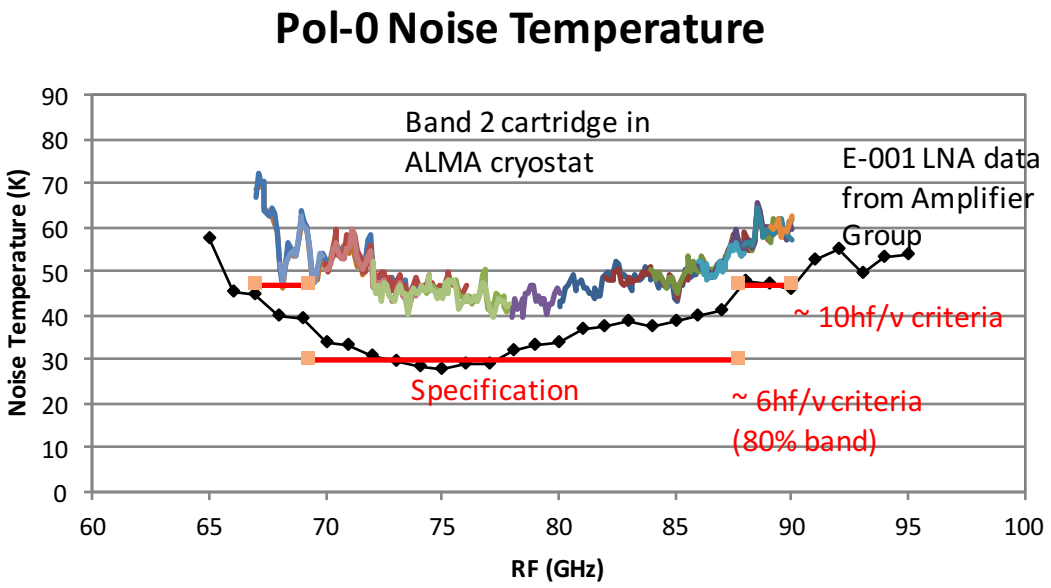
ALMA Band 2 Receiver Prototype

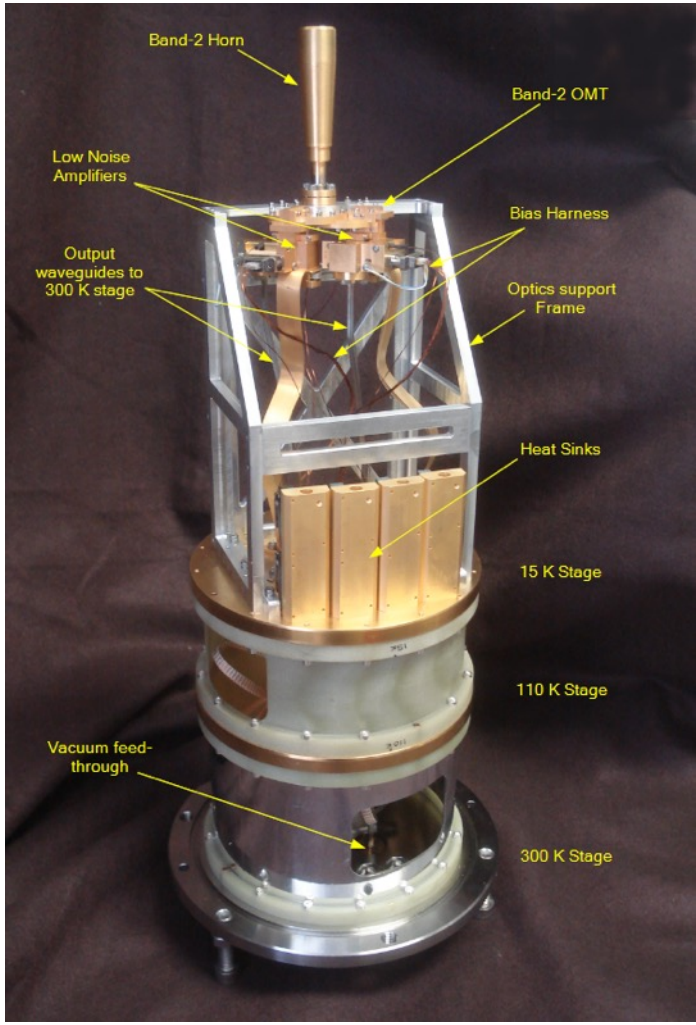
Evaluation in the ALMA Cryostat



NSI Beam Scanner

ALMA Band 2: NRAO





- Cartridge built and tested with temporary NRAO design
- Awaiting CRAL MMIC based LNAs for testing and possible incorporation into design
- Some optics features to be addressed
- Note that there is also a EU B2+3 study with some NAOJ involvement.

ALMA Subarray Expansion

- **Central LO Expansion to 5 Sub-arrays Project:**
  - Commissioning tests and acceptance being planned.
  - The fifth sub-array commissioning was completed and the PAS report is being prepared.
  - One of the four (1 of 4) laser synthesizers is defective. The CLO meets engineering requirements without the fourth laser synthesizer.

