The Atacama Large Millimeter/submillimeter Array: Current Status

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Joint ALMA Office

ESO -- October 30, 2007

Overview

- International project to build & operate a large (up to 80-antennas) millimeter/submm (λ ~0.85-3mm) array at high altitude site (5000m) in northern Chile.

(Partners: ESO – US/Canada – Japan – Chile)

- Project began in 2002
- Japan joined in 2004
- site construction, hardware production lines, software development 2007,
- 66 antennas in production, first antennas arrived 2007;
- early science ~2010, full science operations 2012.

- Two orders-of-magnitude improvement in mm radio astronomy capabilities.

Japan – ALMA-J

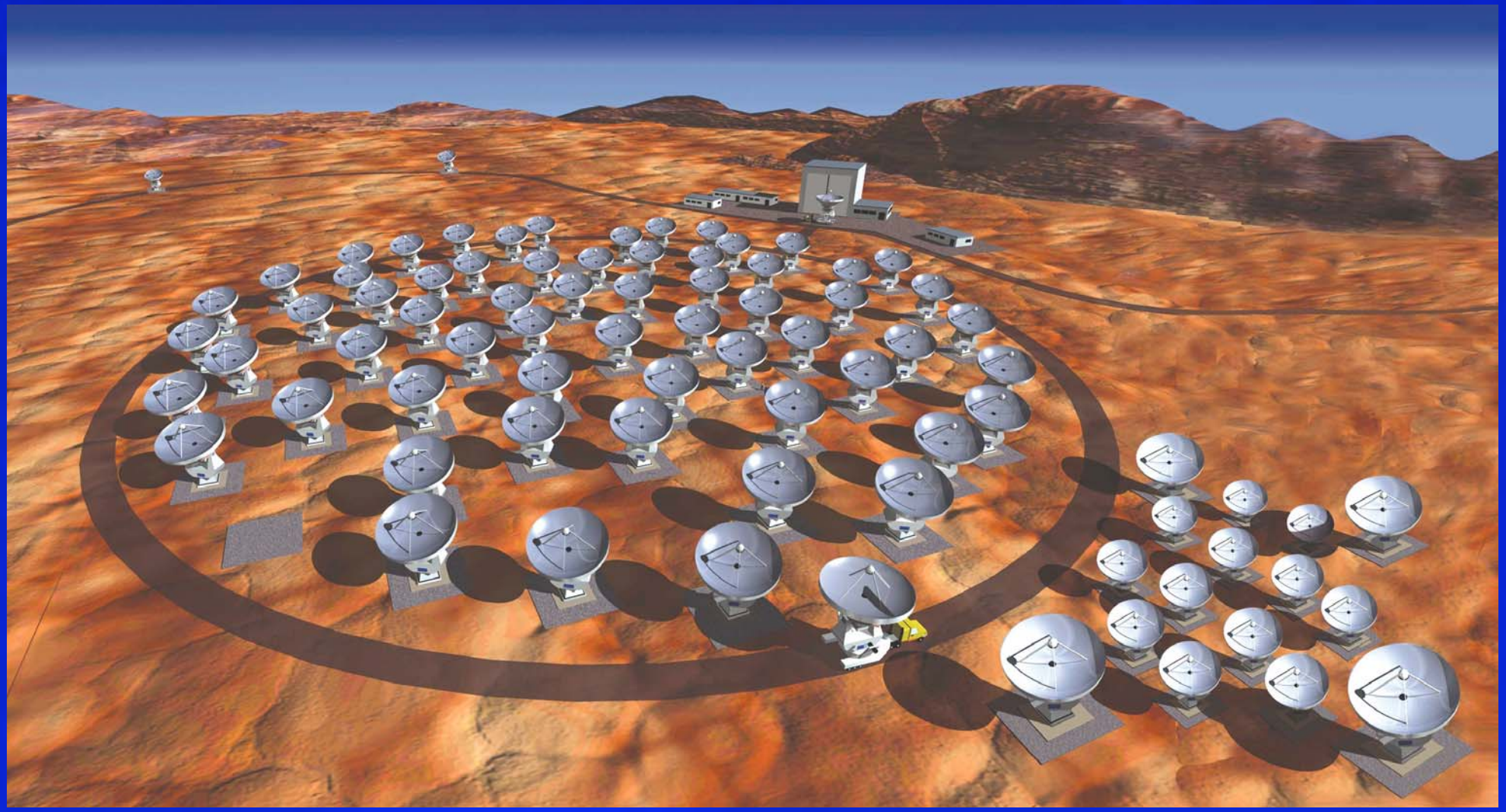
- Agreement signed between the NSF-ESO-NINS Sept 2004/July 2006.

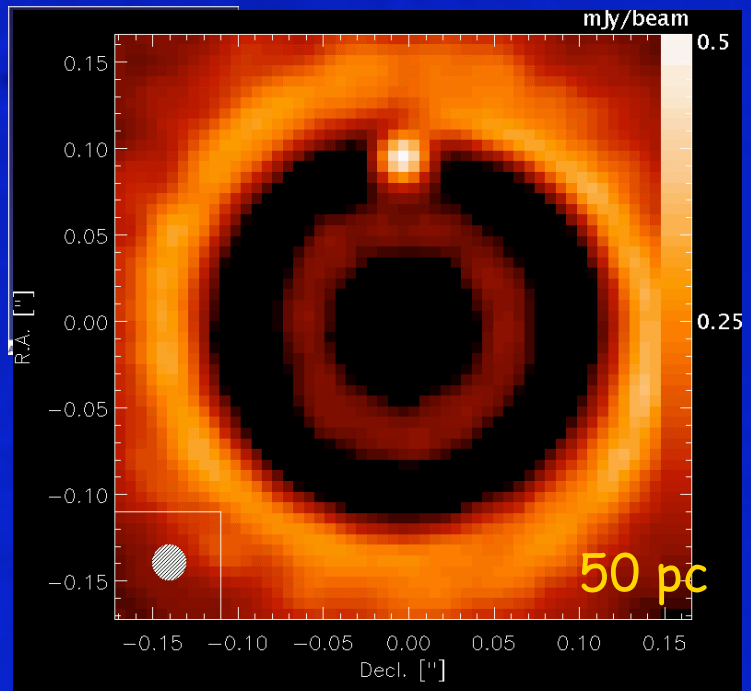
  - Four additional 12-m antennas (total power)
  - Twelve 7-m diameter antennas in compact configuration: Atacama Compact Array
  - Separate ACA correlator
  - Receiver: Bands 4, 8… 10

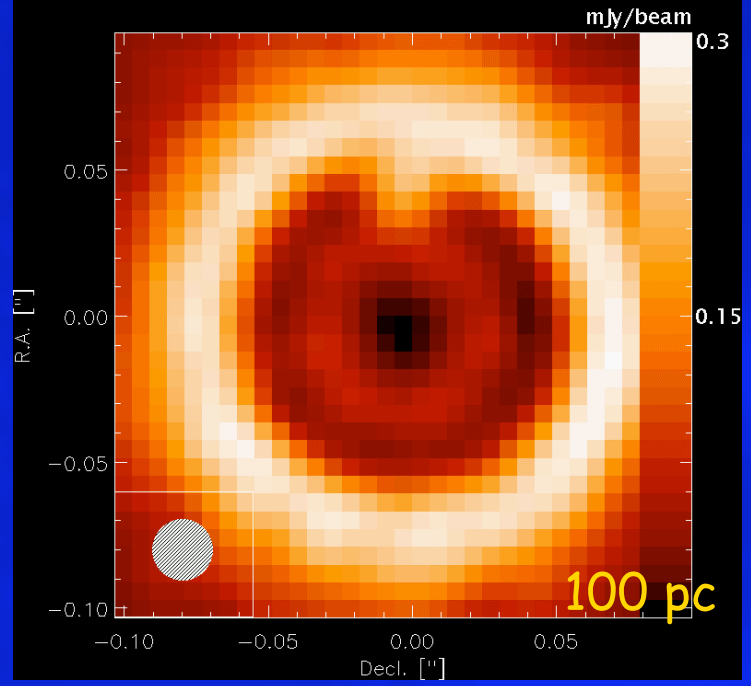
  Atacama Compact Array – ACA

- Significantly improves low surface brightness sensitivity of ALMA; add precision total power data

ALMA + ACA







ALMA Key Science 1:

Planetary regions, nearby disks

$M_{planet} / M_{star} = 0.5\ M_{Jup} / 1\ M_{sun}$

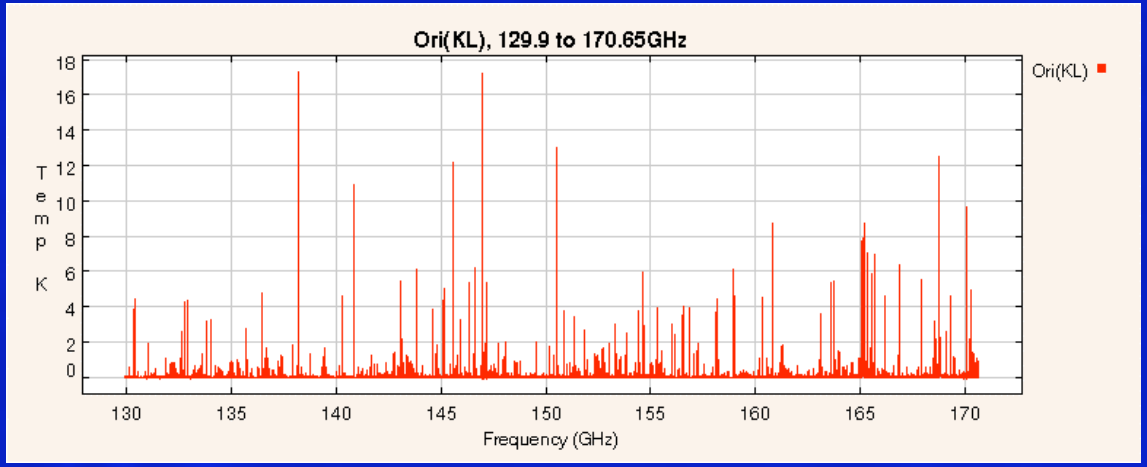
Orbital radius: 5 AU

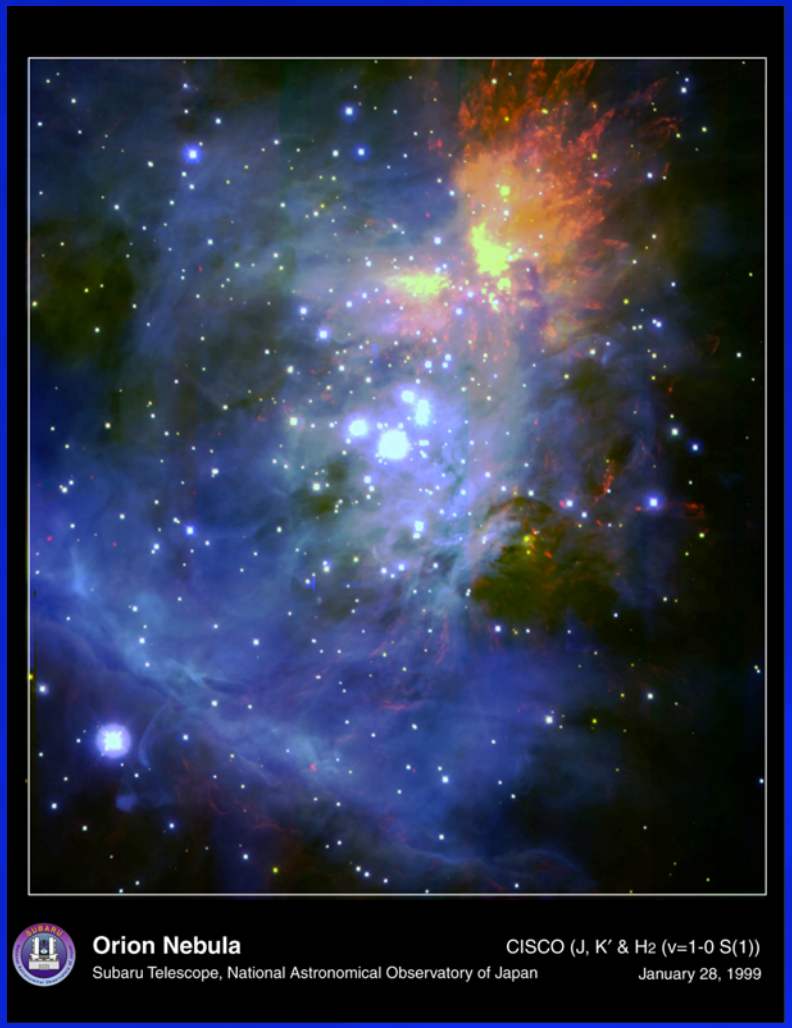
Disk mass as in the circumstellar disk around the Butterfly Star in Taurus

(ALMA: 10km, t_{int}=8h, 30º phase noise)
Wolf & D'Angelo (2005)

ALMA Key Science 2: Astrochemistry

Spectrum courtesy B. Turner (NRAO)





- Millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.

- Most of the observed transitions of the 125 known interstellar molecules lie in the mm/submm spectral region—here some 17,000 lines are seen in a small portion of the spectrum at 2mm.

