NRC·CNRC
Herzberg Institute of Astrophysics

ALMA
ATACAMA LARGE MILLIMETER ARRAY

# Observing with ALMA

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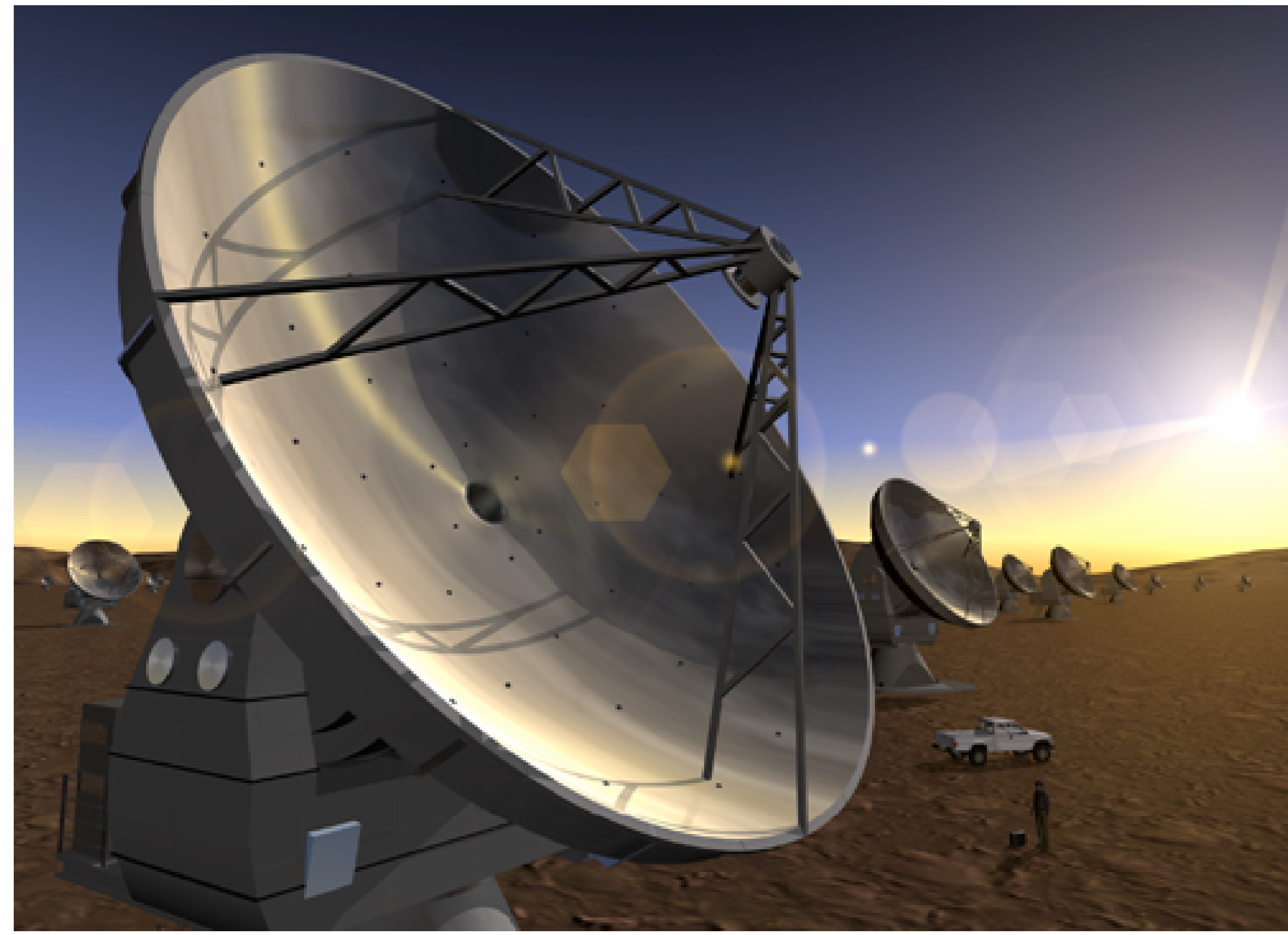
# Introduction

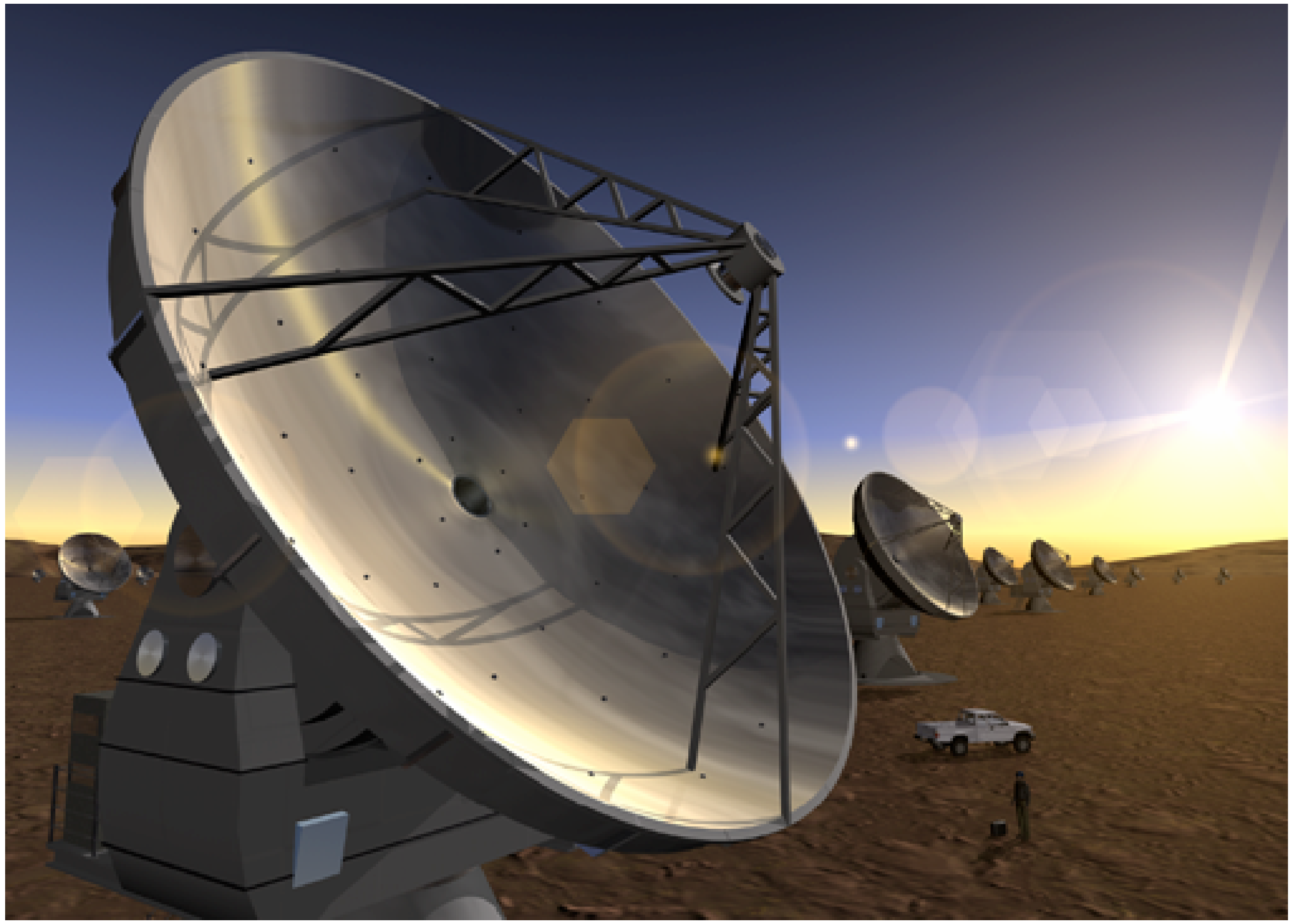
An introduction to observing with ALMA: a challenging task

- Large and complex instrument
- Still under construction
- Development ongoing



# Outline

- ALMA
  - Antennas
  - Array configurations
  - Receivers
  - The correlator
- ACA
  - Its role in imaging with ALMA
- Demo of an ALMA simulator
- Demo of the ALMA Observing Tool



# Antennas

Aperture efficiency

$\eta_A = \eta_{ill} \exp[-(4 \pi \varepsilon / \lambda)^2]$

Illumination efficiency $\eta_{ill}$

Feed pattern, aperture blockage

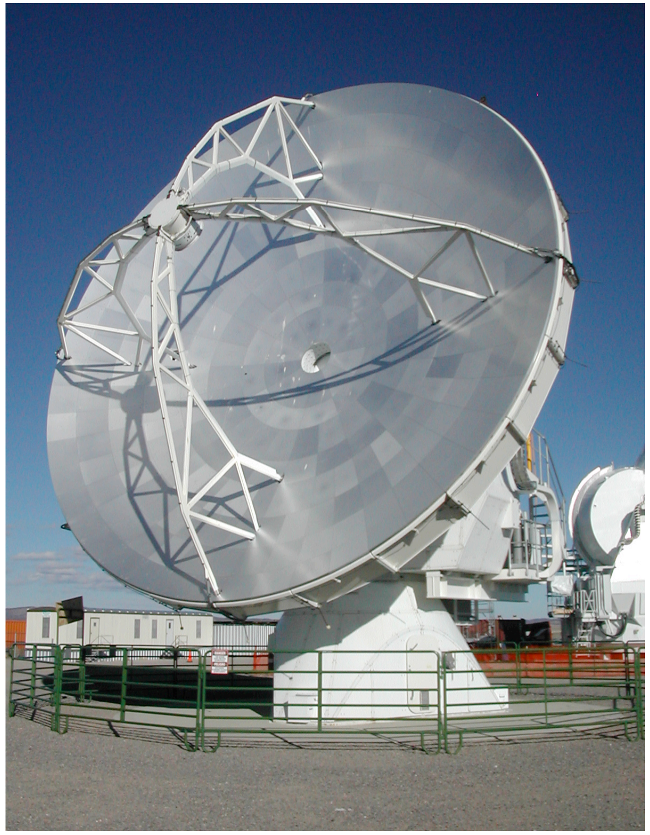
$\eta_{ill} \sim 0.8$

Surface accuracy $\varepsilon$ = 25 μm spec (20 μm goal)

$\eta_A > 0.5$ below 650 GHz (450 μm)

$\eta_A \sim 0.3$ at 950 GHz (315 μm)

ALMA has lots of collecting area (5700 $m^2$ to 7200 $m^2$)



Half of the antennas look like this

... and the other half like this

# Pointing

Pointing performance

- Gain errors
- Mosaicing errors

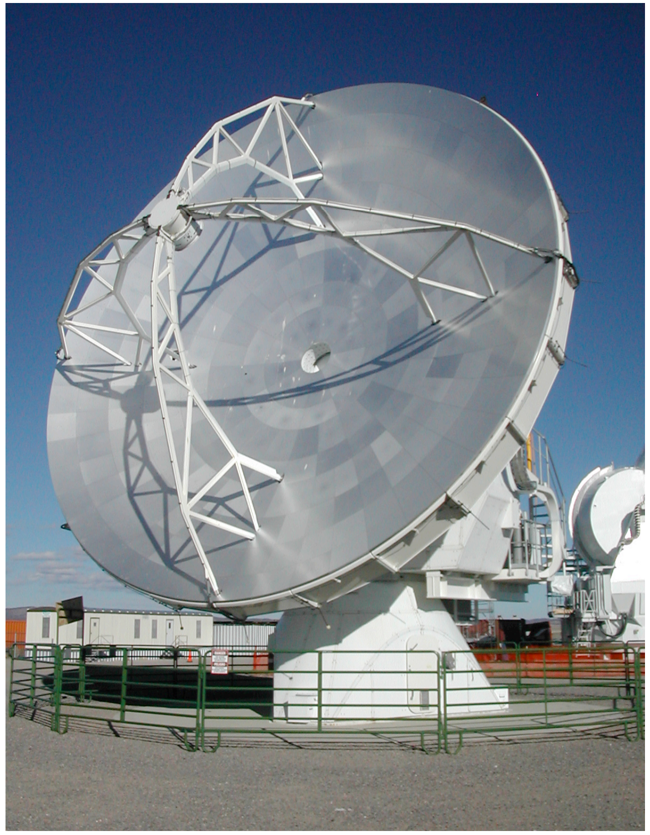
ALMA spec: 2.0” all-sky, 0.6” offset

Loss of gain at pointing centre (offset pointing)

- < 1% at 345 GHz (18” beam)
- < 3% at 950 GHz (6” beam)