Band 3 Magnet and Heater Project

- CNRC has proposed heater circuits to deflux Band 3 cartridges. Chosen option:
  - 1. Modify the bias box to re-route the heater circuit lines to unused lines in the Band 3 cartridges. Pol0 and Pol1 heater circuits would both become functional.
- Stability improvement expected
- The Cold Cartridge is being assembled into a Front End which will be installed in PM-03 for verification (field) testing. An implementation plan (based on assumed positive test results) is in work

2. Removal of hysteresis in PIV curves.

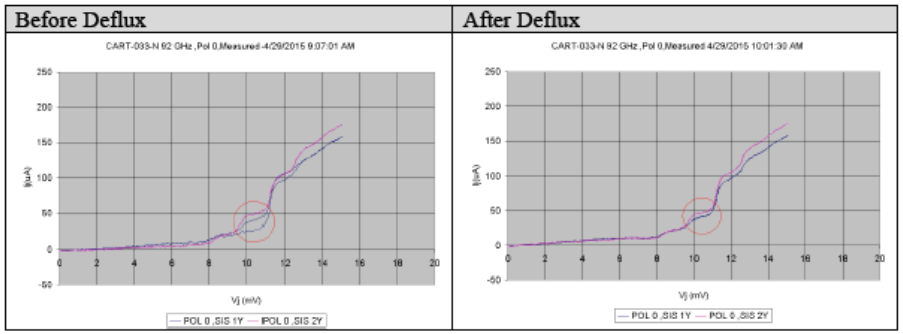


Figure 4: Hysteresis Disappears

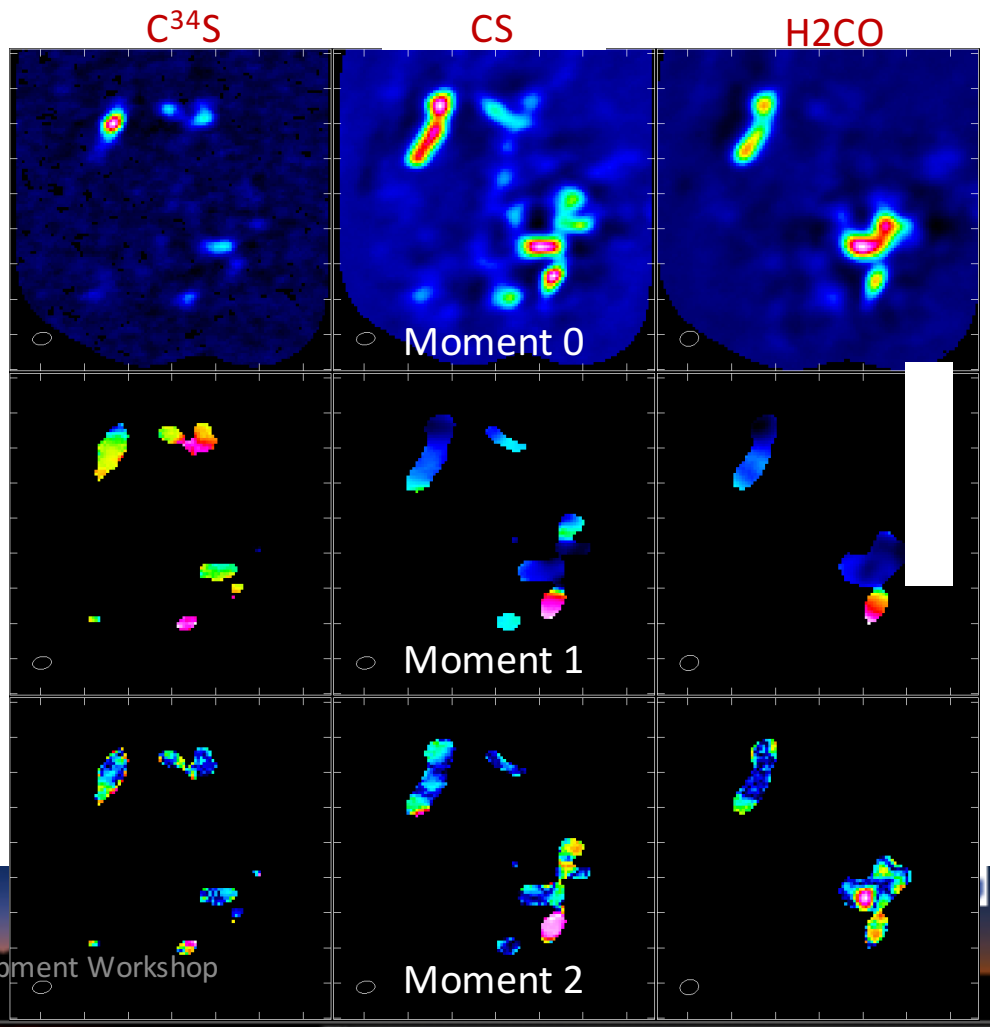
ADMIT

- Operates on data cubes only; cubes can be FITS or casa image format
- Compatible with CASA environment and utilizes CASA routines where possible
- Products are self-documenting with XML; compatible with future ingestion by a database

Each data cube get a full set of products
See: admit.astro.umd.edu/admit-M4 and
click on and xxx.admit directory