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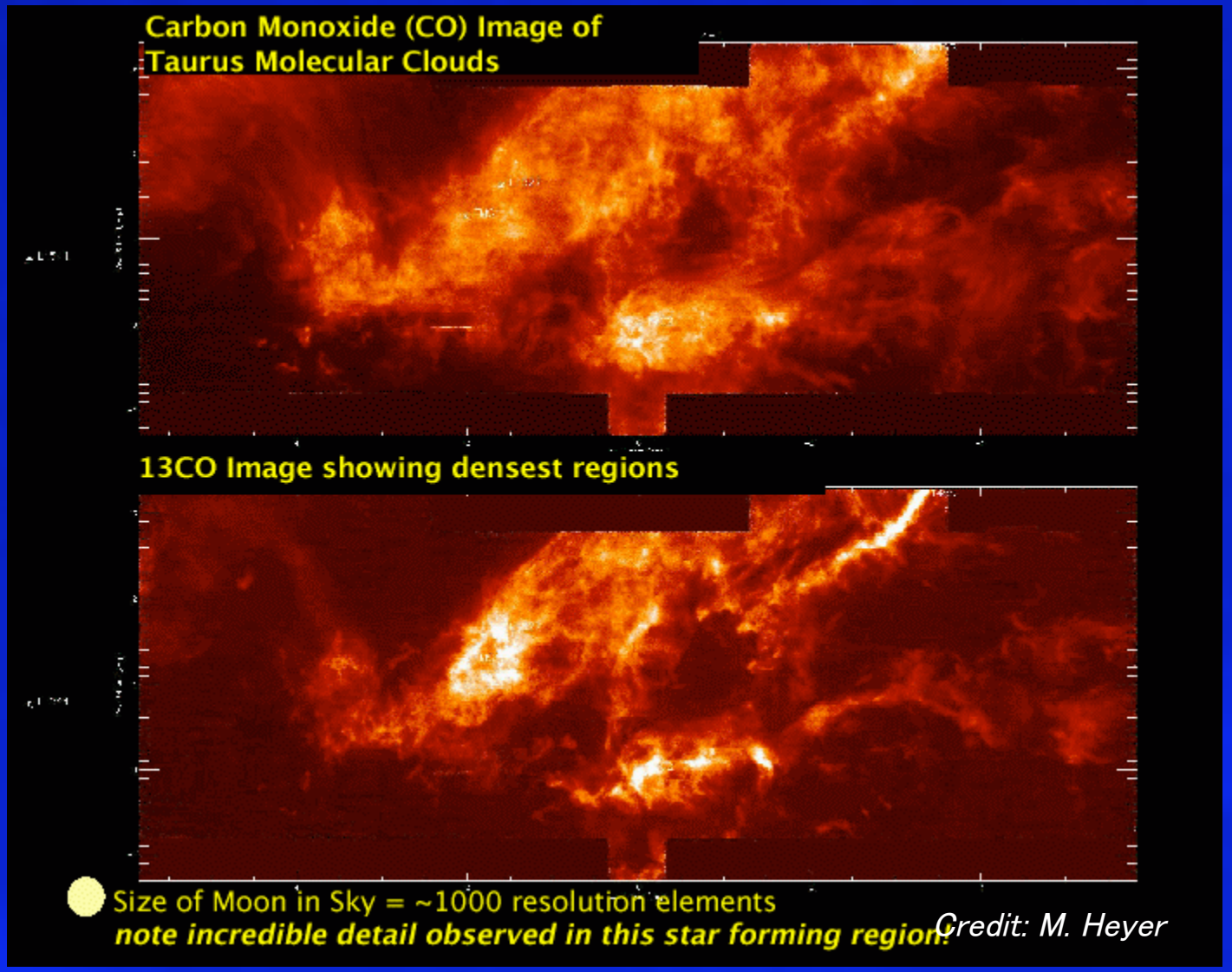
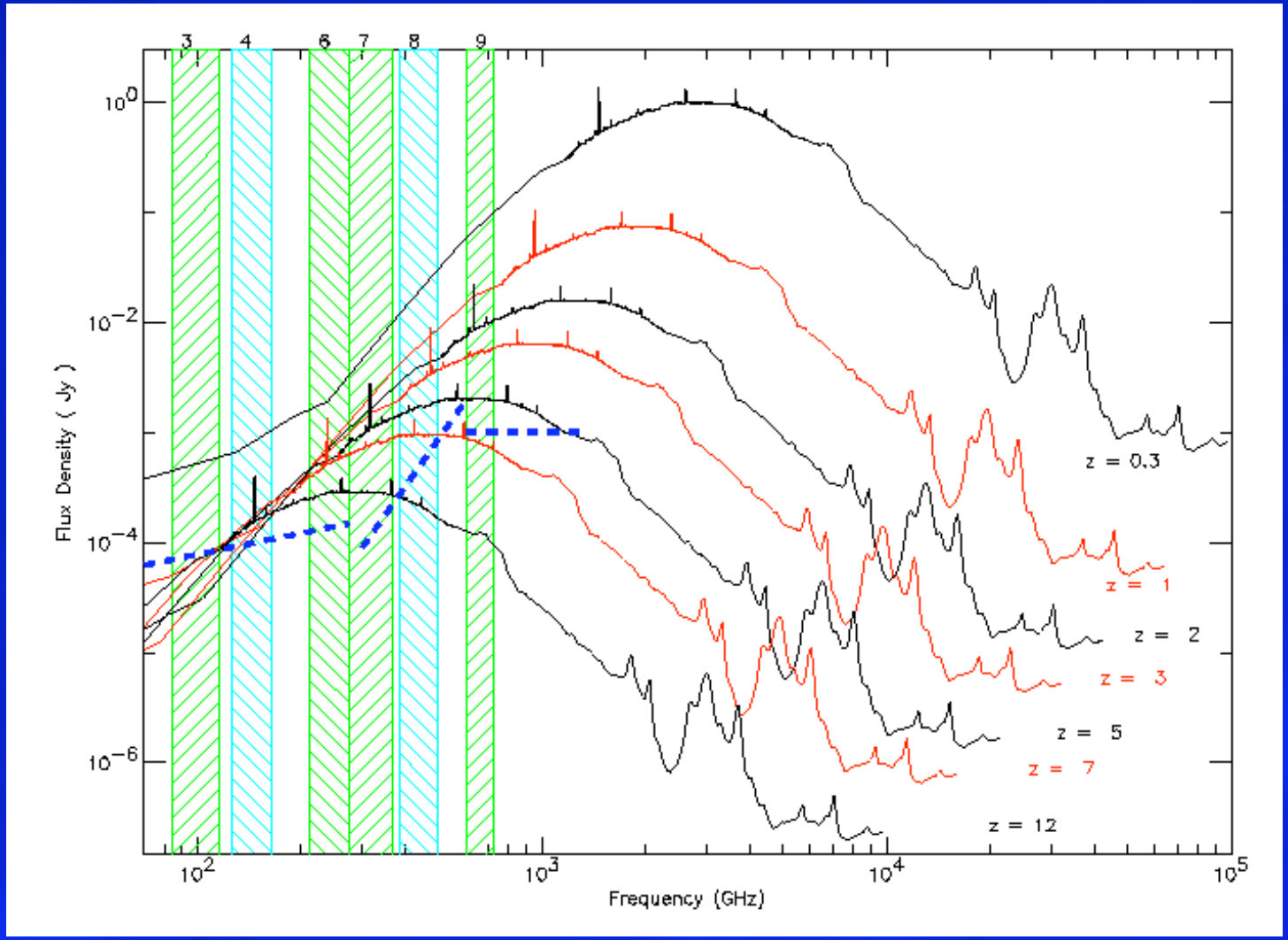
ALMA Key Science 3: Interstellar Medium

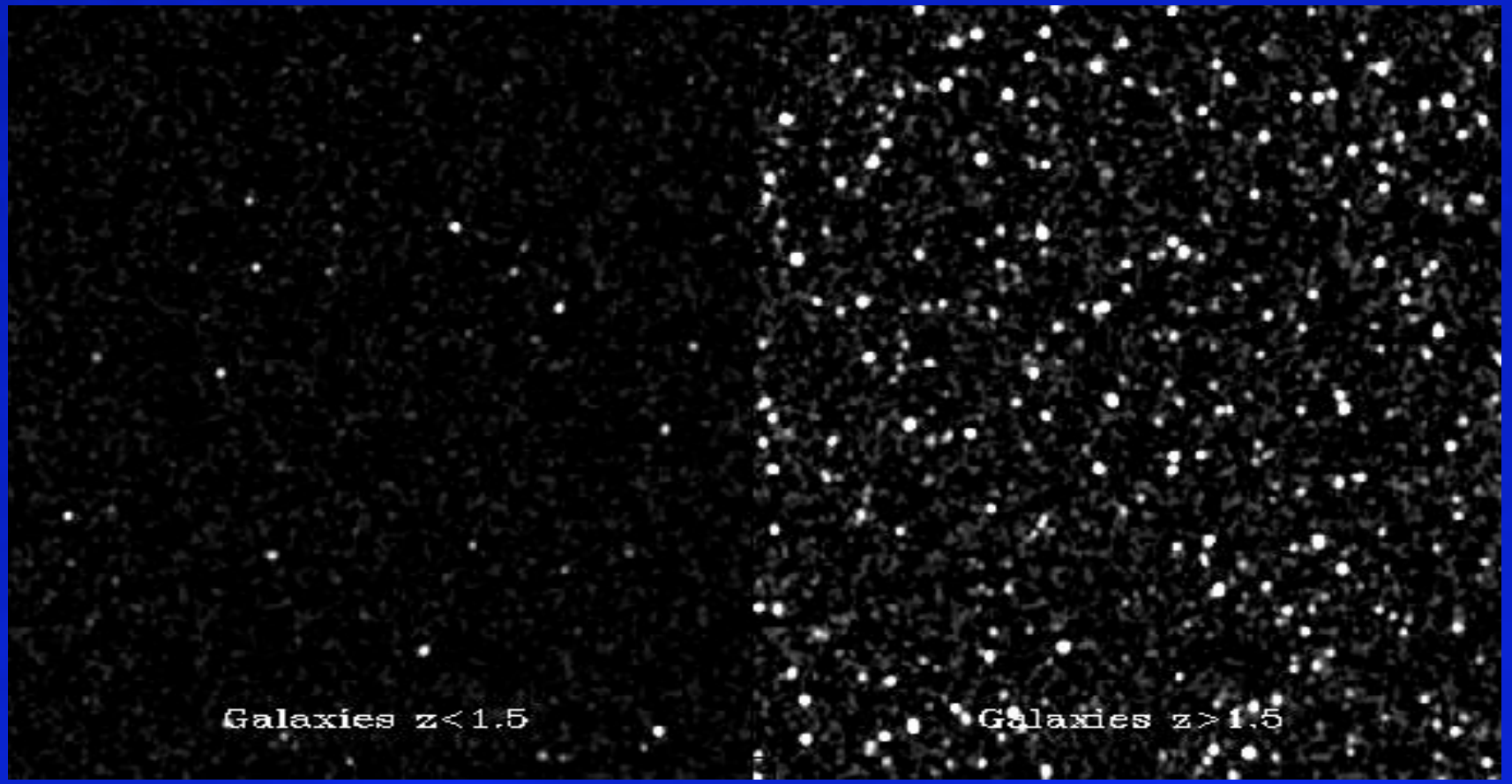


Credit: M. Heyer

ALMA Key Science 4: High redshift deep fields



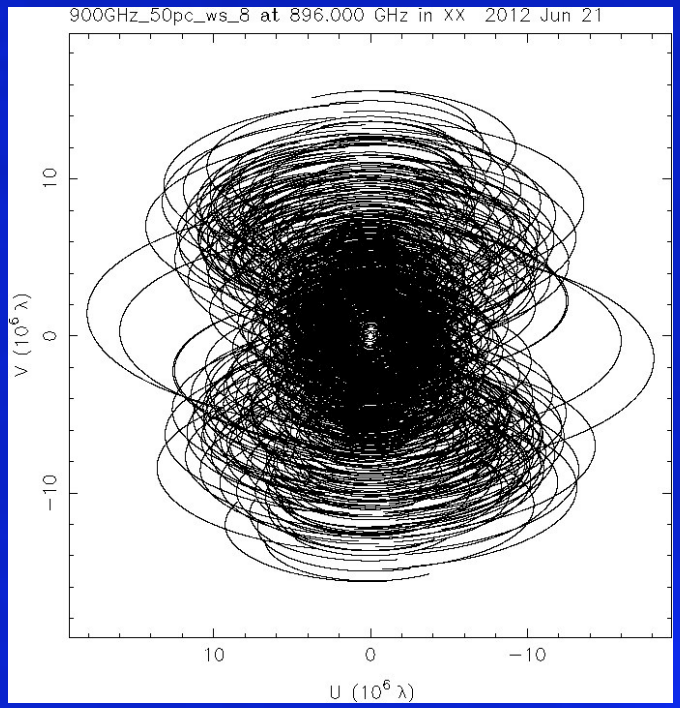
ALMA DF: Rich in Distant Galaxies



Nearby galaxies in ALMA DF

Distant galaxies in ALMA DF

ALMA Science Requirements



CASA beam and u,v coverage simulations soon to be online for proposal planning

- High Fidelity Imaging
- Precise Imaging at 0.1″ Resolution
- Routine Sub-mJy Continuum Sensitivity
- Routine mK Spectral Sensitivity
- Wideband Frequency Coverage
- Wide Field Imaging Mosaicing
- Submillimeter Receiver System
- Full Polarization Capability
- System Flexibility

Technical Specifications

- 54+ 12-m antennas, 12 7-m antennas, at 5000m site
- Surface accuracy ±25 μm, 0.6" reference pointing in 9m/s wind, 2" absolute pointing all-sky.
- Array configurations between 150m to ~15-18km.
- 10 bands in 31-950 GHz + 183 GHz WVR.
- 8 GHz BW, dual polarization.
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6Mb/s average; peak 60-150 Mb/s.
- All data archived (raw + images), pipeline processing.

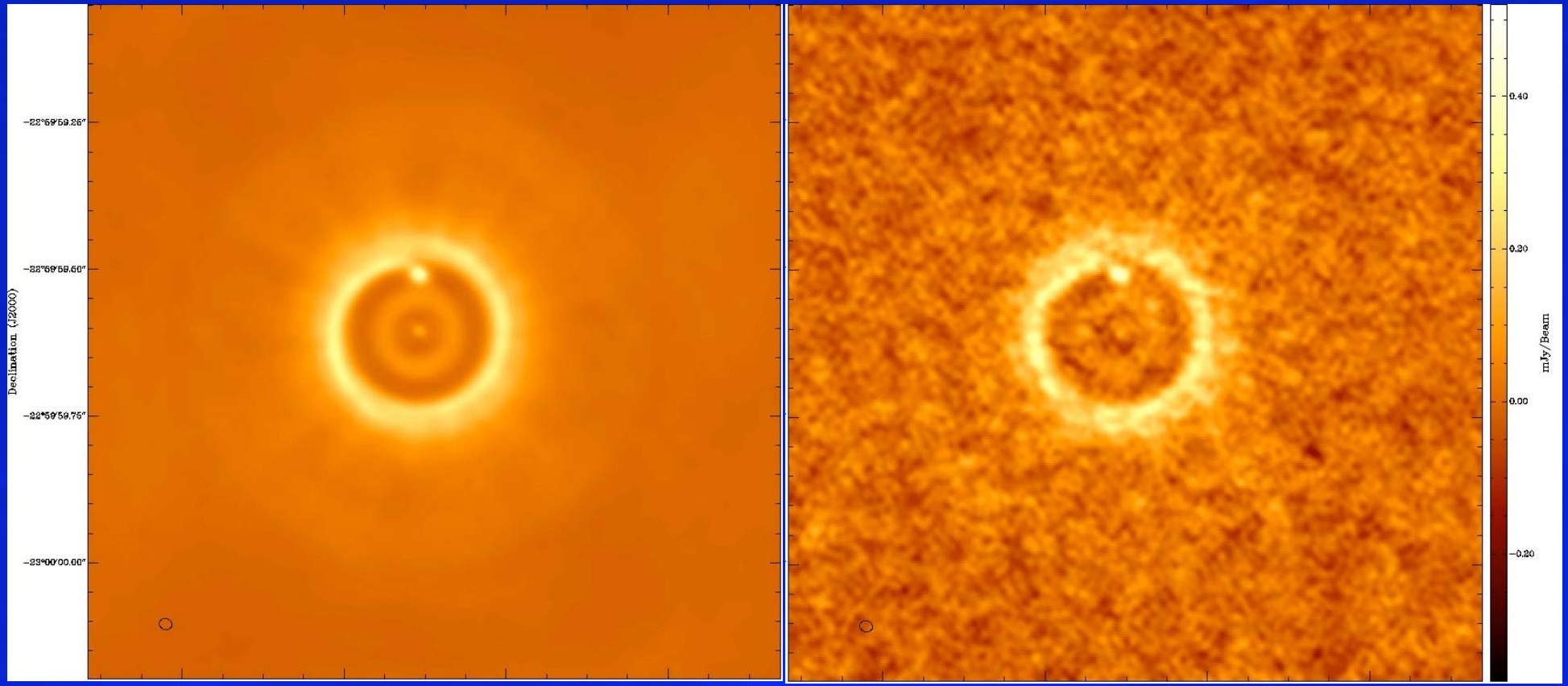
ALMA Median Sensitivity

(1 minute; 75% Quartile opacities λ>1mm, 25% λ <1mm)

