# ALMA's view of maser emission

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IAU 242: Astrophysical Masers and Their Environments

# ALMA – Major Elements

## AOS TB Now on Internet!

Photo H. Heyer (ESO).

- Partners: ESO – US (NSF)+Canada (NRC) – Chile – Japan ...*Taiwan*


- **Array Operations Site – AOS**
- **Operations Support Facility – OSF**
- **Santiago Central Offices – SCO**
- **ALMA Regional Centers – ARCs + ARClets**

- During full operation, the estimated flow into archive ~ 100 Tbytes per year
- Dataset: proposal, u-v data, a reference image with pipeline processing history, calibration data… modern radioastronomy

# Highest Level Science Goals

***Bilateral Agreement Annex B:***

"ALMA has three level-1 science requirements:

- 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 (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), 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". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees. These requirements drive the technical specifications of ALMA. "

**A detailed discussion of them may be found in the new ESA publication *Dusty and Molecular Universe* on ALMA and Herschel.**

# ALMA

- International project to build & operate a large (66-antenna) millimeter/submm ($\lambda$ ~0.35-10mm) array at high altitude site (5000m) in northern Chile.

- Project began in 2002; Japan joined in 2004; project redefined/rebaselined 2005; construction, hardware production lines underway, software in development;

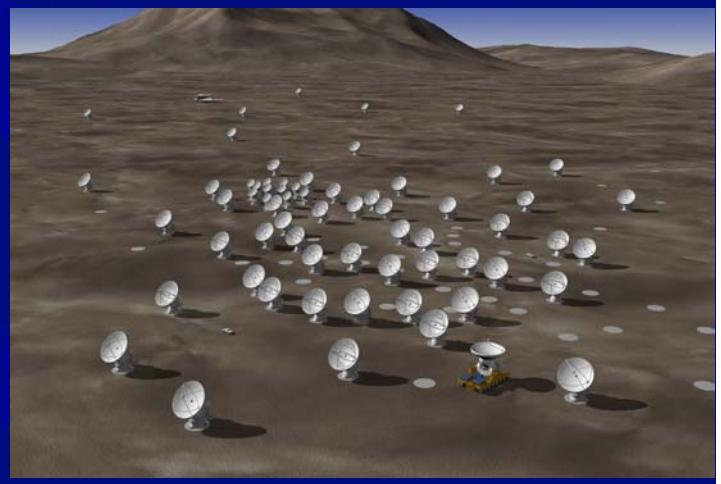
First Fringes 2007 March 2 at 7:13pm MST

early science ~2010, full science operations 2012.

- Considerable infrastructure is on site now leading to the arrival of the first antenna structures next month.

# 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 Mosaicking.
- Superb submillimeter site.
- Full Polarization Capability.
- System Flexibility.