Spectra based on peak flux and noise in each channel

Blue and green spectra highlight impact of missing flux



Two spectra used in line ID of CS J=5-4

ADMIT

Two modes of Operation:

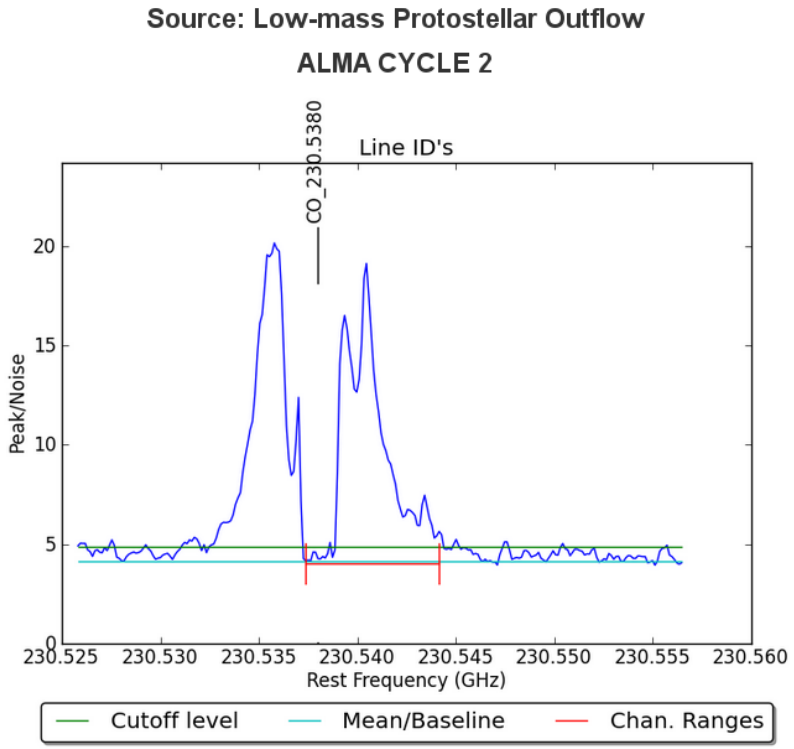
- In-line (pipeline mode producing standard set of products):
  - ADMIT runs after QA2 and before archive ingestion (ideally as a pre-step to the archive ingest process) – details being worked with ALMA Project
  - ALMA archive user can select to download ADMIT tarball (20-40Mb)
    - XML, PNG, and HTML files; limited FITS files – details to be decided with ALMA Project
  - Browser-based viewer allows user inspect products once downloaded
  - ADMIT summary XML file allows user to recreate the ADMIT products

- Off-line (user created data products):
  - The ADMIT Toolkit "add-on" available from the CASA download page
  - Flow-model for creating and re-creating products - viewable in the browser
  - Environment for expanded exploration of data sets:
    - Principle component analysis of emission
    - Overlap integrals
    - Comparisons across multiple windows and multiple sources
    - New tools for examining large data cubes

ADMIT

- Automated line ID which allows line-based operations: moment maps, PV slices, etc
- Pipeline produces set products for users which can be determine by ALMA
- Users can create their own custom products locally, which can be applied across sources

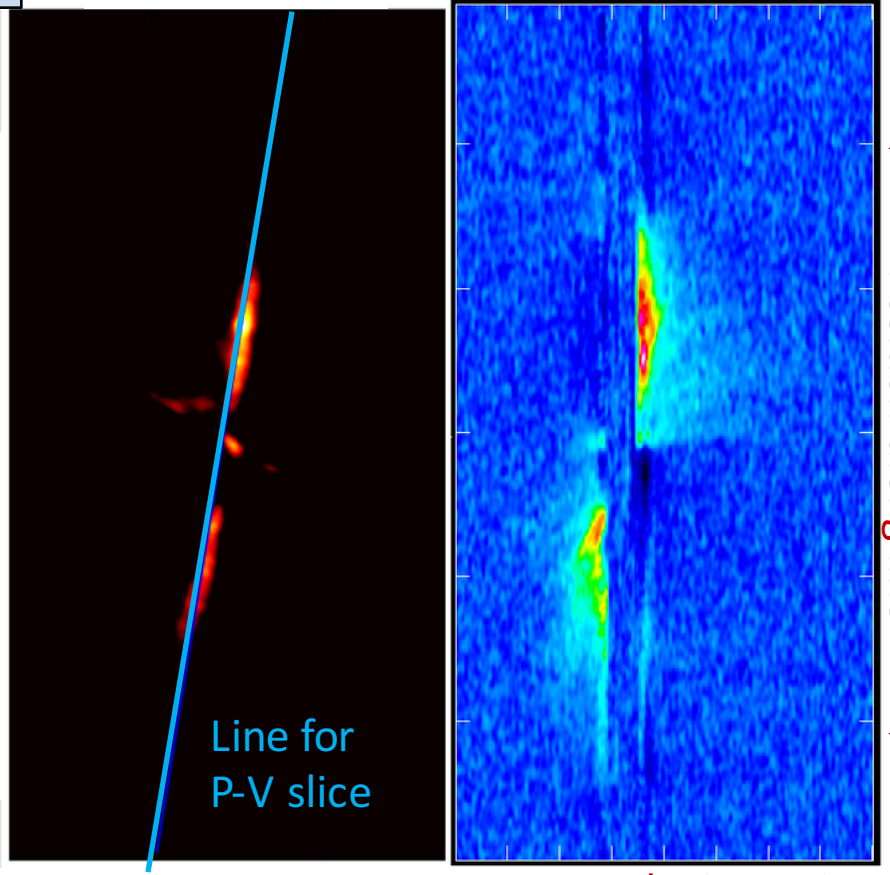
Conservative automated line ID: do no bad ID



