The Atacama Large Millimeter/submillimeter Array: Current Status

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Deputy Project Scientist
Joint ALMA Office

ESO -- October 30, 2007
Overview

- International project to build & operate a large (up to 80-antennas) millimeter/submm ($\lambda \sim 0.85-3\text{mm}$) 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


  • 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 Key Science 1:

Planetary regions, nearby disks

\[ \frac{M_{\text{planet}}}{M_{\text{star}}} = \frac{0.5 \ M_{\text{Jup}}}{1 \ M_{\text{sun}}} \]

Orbital radius: 5 AU

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

(ALMA: 10km, \( t_{\text{int}} = 8h \), 30° phase noise)

Wolf & D’Angelo (2005)

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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.
ALMA Key Science 3: Interstellar Medium

Carbon Monoxide (CO) Image of Taurus Molecular Clouds

13CO Image showing densest regions

Size of Moon in Sky = ~1000 resolution elements

Note incredible detail observed in this star forming region

Credit: M. Heyer

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ALMA Key Science 4: High redshift deep fields
ALMA DF: Rich in Distant Galaxies

Nearby galaxies in ALMA DF

Distant galaxies in ALMA DF

Galaxies $z < 1.5$

Galaxies $z > 1.5$

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ALMA Science Requirements

- 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

CASA beam and u,v coverage simulations soon to be online for proposal planning.
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 $\lambda>1\text{mm}$, 25% $\lambda<1\text{mm}$)

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

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Imaging Performance

CASA simulations by R. Reid

Noiseless  
Thermal noise (672GHz, O21)

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Antennas

- Demanding ALMA antenna specifications:
  - Surface accuracy (25 \( \mu \text{m} \))
  - 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 \( \mu \text{m} \) non-repeatable, 20 \( \mu \text{m} \) 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

27 Mar 2007 Full configuration - 192 pads

- Central+Inner Array
- Y West
- ACA
- Y South
- Y Pampa La Bola

UTM-X

UTM-Y

UTM-X

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Both Short and Long Baselines
External Phase Correction

183 GHz Water Vapour Radiometers, tested at SMA

Mike Reid et al, 2006
## Correlator Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of antennas</td>
<td>64</td>
</tr>
<tr>
<td>Number of IF pairs per antenna</td>
<td>4</td>
</tr>
<tr>
<td>Max. sampling rate per IF pair</td>
<td>2 x 4 GHz</td>
</tr>
<tr>
<td>Digitizing format</td>
<td>3 bit, 8 level</td>
</tr>
<tr>
<td>Correlating format</td>
<td>2 bit, 4 level</td>
</tr>
<tr>
<td>Max. delay range</td>
<td>30 km</td>
</tr>
<tr>
<td>Channels per IF pair</td>
<td>4096</td>
</tr>
<tr>
<td>Autocorrelation channels per baseline</td>
<td>1024</td>
</tr>
<tr>
<td>Polarization</td>
<td>Full stokes (4 products)</td>
</tr>
</tbody>
</table>

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

CRL 618
Young et al

CO J=6-5

Gurwell et al

CO J=2-1 in Mars atmosphere

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Approximate Schedule

- Front Ends: #1, #2 2007, → production.
- BE/DTS: → production.

- 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

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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

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Equipment available

- 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

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

- Dual, linear polarization channels:
  - Increased sensitivity
  - Measurement of 4 Stokes parameters

- 183 GHz water vapour radiometer:
  - Used for atmospheric path length correction

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Atmospheric Opacity

Chajnantor - 5000m, 0.25mm pwv

Transmission vs. Frequency (GHz)
First Front End on Tilt Table
Initially Only Compact Configurations
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
(almasisimmos in CASA)

```plaintext
... 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: 6
Python Plotting time: 1.825 sec.

```
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
San Pedro de Atacama,
Atacama Desert, Northern Chile
Operations Support Facility (OSF): Technical Facilities 3000m

Contractor’s Camp holds ~440 persons
OSF Warehouse
ALMA Camp - OSF

First dorms

New dorms

Much nicer!