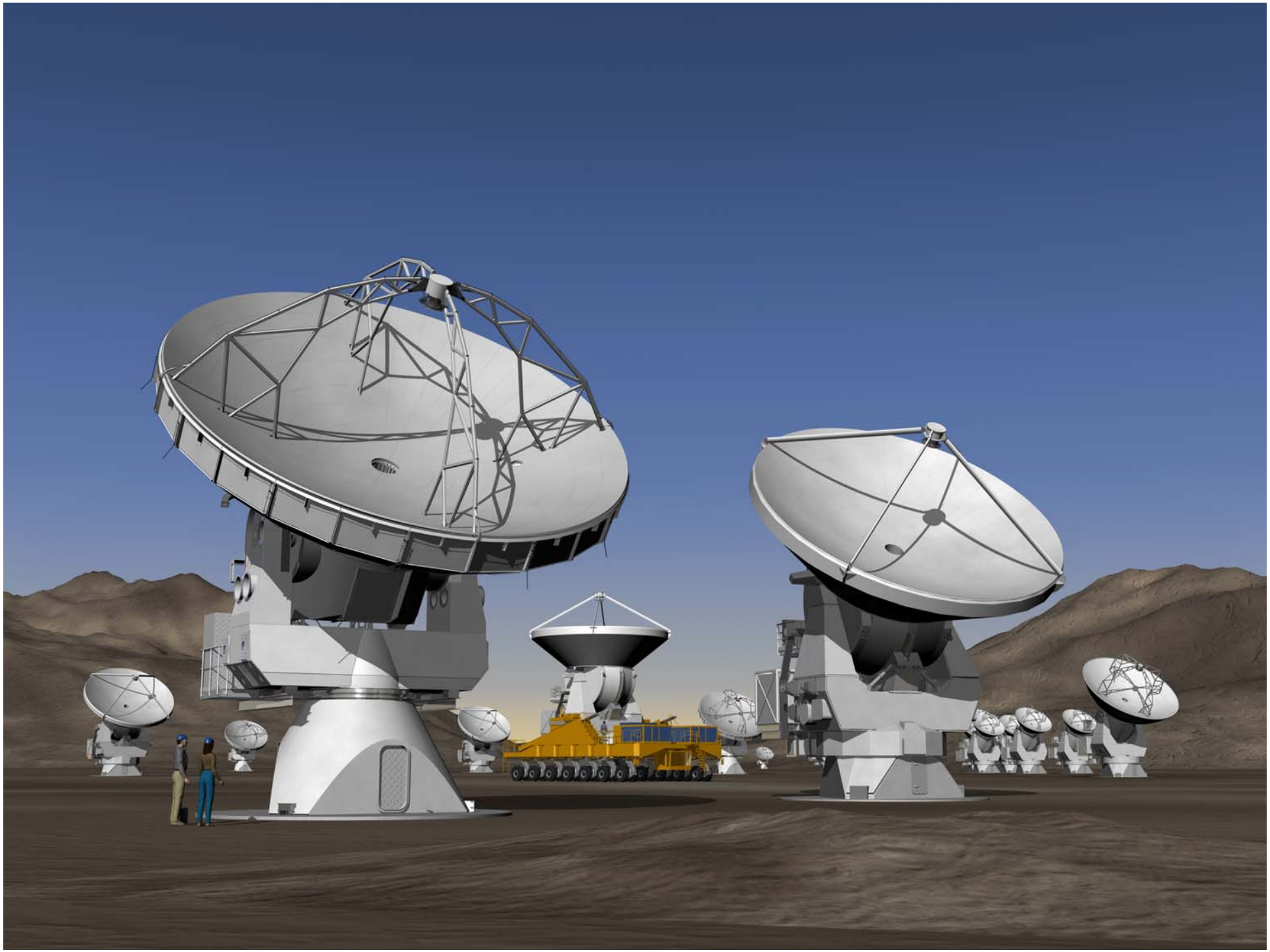


# Technical Specifications

- 54 12-m antennas, 12 7-m antennas, at 5000 m altitude 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. Initially:
- 84-116 GHz "3"
- 125-169 GHz "4"
- 163-211 GHz "5" 6 rx only, single polzn
- 211-275 GHz "6"
- 275-373 GHz "7"
- 385-500 GHz "8"
- 602-720 GHz "9"
- 787-950 GHz "10" initially partially populated
- 8 GHz BW, dual polarization.
- Flux sensitivity 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60 MB/s.
- All data archived (raw + images), pipeline processing.

# Key features for maser observation enhanced since AMII

- Extensive frequency access--additional frequency bands populated at first light
  - Previous plan: 3mm, 1.3mm, .87mm, .45mm
  - Additions: 2mm (JP), 1.6mm (EU; partial), .61mm (JP), .35mm (JP; partial)
- Large collecting area, high brightness temperature sensitivity
  - Additional antennas (JP), 16 element array 'Atacama Compact Array'
- Versatile correlator system
  - Tunable filter banks added (EU-Ubx), more flexible system, more channels
  - Additional ACA correlator (JP)
- Southern hemisphere location, but within the tropics.
  - Excellent for Galactic center, Carina arm, Magellanic clouds.