Spectrum: peak emission over noise per channel

Moment 0

Position-Velocity Slice



Identified lines

frequency	formula	transition	velocity	fwhm	startchan	endchan
230.53800	CO	2-1	1.200E+01	3.503E+00	100	155

ADMIT

Timeline for Science users:

- November 2015: Requested start date for testing of Cycle 3 data from imaging pipeline at ARCS.
  - Needed for robustness testing against operational products in April 2016
  - Allows interaction with interested scientists to verify/improve products

- TBD: Deployment of ADMIT pipeline within ALMA to create products for archive ingestion.
  - Date and final design to be decided in discussion with the ALMA project

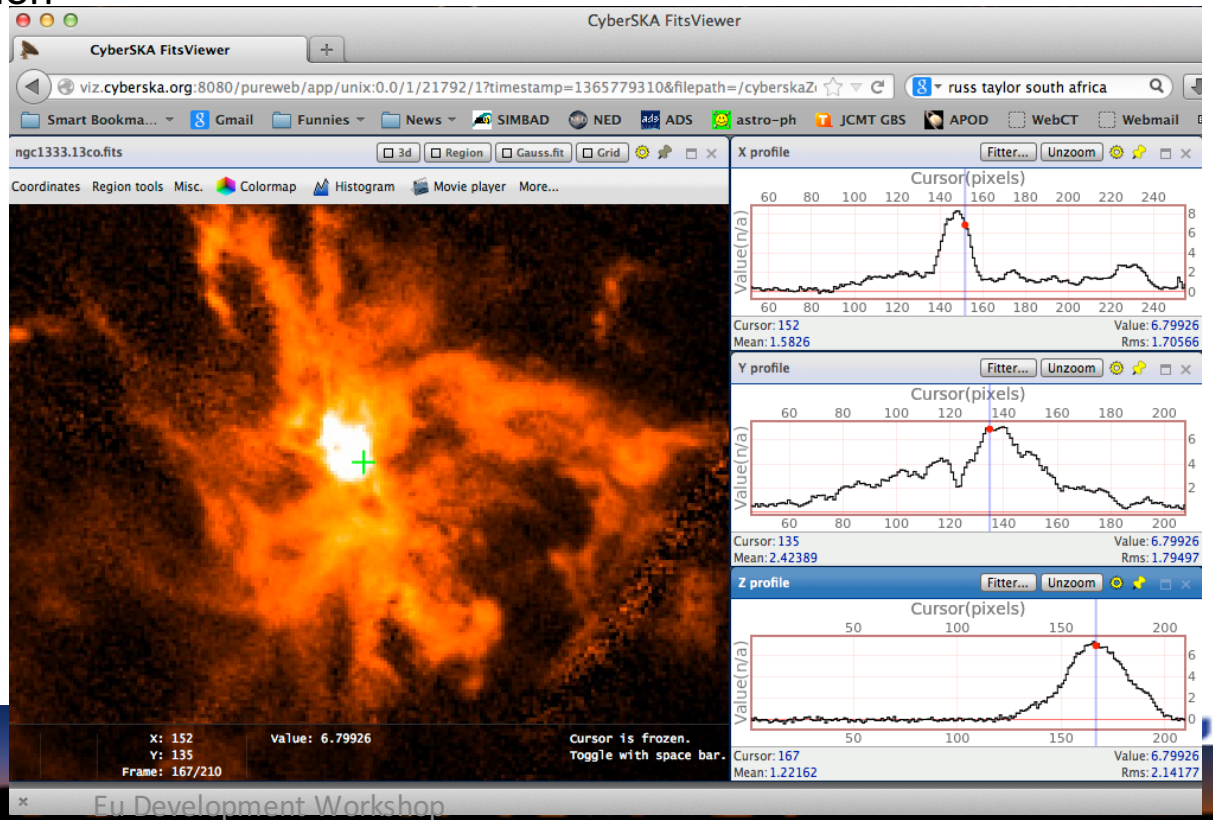
- Status: Delivery of completed software system seeks no-cost extension
  - End of funded ALMA Development Project is April 30, 2016
  - Contract requires delivery of all software and documentation
  - Options for continued support will be explored with ALMA/NRAO

Archive Enhancement- II

- CARTA: Cube Analysis and Rendering Tool for Astronomy (also known as the "Next Generation ALMA Viewer")
  - Designed to navigate and analyze large data cubes as a replacement for the CASA image viewer tool
  - Operates stand alone or as web-server co-located with archive
  - Provides scripted interaction

October 2015 -- Beta testing and design review. Email Erik Rosolowsky (rosolowsky@ualberta.ca) if you would like to participate.