Frequency (GHz)	Continuum (mJy)	Line 1 km s^{-1} (mJy)	Line 25 km s^{-1} (mJy)
35	0.02	5.1	1.03
110	0.027	4.4	0.89
140	0.039	5.1	1.01
230	0.071	7.2	1.44
345	0.12	10	1.99
675	0.85	51	10.2
850	1.26	66	13.3

Imaging Performance

CASA simulations by R. Reid



Noiseless

Thermal noise (672GHz, O21)

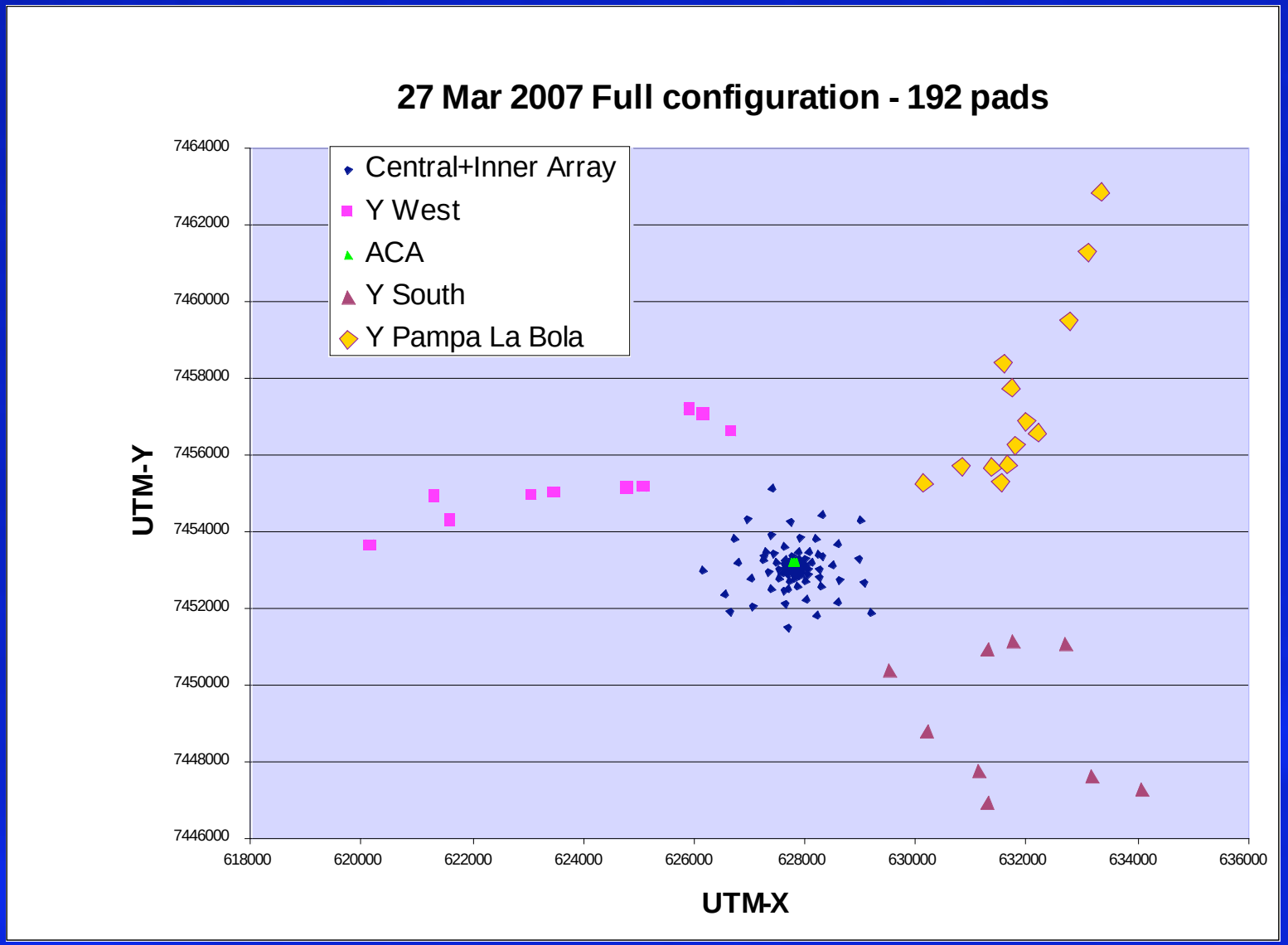
Antennas

- Demanding ALMA antenna specifications:
  - Surface accuracy (25 μm)
  - Absolute and offset pointing accuracy (2 arcsec absolute, 0.6 arcsec offset)
  - Fast switching (1.5 deg sky in 1.5 sec)
  - Path length (15 μm non-repeatable, 20 μm repeatable)

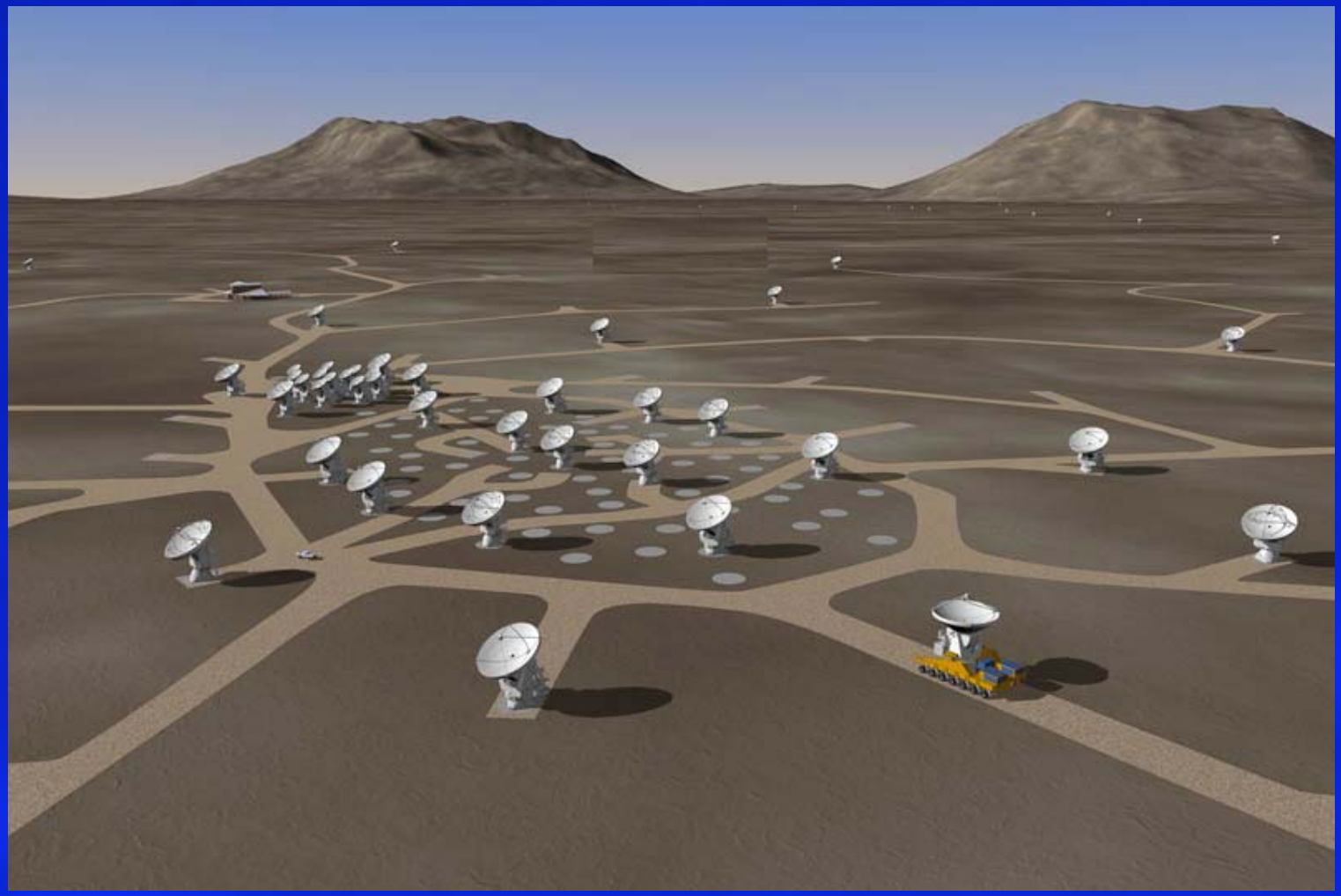
- To validate these specifications: three prototype antennas built & evaluated at ATF

- Three production contracts – US (General Dynamics/Vertex)
  Europe (Alcatel EIE MT Aerospace)
  Japan (Mitsubishi)

Array Configurations

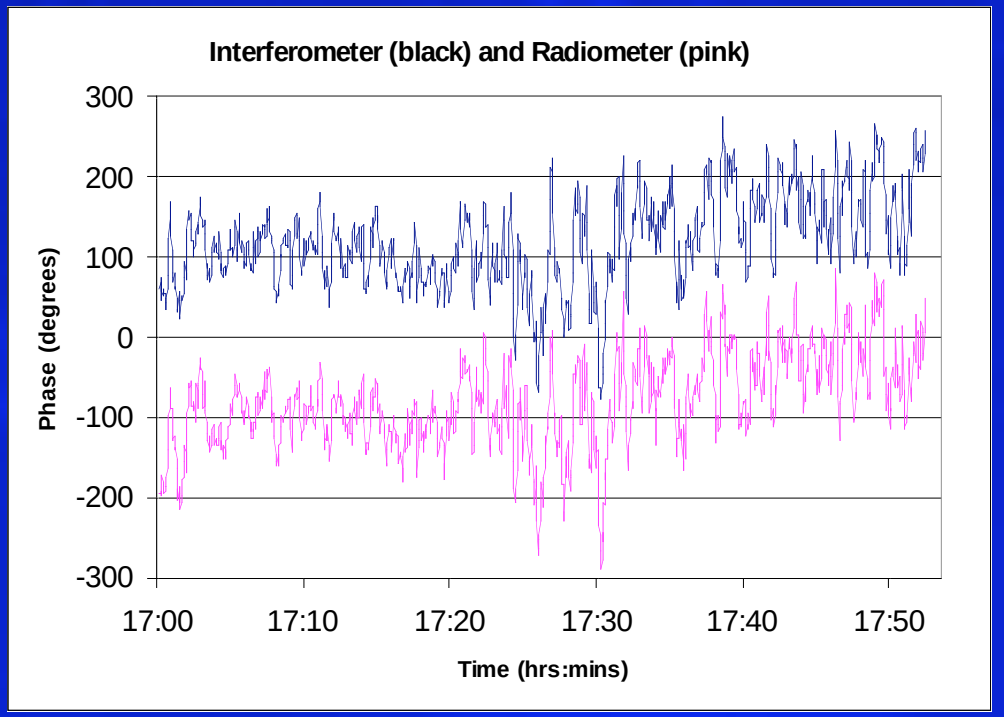


Both Short and Long Baselines



External Phase Correction

183 GHz Water Vapour Radiometers, tested at SMA



Mike Reid et al, 2006

Correlator Specifications

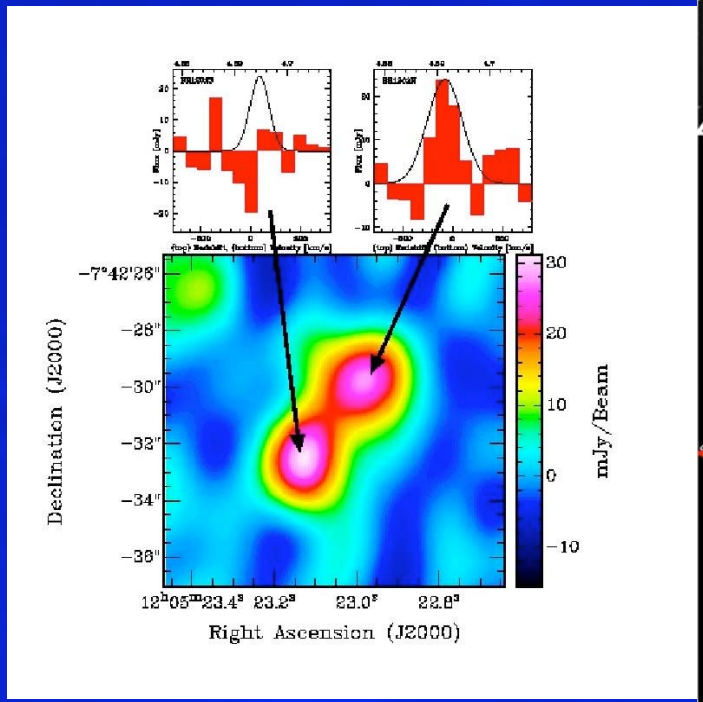
Number of antennas	64
Number of IF pairs per antenna	4
Max. sampling rate per IF pair	2 x 4 GHz
Digitizing format	3 bit, 8 level
Correlating format	2 bit, 4 level
Max. delay range	30 km
Channels per IF pair	4096
Autocorrelation channels per baseline	1024
Polarization	Full stokes (4 products)

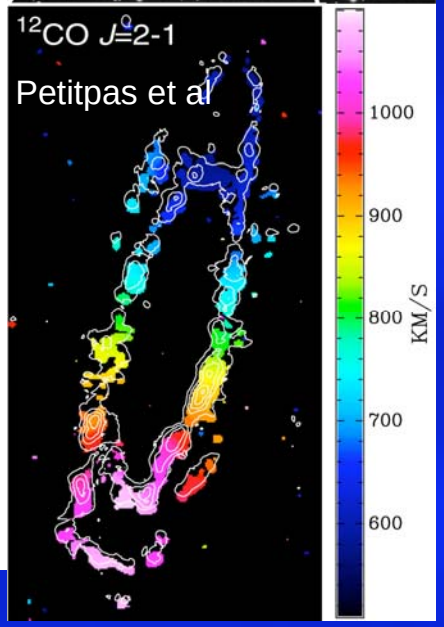
During full operation, the estimated flow of int/SD data into archive ~ 100 Tb per year.