# ALMA and Contractor Camps

**View to the ALMA Camp**

# ALMA and Contractor Camps

**View to the Contractor Camp**

# Operation Support Facility (OSF)

**View from East to West**

# Operation Support Facility (OSF)

**View of Technical Building**

# AOS Technical Building

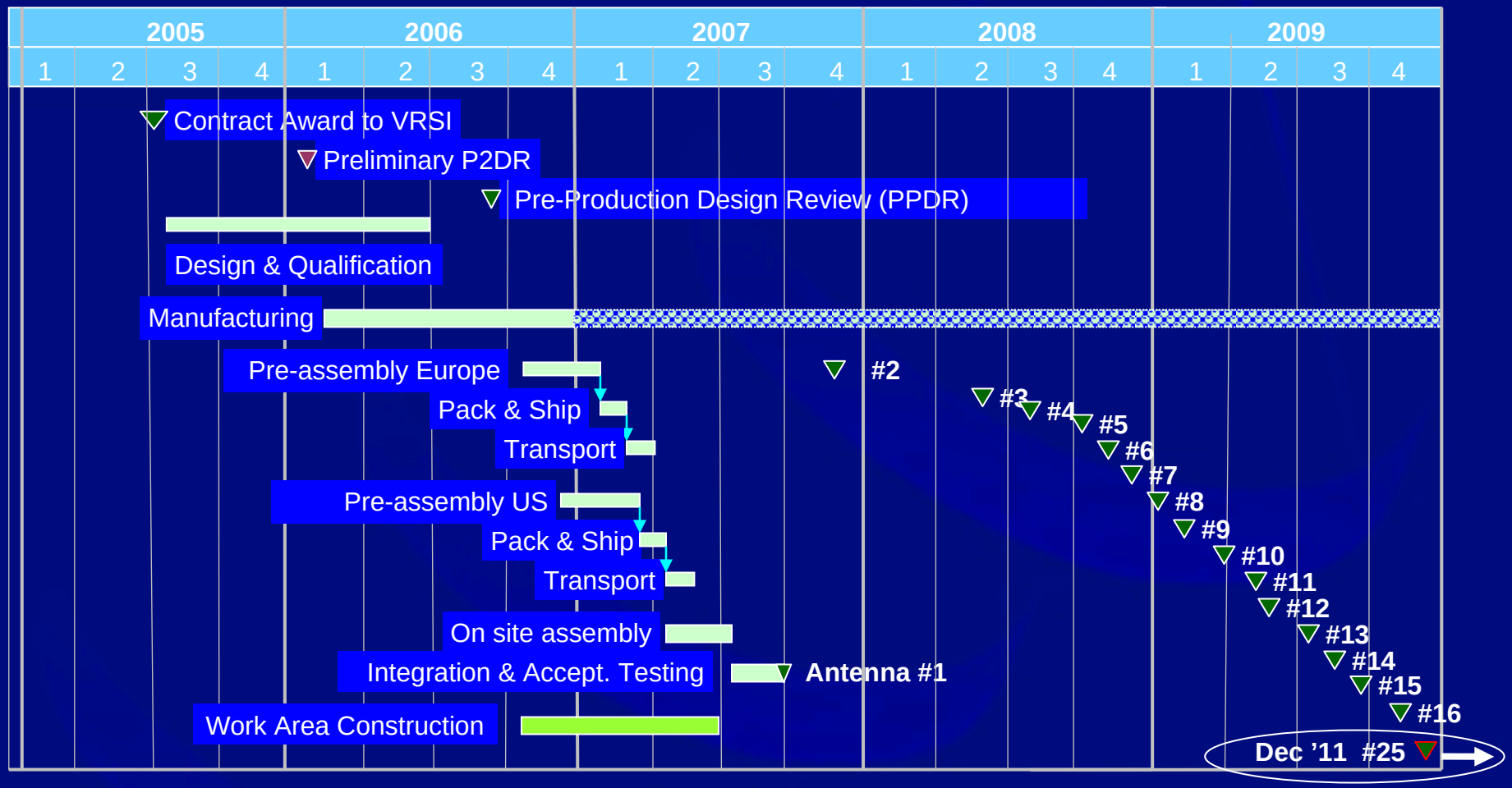
**View of AOS Technical Building**

# Antenna Vendor Areas

View of Vertex hangar construction

# NA ALMA Antenna #1 - Pedestal Structure


# NA Antenna Contract – Partial Schedule



# Antenna Transporter Manufacturing: FDR Status

# Some Molecules Known to Mase at ALMA

$\nu$s

| Species | Bands |
|---|---|
| $H_2O$ | B3, B5, B6, B7, B8, B9 |
| $CH_3OH$ | B1, B3, B4, B6 |
| SiO | B1, B2, B3, B4, B5, B6, B7 |
| HCN | B3, B5, B6, B7, B9 |
| Etc: Hn$\alpha$, SiS | B3, B4, B6, B7, B9 |

Ref: Menten

## Brightness Temperature Sensitivity

1 min, AM 1.3, 1.5mm, *0.35 PWV, 1 km/s

| Frequency (GHz) | $B_{max}$ 0.2km $\Delta T_{cont}$ (K) | $B_{max}$ 0.2km $\Delta T_{line}$ (K) | $B_{max}$ 10km $\Delta T_{cont}$ (K) | $B_{max}$ 10km $\Delta T_{line}$ (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 |
| 409 | 0.0030 | 0.23 | 7.6 | 580 |
| 675* | 0.0046 | 0.28 | 12 | 690 |
| 850* | 0.011 | 0.58 | 27 | 1400 |

For $\nu$<430 GHz, PWV=1.5mm; $\nu$ >430 GHz, PWV=0.35mm

# The ALMA Correlators

- NRAO Baseline Correlator (four quadrants for 64 antennas, BW: 8 GHz x 2; 2 bit sampling with limited 3 or 4 bit sampling)
  - First quadrant operating in NRAO NTC, to be retrofitted with Tunable Filter Bank enhancement (UBx)
  - Second quadrant being completed at NRAO NTC
  - First installation at AOS TB next year.
  - Detailed list of Observational Modes in ALMA Memo 556 (available at www.alma.nrao.edu)
- ACA Correlator (NAOJ)
  - First installation at AOS TB next year.