Mosaicing: large errors near half-power in the primary beam

- Rule of thumb: pointing error < 5% of FWHM
- Challenging above 490 GHz



Half of the antennas look like this

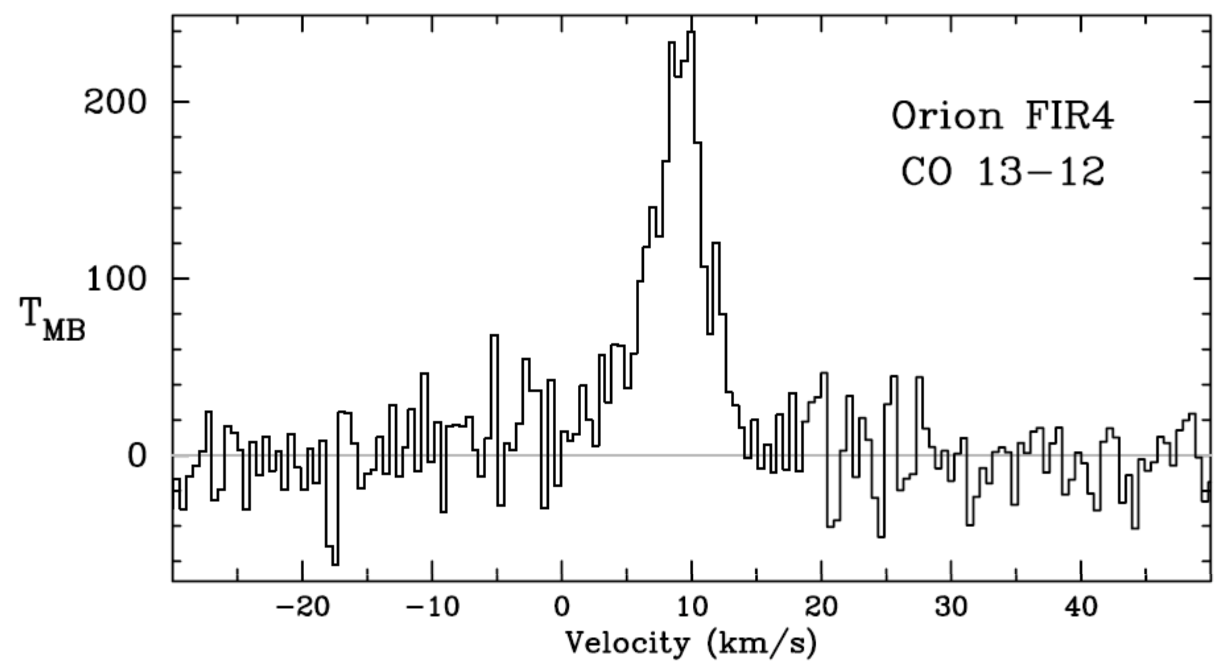
... and the other half like this

# APEX

An ALMA prototype already operating on Chajnantor: APEX

- Surface accuracy ~ 15 µm
- Operates to 1.5 THz (200 µm)

Astronomy & Astrophysics Special APEX Issue (Volume 454, No. 2, 2006)




CO(J=13-12) at 1.497 THz
(Weidner et al 2006)

# Sensitivities

ALMA sensitivities in comparison to the competition

Table 1: Point source continuum sensitivity (mJy) - 5 hr, 1 $\sigma$

| Freq. GHz | PdB | PdB$^+$ | OVRO | BIMA | CARMA | NMA | RB | SMA | eSMA | ALMA 6 | ALMA 12 | ALMA 64 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 110 | 0.3 | 0.06 | 0.6 | 1.1 | 0.04 | 0.7 | 0.5 | - | - | 0.028 | 0.013 | 0.0024 |
| 230 | 0.9 | 0.14 | 1.6 | 2.5 | 0.10 | 6.3 | 3.2 | 0.4 | 0.2 | 0.056 | 0.027 | 0.0049 |
| 345 | - | - | - | - | 0.70 | - | - | 0.9 | 0.46 | 0.088 | 0.042 | 0.0076 |
| 675 | - | - | - | - | - | - | - | 8.5 | 4.9 | 0.69 | 0.33 | 0.060 |

Table 2: Line sensitivity (K) for 1 $\mathrm{km\,s^{-1}}$ line width, 5 hr 1 $\sigma$, 150 meter baseline

| Freq. GHz | $\theta$ $''$ | PdB | PdB$^+$ | OVRO | BIMA | CARMA | NMA | RB | SMA | eSMA | ALMA 6 | ALMA 12 | ALMA 64 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 110 | 4.5 | 0.11 | 0.07 | 0.35 | 0.24 | 0.04 | 0.40 | 0.28 | - | - | 0.03 | 0.014 | 0.003 |
| 230 | 2.1 | 0.27 | 0.11 | 0.48 | 0.62 | 0.06 | 2.31 | 1.6 | 0.15 | 0.07 | 0.04 | 0.020 | 0.004 |
| 345 | 1.4 | - | - | - | - | - | - | - | 0.27 | 0.14 | 0.05 | 0.025 | 0.005 |
| 675 | 0.7 | - | - | - | - | - | - | - | 1.8 | 1.1 | 0.3 | 0.14 | 0.03 |

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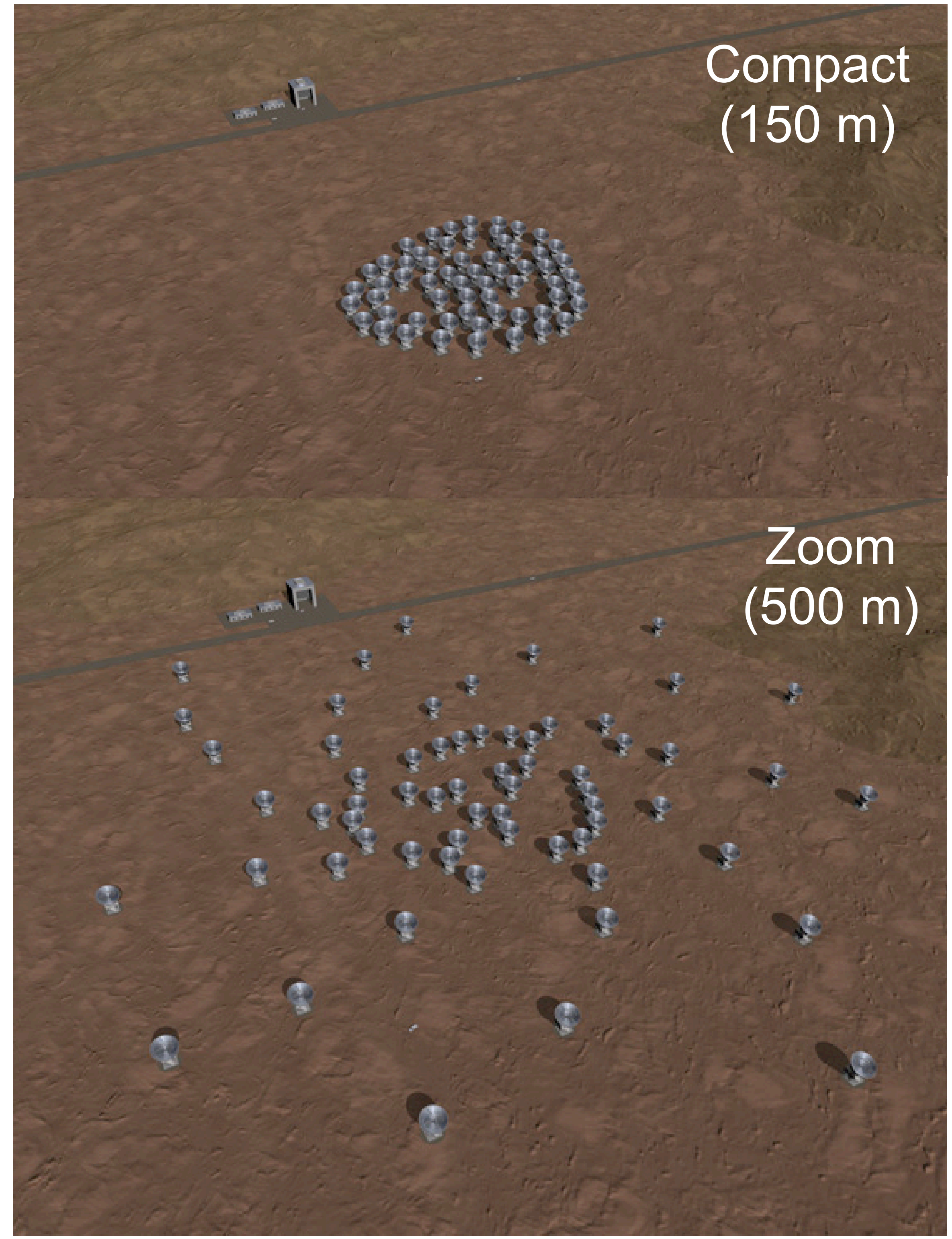
# Array Configurations

ALMA designed to be flexible

- "Snapshot" observations
- User-selectable
  - Angular resolution
  - Brightness sensitivity

Design principles

- Single-configuration imaging as much as possible
- Continuous array reconfiguration scheme



# Resolution and Brightness Temperature Sensitivity

Angular resolution $\theta$

$\theta = \lambda / B_{max}$

$\theta$ [arcsec] = 0.21 $\lambda$ [mm] / $B_{max}$ [km]

Brightness temperature sensitivity

$\Delta T_B \propto T_{sys} / [\, f\, \eta_A\, \mathrm{sqrt}(\Delta t\, \Delta \nu)\, ]$

f = filling factor = 1 for a filled aperture (single dish)

f = $\propto 1 / (B_{max})^2$ for an interferometer array

For an interferometer, you have to compromise

$\theta \propto 1 / B_{max}$

$\Delta T_B \propto (B_{max})^2$

# Optimization Criteria

Good uv coverage over wide δ range

- Approximately circular beams
- Minimize sidelobes

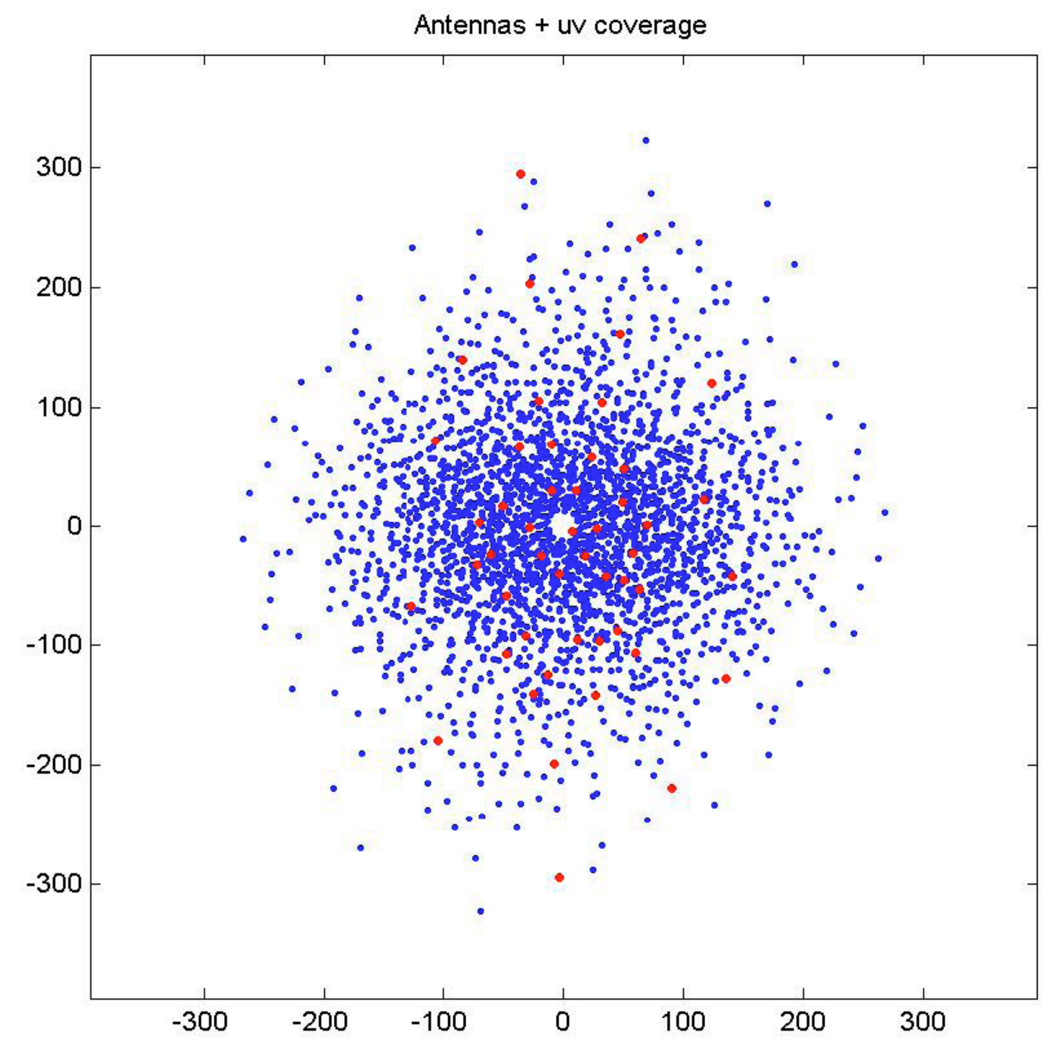
Wide range of baselines in each configuration

- Good spatial dynamic range

Continuous range of resolutions

- To match the science needs

Avoid antenna shadowing in compact configurations




Snapshot transit uv coverage (blue) for 600 m zoom configuration (red) at δ = +40°

Solution: Spiral zoom array growing from a compact configuration

# Compact Configuration

Worst θ and best $\Delta T_B$ configuration

- All antennas within 150 m
- θ ~ 1.2" at 345 GHz

Shadowing for δ outside the -55° to +15° range

A "Compact North-South" configuration avoids shadowing at transit as far south as -75° and as far north as +35°