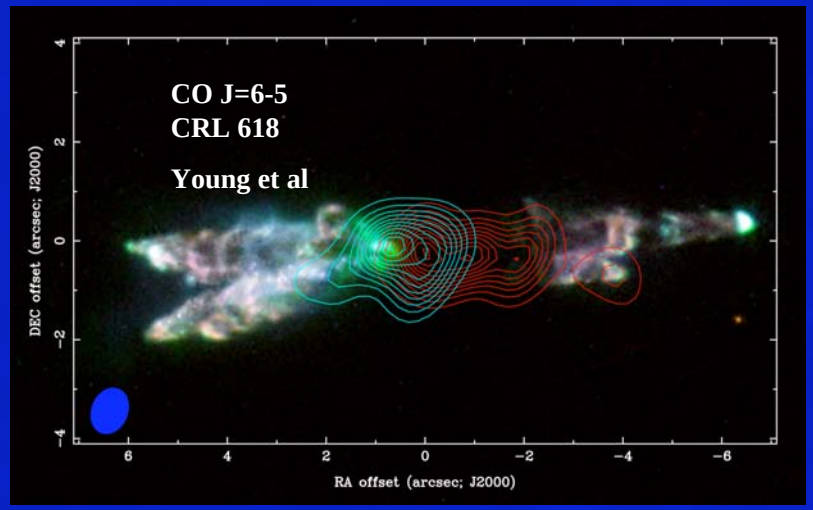
Project lifecycle: online proposal, script, dynamic scheduling, raw data available plus a reference image with pipeline processing history, calibration data…
-sufficient assistance for non-blackbelt radio astronomers

ALMA Science Precursors

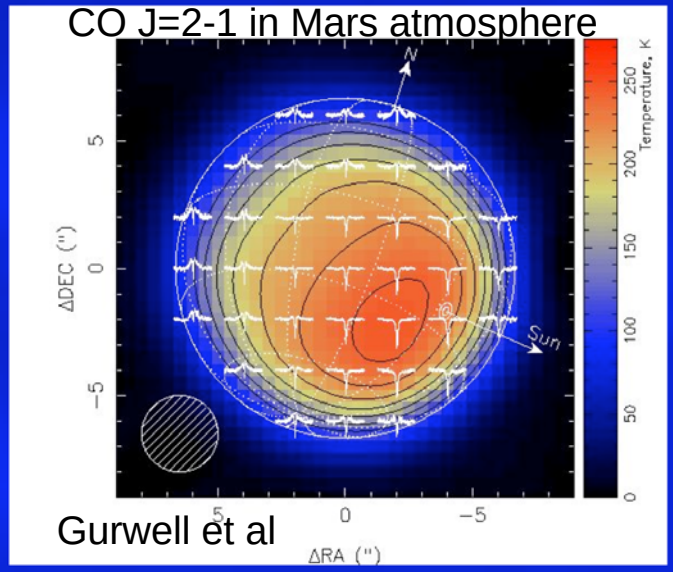
BR1202-0725 CII at z=4.7
Iono et al 2006







CO J=2-1 in Mars atmosphere



Gurwell et al

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Approximate Schedule

- First fringes: ATF Q2 2007 ✓ ("dynamic fringes" – Oct 19, 2007)
- AOS, OSF: Complete early 2008.
- Antennas: #1 2007 ✓, #2 2007 ✓ ··· #66 2011. (5 as of Oct 2007)
- Front Ends: #1, #2 2007, → production.
- BE/DTS: → production.
- Correlator: Q1 complete··· Q4 2008; ACA 2008.
- Software: R4··· AIVC 2007, Ops 2008.

- **CSV: handover of verified 3-element interferometer at AOS (currently 2009Q1)**

- Call for Early Science: Q1 2010
- Early Science: Q4 2010
- Full Operations: 04 Sep 2012

Correlator Quadrant #1 (of 4)

Completed, in testing. Complete correlator contains 2912 printed circuit boards and 5200 interface cables; there are more than 20 million solder joints.

June 2007 – second quadrant in production in Charlottesville + new test correlator in Socorro

Commissioning

Commissioning commences with arrival of the third antenna to the high site, when phase closure is expected to be achieved, and continues until handover to Operations at the end of 2012.

Current activities:

–Revising Commissioning Plan (esp schedule and staffing)

–assisting with Antenna Integration at the Operations Support Facility

–involved with development of the Operations Plan, with Ops Working Group

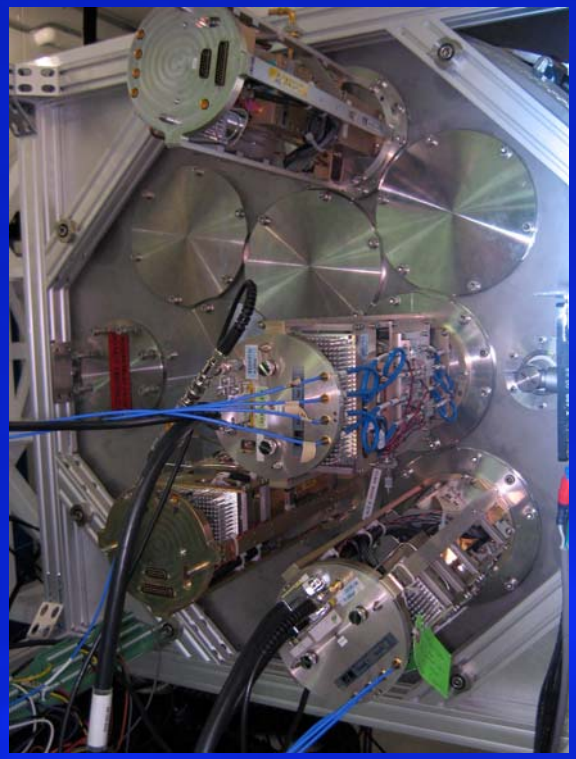
–Working at ALMA Test Facility with Computing, System Engineering, Antenna, Front End and other teams on adding functionality to software

Resources will be needed from AIV, Operations, Science IPT and ARCs

Equipment available

FE #1 (4 cartridges) – Mar07

Band 3



Band 7

Band 6

Band 9

⇒Bands 3, 6, 7, 9 available (4 and 8 may be added soon after)

⇒All types of 12m antenna used for interferometric commissioning

⇒2 subarrays; can test single-dish and interferometric observing in parallel;

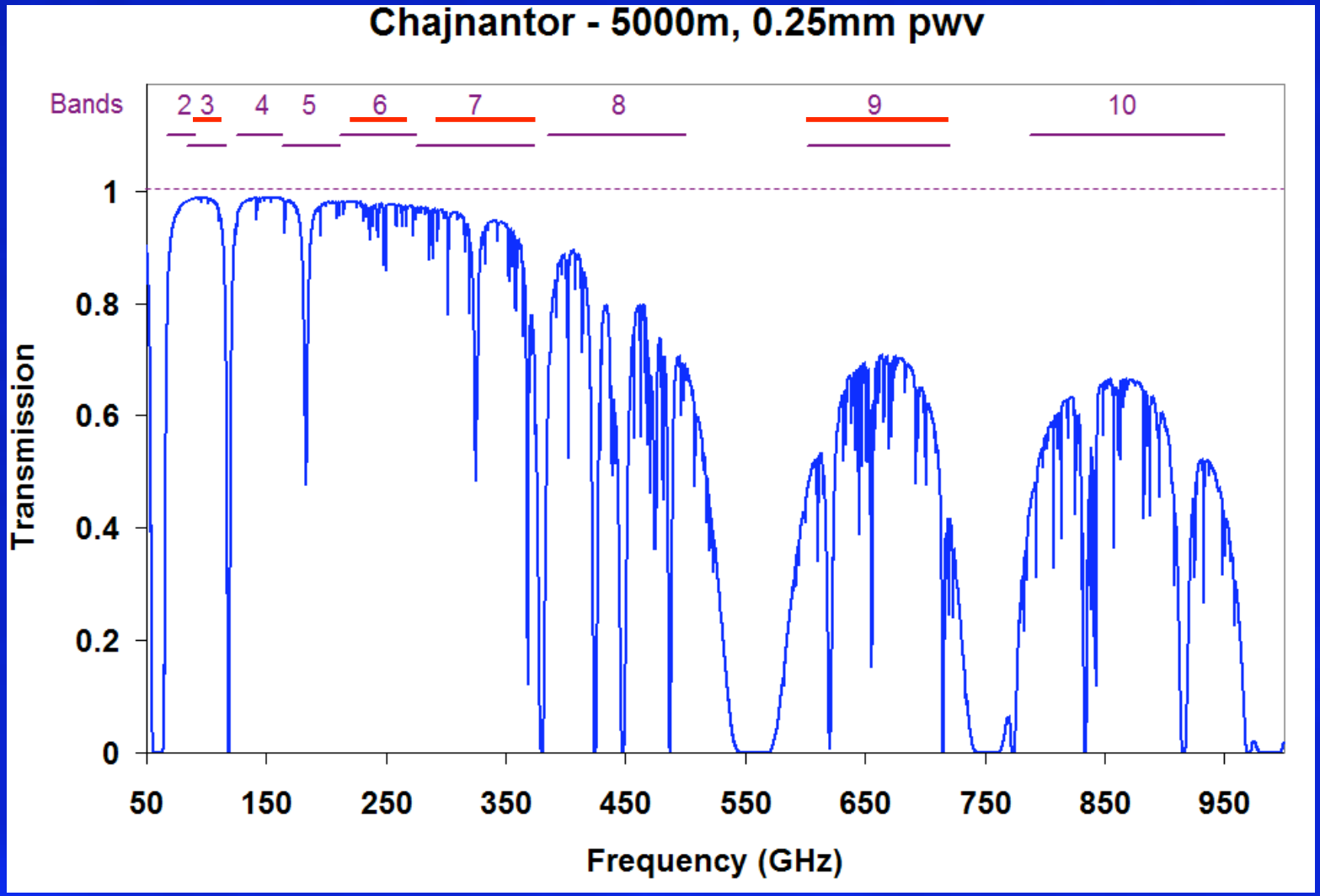
⇒Initial configurations compact; thereafter First Science Configurations as already defined

Receivers / Front Ends

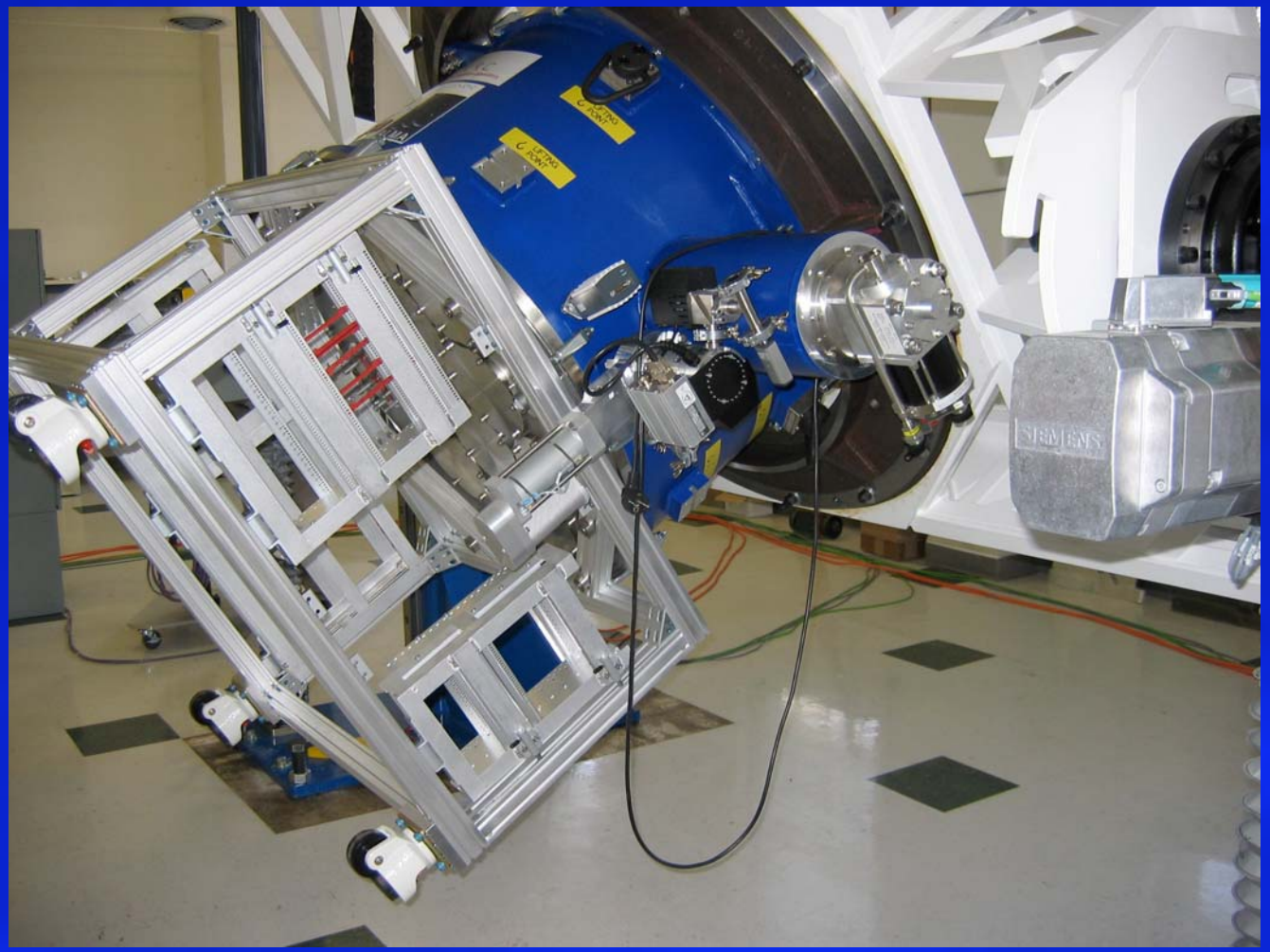
ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology
		T_{Rx} over 80% of the RF band	T_{Rx} at any RF frequency		
1	31.3 - 45 GHz	17 K	28 K	USB	HEMT
2	67 - 90 GHz	30 K	50 K	LSB	HEMT
3	84 - 116 GHz	37 K	62 K	2SB	SIS
4	125 - 169 GHz	51 K	85 K	2SB	SIS
5	163 – 211 GHz	65 K	108 K	2SB	SIS
6	211 - 275 GHz	83 K	138 K	2SB	SIS
7	275 - 373 GHz	147 K	221 K	2SB	SIS
8	385 - 500 GHz	98 K	147 K	DSB	SIS
9	602 - 720 GHz	175 K	263 K	DSB	SIS
10	787 - 950 GHz	230 K	345 K	DSB	SIS

