# ESO/ALBiUS activities in ALMA imaging with CASA

Dirk Petry (ESO), August 2010

**Outline**

→ ALMA Overview

→ ALMA CALIM challenges

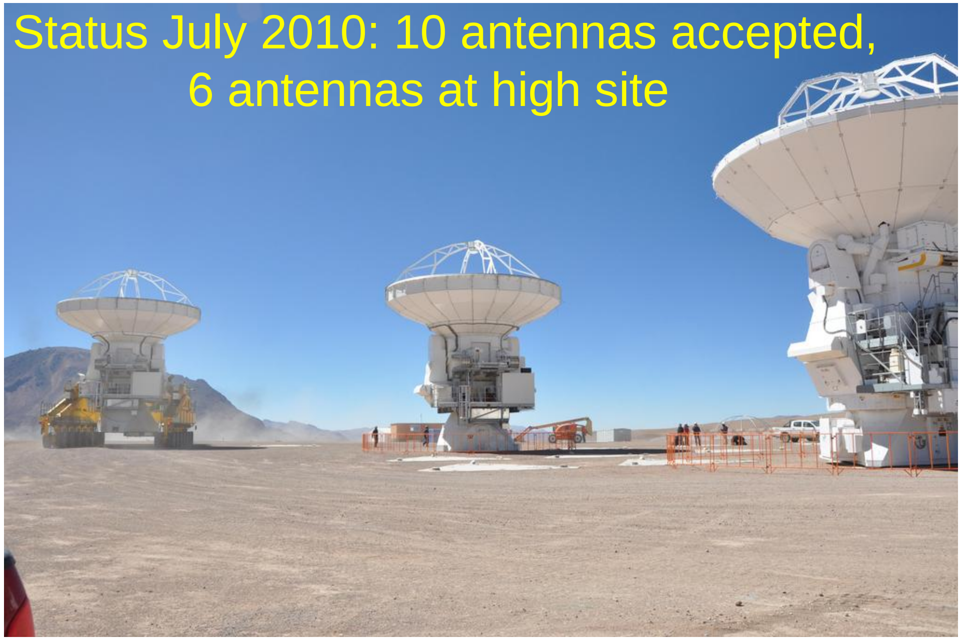
→ CASA status

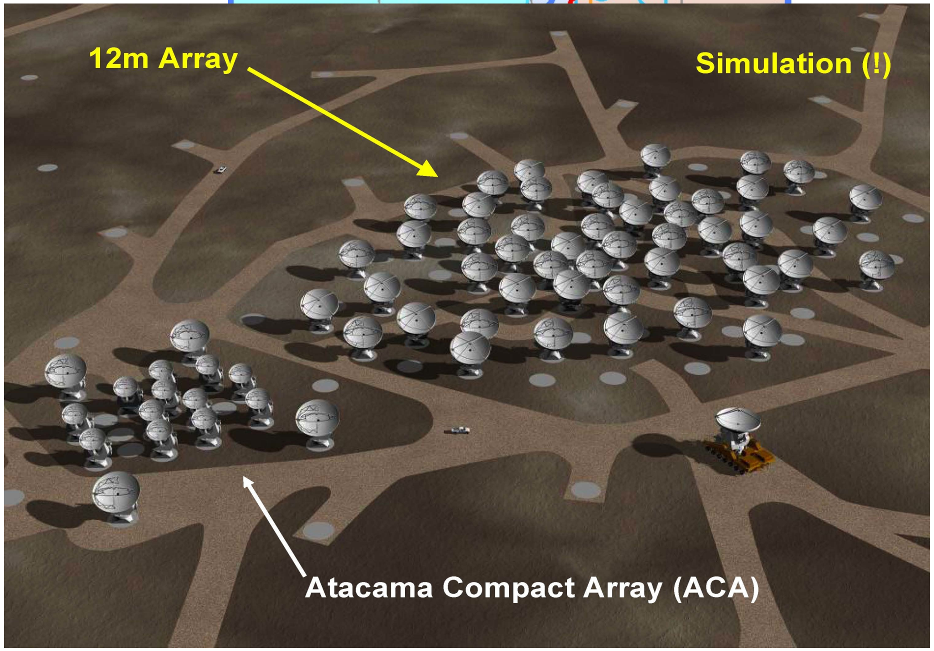
→ Ongoing work at ESO

# ALMA Overview

The **Atacama Large Mm/sub-mm Array**
- a collaboration between America (US, Canada, Chile), Europe (ESO member states), and East Asia (Japan, Taiwan)