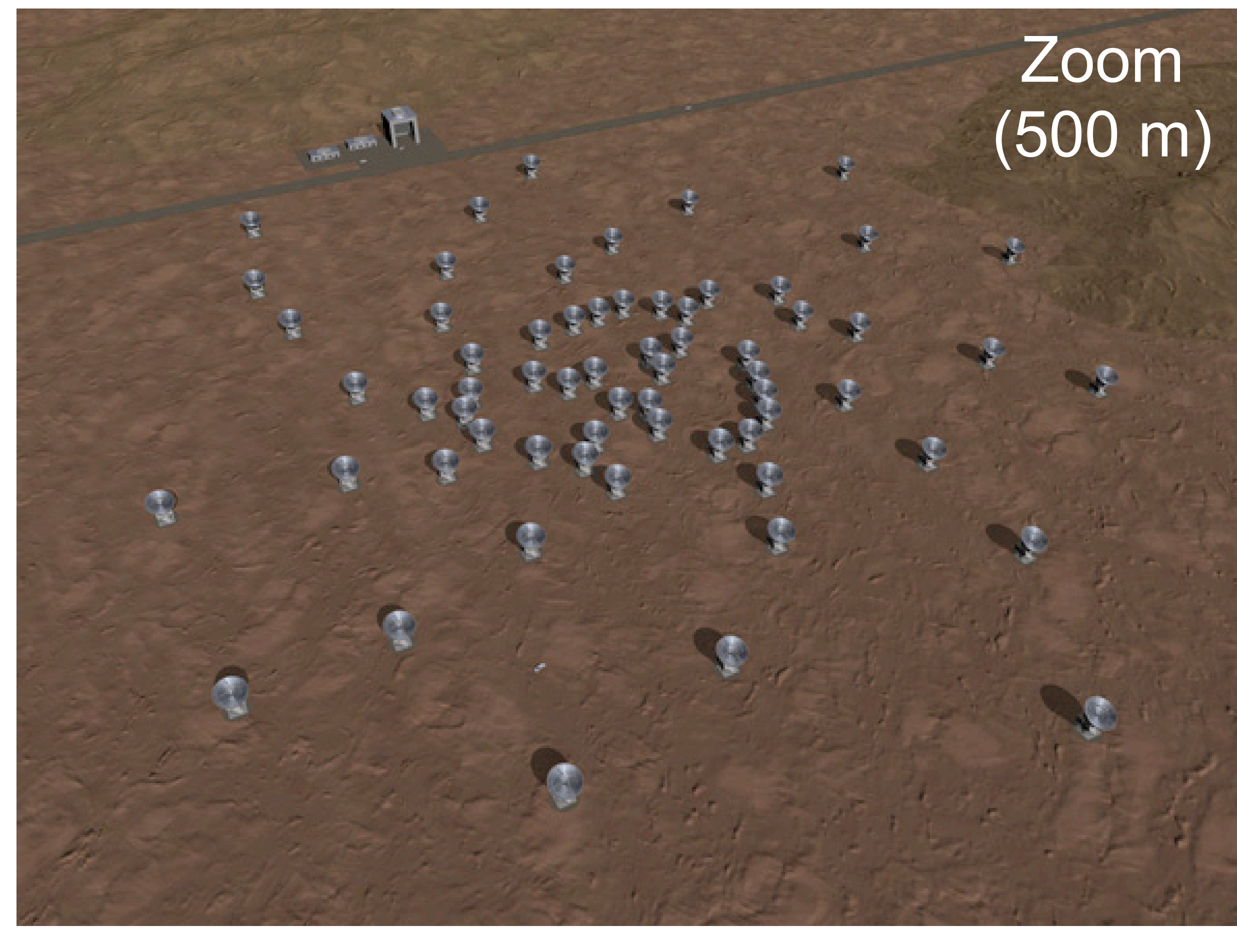
# Zoom Configurations

ALMA moves through a series of spiral arrays

- Spiral is stretched by 10%
- Better beam circularity over wide declination range