- **Dual, linear polarization channels:**
  - **Increased sensitivity**
  - **Measurement of 4 Stokes parameters**
- **183 GHz water vapour radiometer:**
  - **Used for atmospheric path length correction**

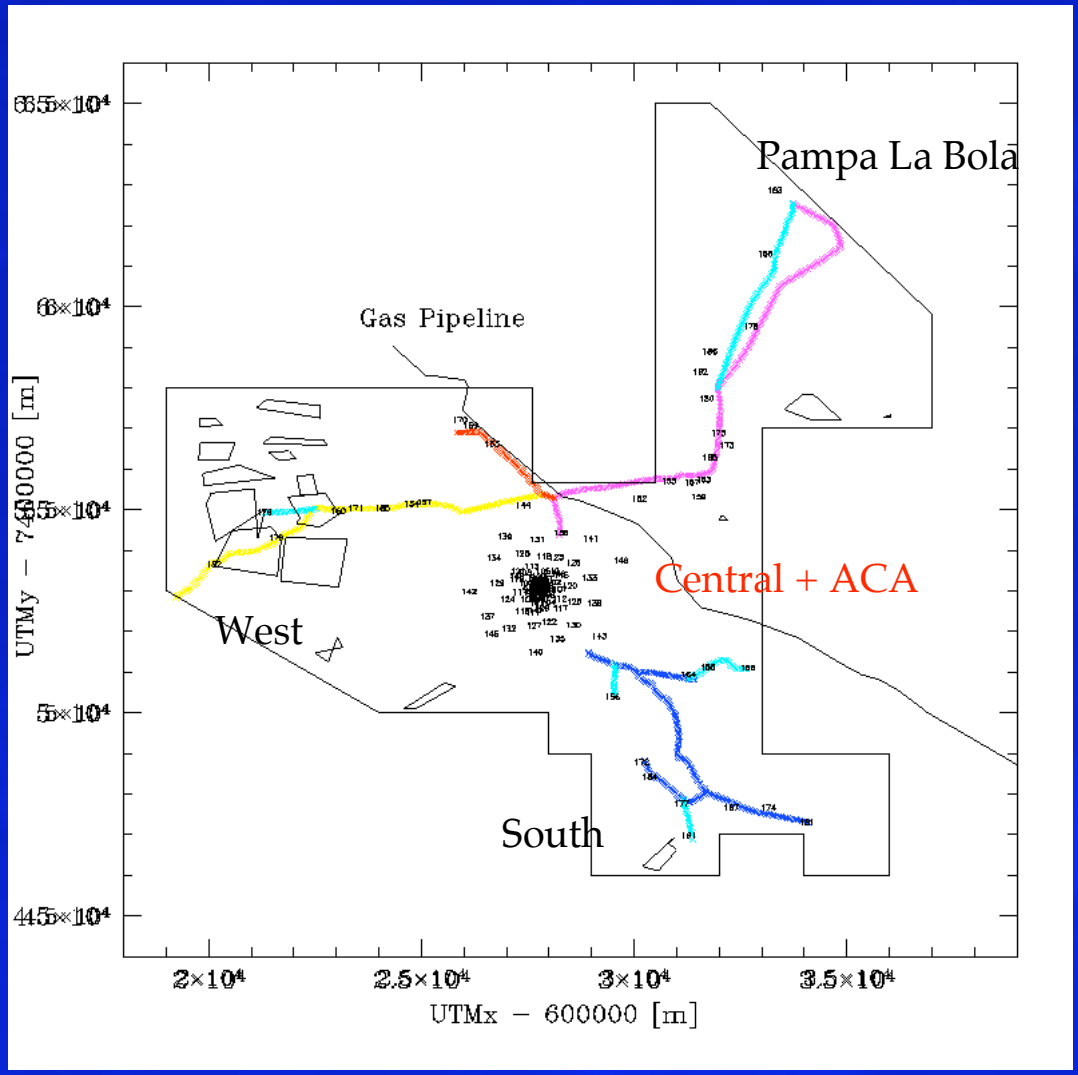
Atmospheric Opacity



First Front End on Tilt Table



Initially Only Compact Configurations



Early Science 2010 – current definition

- At least 16 antennas fully commissioned (more in process of integration)
- Receiver bands 3, 4, 6, 7, 8, 9
- Interferometry in single field or pointed mosaic mode
- A range of spectral modes, (initial priorities identified)
- Circular and linear polarization (not mosaic)
- Single-dish mosaic (position and beam-switch) and OTF.
- 2 subarrays operational

Project Simulations (almasimmos in CASA)