Located at the Atacama desert, Chile, 5000 m a.s.l.
Total cost approx. 1 Billion Euros
Main Array: 50 x 12m antennas (up to 64)
+ 4 x 12m (total power)
+ Atacama Compact Array: 12 x 7m antennas

# ALMA Overview

**Array reconfigurable (zooming), extension from 0.2 km to 16 km**

**Imaging between 84 to 950 GHz (3 mm to 350 μm),**
**primary beams between 56” and 7”,**
**angular resolutions between 3” and 0.005”.**

**Flexible correlator: up to 2016 baselines, 8 baseband channels of up to 2 GHz width,**
**up to 4096 x (4/N) x (2/P) spectral points per baseband channel,**
(*where N = 1, 2 or 4 is the number of baseband channels per polarization and P=2 for full polarization; 1 for parallel hands only).*
**Spectral resolution: 3.8 kHz at 31.25 MHz baseband channel width**
**down to 2 GHz at 2 GHz baseband channel width**
**Velocity resolution: 0.5 x (300/ν[GHz]) km/s for 2 GHz subband-width**
**0.008 x (300/ν[GHz]) km/s for 125 MHz bandwidth**
**(e.g. at 660 GHz: max. resolution = 0.004 km/s)**

**Data rate: 6Mb/s average; peak 64 Mb/s;**
**estimate 1 TB per day to be archived**

# ALMA Overview

**ALMA performance ($\tau$=60s, 50 antennas)**

*ALMA data can only be taken in one band at a time.*

| Band | frequency range (GHz) | wavelength range (mm) | angular resolution $b_{max}$=200m ... 16km (arcsec) | line sensitivity (mJy) | continuum sensitivity (mJy) | primary beam (arcsec) | largest scale (arcsec) |
|---|---|---|---|---|---|---|---|
| 3 | 84-116 | 2.6-3.6 | 3.0 ... 0.034 | 8.9 | 0.060 | 56 | 37 |
| 4 | 125-169 | 1.8-2.4 | 2.1 ... 0.023 | 9.1 | 0.070 | 48 | 32 |
| 5 | 163-211 | 1.4-1.8 | 1.6 ... 0.018 | 150 | 1.3 | 35 | 23 |
| 6 | 211-275 | 1.1-1.4 | 1.3 ... 0.014 | 13 | 0.14 | 27 | 18 |
| 7 | 275-373 | 0.8-1.1 | 1.0 ... 0.011 | 21 | 0.25 | 18 | 12 |
| 8 | 385-500 | 0.6-0.8 | 0.7 ... 0.008 | 63 | 0.86 | 12 | 9 |
| 9 | 602-720 | 0.4-0.5 | 0.5 ... 0.005 | 80 | 1.3 | 9 | 6 |
| 10 | 787-950 | 0.3-0.4 | 0.36 ... 0.0045 | 118 | 2.0 | 7 | 5 |

Bands 3, 6, 7, and 9 will be available for Early Science in 2011.

Initially, band 5 will only be available on 6 antennas.

Bands 1 (31-45 GHz) , 2 (67-90GHz) and the completion of band 5 are being discussed.