# Baseline Correlator Overview

- Observer may specify a set of disjoint or overlapping spectral regions, each characterized by
  - Bandwidth (31.25 MHz to 2 GHz)
    - Each 2 GHz baseband input (8 available) drives 32 tunable digital filters
  - Frequency (Central or starting)
  - Resolution (number of spectral points)
  - Number of polarization products: 1 (XX or YY), 2 (XX and YY) or 4 (XX, YY, XY, YX cross-polarization products)
  - Improved sensitivity options (4x4 bit correlation, or double Nyquist modes)
  - Temporal resolution depends upon mode (from 16 msec to 512 msec)
- Simultaneous pseudo-continuum and spectral line operation

# Multiple Spectral Line Windows

- Multiple spectral windows
  - Within the 2 GHz IF bandwidth
  - For modes with total bandwidth 125 MHz to 1 GHz
  - Useful for high spectral resolution observations of e.g. several lines within IF bandwidth (examples to be shown)
- Multi-resolution modes
  - Simultaneous high and low resolution
  - Line core and line wings simultaneously
    - Planetary Observations
    - Outflow/Core Observations

- As an ALMA goal is ease of use, the Observing Tool will guide the observer through the maze of spectral line possibilities

# Water

- Star-forming Regions
  - Shocks, Warm chemically active regions
  - ALMA brings: High resolution, high brightness temperature sensitivity, spectral coverage & flexibility, polarization
- Stars
  - Near-stellar environment, flow, B-fields
  - ALMA brings: High resolution, spectral coverage & flexibility, polarization
- Galactic Nuclei
  - ALMA brings: High resolution, high sensitivity, spectral coverage, polarization

# It Moves!

ALMA B10 Beam

## Water masers in NGC1333 4B (north):

## A flow in motion

- Each shock lasts <2 months
- Any parcel of gas must be exposed to a succession of shocks
- ALMA will reveal the complex chemical evolution of these shocks.
- Excellent brightness temperature sensitivity
- Excellent, near-VLBI, resolution.