2016 -- Installation into ALMA archive and distribution with CASA.



Towards a Second Generation SIS Receiver for ALMA Band 10

A. R. Kerr, J. Effland, A. W. Lichtenberger, and J. Mangum

- Nb/Al-AlOx/Nb SIS junctions used above the energy gap frequency of Nb resultq in relatively high noise temperatures
- These junctions also have a greater variation in T_{noise} across the band, as making high quality junctions with low enough capacitance to allow a broadband mixing circuit to be incorporated within the mixer is difficult.
- Solution:
  - design of mixers with NbTiN counter-electrodes whose higher superconducting energy gap increases the frequency limit above which the mixer performance degrades
  - Nb/Al-AlN/Nb SIS junctions have been made with critical current densities as high as 30,000 A/cm2, allowing the area to be reduced by a factor of 3 to 4, and the capacitance correspondingly reduced, while maintaining a desired junction conductance.
  - initial development has been done using half-frequency-scale SIS mixers (approximately ALMA Band 8) with Nb/Al-AlN/Nb junctions.
  - Nb/AlN/NbTiN SIS junctions will be used for the new Band 10 mixers

New NA Studies

Seven Studies from 33 proposers representing ten institutions fit within the funding envelope and were proposed for North American funding with the consent of the National Science Foundation.

Study	PI	Institution	Co-Is	Institutions
Digital Correlator and Phased Array Architectures for Upgrading ALMA	Weintroub	Smithsonian Astrophysical Observatory	Weintroub,Baudry, Carlson, Doeleman, Escoffier, Lacasse, Rosenfeld, Rupen	Smithsonian Astrophysical Observatory, U. Bdx, NRC, NRAO
Improving the calibration of atmospheric spectral features in ALMA data	Hunter	NRAO	Hunter,Phillips, Broguiere	JAO, IRAM, NRAO
Pulsars, Magnetars, and Transients with Phased ALMA	Cordes	Cornell University	Cordes, Chatterjee, Crew, Doeleman, Kramer, Lazio, Ransom	MIT/Haystack Observatory, Max Plank, NRAO
ALMA Study Project: Extensions and Enhancements to the ALMA Phasing System	Matthews	MIT	Matthews, Crew, Doeleman, Fish, Hecht	MIT
Feature extraction and visualization of ALMA data cubes through topological data	Rosen	University of Utah	Rosen, Wang, Johnson, Kern, Mills	University of Utah, NRAO
Advanced materials and on wafer chip evaluation for second generation ALMA	Lichtenberger	University of Virginia	Lichtenberger, Lu	University of Virginia
Spectral Resolution and Bandwidth Upgrade of the ALMA Correlator	Lacasse	NRAO	Lacasse, Escoffier, Greenberg, Saez, Treacy, Webber, Baudry, Amestica, Stan	NRAO, retired consultant, JAO, Universite de Bordeaux

Correlator Upgrade Performance Enhancements
Lacasse, PI

- X8 ***enhancement in frequency resolution***.
  - Spectral resolution for every mode increases by a factor of **eight** for integration times of 128 msec and greater. For example, from Table 2 of the correlator specification (next slide) (http://edm.alma.cl/forums/alma/dispatch.cgi/documents/docProfile/100591)
  - Broader band coverage at high resolution
- ***Time resolution enhancement*** for auto and cross products
- ***Higher sensitivity or shorter observing times*** can be obtained using 4-bit x 4-bit modes and/or double Nyquist mode (95% efficiency versus 85% including the effect of the 3-bit sampler). This is equivalent to adding about 8 antennas to the array or cutting integration times down by 12%! See comparison of modes 2 and 53 on the next slide…note bandwidth restrictions.
- ***Potential for subsequent upgrade to 2x16GHz processsing.***