# ALMA Overview

**Summary of mm/sub-mm interferometers (existing and under construction)**

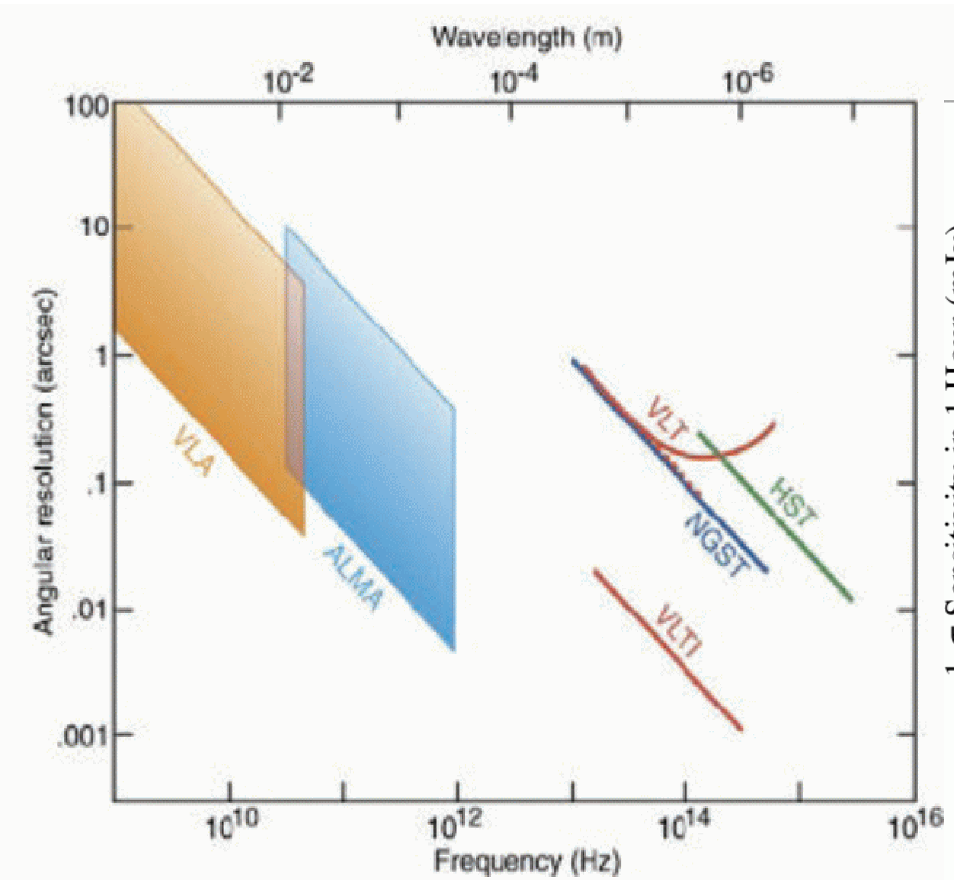
| Telescope | altitude [m] | diam. [m] | No. dishes | A [m²] | $\nu_{max}$ [GHz] |
|---|---|---|---|---|---|
| NMA | 600 | 10 | 6 | 470 | 250 |
| EVLA | 2150 | 25 | 27 | 13250 | 43 |
| CARMA | 2230 | 3.5/6/10 | 23 | 800 | 250 |
| IRAM PdB | 2440 | 15 | 6 | 1060 | 250 |
| SMA | 4150 | 6 | 8 | 230 | 650 |
| eSMA | 4150 | 6/10/15 | 10 | 490 | 345 |
| ALMA | 5000 | 12 | 54 | 6100 | 950 |
| ACA | 5000 | 7 | 12 | 490 | 950 |

(courtesy of C. Brogan)

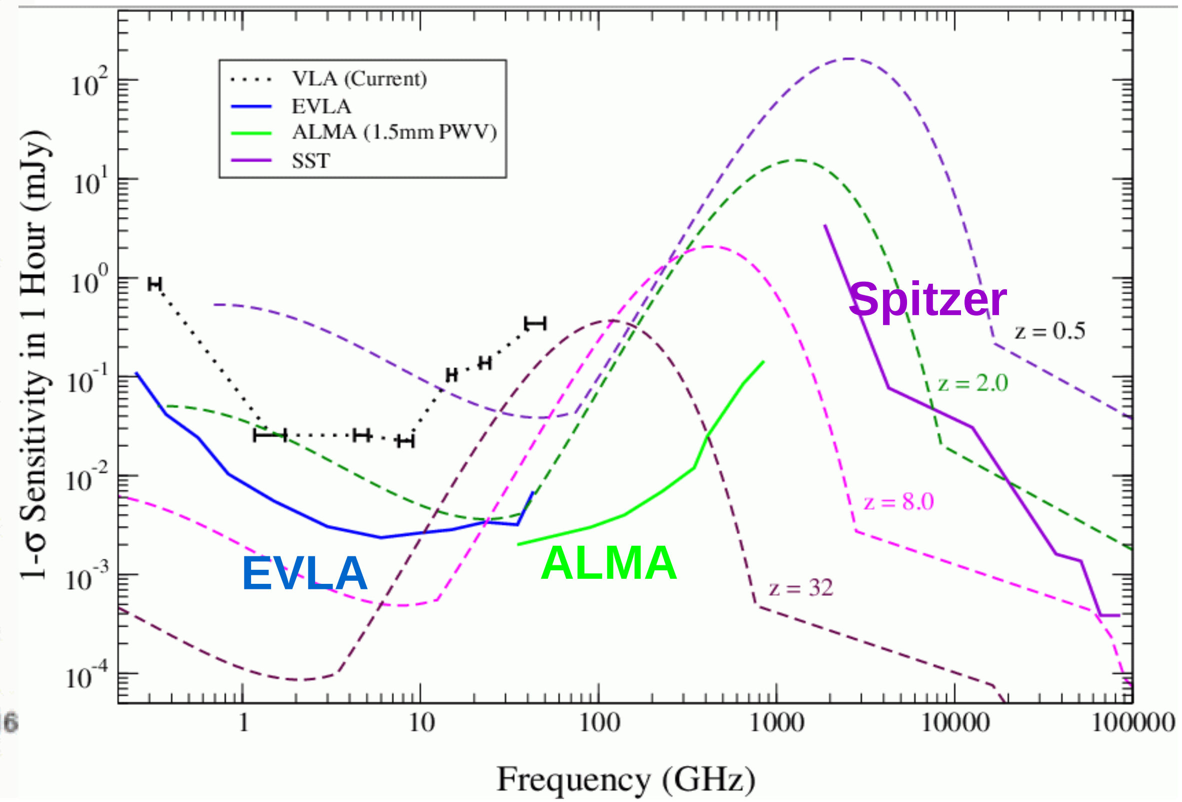
**In addition to its high spectral bandwidth, ALMA will have the highest sensitivity and highest angular resolution of all mm/Sub-mm radio interferometers in the coming years.**