4 antennas move between steps

- Bmax / Bmin ≥ 45

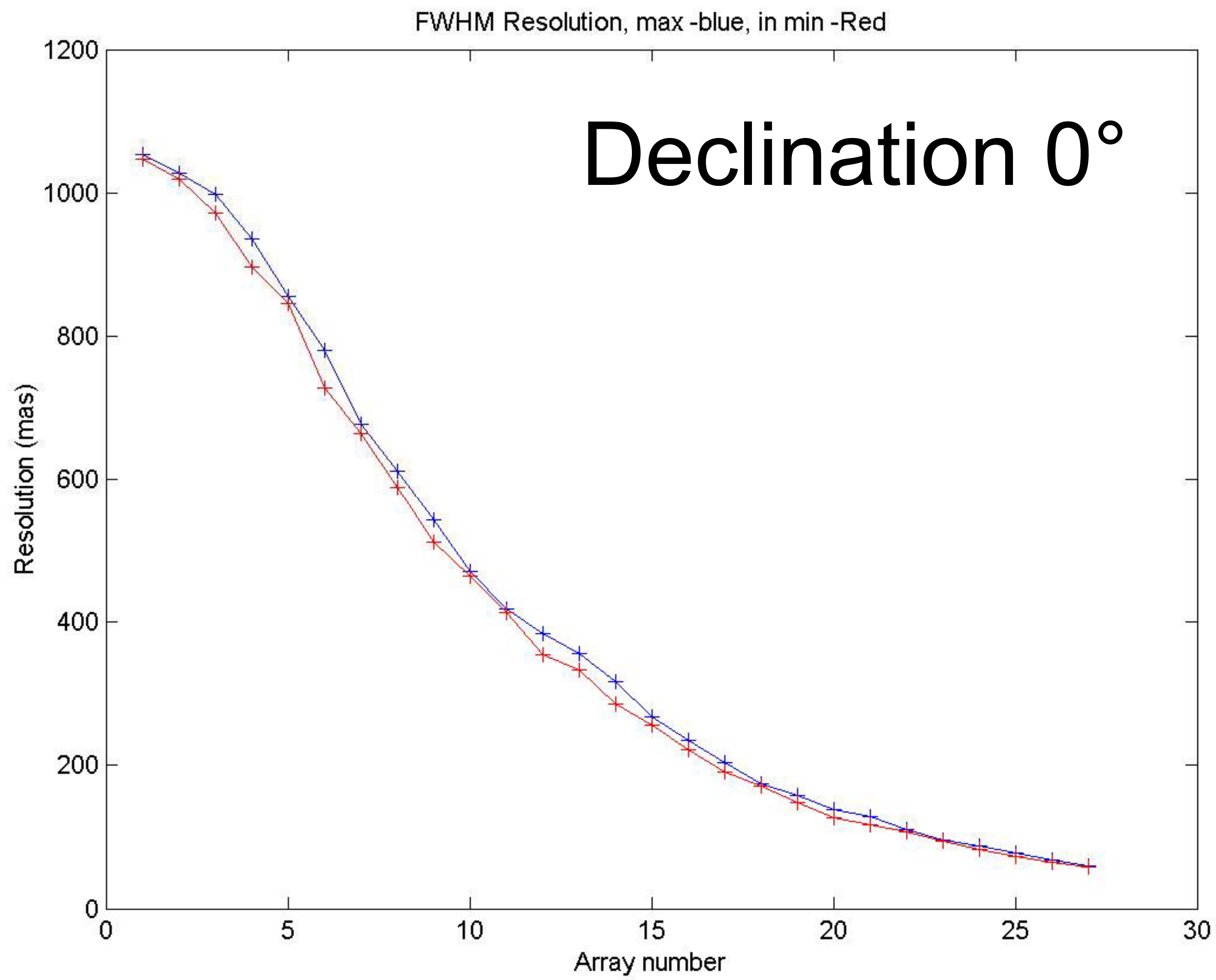


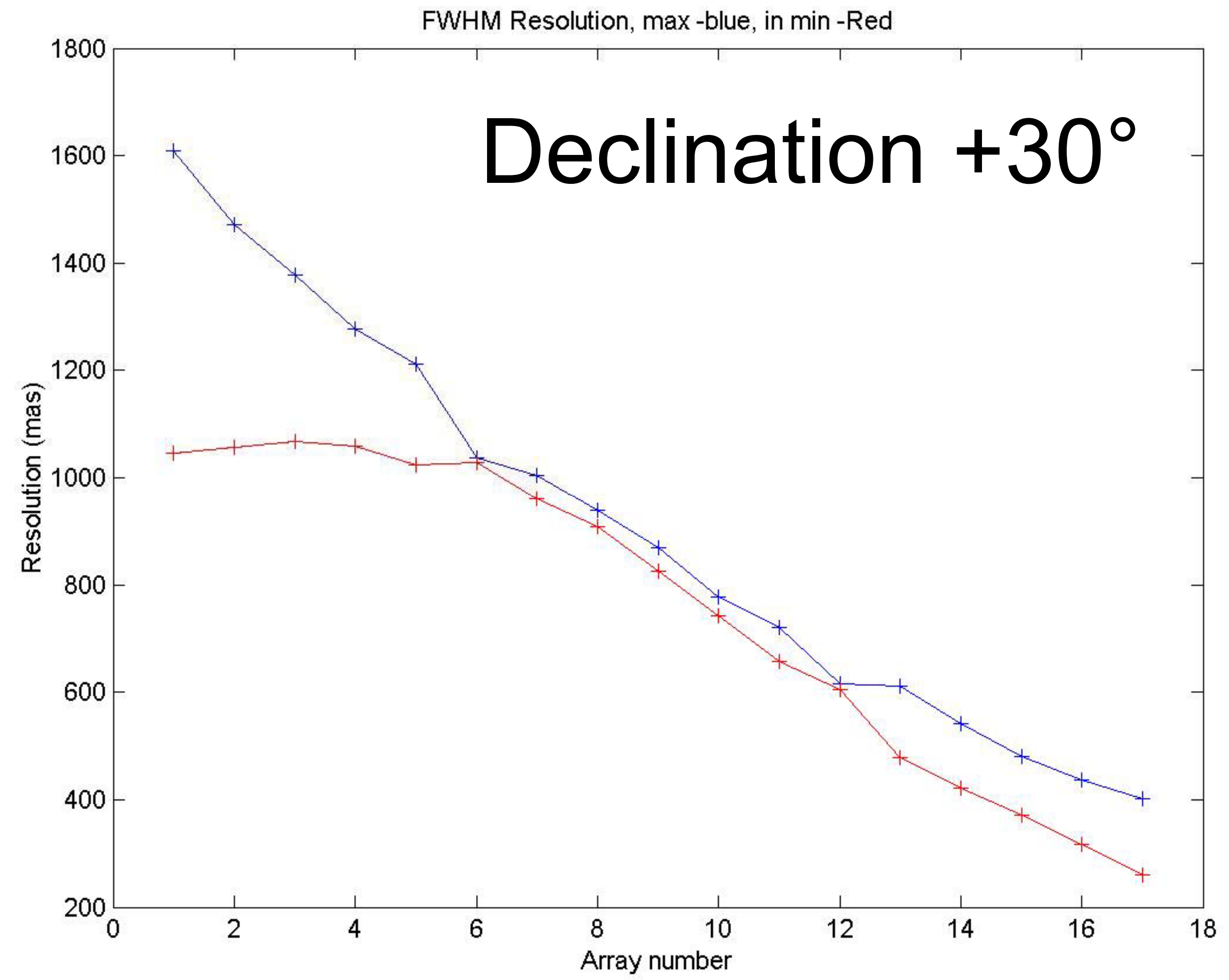

Resolution zoom ~ 1.17 per step

- $\theta \sim 41$ mas at 345 GHz for $B_{max} = 4.5$ km

# Zoom Resolutions

345 GHz transit snapshots




Blue: major axis Red: minor axis

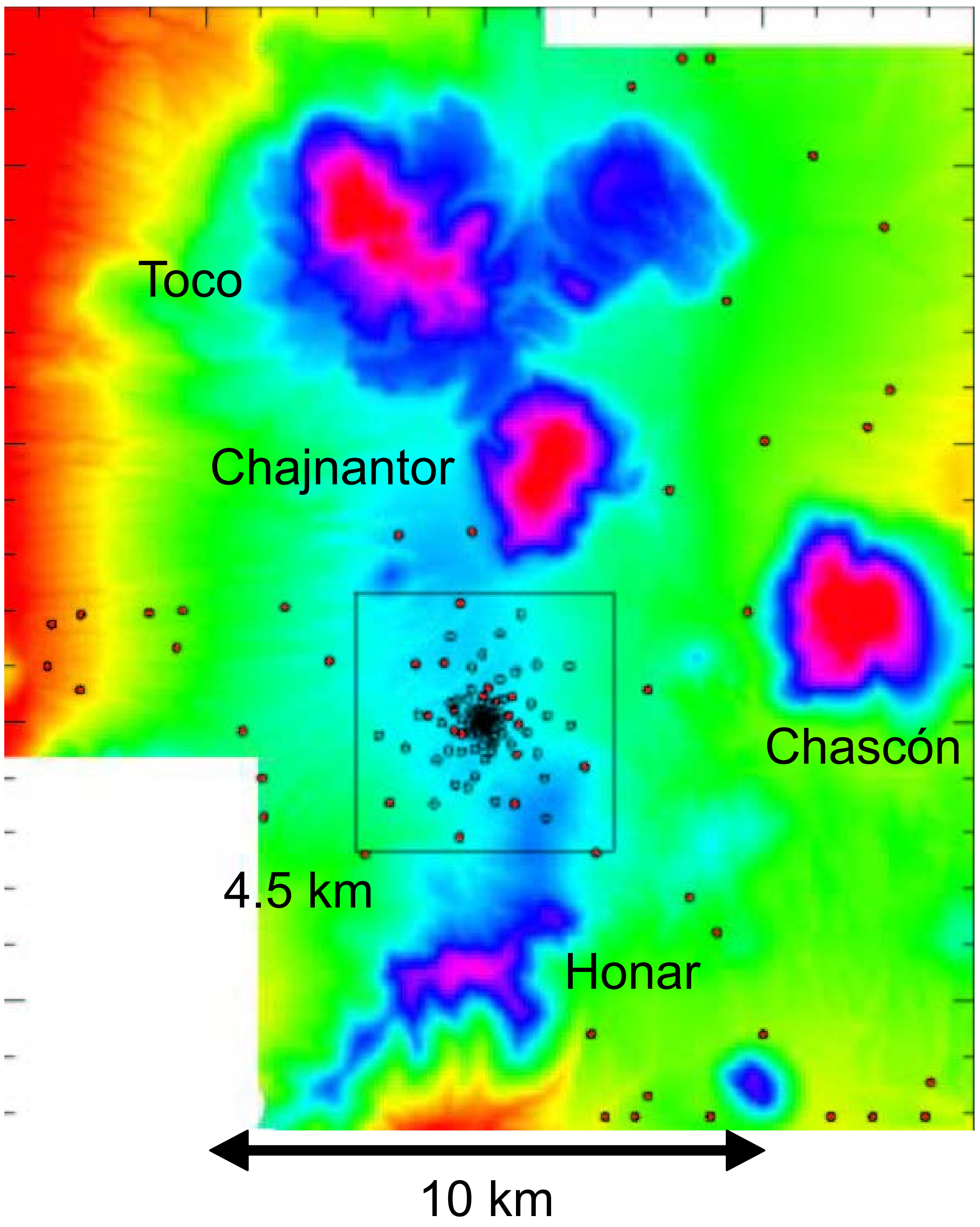
# Longest Baselines

Terrain is issue beyond 4.5 km

Optimal arrangement y-shape

- $B_{max}$ ~ 18.5 km
- 10 mas at 345 GHz

"Y+" configurations still under study

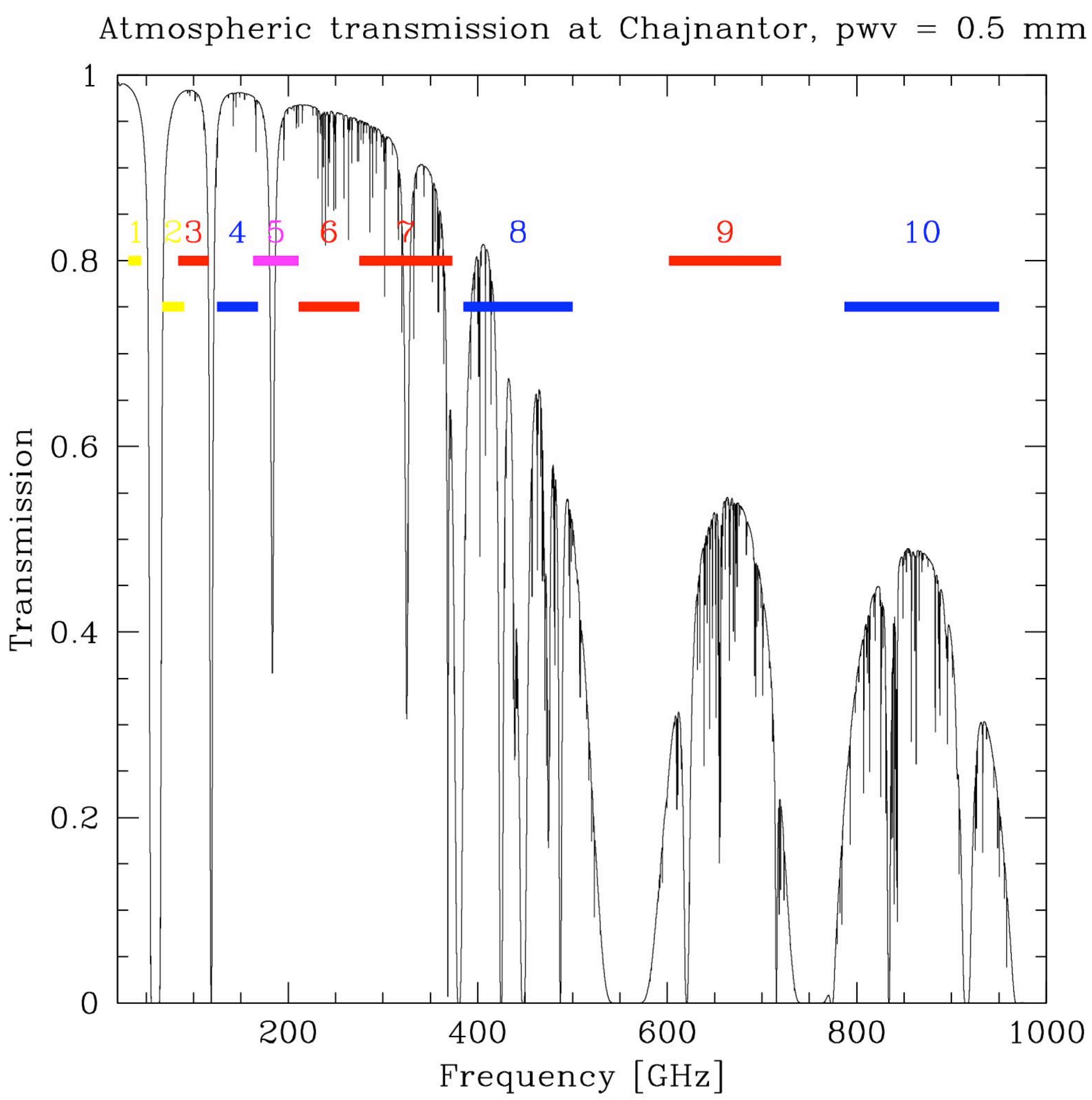


# Receivers

10-band receiver system covers 31.3 to 950 GHz
    (initially only 84 to 720 GHz)

Dual orthogonal linear polarization

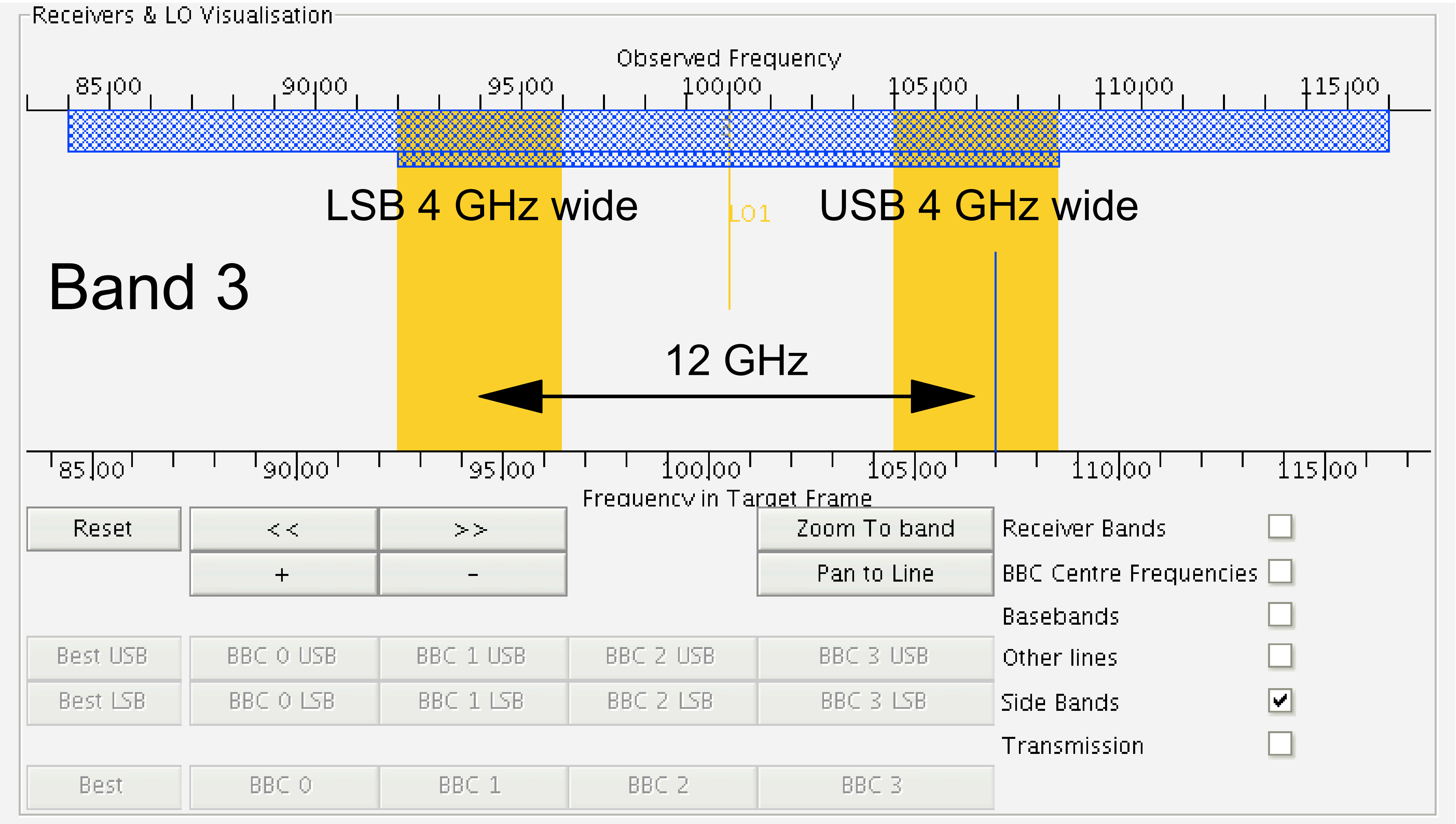
Minimum of 16 GHz IF bandwidth (8 GHz per polarization)



# Receivers

ALMA receivers are heterodyne systems: RF detected in two sidebands, LSB and USB

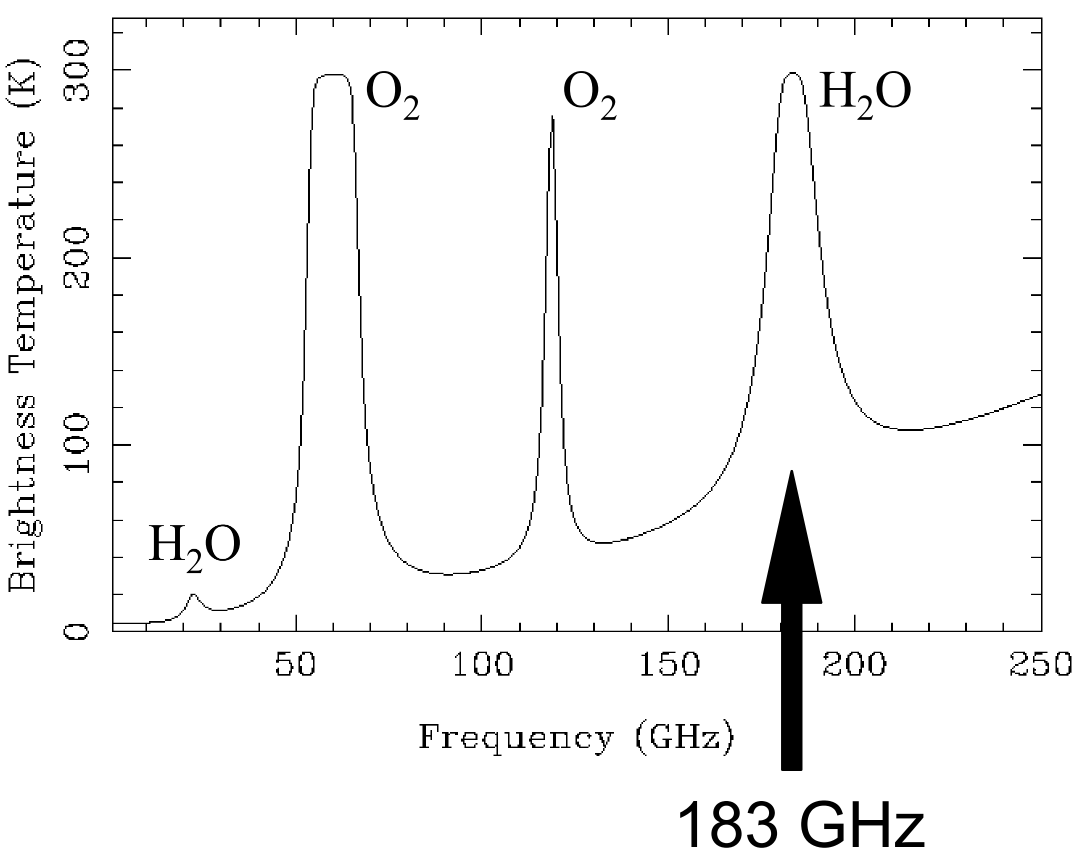
- Separable for Bands 3 to 7 (2SB) but not for 8 and 9 (DSB)
- Flexibility in selection of target frequency ranges