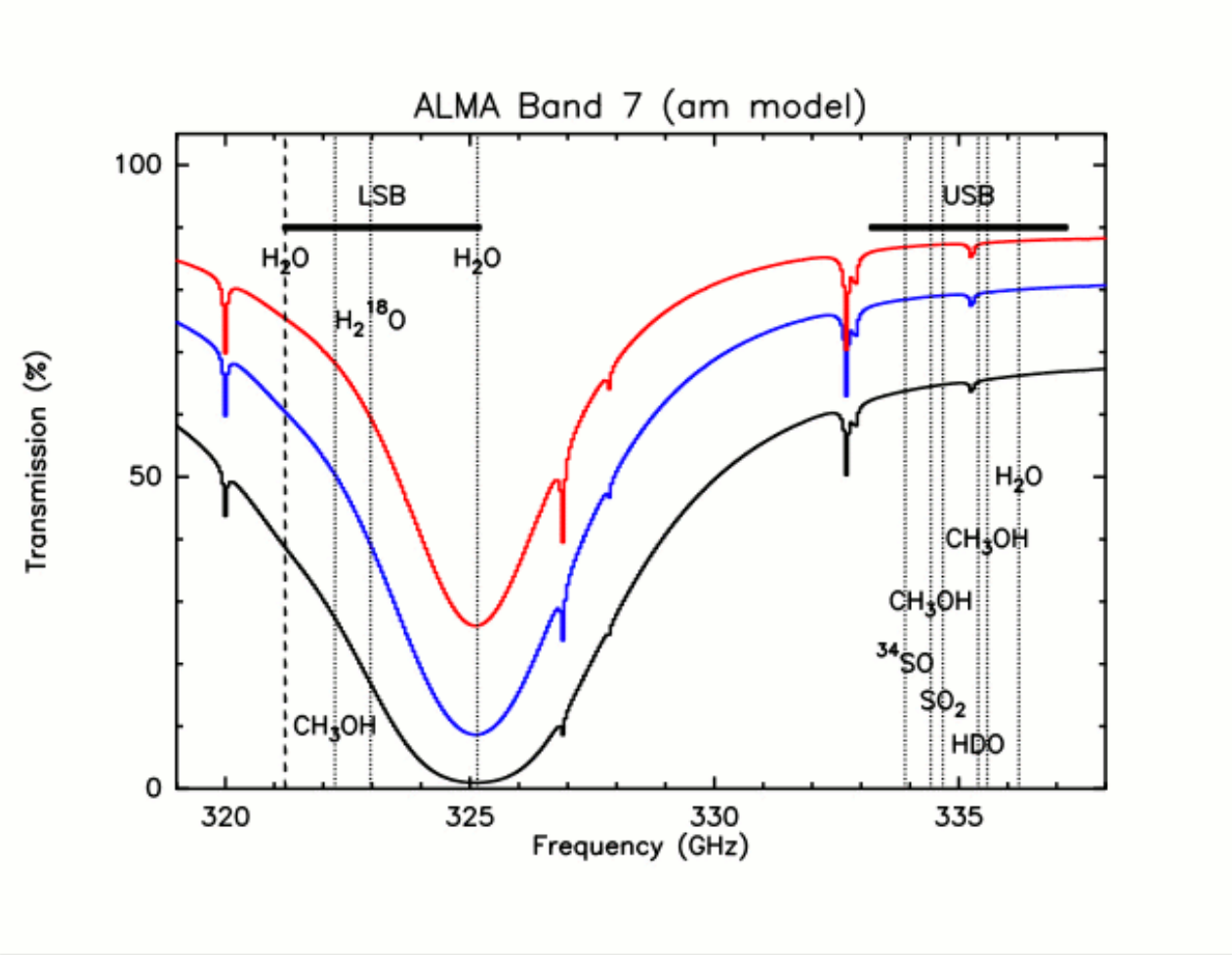
# Example multi-transition setup

- Goal: Measure water in five transitions simultaneously, some of which mase.
  - $H_2O$ J $_{Ka,Kc}$ $10_{29}$ $9_{36}$ 321.23 GHz E~1862 K ortho
    - E.g. 3-4 Jy SMA; <1” => $T_b$ >? K
  - $H_2{}^{18}O$ J $_{Ka,Kc}$ $5_{15}$ $4_{22}$ 322.97 GHz E~470 K para
  - $H_2O$ J $_{Ka,Kc}$ $5_{15}$ $4_{22}$ 325.15 GHz E~470 K para
  - $H_2O$ J $_{Ka,Kc}$ $5_{23}$ $6_{16}$ v2 =1 336.23 GHz E~2939 K ortho
  - HDO $3_{31}$-$4_{22}$ 335.396 E~319 K
  - Also $CH_3OH$, SO, $SO_2$ lines
  - Use B7, LSB on maser lines, largest array
  - Dynamic Schedule picks superb weather
    - PWV=0.35mm
  - Beamsize = 0”.013; $T_b$ rms~52K 8 hrs, $\Delta$S~0.8mJy
  - 5s ints, data rate~30MB/s, dataset size ~860GB.

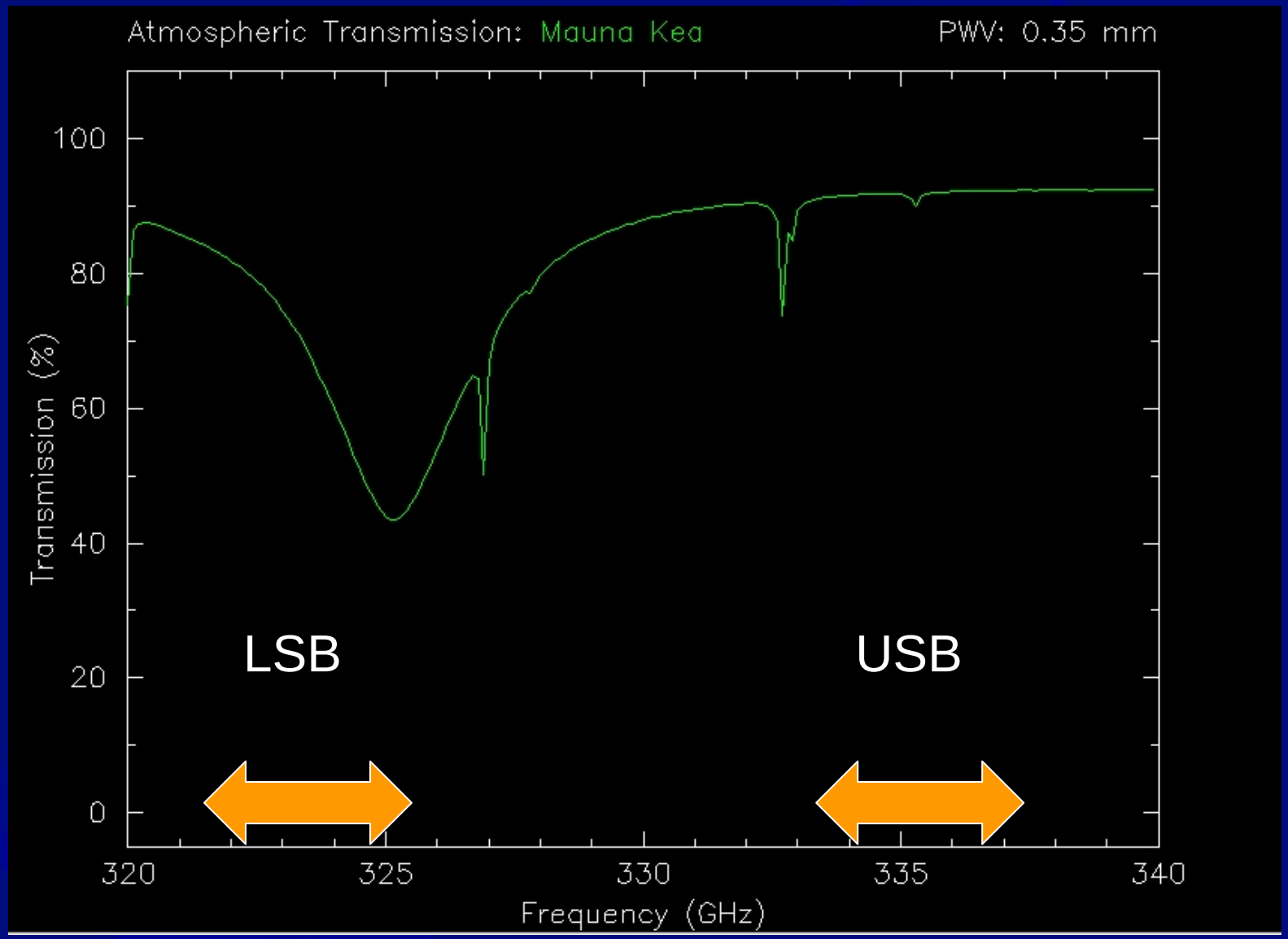
# An unfriendly but not obstinate atmosphere…