# ALMA Overview

ALMA angular resolution and sensitivity compared to the VLA/EVLA




(L.Testi)




(C. Brogan)

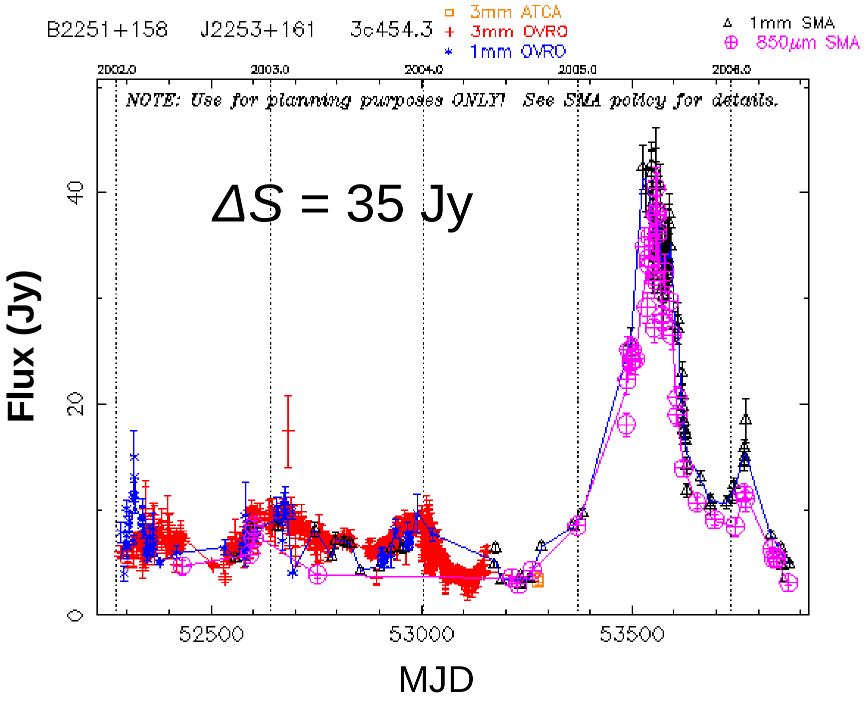
# ALMA CALIM Challenges

**The price for the improved performance**
***mm/sub-mm calibration and imaging problems***

**1) Absolute gain calibration**

- **no non-variable Quasars at mm/sub-mm wavelength**
- **need to use planets, moons, and asteroids as calibrator sources**
- **need good models, some of the objects rotate quickly and are not spherical**

**Example of a SMA lightcurve of the Quasar B2251+158**
(courtesy C. Brogan)



**The price for the improved performance**

***mm/sub-mm calibration and imaging problems (continued)***

**2) Atmospheric opacity τ strongly dependent on frequency and on PWV**

**- with increasing opacity, the system temperature increases exponentially**

$$T_{sys} = T_{noise}\, e^{\tau} \approx T_{atm}(e^{\tau} - 1) + T_{rx} e^{\tau}$$

Atmospheric and Receiver Temperatures

- **ALMA will have two-load system to measure $T_{rx}$ independently and frequently (since it is not stable for mm/sub-mm receivers).**
- **$T_{atm}$ measured separately**