Mode Table Changes

Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points		Spectral Resolution (KHz)		Correlation	Sampling	Sensitivity (x 0.96)
			Current	Proposed	Current	Proposed			
1	32	2 GHz	8192	65536	244	30.5	2-bit x 2-bit	Nyquist	0.88
19	32	2 GHz	4096	32768	488	61	2-bit x 2-bit	Twice Nyquist	0.94
38	32	2 GHz	2048	16384	976	122	4-bit x 4-bit	Nyquist	0.99
2	16	1 GHz	8192	65536	122	15.25	2-bit x 2-bit	Nyquist	0.88
20	16	1 GHz	4096	32768	244	30.5	2-bit x 2-bit	Twice Nyquist	0.94
39	16	1 GHz	2048	16384	488	61	4-bit x 4-bit	Nyquist	0.99
53	16	1 GHz	1024	8192	976	122	4-bit x 4-bit	Twice Nyquist	0.99
3	8	500 MHz	8192	65536	61	7.625	2-bit x 2-bit	Nyquist	0.88
21	8	500 MHz	4096	32768	122	15.25	2-bit x 2-bit	Twice Nyquist	0.94
40	8	500 MHz	2048	16384	244	30.5	4-bit x 4-bit	Nyquist	0.99
54	8	500 MHz	1024	8192	488	61	4-bit x 4-bit	Twice Nyquist	0.99
4	4	250 MHz	8192	65536	30	3.75	2-bit x 2-bit	Nyquist	0.88
22	4	250 MHz	4096	32768	61	7.625	2-bit x 2-bit	Twice Nyquist	0.94
41	4	250 MHz	2048	16384	122	15.25	4-bit x 4-bit	Nyquist	0.99
55	4	250 MHz	1024	8192	244	30.5	4-bit x 4-bit	Twice Nyquist	0.99
5	2	125 MHz	8192	65536	15	1.875	2-bit x 2-bit	Nyquist	0.88
23	2	125 MHz	4096	32768	30	3.75	2-bit x 2-bit	Twice Nyquist	0.94
42	2	125 MHz	2048	16384	61	7.625	4-bit x 4-bit	Nyquist	0.99
56	2	125 MHz	1024	8192	122	15.25	4-bit x 4-bit	Twice Nyquist	0.99
6	1	62.5 MHz	8192	65536	7.6	0.95	2-bit x 2-bit	Nyquist	0.88
24	1	62.5 MHz	4096	32768	15	1.875	2-bit x 2-bit	Twice Nyquist	0.94
43	1	62.5 MHz	2048	16384	30	3.75	4-bit x 4-bit	Nyquist	0.99
57	1	62.5 MHz	1024	8192	61	7.625	4-bit x 4-bit	Twice Nyquist	0.99
25	1	31.25 MHz	8192	65536	3.8	0.475	2-bit x 2-bit	Twice Nyquist	0.94
58	1	31.25 MHz	2048	16384	15	1.875	4-bit x 4-bit	Twice Nyquist	0.99

A New Correlator for ALMA
Weintroub, PI

- Next Generation Correlator:
  - The correlator architecture will be FX, as opposed to XF or FXF.
  - Future available bandwidth will be 16 GHz per sideband per polarization
  - Though the analog bandwidth may be sub-divided arbitrarily, it is far preferred to sample as large a sub-band as possible with the highest speed ADCs available
  - The ADCs or samplers will remain at the antennas as presently the case with ALMA with digital data sent over fiber
  - Fine spectral resolution is needed in many science projects
  - Reduce the required power and size of the ALMA correlator
  - Integrate natively features such as phased array recording for VLBI and pulsar work
  - ngVLA synergies possible

Comparison

Telescope	Algorithm	Antennas	BW/poln	SpRes	Efficiency	Time res	Sample Rate
			(GHz)	kHz (1)		(ms)	Gsps
ALMA	FXF	64	8	3.8	0.85 to 0.98	1, 16	4
ACA	FX	16	8	3.8		16	
ALMA-2	FXF	64	16	0.475	0.95 to 0.99	1, 2, …, 16	8
NextGenALMA	FX	66	16	0.001	0.96*	?	16
SMA	ASIC XF	8	8	25			0.204
SMA	SWARMFX	8	8	150			4.6
EVLA	WIDAR FXF	27	8	0.122			4
IRAM	WIDEX XF	8	3.6	39			4
IRAM	NOEMA FXF	12	3.6	39			8
CARMA	XF	15	4	31			1

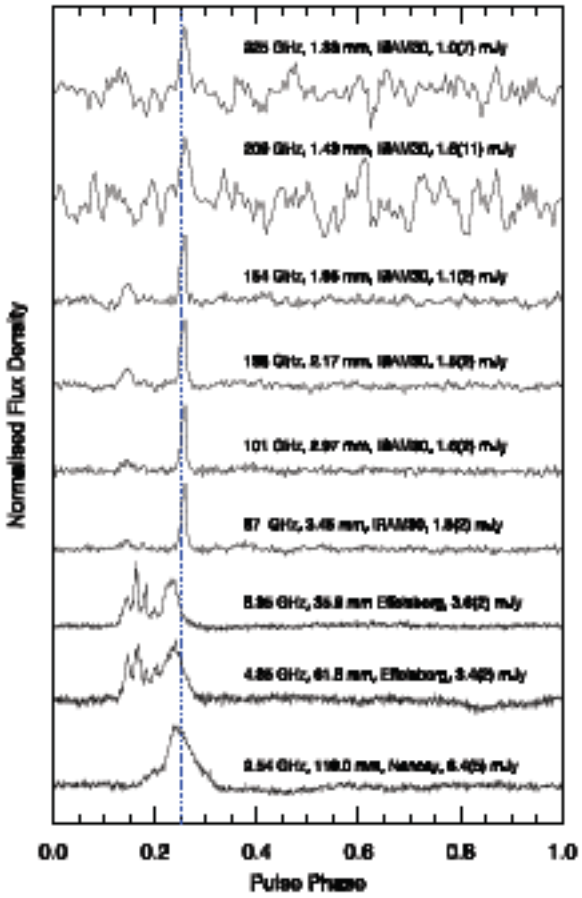
Note unknown cost in software effort of implementation of NextGenALMA

Improving the calibration of atmospheric spectral features in ALMA data
Hunter, PI

- Problem: Coarse resolution (TDM) calibration dilutes instrumental calibration of narrow atmospheric lines, giving poorer calibration
- Proposition: finer resolution calibration through TelCal application alleviates this