Chajnantor Atmosphere: 25%=> $T_b$ rms~760K 8 hrs, $\Delta S$~12mJy

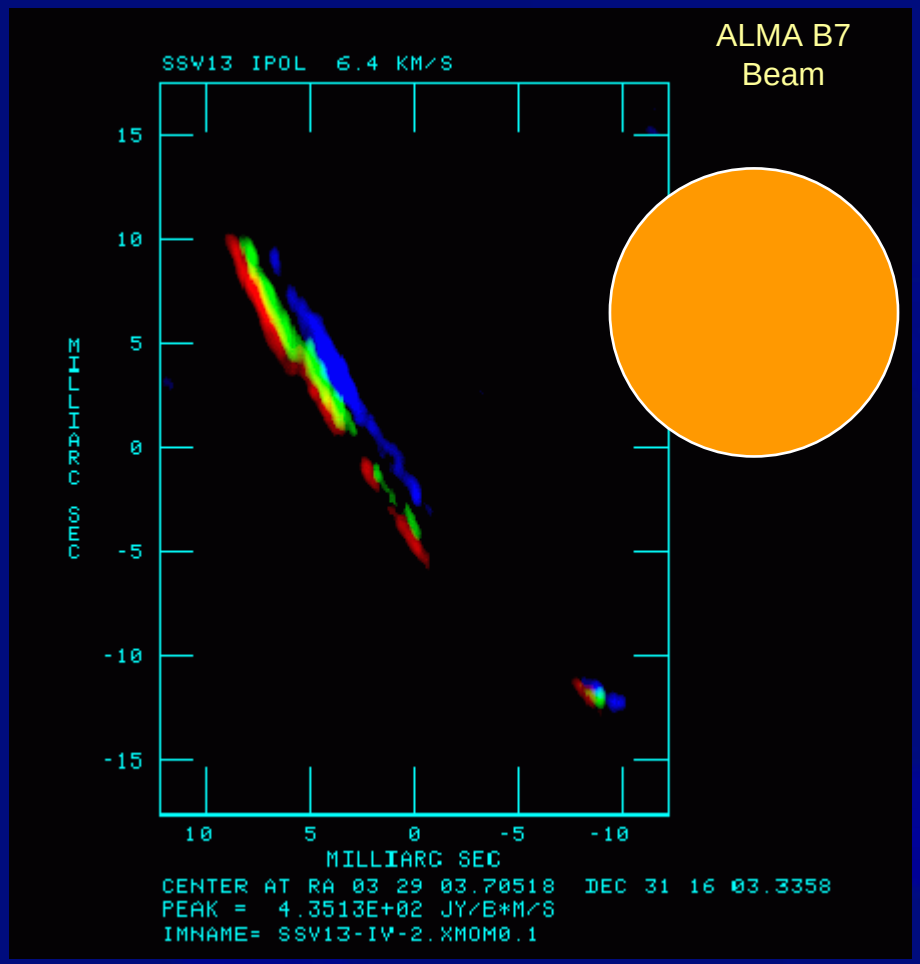
| Q | $\tau_{225}$ | pwv |
|---|---|---|
| 1 | .029 | .52 |
| 2 | .037 | .66 |
| 3 | .048 | .86 |
| 4 | .063 | 1.13 |
| 5 | .086 | 1.54 |
| 6 | .127 | 2.26 |
| 7 | .232 | 4.14 |



# An unfriendly but not obstinate atmosphere…



# Proper Motion and Structure of Shocks in Dense Clouds




*Masers near SVS13; 1mas=0.34AU*
*Blue Epoch I, Green Epoch III, Blue Epoch IV*
*Wootten, Marvel, Claussen and Wilking*

Water masers observed over four epochs encompassing 50 days (22 GHz, VLBA). Several of the masers define an arc structure about 5AU in length. This consistently moved at a rate of 0.023 mas/day, or 13.6 km/s.