xterm

```
0%....10....20....30....40....50....60....70....80....90....100%
Warning no plotter attached.  Attach a plotter to get plots
Reading data...
Time spent reading from disk : 0 sec.
Number of points being plotted : 6
Python Plotting time : 1.407 sec.
Reading data...
Time spent reading from disk : 0 sec.
Number of points being plotted : 166
Python Plotting time : 1.525 sec.

CASA <6>: inp almasimmos
--------> inp(almasimmos)
project             = 'mysim_compact'  #  Name of project simulated
modelimage          = 'glmtest.modim/' #  name of an image to simulate visibilities for
complist            = '           '    #  componentlist table to simulate visibilities
antennalist         = 'almacompact.txt'       #  antenna position ascii file
direction           = 'J2000 17h04m13.0 -42d19m58.0'   #  mosaic center direction
nmosx               = '        11'     #  number of pointings along x
nmosy               = '        11'     #  number of pointings along y
pointingspacing     = '  24arcsec'     #  spacing in between beams
refdate             = '2007/02/05/22:05:00'    #  Time around which observation
totaltime           = '     3600s'     #  total time of observation
integration         = '       10s'     #  Time interval for each integration
mode                = '   channel'     #  Type of selection
alg                 = '     clark'     #  Algorithm to use for deconvolution
niter               = '       500'     #  Number iterations
nchan               = '        -1'     #  Number of channels to select
startfreq           = '   86.0GHz'     #  Frequency of first channel
chanwidth           = '    2.0GHz'     #  Channel width
cell                = '   1arcsec'     #  Cell size e.g., 10arcsec
imsize              = '[250, 250]'     #  Image size in spatial pixels (x,y)
stokes              = '         I'     #  Stokes parameters to image
weighting           = '   natural'     #  Weighting to apply to visibilities
rmode               = '      none'     #  Robustness mode (for use with Briggs weightin
robust              = '       0.0'     #  Briggs robustness parameter
display             = '      True'     #  Plot simulation result images,figures

CASA <7>:
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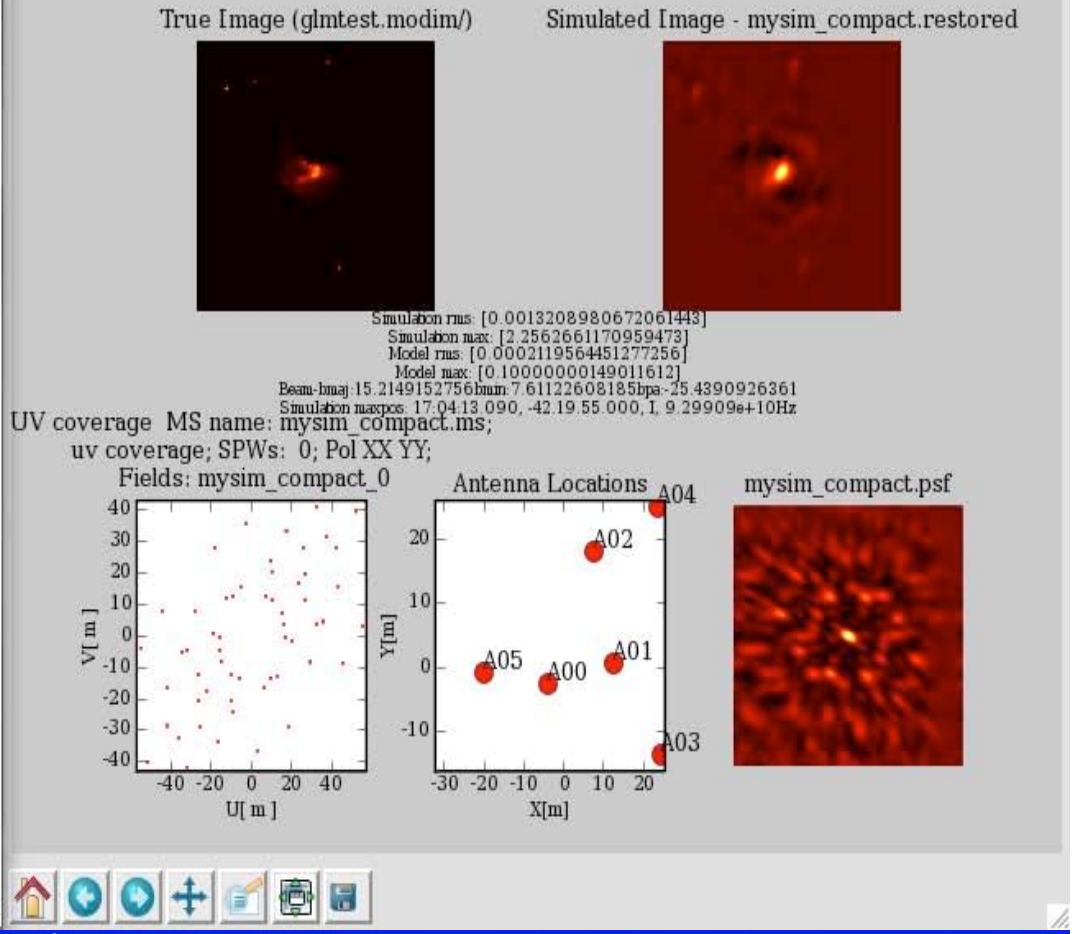
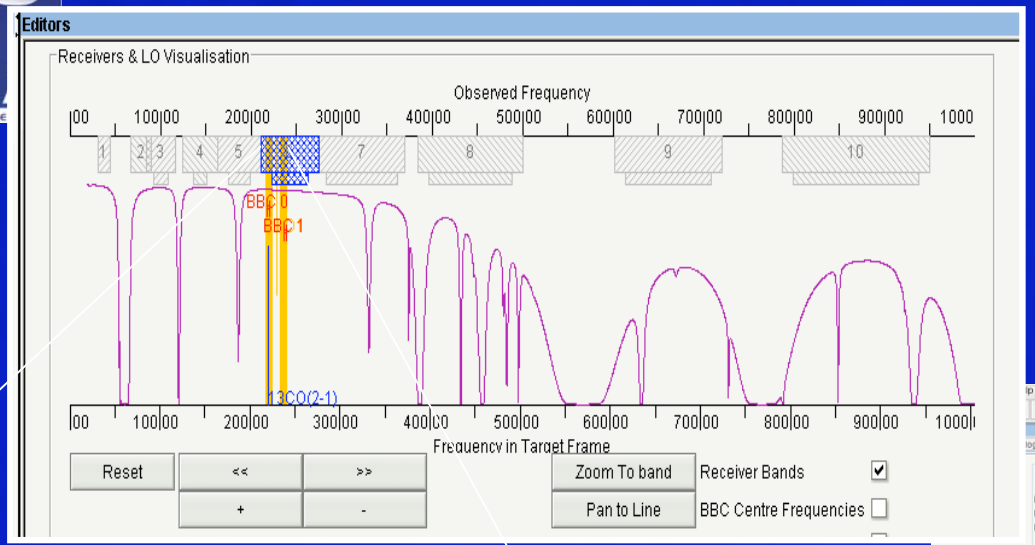
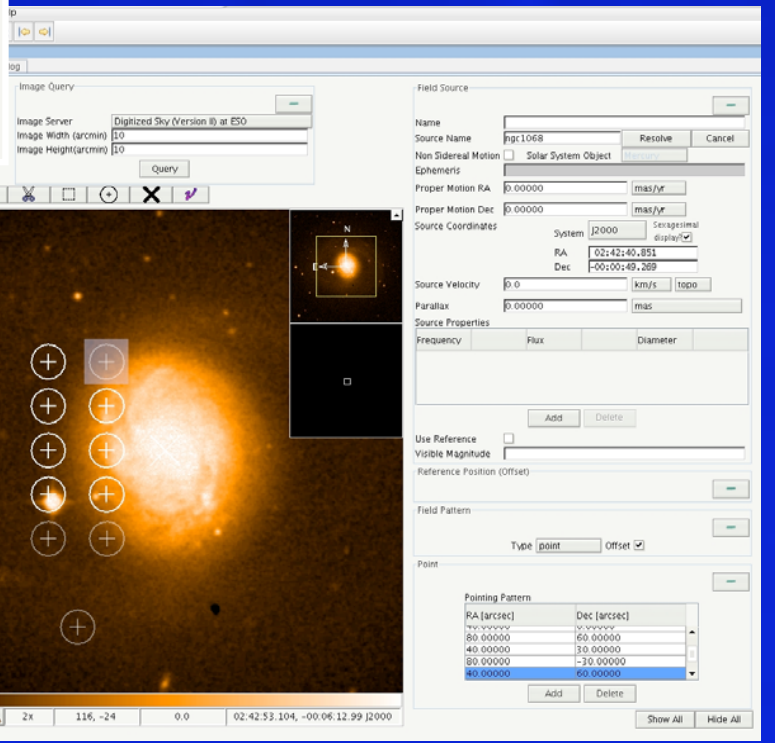
Figure 1

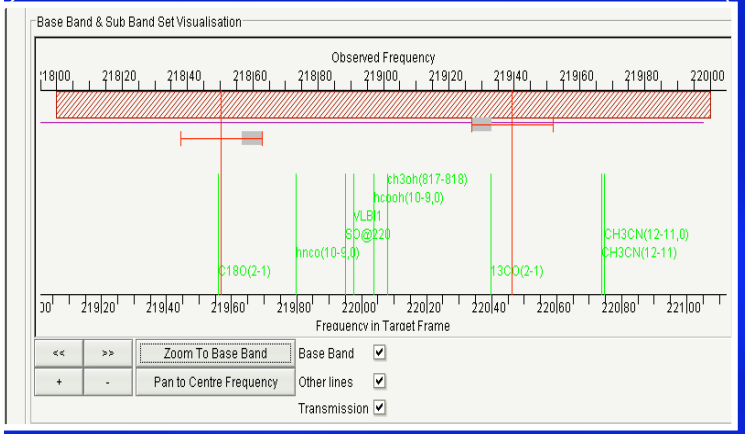


Observing Preparation (OT)



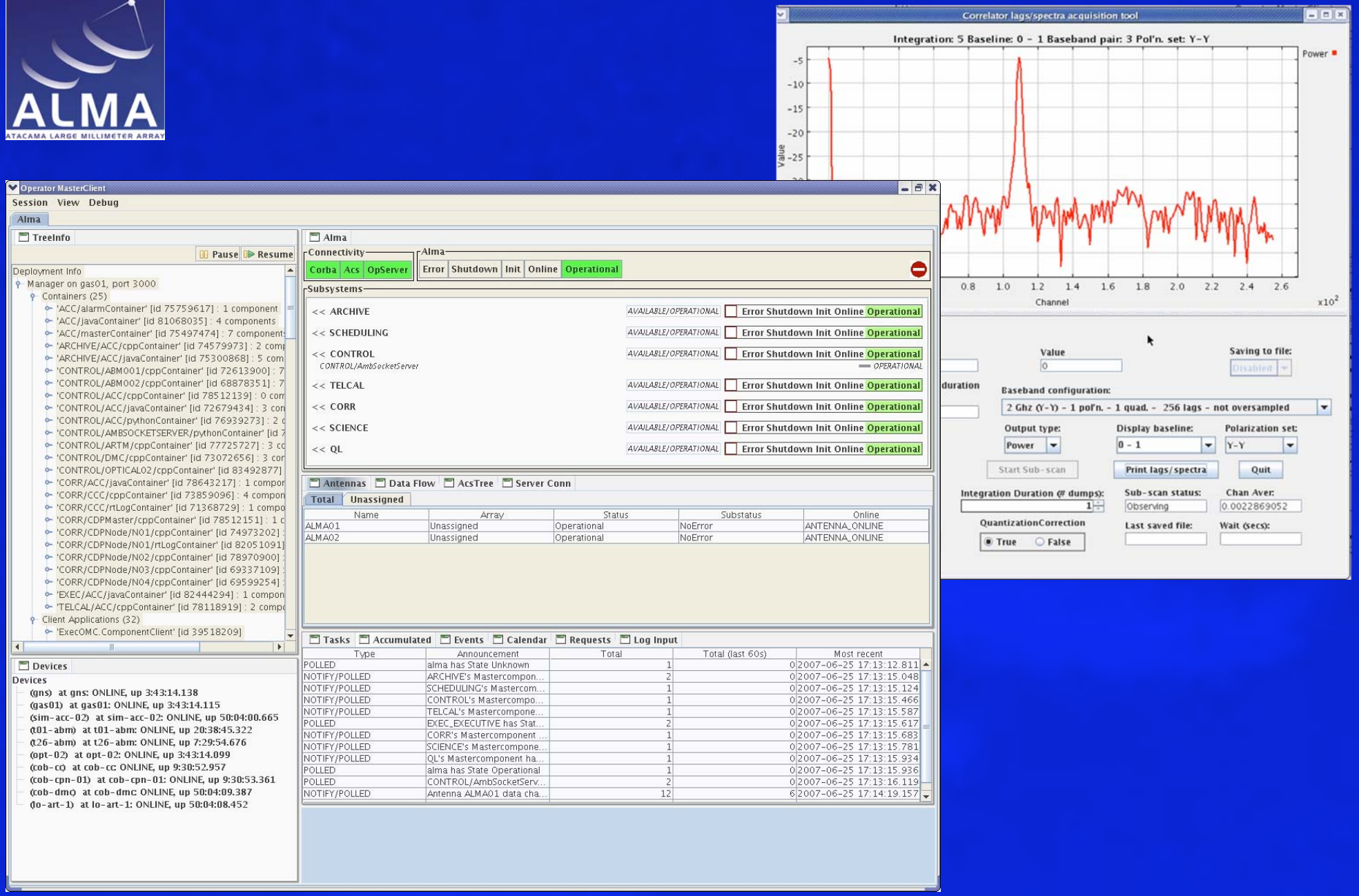
Choose pointing center(s)





Choose spectral windows

Array Control and Monitoring (OMC)



Sites

- **Antenna Test Facility (ATF) - Socorro, NM**
- **Array Operations Site (AOS) - Chajnantor**
- **Operations Support Facility (OSF) - near San Pedro**
- **Santiago Central Offices (SCO) - Santiago**
- **ALMA Regional Centers – ARCs + ARClets**

ARC: Charlottesville (NA)
Garching (EU)
Tokyo (EA)

- ARClets: Bonn, IRAM, Bologna, Leiden, Onsala, Manchester, Taipei?…

Purpose of ARCs and ARClets

- Establish community (already underway)
- Provide face-to-face user support (post-obs.)
- Offer round-the-clock help, with sites in different time zones
- Offer help with specific expertise where available
- Be involved with software development, testing, manuals, cookbooks
- Collect user feedback to provide to SCO and Ops
- Hopefully… be involved in commissioning and science verification, both OSF and ATF

Staffing available

- Project Scientist + Deputy (R Hills and A Peck)
- 3 commissioning scientists
- Operations astronomers
- Science IPT staff on rotation
- Postdocs (Europe and NA)

- Ad hoc specialists
- ARC (and ARClet) staff on rotation