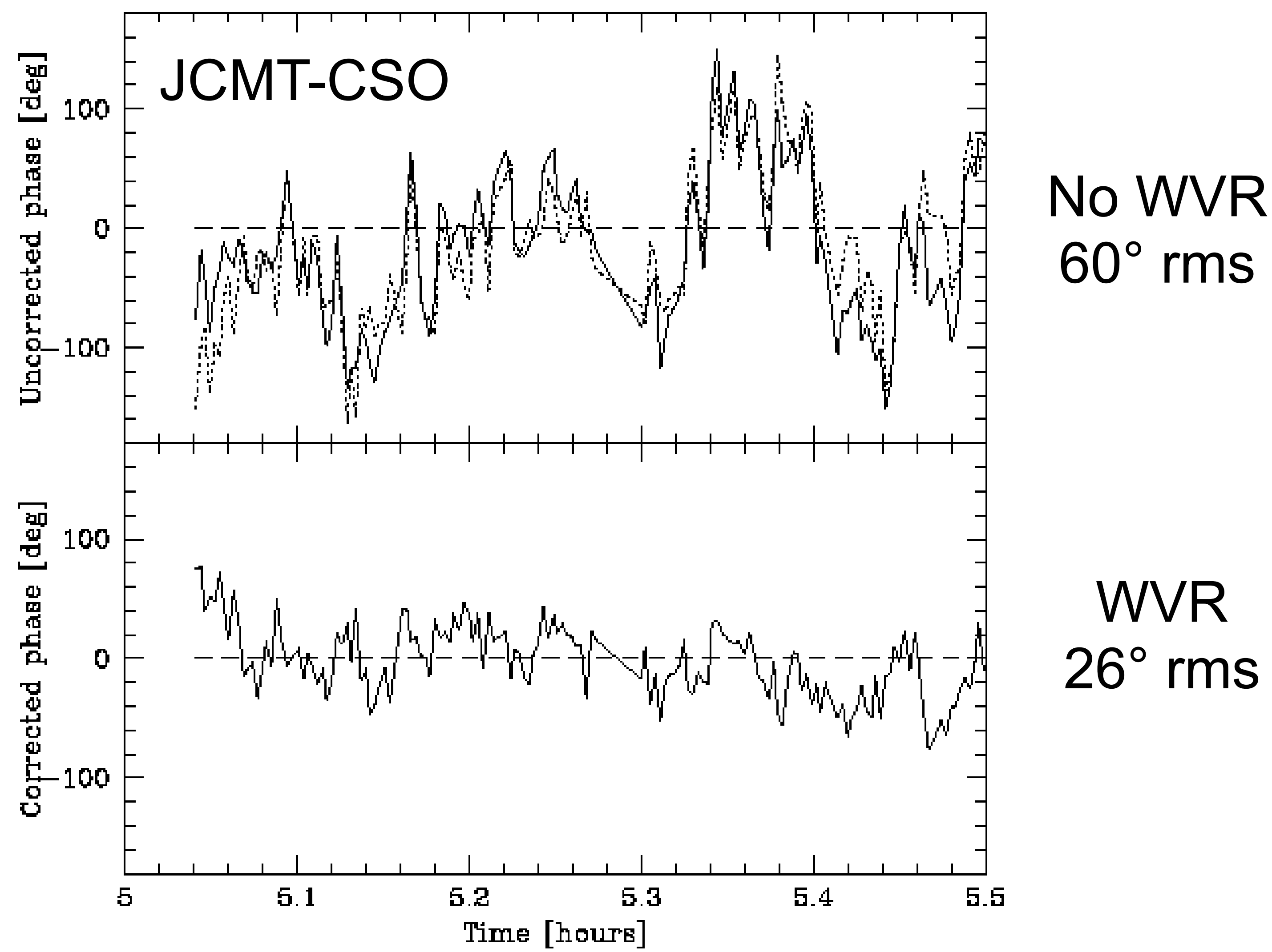


# WVRs

Each antenna has self-contained receiver tuned to 183 GHz line of atmospheric water vapour

- Monitors fluctuations of PWVC to correct for phase delays
- Particularly important on long baselines

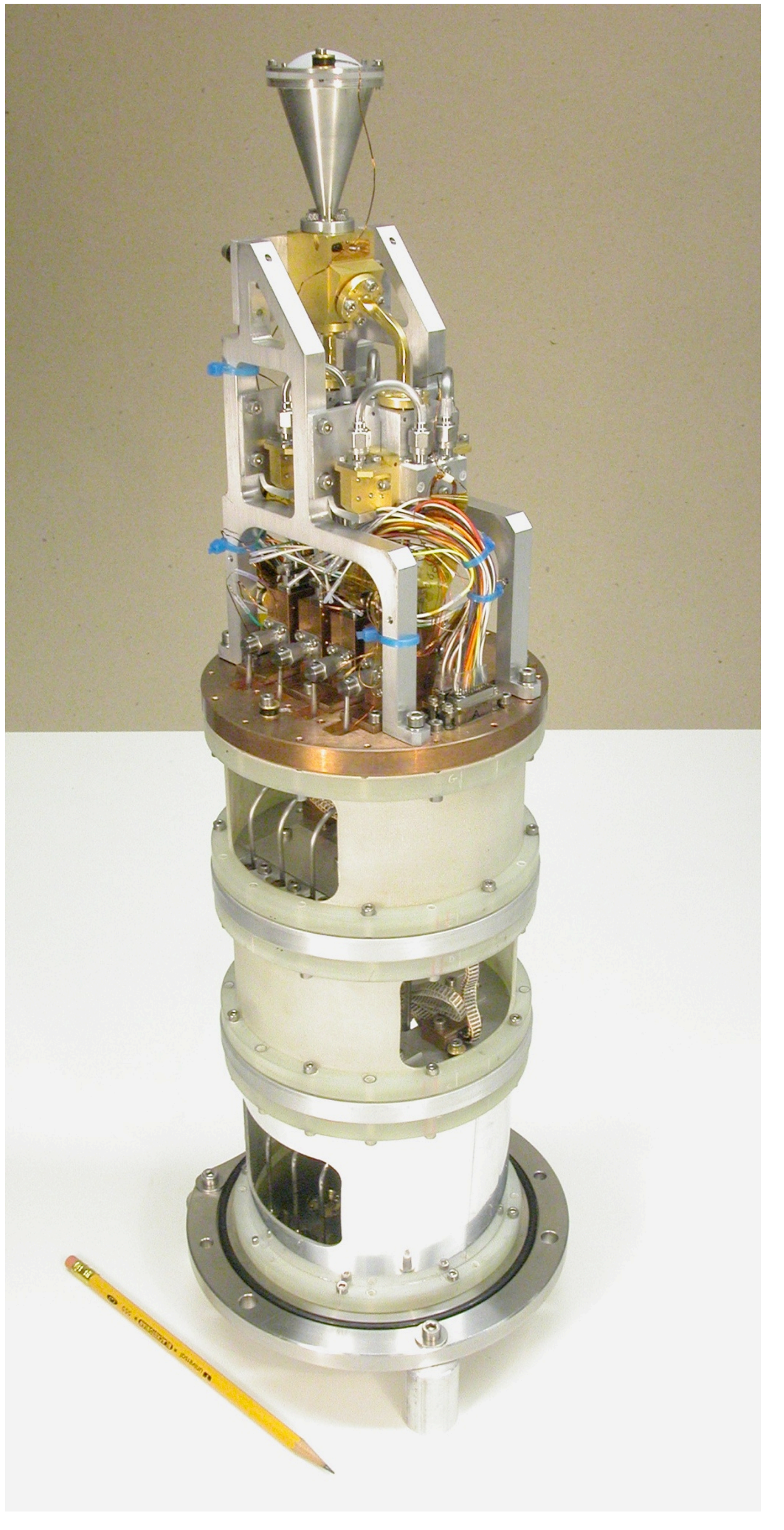



Weidner et al (2001)

# Key Role of Band 3

- ALMA can observe with only one band at a time (plus the WVRs)
  - Fast receiver switching possible
- Phase calibration by observation of bright point sources
  - Few calibrators at high frequencies
- Calibrate at 90 GHz with Band 3 and transfer to target frequency
- Band 3 must always be on-line and ready for use
- Band 3 also useful for pointing, baseline calibration, commissioning...
- Most sensitive, “all-weather” band



# The ALMA Correlator

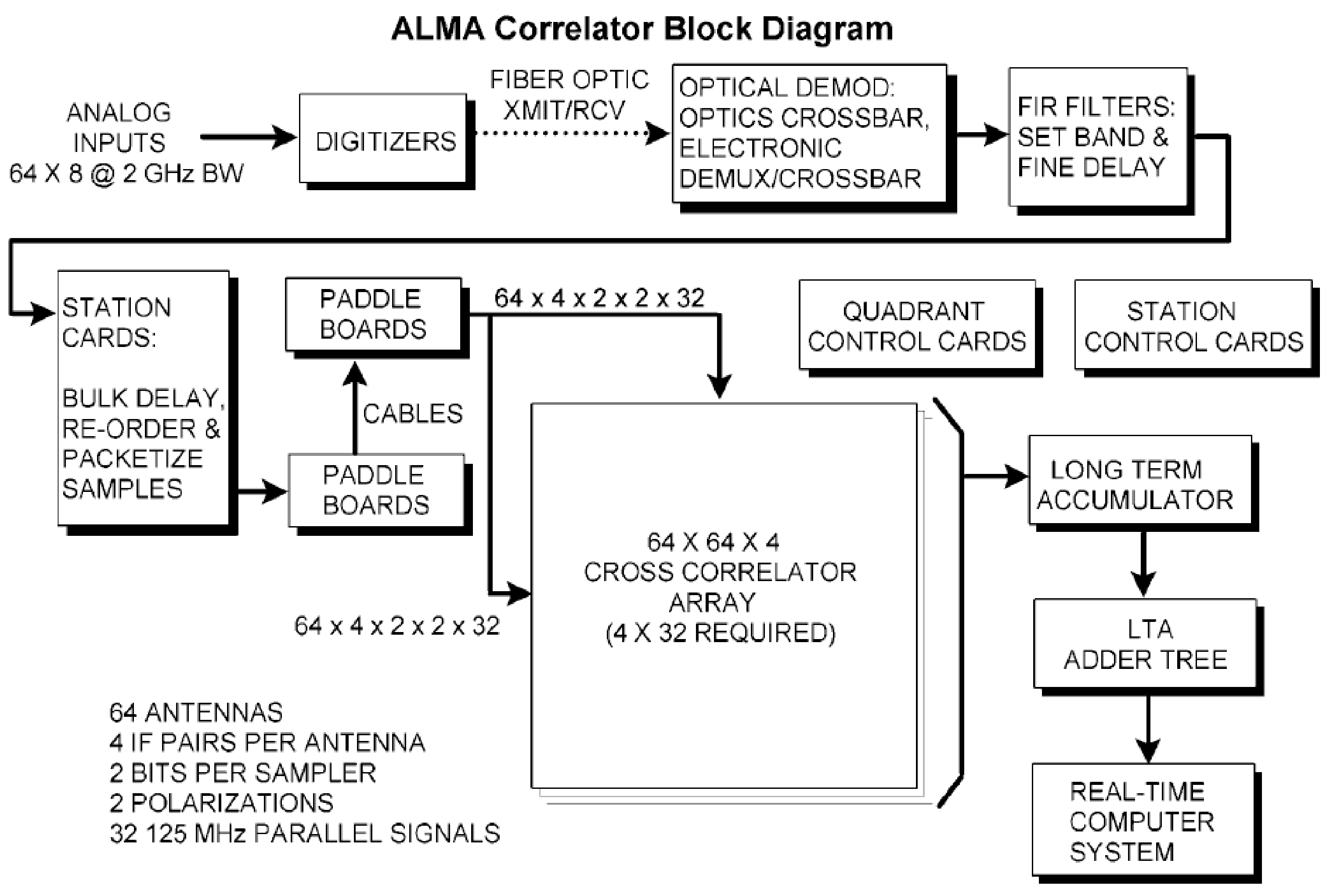
Correlates voltages from antennas: visibilities