Including the radial velocity offset, a space velocity of 13.7 km/s is calculated at an inclination of 6 degrees from the plane of the sky.

These structures apparently represent water emission from interstellar shocks driven by the outflow from SVS13. ALMA can provide images of chemistry in action in shocks such as this.

# Stars

- SiO masers can be substituted for methanol or HDO in the same setup.
- One could employ cross polarization correlator modes to explore magnetic fields.
- ALMA sensitivity would allow observing SiO masers or HCN masers in the Magellanic Clouds.

# ALMA:
# Summary of detailed requirements

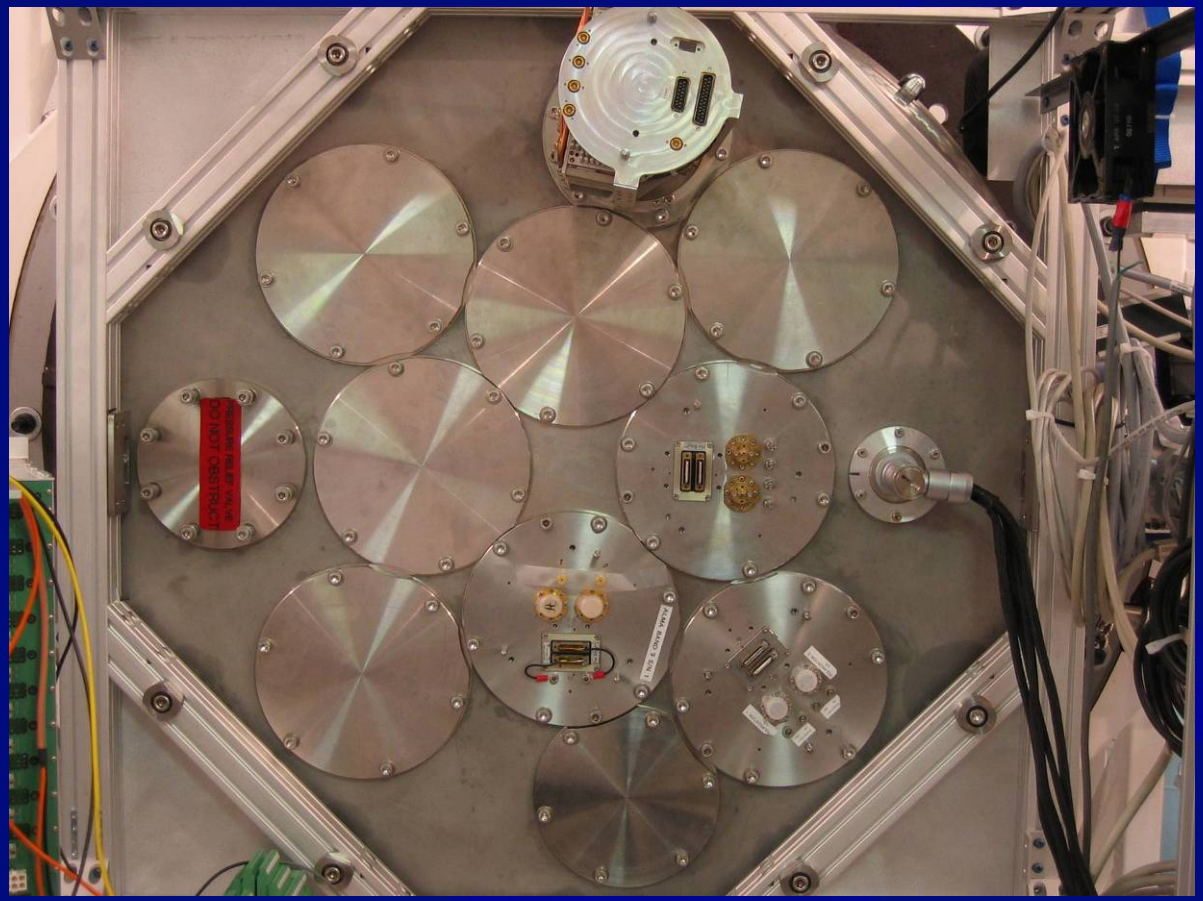
| | |
|---|---|
| Frequency | 30 to 950 GHz (initially only 84-720 GHz fully instrumented) |
| Bandwidth | 8 GHz, fully tunable |
| Spectral resolution | 31.5 kHz (0.01 km/s) at 100 GHz |
| Angular resolution | 30 to 0.015” at 300 GHz |
| Dynamic range | 10000:1 (spectral); 50000:1 (imaging) |
| Flux sensitivity | 0.2 mJy in 1 min at 345 GHz (median conditions) |
| Antenna complement | 50 antennas of 12m diameter, plus compact array of 4 x 12m and 12 x 7m antennas (Japan) |
| Polarization | All cross products simultaneously |