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Vertex Site Erection Facility
Temporary AIV Lab & Holography Tower
ALMA Science Reserve
5000m Chajnantor plateau – looking south
Array Operations Site

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Chajnantor Plateau – looking north

V. Licancabur

Cº Chajnantor

Pampa La Bola

Center of Array

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

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Inside AOS technical building
Prototype Antennas at ATF

Mitsubishi antenna

Vertex antenna

AEC antenna

12-m, Carbon Fiber Support Structure
Transporting an ALMA Antenna (Artist's Impression)

ESO Press Photo 321/07 (30 July 2007)
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Transporter – Germany, July 2007

The ALMA Transporter

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

Vertex #1 - Mar 19th 2007
Vertex #1 at OSF -
All 8 rows of panels now installed and cladding finished (October)
3 ACA 12-m antennas en route to OSF

(15 km/hr for 3 days)
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

<table>
<thead>
<tr>
<th>Location</th>
<th>Week 1</th>
<th>Week 2</th>
<th>Week 3</th>
<th>Week 4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSF</td>
<td>2–3 day shift</td>
<td>2–3 day shift</td>
<td>2–3 day shift</td>
<td>2–3 day shift</td>
<td>18 people</td>
</tr>
<tr>
<td></td>
<td>2 night shift</td>
<td>2 night shift</td>
<td>2 night shift</td>
<td>2 night shift</td>
<td></td>
</tr>
<tr>
<td>SCO</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Off duty</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Research, travel</td>
<td>2–3</td>
<td>2–3</td>
<td>2–3</td>
<td>2–3</td>
<td>4</td>
</tr>
<tr>
<td>or leave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>18 people</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Modified turno system (8/28)
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

04/27/2007
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
# Budget

<table>
<thead>
<tr>
<th>IPT</th>
<th>Labor</th>
<th>Material</th>
<th>Travel</th>
<th>Total Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.01 Management</td>
<td>$17,090</td>
<td>$59,101</td>
<td>$5,300</td>
<td>$81,491</td>
</tr>
<tr>
<td>1.02 Site</td>
<td>$4,166</td>
<td>$109,293</td>
<td>$705</td>
<td>$114,164</td>
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<tr>
<td>1.03 Antenna</td>
<td>$8,641</td>
<td>$8,497</td>
<td>$1,829</td>
<td>$18,967</td>
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<tr>
<td>1.03 EU Antenna Contract</td>
<td>$0</td>
<td>$123,051</td>
<td>$649</td>
<td>$123,700</td>
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<tr>
<td>1.03 NA Antenna Contract</td>
<td>$0</td>
<td>$136,982</td>
<td>$649</td>
<td>$137,631</td>
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<td>1.04 Front End</td>
<td>$20,358</td>
<td>$76,249</td>
<td>$1,459</td>
<td>$98,067</td>
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<td>1.05 Back End</td>
<td>$15,390</td>
<td>$32,218</td>
<td>$1,053</td>
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<td>1.06 Correlator</td>
<td>$3,381</td>
<td>$6,327</td>
<td>$242</td>
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<tr>
<td>1.07 Computing</td>
<td>$19,128</td>
<td>$12,590</td>
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<td>1.09 Science</td>
<td>$6,850</td>
<td>$1,338</td>
<td>$1,005</td>
<td>$9,192</td>
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<tr>
<td>Contingency</td>
<td></td>
<td></td>
<td></td>
<td>$74,301</td>
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<tr>
<td>Grand Total, 1000’s of Y2000 Dollars</td>
<td>$119,317</td>
<td>$577,534</td>
<td>$20,651</td>
<td>$791,803</td>
</tr>
</tbody>
</table>

+ Japan (~$300M)

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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

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$B_{\text{max}}$ 0.2km</th>
<th>$B_{\text{max}}$ 0.2km</th>
<th>$B_{\text{max}}$ 10km</th>
<th>$B_{\text{max}}$ 10km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{\text{cont}}$ (K)</td>
<td>$T_{\text{line}}$ (K)</td>
<td>$T_{\text{cont}}$ (K)</td>
<td>$T_{\text{line}}$ (K)</td>
</tr>
<tr>
<td>35</td>
<td>0.002</td>
<td>0.050</td>
<td>0.48</td>
<td>130</td>
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<tr>
<td>110</td>
<td>0.003</td>
<td>0.049</td>
<td>0.84</td>
<td>120</td>
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<td>230</td>
<td>0.0005</td>
<td>0.054</td>
<td>1.3</td>
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<td>345</td>
<td>0.0014</td>
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<td>300</td>
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<td>490</td>
<td>0.0030</td>
<td>0.23</td>
<td>7.6</td>
<td>580</td>
</tr>
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<td>675*</td>
<td>0.0046</td>
<td>0.28</td>
<td>12</td>
<td>690</td>
</tr>
<tr>
<td>850*</td>
<td>0.011</td>
<td>0.58</td>
<td>27</td>
<td>1400</td>
</tr>
</tbody>
</table>

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AEM - PPDR Design Analysis – Jan 2007

Air velocity [m/s]
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