The new Operations staff being hired will form an integral part of the Commissioning team, and the AIV scientists will move to Commissioning as well; there is no “handover” point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ALMA Site

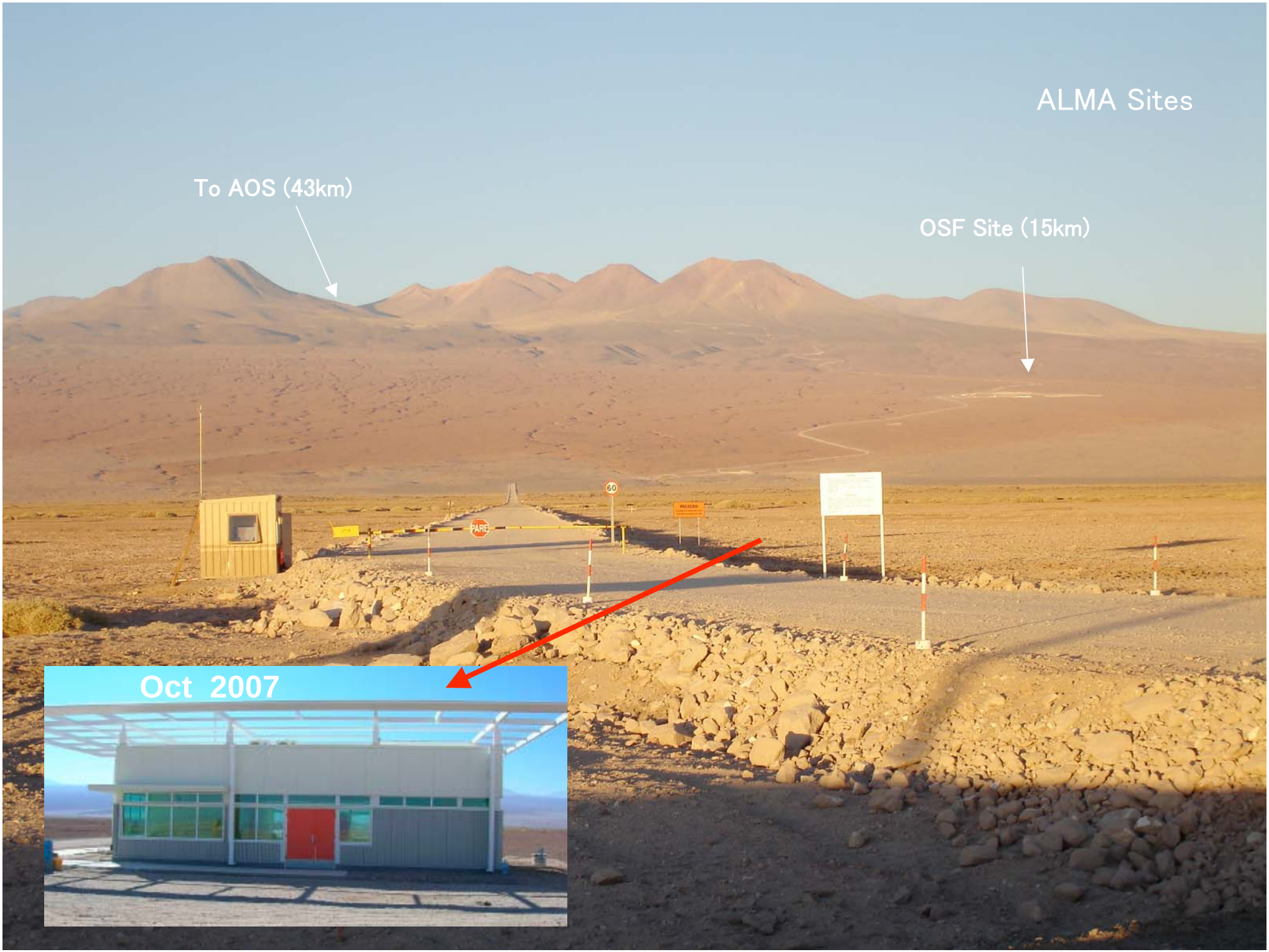
ALMA

Paranal

La Serena

Santiago

San Pedro de Atacama,
Atacama Desert, Northern Chile


ALMA Sites
To AOS (43km)
OSF Site (15km)
Oct 2007

Lascar – April + October 2006

Operations Support Facility (OSF): Technical Facilities 3000m

Contractor's Camp holds ~440 persons

OSF Warehouse

ALMA Camp - OSF

AIV Lab

Offices and cantina

Tennis court

First dorms

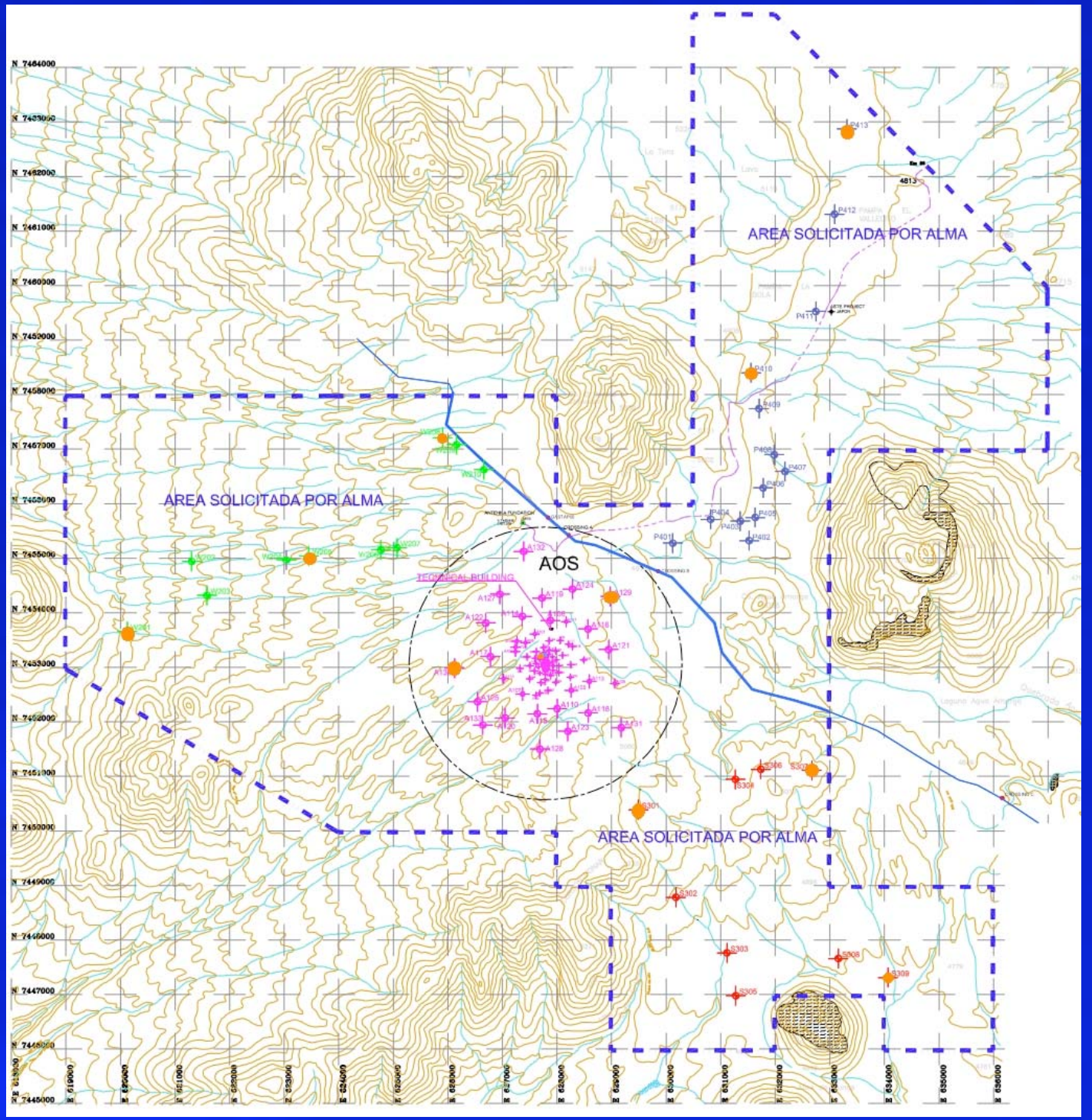
New dorms

Much nicer!

Vertex Site Erection Facility

Temporary AIV Lab & Holography Tower

ALMA Science Reserve



5000m Chajnantor plateau – looking south
Array Operations Site

Chajnantor Plateau – looking north

AOS Technical Building - wiring and furnishing being done (Sept 2007)

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Inside AOS technical building

Prototype Antennas at ATF

12-m, Carbon Fiber Support Structure

Transporting an ALMA Antenna (Artist's Impression)

ESO Press Photo 32f/07 (30 July 2007)

The ALMA Transporter – Rear View

ESO Press Photo 32e/07 (30 July 2007)

The ALMA Transporter

ESO Press Photo 32b/07 (30 July 2007)

Transporter – Germany, July 2007

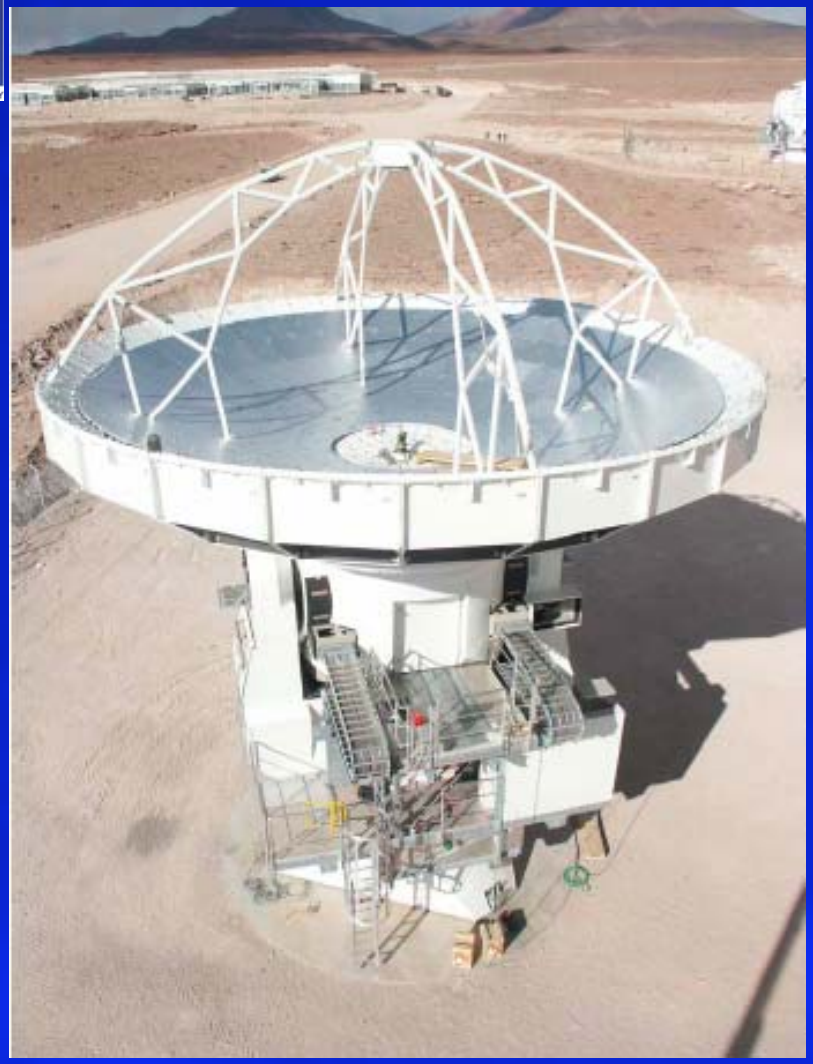
Road: OSF-AOS - Transporter


Vertex in Texas
KILGORE POLICE
NORTH BUSINESS 259
SOUTH BUSINESS 259
Vertex #1 - Mar 19th 2007

Vertex #1 in Antofagasta - April 2007

Vertex #1 at OSF -

All 8 rows of panels now installed and cladding finished (October)



Melco #1 - Mar 2007 - at Mitsubishi

3 ACA 12-m antennas en route to OSF

(15 km/hr for 3 days)

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Three Headless Melcos at OSF - August

Third Mitsubishi Antenna under construction

Photogrammetry and mechanical tests began on Melco #1
September, 2007

Latest - Holography began in October

Vertex #2, straight off the truck, Sept 27, 2007

Vertex #1 - Fully assembled, Oct 22, 2007

For more info:

www.alma.info

Or email apeck@alma.cl

The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.

Computing

- Ongoing development of “end to end” software system running on over 200 computers on 4 continents.
- Difficult distributed development – software engineering practices, travel
- Using OT for proposal and script preparation
- Using CASA as the offline system (also AIVC)

Commissioning activities

- Antenna and array calibrations
  - –Pointing and focus software

    (initial SD pointing and focus done by AIV, we optimize)
  - –Primary beam and surface measurement (likewise)
  - –Antenna location (baseline)
  - –Delay

- Observing calibration tasks
  - –Phase calibration, fast switching and WVR development
  - –Calibrator surveys (need dense grid for fast switching)
  - –Temperature and flux scale
  - –Bandpass
  - –Instrumental polarization

More Commissioning activities

- Single-dish modes
  - Mosaic with beam and position switching
  - On-the-fly mapping
  - Autocorrelation and continuum total power
  - [Frequency switching]
  - Total power calibration

- ACA 7m array (from CSV + 12 months, roughly)

Expected Task Durations

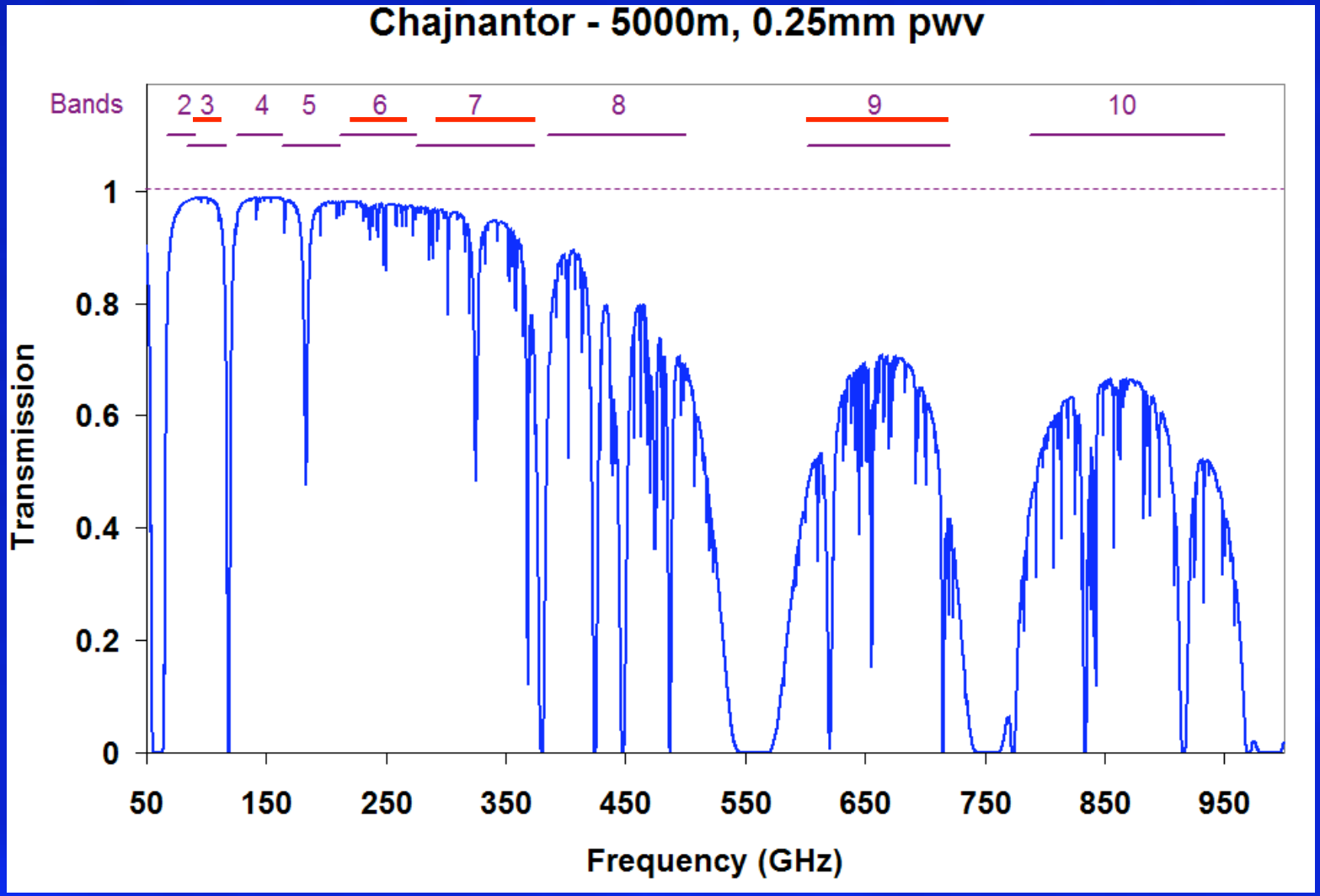
- Current numbers:
  - –Array/antenna calibration -- 95 days
  - –Testing calibration strategies -- 150 days
  - –Commissioning observing modes -- 230 days
  - –Single dish observing modes -- 60 days (in parallel)
  - –ACA 7m array (in parallel)
- Assume 20% downtime from outside factors
- Delaying factors include inclement weather, hardware/software problems, staffing shortfalls…