Flexible multi-mode instrument

N (N -1) / 2 = 2016 baselines for N = 64 antennas

16 GHz (8 GHz Pol0, 8 GHz Pol1)

Wide bandwidth, high resolution



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# Correlator Modes

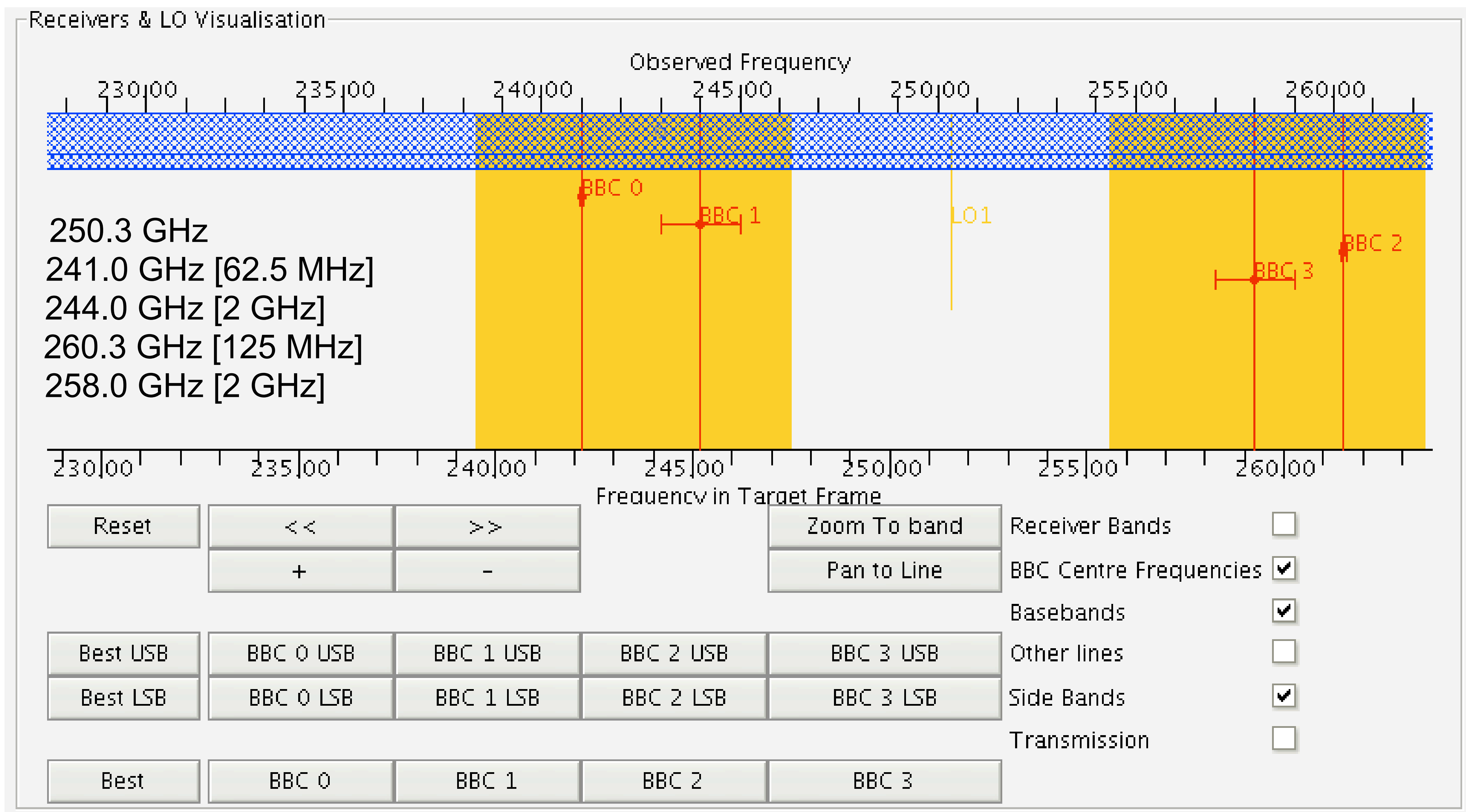
| # of Digitizers | Bandwidth/ Digitizer | Cross-pol Products? | Channels/ Product | At 230 GHz, in velocity space: Range | Resolution km/s |
|---|---|---|---|---|---|
| 8 | 2 GHz | Yes | 64 | 9391 | 40.8 |
| 8 | 2 GHz | No | 128 | 18783 | 20.4 |
| 8 | 1 GHz | No | 256 | 9391 | 5.1 |
| 8 | 500 MHz | Yes | 256 | 2348 | 2.5 |
| 8 | 250 MHz | No | 1024 | 2348 | 0.32 |
| 4 | 2 GHz | Yes | 128 | 4696 | 20.4 |
| 4 | 1 GHz | No | 512 | 4696 | 2.5 |
| 4 | 500 MHz | Yes | 512 | 1174 | 1.3 |
| 4 | 250 MHz | No | 2048 | 1174 | 0.16 |
| 2 | 2 GHz | Yes | 256 | 2348 | 10.2 |
| 2 | 1 GHz | No | 1024 | 2348 | 1.3 |
| 2 | 500 MHz | Yes | 1024 | 587 | 0.64 |
| 2 | 250 MHz | No | 4096 | 587 | 0.08 |

# Subband Capability

16 GHZ → 4 baseband pairs (2 GHz to 31.25 MHz, step x2)
4 subbands per baseband (different resolutions selectable)
All polarization products HH, VV, HV, VH
Maximum spectral resolution 3.8 kHz (5 m/s at 230 GHz)

## Band 6

| | | |
|---|---|---|
| | LO1 | 250.3 GHz |
| $C^{34}S(J=5\text{-}4)$ | BBC0 | 241.0 GHz [62.5 MHz] |
| Continuum | BBC1 | 244.0 GHz [2 GHz] |
| $H^{13}CO+(J=3\text{-}2)$ | BBC2 | 260.3 GHz [125 MHz] |
| Continuum | BBC3 | 258.0 GHz [2 GHz] |



# Subarrays

Groups of antennas can operate independently
- Simultaneous multi-band observations
- Visitor instruments (e.g. 6 European Band 5 cartridges)
- Paired array calibration
- Facilitates early science with incomplete array

Correlator permits 16 subarrays, but likely fewer to be offered

# Observing Extended Sources

Primary beam defines field of view in a single pointing

- Imaging larger objects requires multiple fields - mosaics
- Spacings < 15 m are not sampled

| Frequency (GHz) | HPBW (arcsec) |
|---|---|
| 115 | 54 |
| 230 | 27 |
| 345 | 18 |
| 492 | 13 |
| 650 | 9 |
| 950 | 6 |

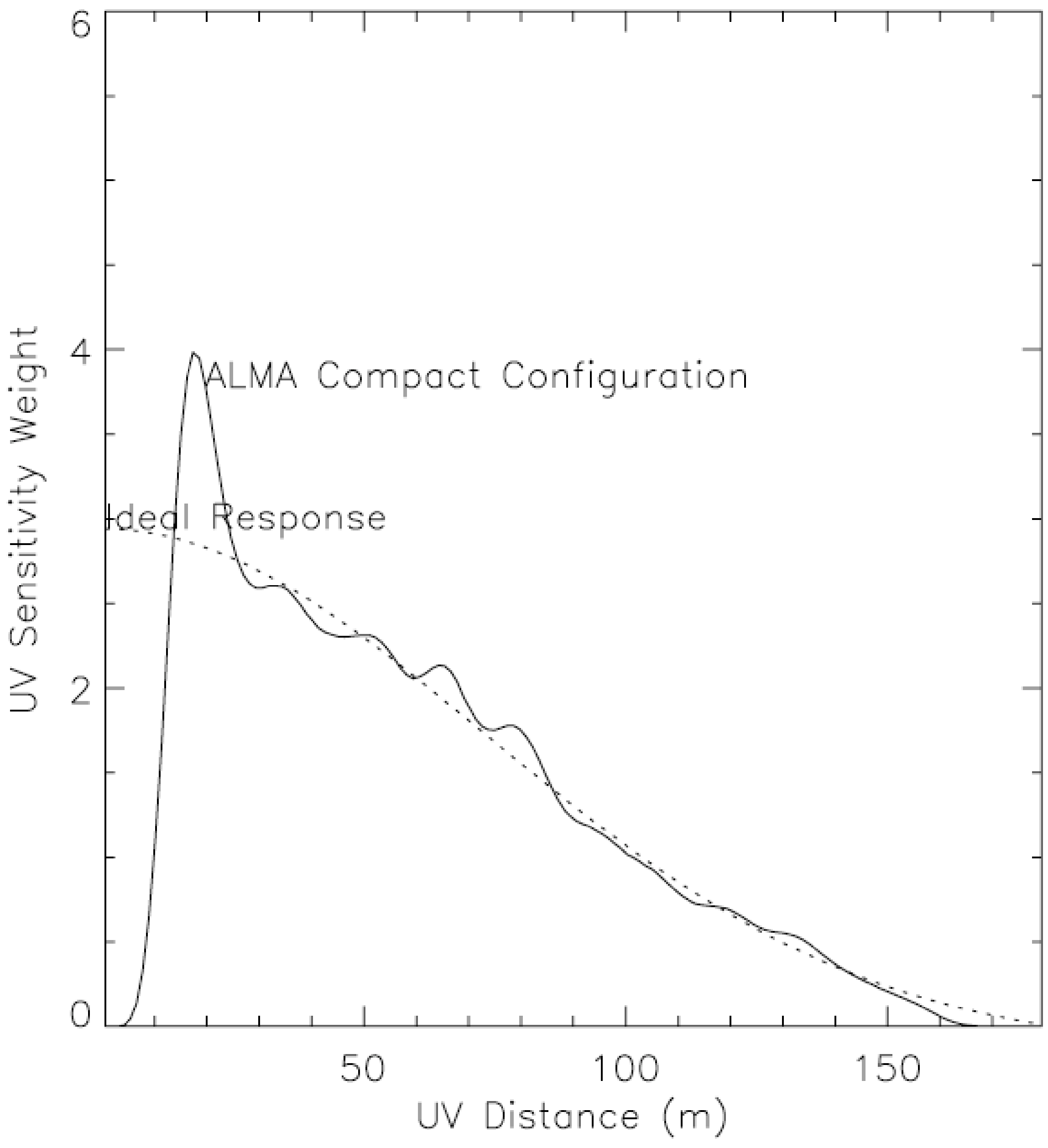
# The Short-spacing Problem

Compact array

Smallest scale $\lambda / B_{max}$ ~ 1.2" (345 GHz, $B_{max}$ ~ 150 m)

Largest angular scale $\lambda / B_{min}$ ~ 12" ($B_{min}$ ~ 15 m)

Interferometer filters out source power on scales > 12"



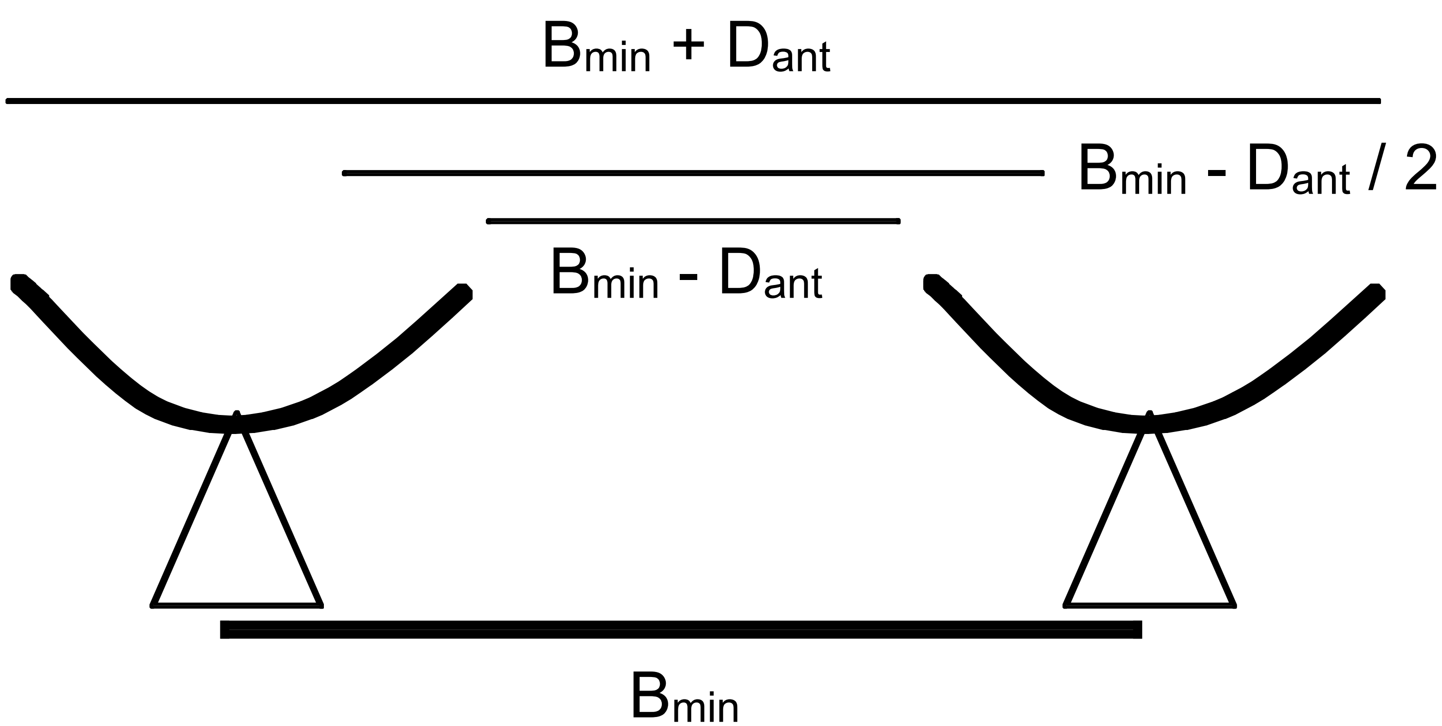
# Interferometric Mosaicing

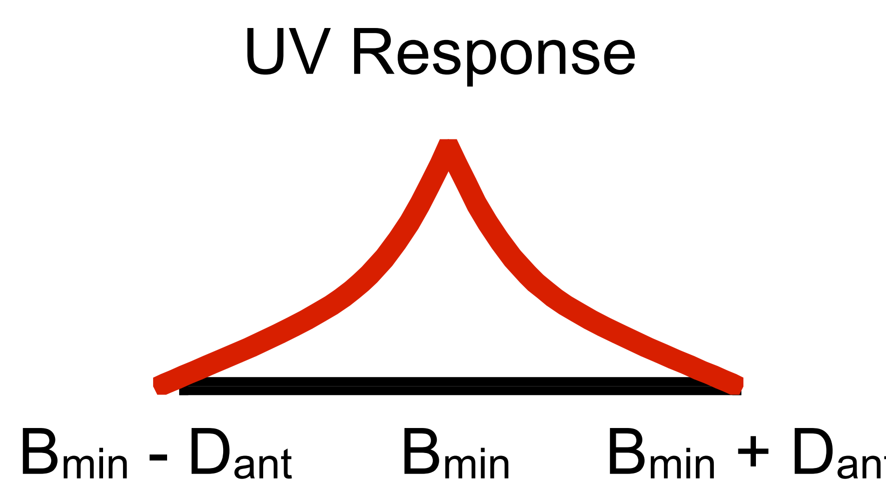
Partial solution to short-spacing problem