Pulsars, Magnetars, and Transients with Phased ALMA
PI: Cordes

- Pulsars near SgrA* are of compelling interest; there are probably many but scattering in the turbulent GC medium limits detection at low frequencies
- Magnetar J1745-2900 (0.1 pc from SgrA*) suggests scattering is variable
  - Its pulses have been seen to 295 GHz
- Study will develop two software modules to provide a capability parallel to that available on the VLA for broadband fast phased array observations



ALMA Study Project: Extensions and Enhancements to the ALMA Phasing System PI: Matthews

- Study comprises four components:
  - Extension of phasing capabilities, now offered for B3 (90 GHz) and B6 (240 GHz), to B7 (345 GHz)
    - SMA, JCMT, SMT, APEX, Pico Veleta, Plateau de Bure, potentially SPT and LMT
  - Development of correlation techniques to compensate for the mismatch in sampling rates between ALMA and other VLBI stations
  - Optimization of ALMA baseband delay application to avoid unnecessary decorrelation losses
  - Exploration of data reduction and analysis pathways for experiments utilizing phased ALMA data
- Among the deliverables will be a cookbook describing recommended calibration and analysis procedures for VLBI data that include phased ALMA as a participating station

Feature extraction and visualization of ALMA data cubes through topological data

PI: Rosen

- A feasibility study for applying forms of data analysis and visualization never before tested by the ALMA community
- A contour tree-based TDA (topological data analysis) will be used to improve upon existing data cube analysis and visualization

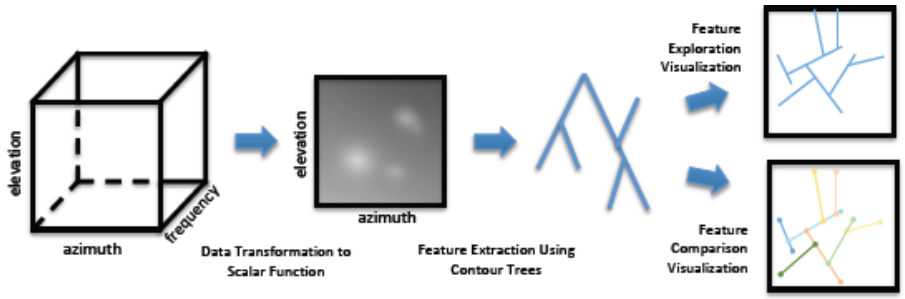


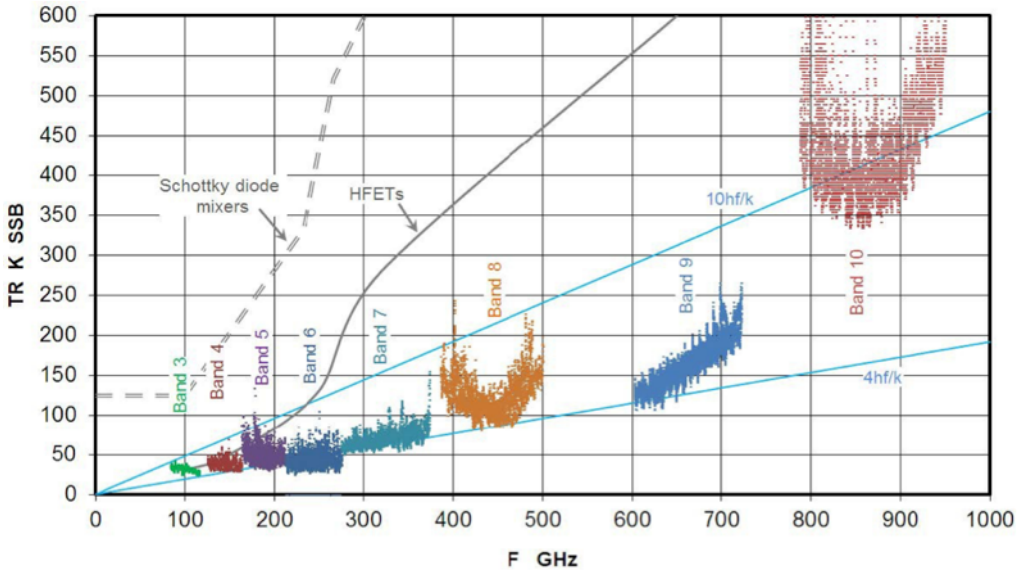
Figure 2: Overview of proposed approach.

Advanced materials and on wafer chip evaluation for second generation ALMA

PI: Lichtenberger

- Investigate an alternative materials deposition technology to realize high gap, all NbTiN SIS mixer devices
  - Incorporating such devices into B9, B10 at ALMA or superTHz mixers should markedly improve performance.
- Investigate an all-wafer SIS device I-V characterization screening technique
  - Allows screening of wafer before proceeding to labor and time-intensive detailed characterization

Single-sideband receiver noise temperature vs frequency for typical ALMA SIS receivers. Bands 3-8 have sideband-separating mixers and Bands 9 and 10 have double-sideband mixers. The performance of the upper half of band9 and the entire band10 could be improved substantially with high energy gap NbTiN/AlN/NbTiN mixers.