- Additional downtime from failures during CSV tests are included in the estimates (may expect 40-50% downtime in total based on experience at other telescopes)
- <10% SV fraction
- Consistent with a ~20-month program

One Month Outline of Commissioning Staff in Chile

Location	Week 1	Week 2	Week 3	Week 4	Total
OSF	2-3 day shift 2 night shift	2-3 day shift 2 night shift	2-3 day shift 2 night shift	2-3 day shift 2 night shift	18 people
SCO	6	6	6	6	
Off duty	4	4	4	4	
Research, travel or leave	2-3	2-3	2-3	2-3	
Total	18 people				

Modified turno system (8/28)

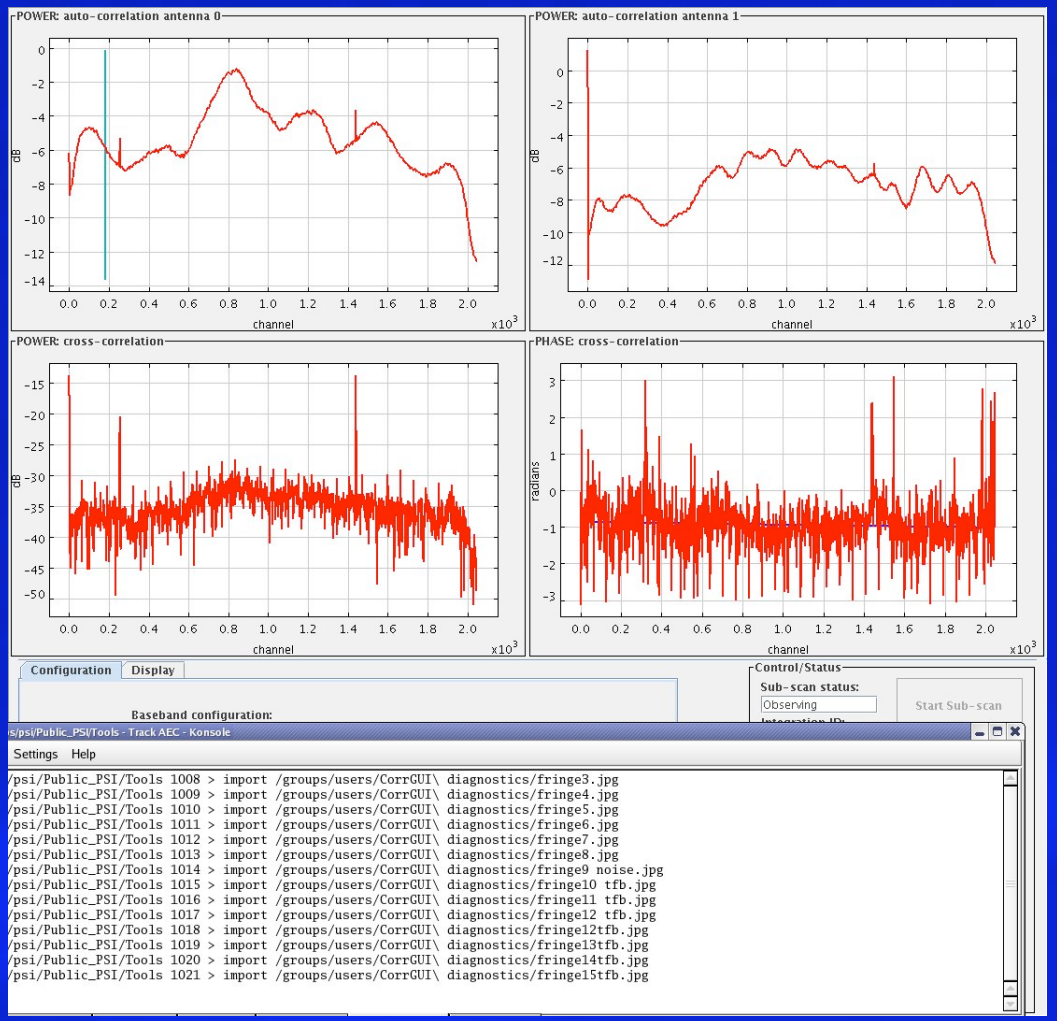
Atmospheric Opacity



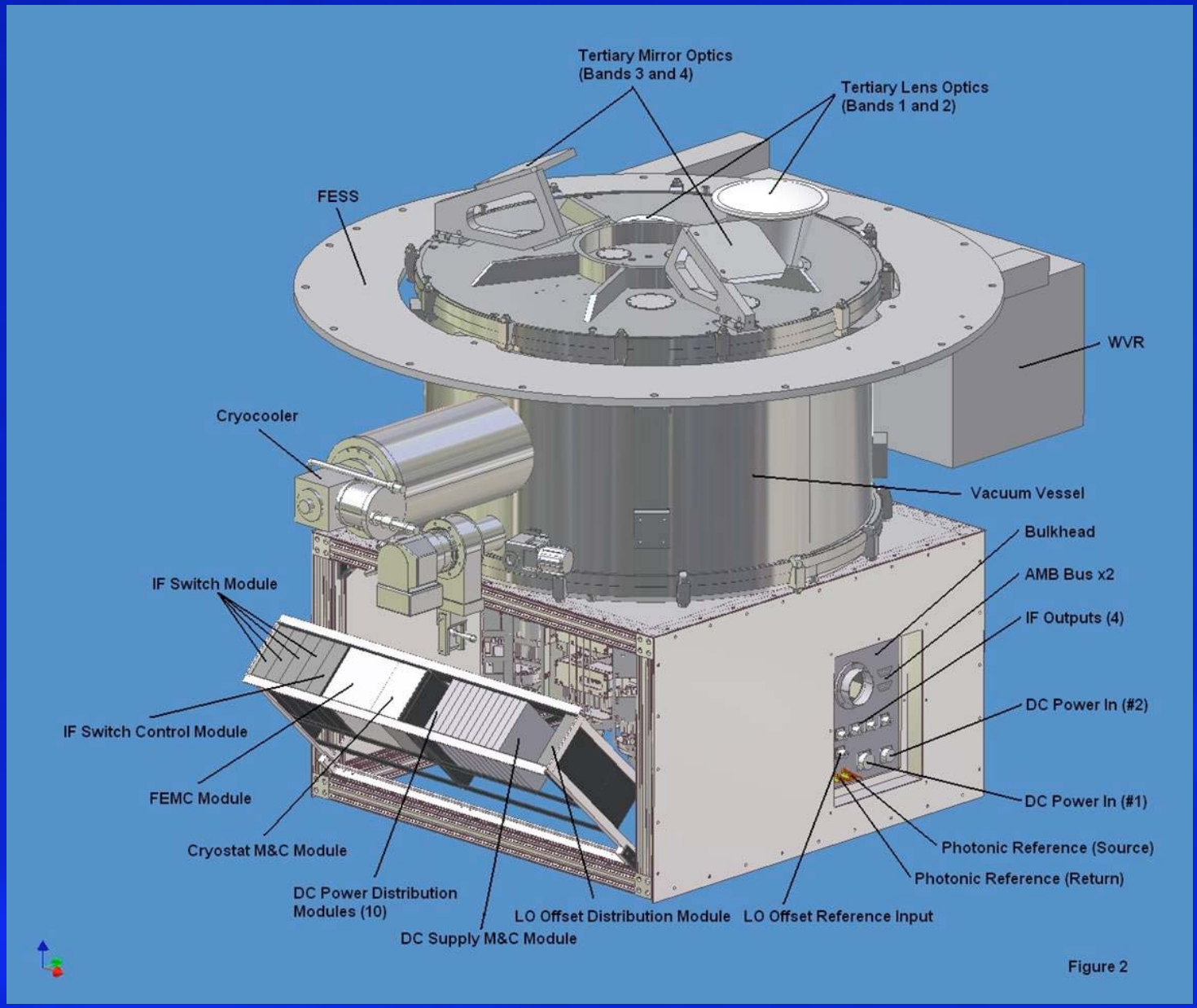
ATF Static Fringes on Mercury

Using new 2-antenna correlator, Aug 31, 2007

More recently, fringes detected toward 3C279 and 3C454.3 as well



Front End assembly

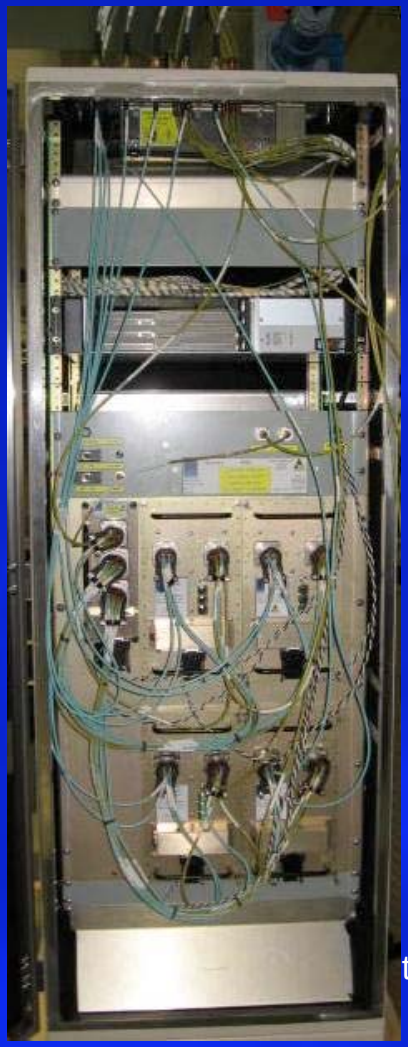


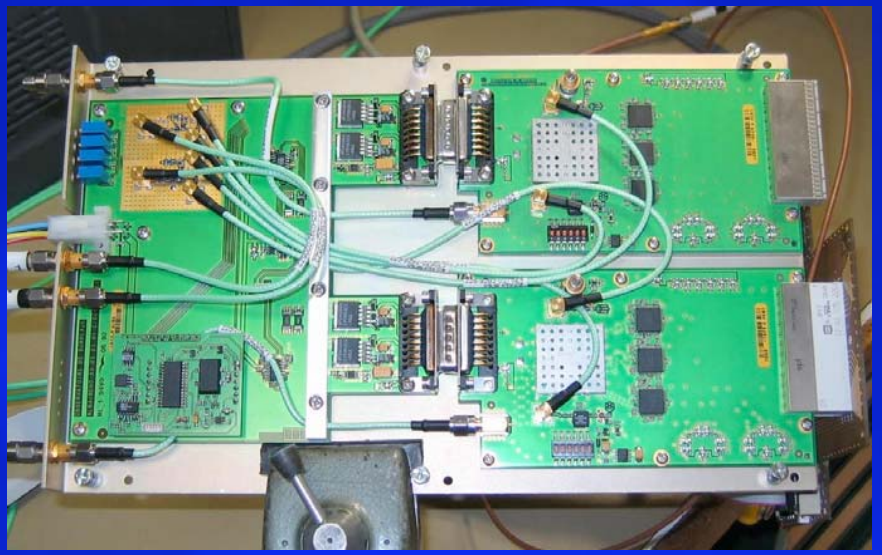
Vertex #1

European ARClet Specialties

- German node (contact Bertoldi): Advance data analysis (MAGIX), pipeline heuristics (calibration, data capture)
- Italian node (contact Brand): Data handling (GRID techniques),
- surveys, mosaicing, polarimetry
- Nordic node (contact Conway): Remote reduction, GRID computing, multi-frequency synthesis, phase modeling, self-calibration
- French/Spanish node (contact Gueth): Calibration, phase correction, polarimetry, imaging simulator, schools
- Dutch node (contact Hogerheijde): High-frequency, wide-field imaging, data analysis tools.
- UK node (contact Muxlow): Data analysis, archive, data reduction heuristics, proposal preparation

Back End – LO, DTS






BE Racks - January 2007

Budget

	IPT	Labor Y2000 K Dollars	Material Y2000 K Dollars	Travel Y2000 K Dollars	Total Budget Y2000 K Dollars
COMBINED	1.01 Management	$17,090	$59,101	$5,300	**$81,491**
	1.02 Site	$4,166	$109,293	$705	**$114,164**
	1.03 Antenna	$8,641	$8,497	$1,829	**$18,967**
	1.03 EU Antenna Contract	$0	$123,051	$649	**$123,700**
	1.03 NA Antenna Contract	$0	$136,982	$649	**$137,631**
	1.04 Front End	$20,358	$76,249	$1,459	**$98,067**
	1.05 Back End	$15,390	$32,218	$1,053	**$48,660**
	1.06 Correlator	$3,381	$6,327	$242	**$9,951**
	1.07 Computing	$19,128	$12,590	$1,645	**$33,363**
	1.08 SE&I	$24,313	$11,887	$6,115	**$42,316**
	1.09 Science	$6,850	$1,338	$1,005	**$9,192**
	Contingency				**$74,301**
Grand Total, 1000's of Y2000 Dollars		**$119,317**	**$577,534**	**$20,651**	**$791,803**

2007Apr01

+ Japan (~$300M)

Budget/History

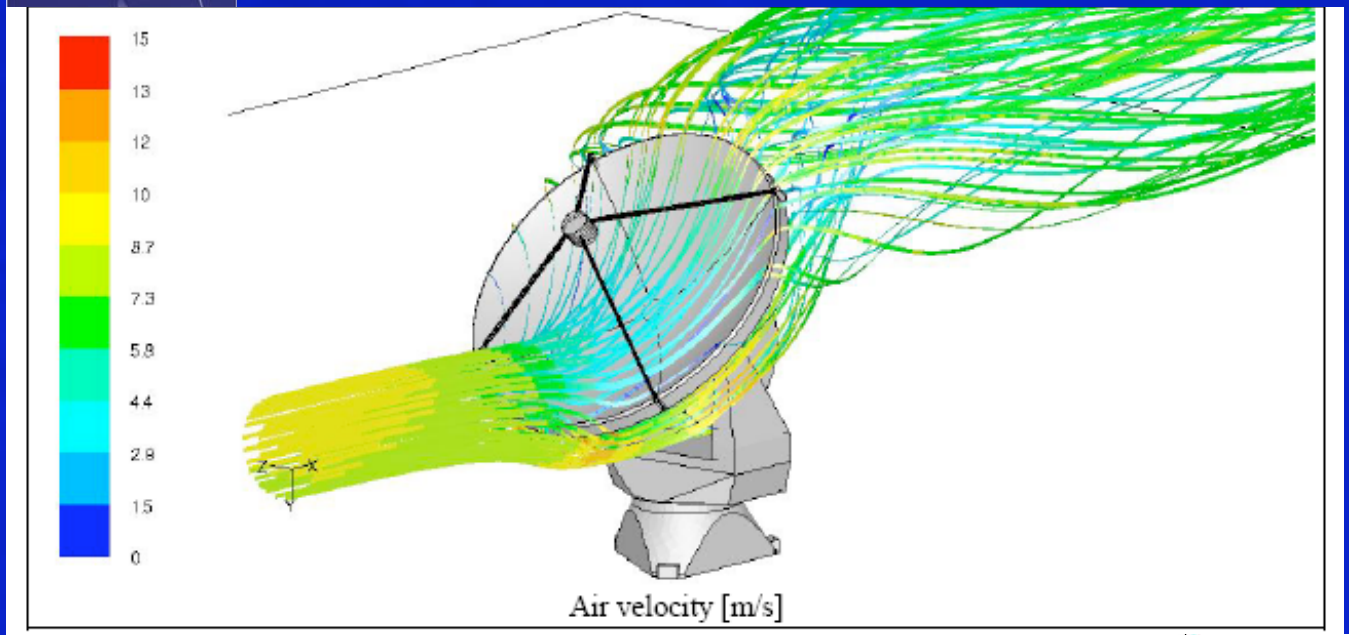
- ALMA concept: mid 90s….
- Original project budget (2002): $592M
- (scope, collaboration, political, personal,…)
- 2004: rebaselining (scope, budget, sched)
- Budget: 40% ↑ N: 64-->50
- Since 2005: tight EVMS control…

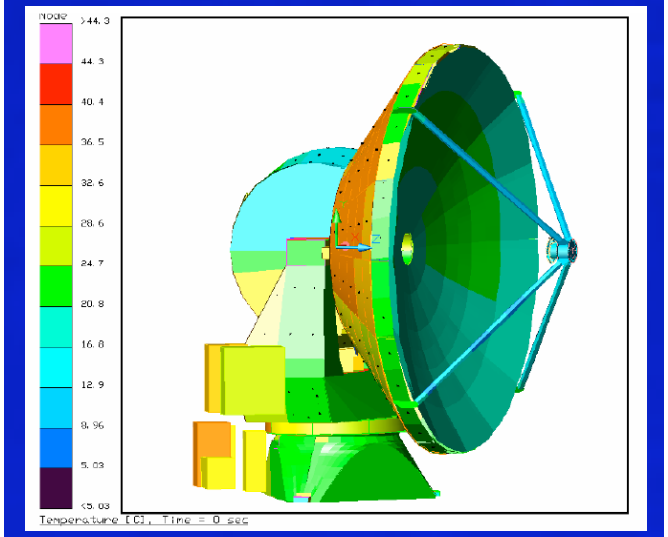
Brightness Temperature Sensitivity

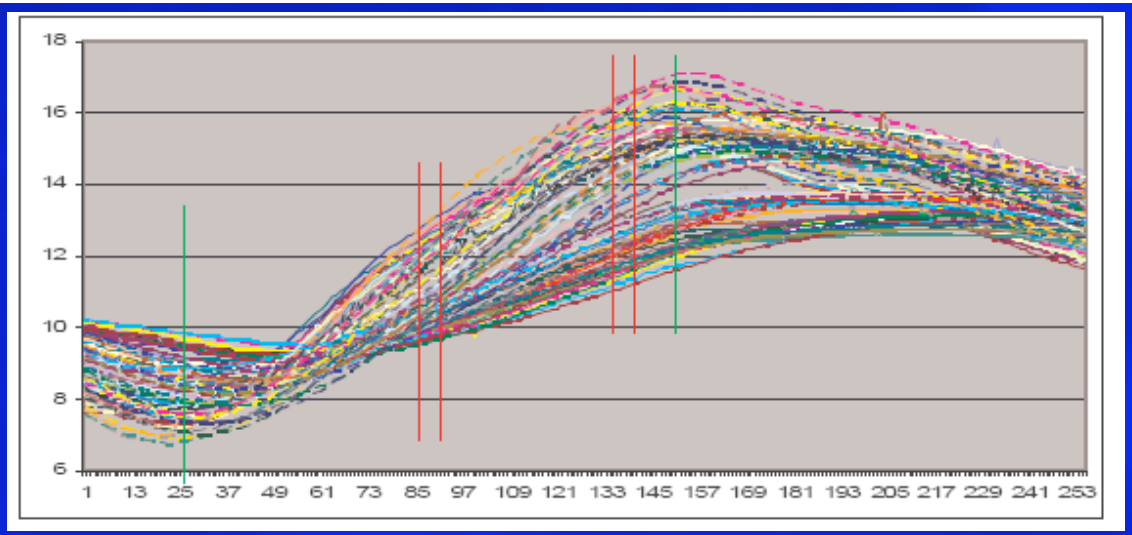
1 min, 1.5mm, *0.35 PWV, 1 km/s

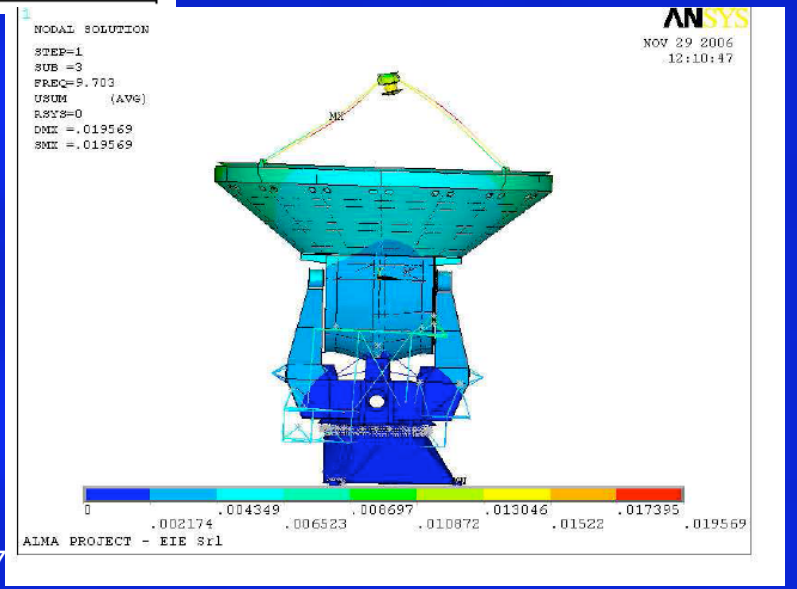
Frequency (GHz)	B_{max} 0.2km T_{cont} (K)	B_{max} 0.2km T_{line} (K)	B_{max} 10km T_{cont} (K)	B_{max} 10km T_{line} (K)
35	0.002	0.050	0.48	130
110	0.003	0.049	0.84	120
230	0.0005	0.054	1.3	140
345	0.0014	0.12	3.6	300
490	0.0030	0.23	7.6	580
675*	0.0046	0.28	12	690
850*	0.011	0.58	27	1400

AEM - PPDR Design Analysis – Jan 2007









Science Verification

- Main goals
  - Test ALMA modes end-to-end (includes projects from user community)
  - Feedback to CSV team
  - Early access to ALMA data for the community
- Modes fully commissioned before SV; PS responsible for decision to issue call
- Open call for proposals, fast, not using formal machinery; review for scientific value (+external) and feasibility (CSV team)
- Data public immediately
- Projects executed by CSV team/Operations; include QA
- ALMA Public Images are a subset of SV