## The price for the improved performance

***mm/sub-mm calibration and imaging problems (continued)***

**3) PWV changes quickly with time and causes severe phase fluctuations**

- **Self-calibration:** OK for bright sources that can be detected in a few seconds.
- **Fast switching:** used at the EVLA for high frequencies and will be used at ALMA. Choose fast switching cycle time, $t_{\mathbf{cyc}}$, short enough to reduce phase rms to an acceptable level. Calibrate in the normal way.
- **Phase transfer:** simultaneously observe low (90 GHz) and high frequencies, and transfer scaled phase solutions to high frequency. Can be tricky, requires well characterized system due to differing electronics in different bands, good atmospheric model, and instrumental phase stability.
- **Water Vapour Radiometry**

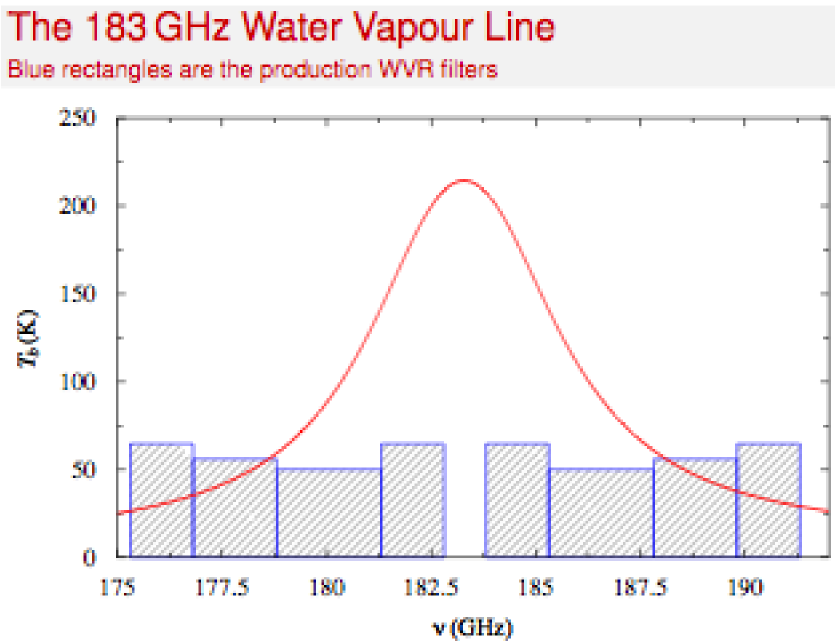
  measure fluctuations in $T_B^{atm}$ with a radiometer, use these to derive changes in PWV column ($w$) and convert this into a phase correction using

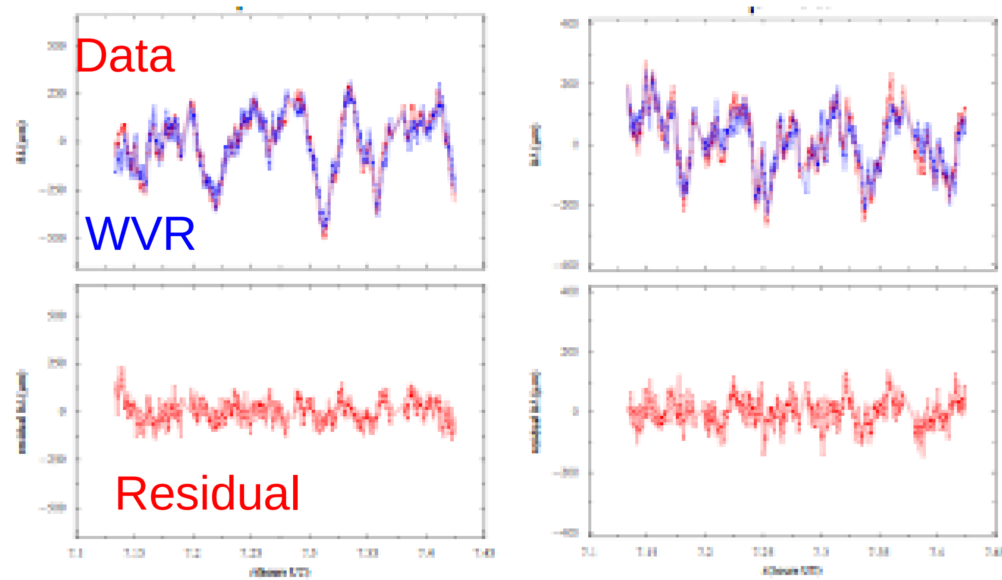
  $$\text{phase} = 12.6\ \pi/\lambda\ w$$