European ALMA News (www.eso.org),
ALMA/NA Biweekly Calendar (www.cv.nrao.edu/~awootten/mmaimcal/ALMACalendars.html)

www.alma.info

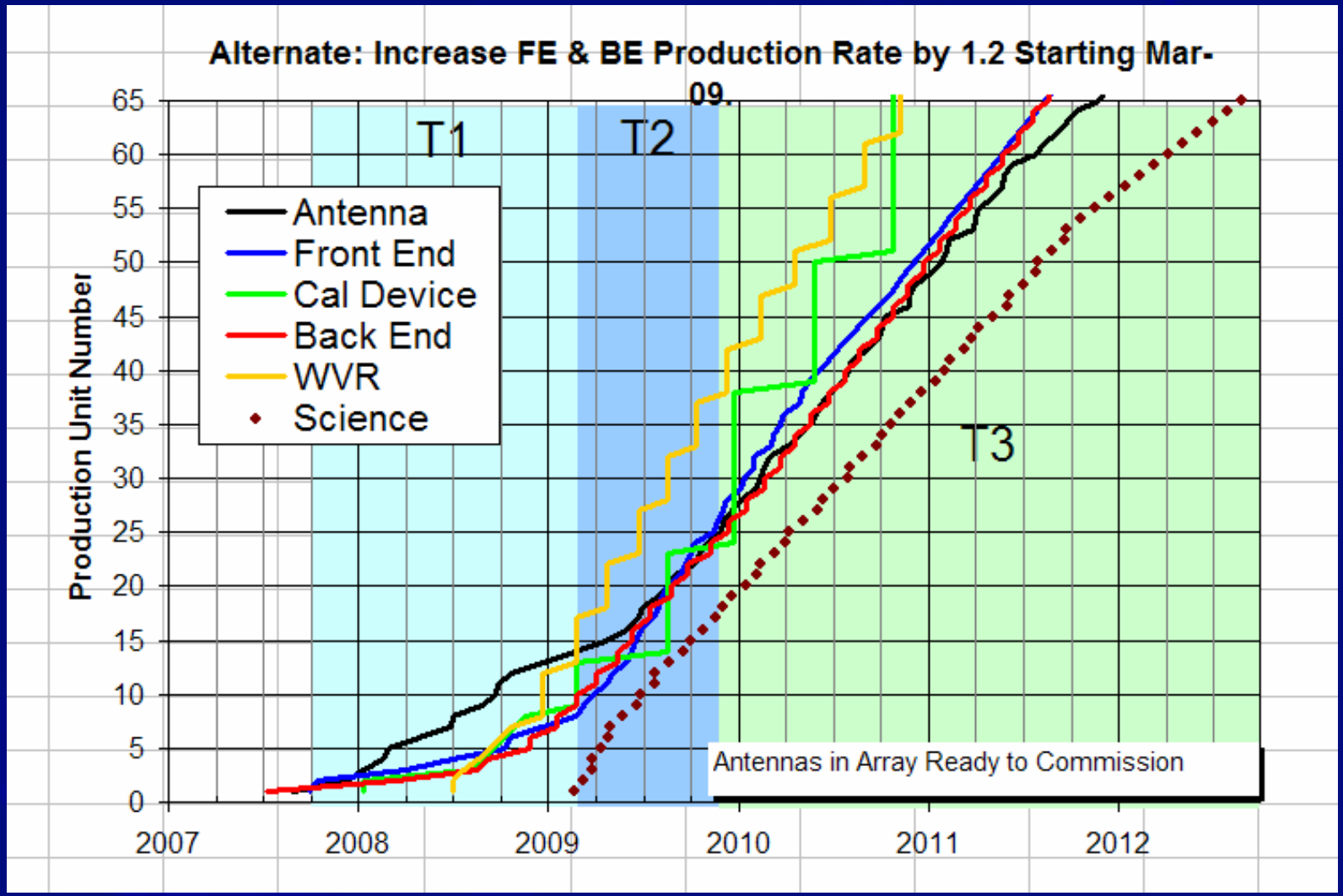
The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research 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.

# Front End Under Test




Bottom of cryostat #2 with four cold cartridges installed. Band 3 cartridge at top has WCA attached but not cabled. Other cartridges, top to bottom, are Band 7, Band 9, and Band 6.

# ALMA Rampup


Alternate: Increase FE & BE Production Rate by 1.2 Starting Mar-09.
Production Unit Number
65
60
55
50
45
40
35
30
25
20
15
10
5
0
2007
2008
2009
2010
2011
2012
T1
T2
T3
Antenna
Front End
Cal Device
Back End
WVR
Science
Antennas in Array Ready to Commission