- Observe grid of Nyquist-sampled fields, step ~ $\lambda$ / (2 $D_{ant}$)
- On-the-fly interferometric scanning

Can recover spacings down to ~ ($B_{min}$ - $D_{ant}$ / 2) = 9 m

Single dish with same $D_{ant}$ provides zero-spacing data




“Homogenous Array” concept

# Homogenous Array

Limitations

- Missing spacings between 0 and ($B_{min}$ - $D_{ant}$ / 2)
- Image fidelity limited by
  - Pointing errors
  - Knowledge of primary beam shape

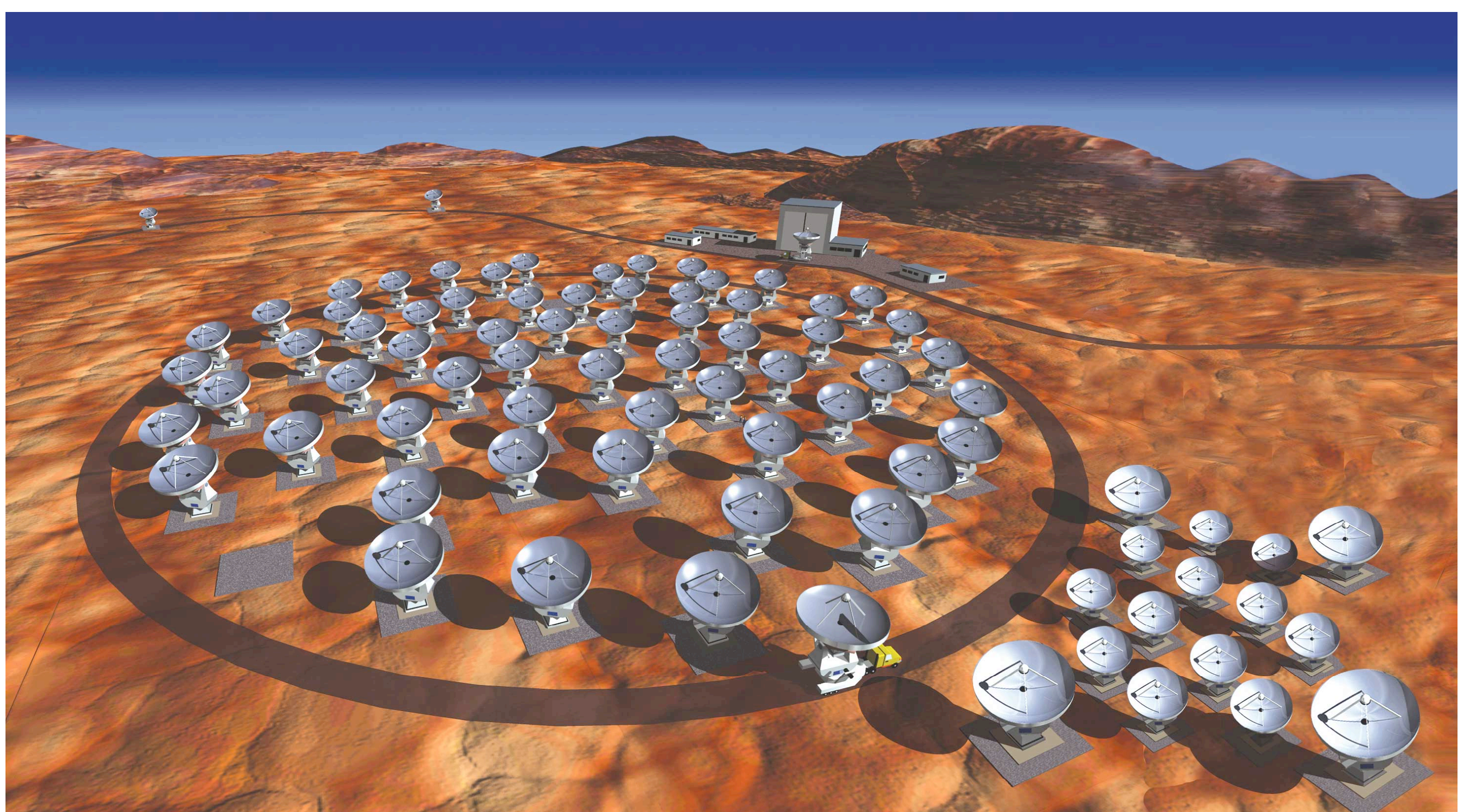
Dynamic range > 1000 and < 5% relative error requires

- Pointing error < 5% of primary beam
- Equivalent surface error < $\lambda$ / 40

Homogeneous mosaicing a challenge above 300 GHz

# ALMA Compact Array

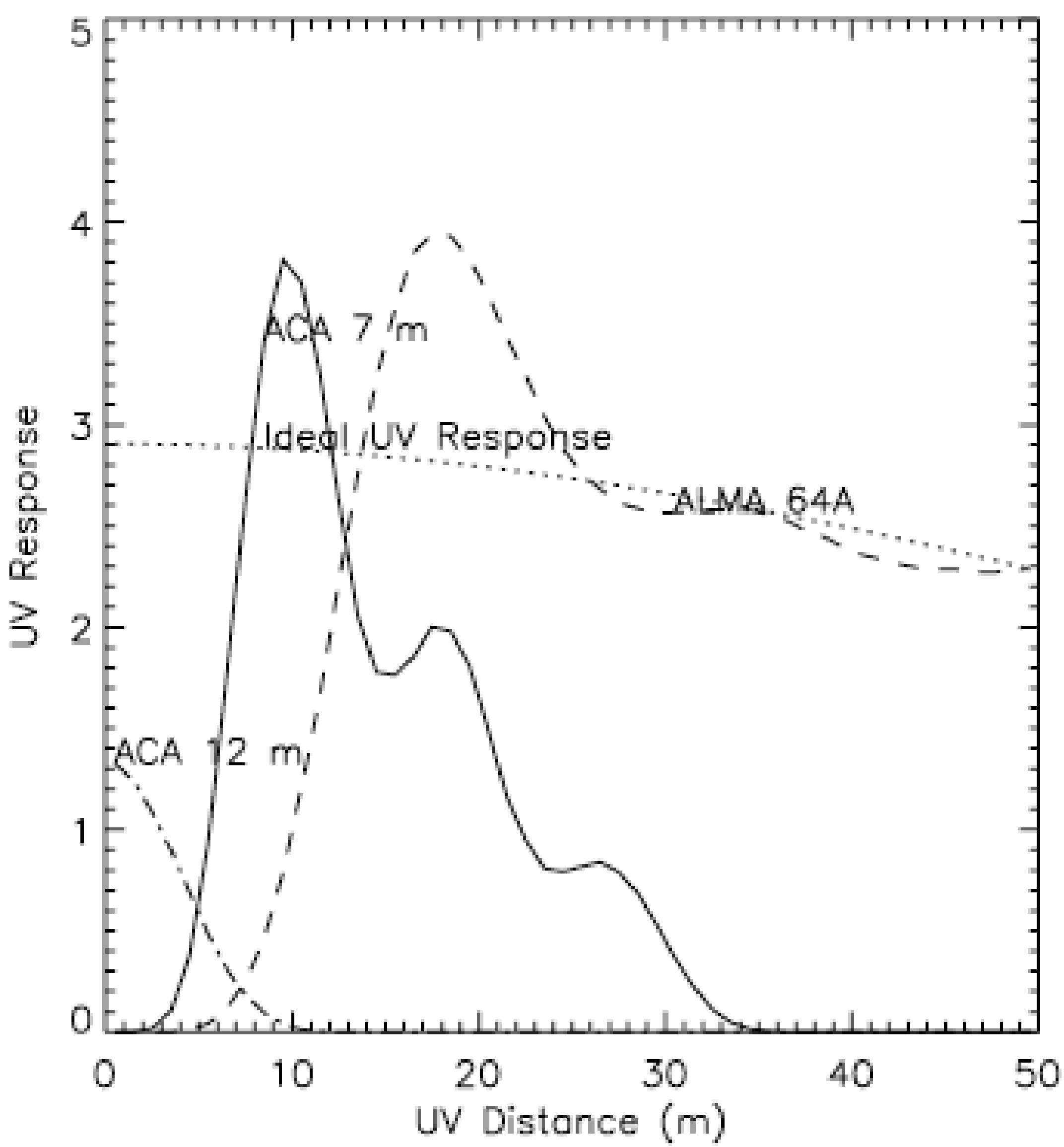
- Japan joined ALMA in late 2004
  - Band 4, 8
  - ALMA Compact Array
    - Interferometer with 12 7-metre dishes
    - Total power (single dish) in 4 12-metre dishes
- Improves surface brightness sensitivity of ALMA
- Solution to limitations of homogeneous array mosaicing

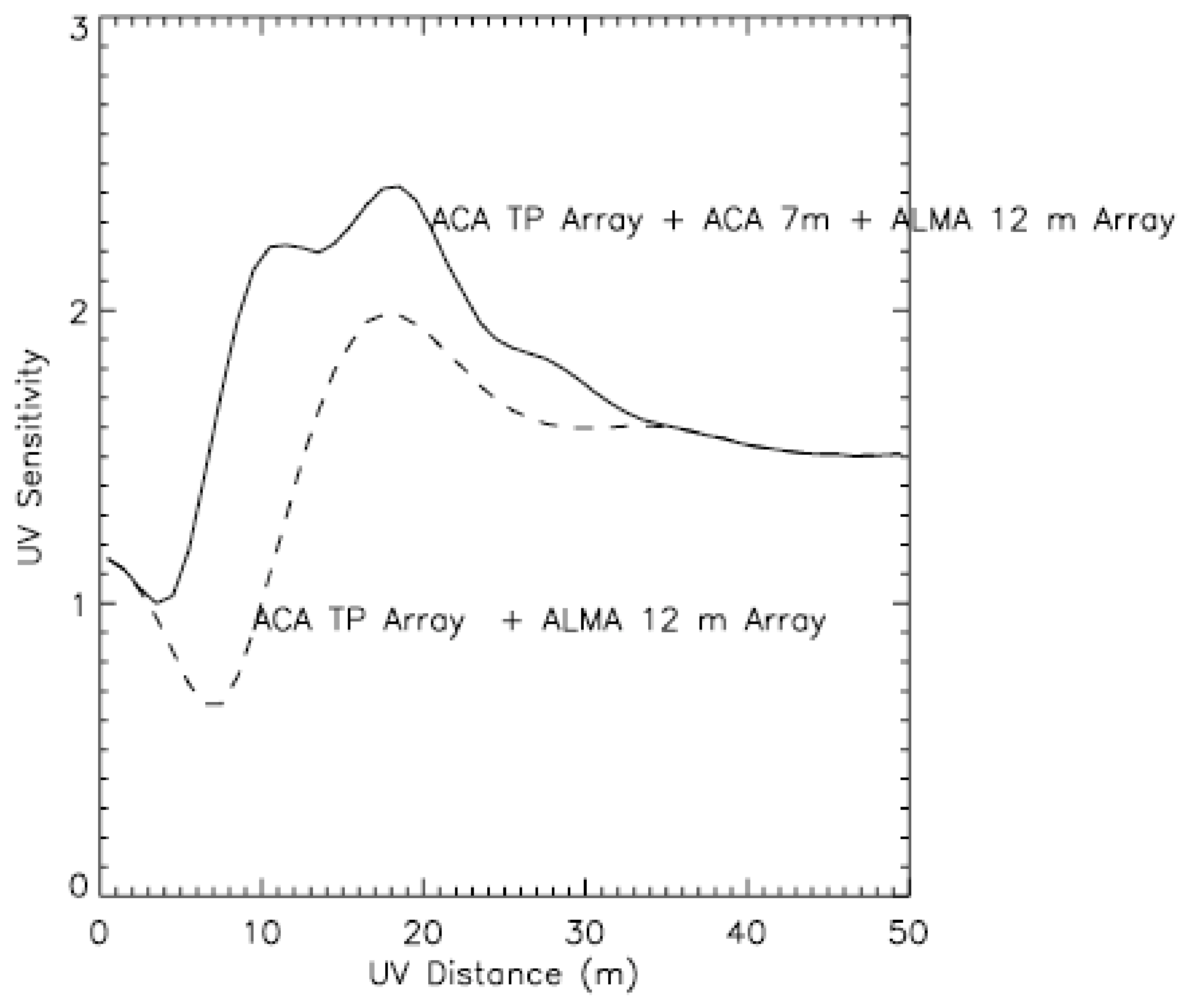


ACA will also operate as stand-alone array

# Heterogeneous Mosaicing

ALMA 12-m spacings down to ~ 13 m
ACA 7-m “bridges the gap” between 13 m and 5 m
ACA 12-m from 5 m to zero-spacing