  ALMA WVR monitors the 183 GHz water line

**The ALMA WVR system performs as expected so far, tests ongoing**

Two different baselines Jan 4, 2010




Residual RMS: 60 μm

Residual RMS: 46 μm

There are 4 "channels" flanking the peak of the 183 GHz line

Matching data from opposite sides are averaged

The four channels allow flexibility for avoiding saturation

Next challenges are to perfect models for relating the WVR data to the correction for the data to reduce residual

ALMA CALIM Challenges

**The price for the improved performance**

***mm/sub-mm calibration and imaging problems (continued)***

**4) Small primary beam requires very good pointing**

- **specification for ALMA 12 m antenna pointing RMS: 0.6”**
- **need complex antenna metrology systems to achieve this (e.g. compensate for wind gusts)**

| Band | primary beam | pointing RMS [% of primary beam] |
|---|---|---|
| 3 | 56” | 1.1 |
| 6 | 27” | 2.2 |
| 7 | 18” | 3.3 |
| 9 | 9” | 6.6 |
| 10 | 7” | 8.6 (barely adequate!) |

**The price for the improved performance**

***mm/sub-mm calibration and imaging problems (continued)***

**5) FOV often too small to cover extended objects**

- **i.e. imaging will often be mosaicing, sometimes “wide-field imaging'**
- **direction-dependent effects need to be taken into account more accurately**
- **requires good knowledge of the instrument's primary beam (dropping assumptions like rotational symmetry)**
- **on the other hand, w-term, i.e. the sky curvature, less important: only for largest array extension does image diameter begin to exceed**

$$d_{max}[\text{arcsec}] = 120 \cdot \text{sqrt}(\lambda[\text{cm}] \cdot \text{phase error [deg]} / b_{max}[\text{km}])$$

| Band | $b_{max}$ | 0.2 km | 8 km | 16 km | primary beam |
|---|---|---|---|---|---|
| 3 | $d_{max}$ = | 328” | 52” | 36” | 56” |
| 6 | | 210” | 34” | 24” | 27” |
| 7 | | 182” | 28” | 20” | 18” |
| 9 | | 128” | 20” | 14” | 9” |
| 10 | | 112” | 18” | 12” | 7” |

for phase error = 5°

# ALMA CALIM Challenges

**The price for the improved performance**
***mm/sub-mm calibration and imaging problems***

**6) To achieve high continuum sensitivity, need to integrate over wide band**
- **frequency-dependence of the primary beam becomes important (although less so than for EVLA since franctional bandwidth smaller)**
- **the source spectrum may need to be unfolded in parallel (often have thermal and non-thermal sources in the same image)**

**7) To get full coverage of spatial scales, need to combine with single-dish observations**
- **difficult cross-calibration and weighting**
- **SD need fast switching for noise reductions (presently don't have a nutator)**

**8) Combination of ALMA Main with ACA requires treatment of *heterogeneous baselines***

# CASA status

- Since Dec 2009 in public release under GPL = anybody can download,
  no warranty (see http://casa.nrao.edu ),
  limited support (help desk, needs registration)
- approx. 20 people are working on CASA in North America, Europe, and Japan
- Tutorials for the user community regularly given
- The first public release was CASA 3.0.0 (Dec 2009), release 3.0.2 published in June 2010

- Development platforms: Linux (RHEL) + Mac OS X
- Supported platforms (binary distribution): RHEL, Fedora, openSuSE, Ubuntu, Max OS X

- Code kept in *svn* repository at NRAO, Socorro
- Presently have approx. 4300 modules, 1.5E6 lines of code, 1E6 lines of comments
- The core functionality (*casacore,* also available at http://code.google.com/p/casacore/ ) is also used by other projects

- *Hot topics*:
  - Support for High Performace Computing and Parallelisation
  - Advanced Imaging: wide fields, continuum imaging over wide spectral ranges
  - Interoperability: using CASA for other observatories and VLBI

# CASA status

**Imaging in CASA 3.0.2** (see also talks by U. Rau and S. Bhatnagar):

**Frequency mapping modes**:

mfs - Multi-Frequency Synthesis emulation: frequency-dependent

channel, frequency, velocity - standard

**Weighting options**: natural, uniform, superuniform, radial, briggs, briggsabs

**PSF modes for CLEAN**: Clark, Hogbom

**Multiscale CLEAN:** (prototype)

**CLEAN modes**: single-field, single-field Cotton-Schwab, multi-field (**mosaic**) Cotton-Schwab

In **mosaic** mode:

- **choice of gridding methods and kernels**:
  - standard, single-dish, both, and "mosaic" (use FT of primary beam as kernel)
- **choice of scaling options**:
  - constant flux scale or constant noise level

In single field modes:

- **widefield** option to employ Faceting or the W-Projection
- **aprojection** option to employ parallactic-angle correction for non-symmetric beams

**Combined Single-Dish and Interferometric Imaging (feather)**

CASA status

**Imaging in CASA 3.0.2: Combinations of Major and Minor Cycle Algorithms**

**Imaging (Major Cycle):**

**1) Standard (no dir.-dep. effects, uv-grid sampling uses convolutional regridding)**

**2) with dir.-dep. effects:**

**a) W-term (image domain faceting, uv domain faceting, W projection)**

**b) PB correction (image domain, A projection)**

**c) Pointing Offset correction by phase gradient**

**d) Mosaicing (linear (separate) deconvolution,**
**joined deconv. of combined dirty images,**
**mosaicing by regridding all uv data onto one grid)**

**Deconvolution (Minor Cycle)**

**1) CLEAN (delta function model)**

**2) MS-CLEAN (blob model)**

**3) MSMFS CLEAN (model of blobs with polynomial spectrum)**

**4) MEM (maximum entropy method using prior image and delta function model)**

**see nice overview compiled by Urvashi Rau:**

**https://safe.nrao.edu/wiki/bin/view/Software/AlgorithmList**

# CASA status

**Imaging in CASA 3.0.2 (continued):**

**Primary beam library**:

VLA, ALMA, ATA, ATCA, BIMA, HATCREEK, CARMA, GBT, GMRT, IRAMPDB, SMA, WSRT

*Only VLA, ATCA, GBT, and WSRT (and SMA?) are polynomials or Airy disks fitted to measurements of the beam of the actual telescope.*

*Only VLA includes beam squint.*

***For ALMA, presently a scaled VLA pattern is used.***

# ALMA/CASA Imaging work at ESO

**ALBiUS funds 1/3 FTE for three years at ESO for interoperability work on CASA**

**First contribution was a *FITS-IDI to MS converter* (will be part of release 3.1).**

**Second contribution will be a *library of ALMA primary beams* (based on detailed simulations performed by the company TICRA, Denmark) integrated into CASA.**

**Third contribution will be enabling the use of these simulated beams in all relevant CASA imaging modes, in particular**

- **Heterogeneous Imaging**
- **Wide-field Imaging**
- **Wide-band Imaging**

**Perform extensive testing!**

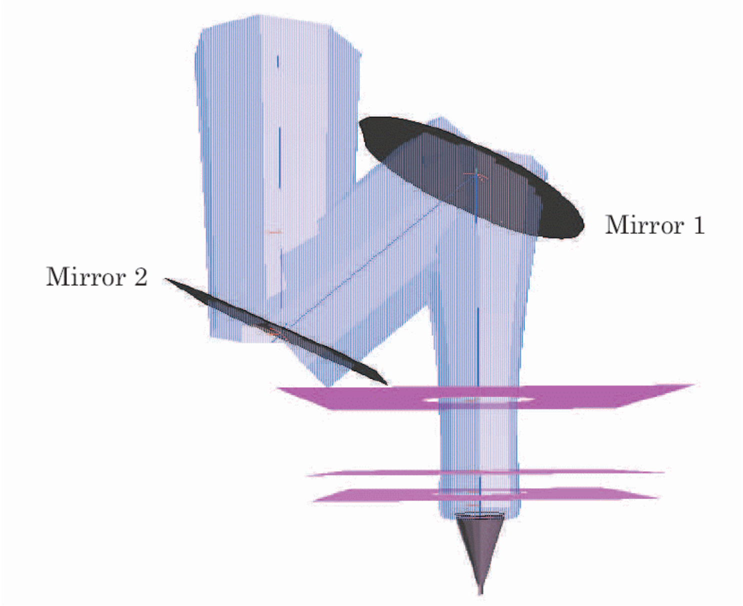
**The TICRA simulations of ALMA aperture illumination functions**