Immediate Future

- NA intends to launch a new Call for Projects 10 October
  - Some studies which could not be funded during the current Call may be accommodated, should PIs be able to garner resources, address concerns expressed in reviews
  - Overall funding pool is expected to be larger
- New Call for Studies also forseen during FY2017

Enhancing ALMA

- ALMA is exceptional in
  - Providing submillimeter sky access (a unique interferometer at the highest frequencies).
  - ALMA's resolution is highest in these highest bands
  - Instrumentally, submm observing is a trying task
- High frequency weather is extremely limited (<15% of time concentrated in austral winter)
- One goal could be to enhance access to these exceptional capabilities?

ALMA Operational Phases

- Construction and commissioning concluded.
- Extension of ALMA capabilities continues.
- Continued Development was featured in the Ops Plan, reviewed by Intl Committee and by NSF Committee then adopted by ALMA Board.
  - No funding agency funds a 'pig in a poke'. The character of development must be defined.
  - The Ops plan provides funding for Studies to define the character and implementation of possible new capabilities
  - ALMA Development Studies funded by the Development funding lines in the three parties form the fabric for 'ALMA 2030' recommendations made by the ASAC
  - ALMA is currently in the process of fashioning a plan for the next decades

ALMA Science Requirements

ALMA now essentially meets three "level I" science goals:

- *The ability to detect spectral line emission from CO or C^+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation;*
- *The ability to image the gas kinematics in a solar-mass protostellar/protoplanetary disk at a distance of 150 pc, enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation;*
- *The ability to provide precise images at an angular resolution of 0.1"*

- **Demonstrated goals**
  - High Fidelity Imaging.
  - Routine sub-mJy Continuum / mK Spectral Sensitivity.
  - Wideband Frequency Coverage.
  - Wide Field Imaging through Mosaicing.
  - Submillimeter Receiver System (..& site..).
  - Full Polarization Capability.
  - System Flexibility (hardware/software).
  - Ease of use—PI receives calibrated data and reference image from ALMA Resource Center, all archived.

Development Items for ALMA 2010-2020

- Science clearly benefits from improving
  - Throughput (collecting area, instantaneous bandwidth, uv coverage)
  - Bandwidth (all accessible frequencies)
  - Resolution
- Many other possibilities
  - ASAC Report
  - Correlator upgrade
  - Longer connected baselines
  - Are any science goals endangered to whose realization development could contribute?

ALMA's Future

- The original specifications and most construction contracts were let ~15 years ago; those specifications are mostly demonstrated
- Technology has advanced tremendously since
- The community is outlining a new vision to extend ALMA science into the future
- ALMA Development funds enable studies which can underpin that vision
  - Studies are available at NAASC Development website, open to community participation
  - SACs and science team combined these into a palette of possible upgrades summarized in 'ALMA2030'
  - Community now engaged in transforming these elements and others into a science-driven vision for the next 5-15 years
- ALMA Development Projects fund upgrades to ALMA to achieve that vision, as they have for Band 5, and will for the remaining Bands and other capital investments

(A Few) Science Drivers

- Protostars, protoplanetary disks and their evolution
  - Disk composition, around stars and around planets; disk evolution (sensitivity, spectral grasp, resolution, imaging precision)
  - Characterization of planets (sensitivity, resolution)
    - Astrometry: measuring stellar reflex motions
    - Transit measurements (sensitivity, spectral grasp)
  - First Galaxies
    - From metal formation in the first stars, to the peak of star formation (sensitivity, spectral grasp)
    - Identification, imaging, composition and kinematics of the first galaxies (sensitivity, resolution, spectral grasp)
    - Particular synergy with large total power instruments
  - Galaxies
    - Probing central masses whether starbursts or black holes
    - Characterizing chemical content and understanding its message

Possible Development Areas

- Sensitivity--could achieve that of 8 additional antennas with each of
  - Use of all available antennas (near-term)
  - Correlator accuracy (spectral line, near-term)
  - Increased bandwidth, correlator upgrade to 2x or 4x
- Resolution—5millarcsec
  - Imaging disks down to habitable zone scales (continuum). Near 350μm corresponds to 16 km, difficult; at lower frequencies ~60km, requires longer baselines
- Field of View
  - Some gains possible with efficiency improvement, On-the-fly
  - Multi-pixel or beam-forming arrays; more important at shorter wavelengths probably

Community Input Meetings

- The Development Vision Working Group will seek advice from throughout the ALMA community
  - Synergy with other large facilities (JWST, LSST, GMST/ELT, Ligo/Virgo/Kagra, FIR Explorer)
  - Seek to inform the vision from discourse with worldwide ALMA partners
- Several community meetings planned

- *NA Development Study proposals received 2 May; being refereed; additional Call in October*
- *EU Development Studies Call: May/June with deadline in September*
- *EU Workshop on Development: May 25-27, 2016 (Chalmers, Sweden)*
- *NA Development splinter session at AAS 14 June*
- *NA Development workshop: 24 August 2016 @NAASC*
- *September 2016: 'Current and Future Development Activities at ALMA' presentation/panel discussion at the ALMA international conference.*

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