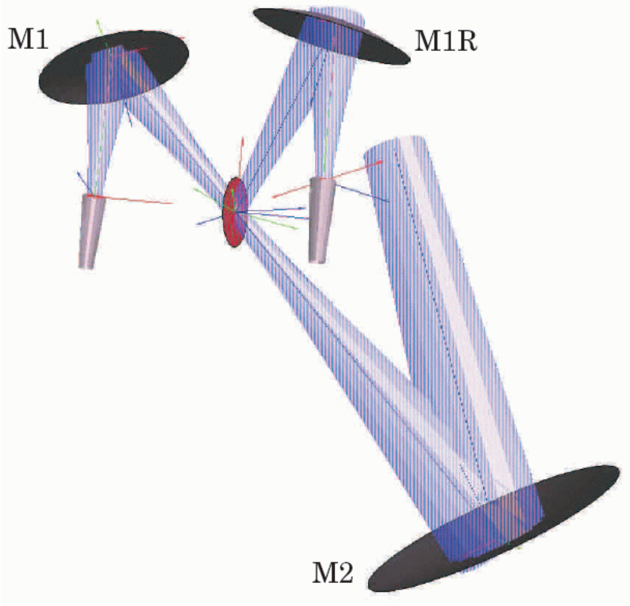
**Simulated were three antenna designs**

1) **Vertex (built by VertexRSI): space framework struts**
2) **AEM (built by Thales Alenia, European Industrial Engineering, and MT Aerospace): elliptical struts with cladding**
3) **ideal antenna: no struts**

**The TICRA simulations of ALMA aperture illumination functions**

**The detailed front end geometry including the secondary mirror were taken into account where available:**
**Bands 1, 5, 8: design still preliminary in 2007, only Gaussian beam simulated**
**Bands 3, 4, 6, 7, 9: complete simulation at 3 or 4 frequencies within band**
**Bands 2, 10: design incomplete in 2007, not simulated**

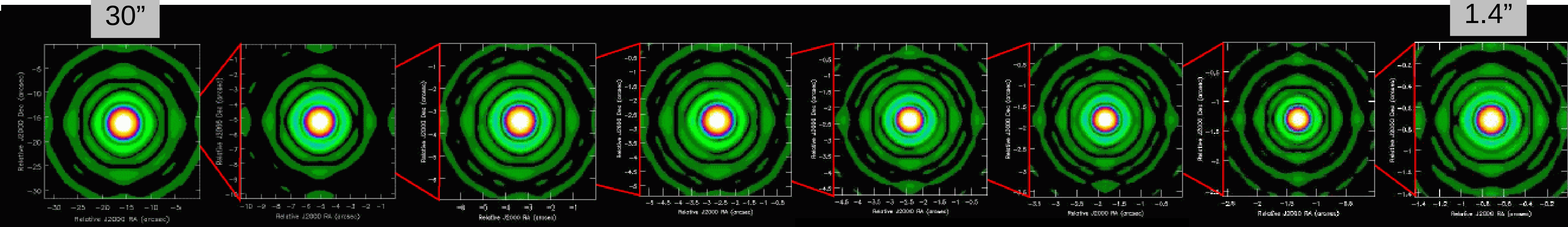


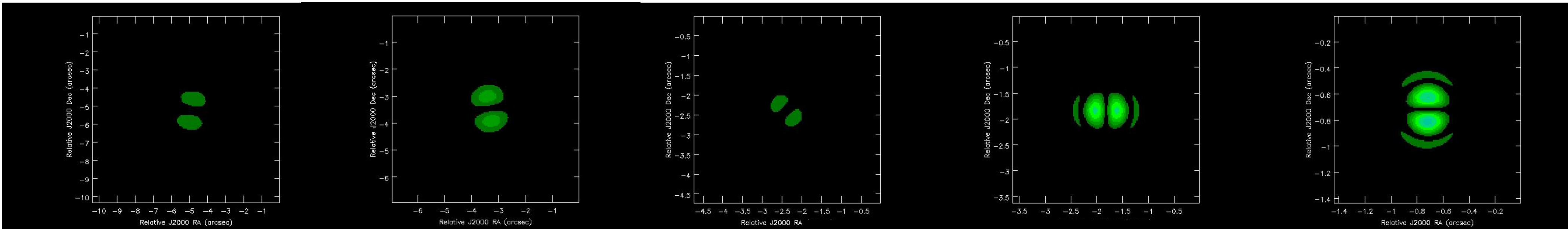

Examples of front end geometries: Band 3 (left), Band 7 (right)

## The TICRA simulations of ALMA aperture illumination functions

Simulated aperture illumination functions (copolar field) for bands 1 and 3 to 9  (Vertex Struts)




Simulated aperture illumination functions (crosspolar field) for bands 3, 4, 6, 7, 9  (Vertex Struts)




Normalised magnitude of E field