# An ALMA Simulator

Developed by IRAM to evaluate ALMA+ACA

Useful to explore ALMA capabilities and limitations

“Official” ALMA simulator under development

Interferometric observations

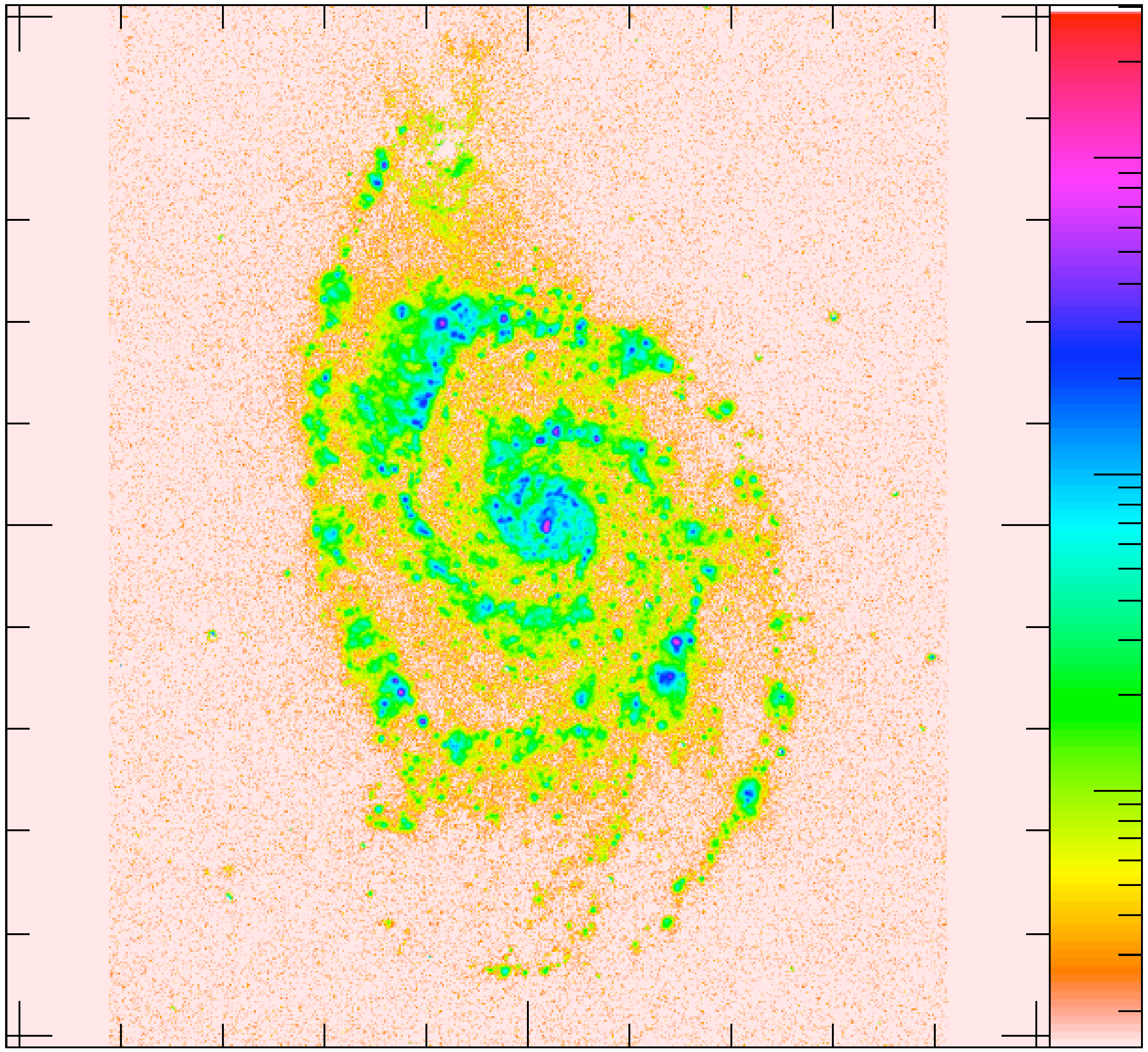
Single dish observations

How do you calibrate

Imaging

Deconvolution

Worrying about errors



Available in the “mapping” tool
of GILDAS software package

# Observing the Source

Simulator “observes” a user-defined input image

Interferometry

- Determine uv coverage from array configuration, source declination, HA range of observation
- Corrupt perfect gains by phase and amplitude errors
- Observe: generate model visibilities (including pointing errors)
- Corrupt model visibilities with error gains

Single dish

- Convolve model with primary beam
- Sample convolved model on grid (with pointing errors)
- Apply any amplitude calibration error
- Generate “pseudovisibilities” if needed

# Imaging and Deconvolution

Imaging

- Merge interferometric and single dish visibilities for each field
- Transform to produce dirty field maps
- Linearly combine fields to produce dirty mosaic

Deconvolution

- Method depends on the data
  - Homogeneous array
    - CLEAN algorithm
  - Heterogeneous array
    - Joint deconvolution by CLEAN
    - “UV hybridization”: CLEAN separately, combine in uv plane

# Errors

Simulator treats errors in sophisticated way

Pointing errors

- Individual
- Systematic (wind, thermal)

Phase errors

- “Moving phase screen” atmosphere model
- Calibrator observations
- WVRs

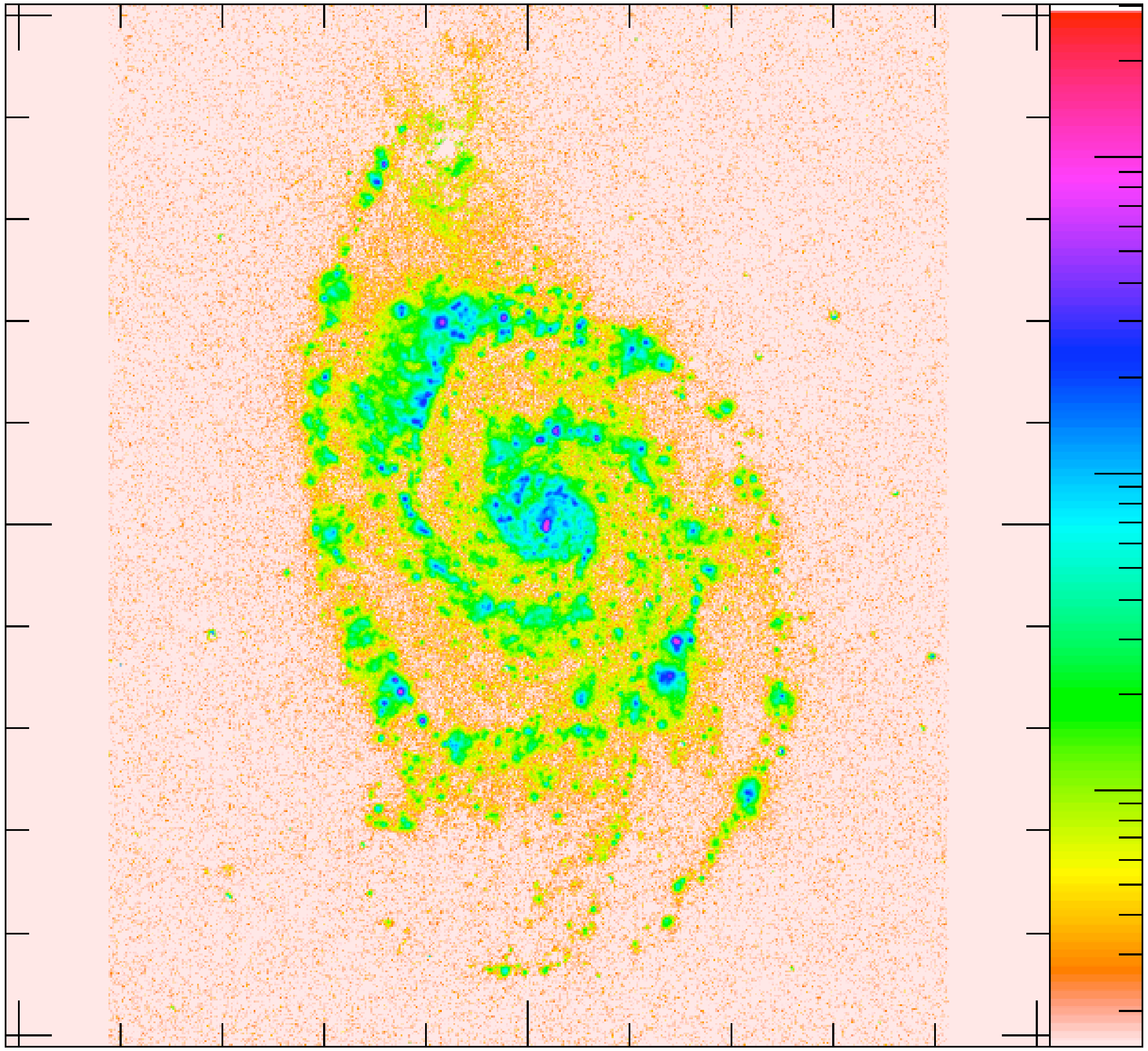
Amplitude errors

- Atmospheric transmission
- Antenna distortion
- Defocussing
- Thermal noise
- Amplitude errors between data sets

# Demo of the Simulator

A single field ALMA observation at 230 GHz of a model galaxy based upon an Hα image of M51

Supplement with ACA 12-m single dish map



# Larger Simulation

Observe a larger galaxy than before, now ~ 40”

ALMA 64 12-m

- 7 field mosaic, compact configuration, HA range -0.15 to +0.15 hours

ACA 12 7-m

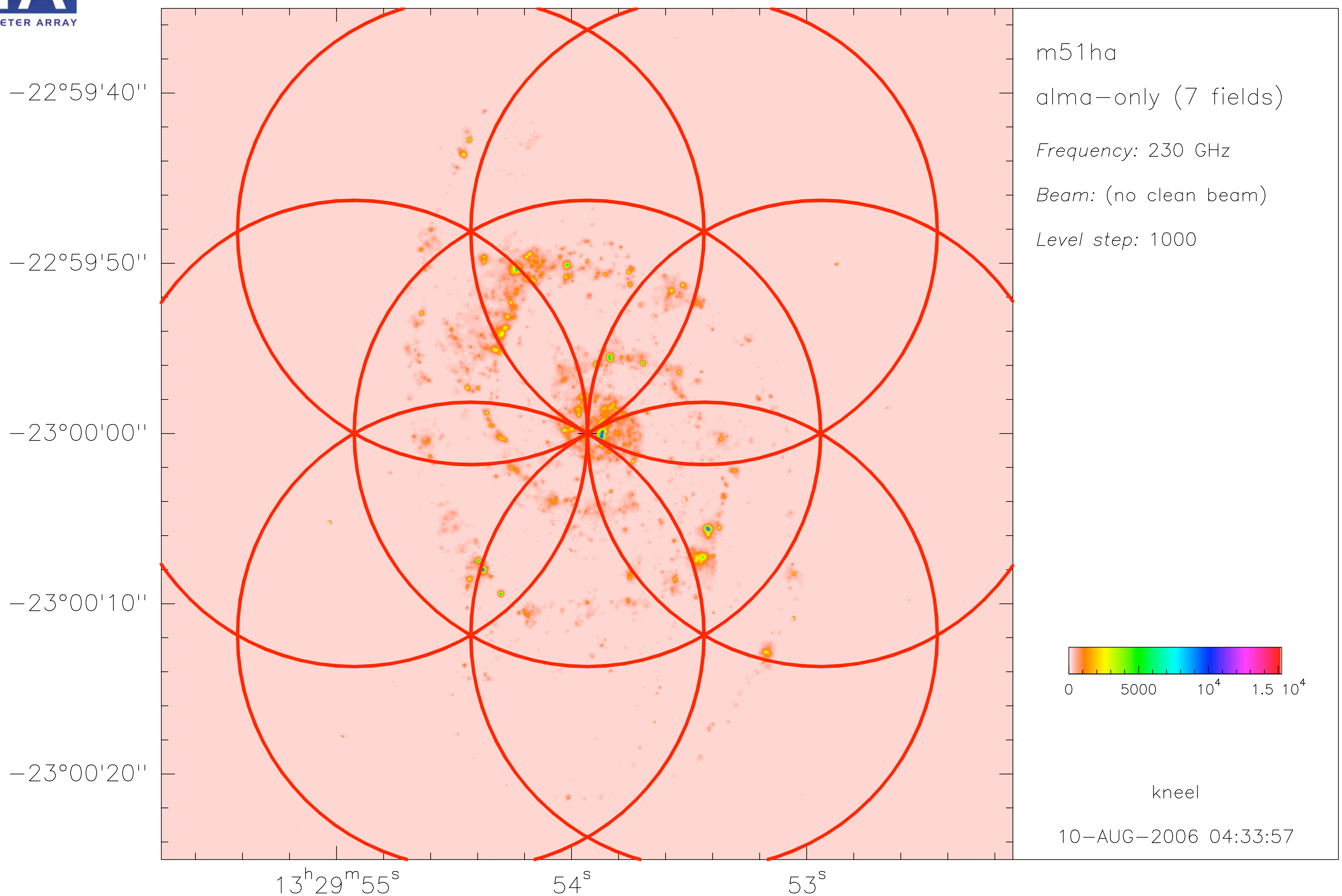
- 7 field mosaic, HA range -0.6 to +0.6 hours

ACA 4 12-m

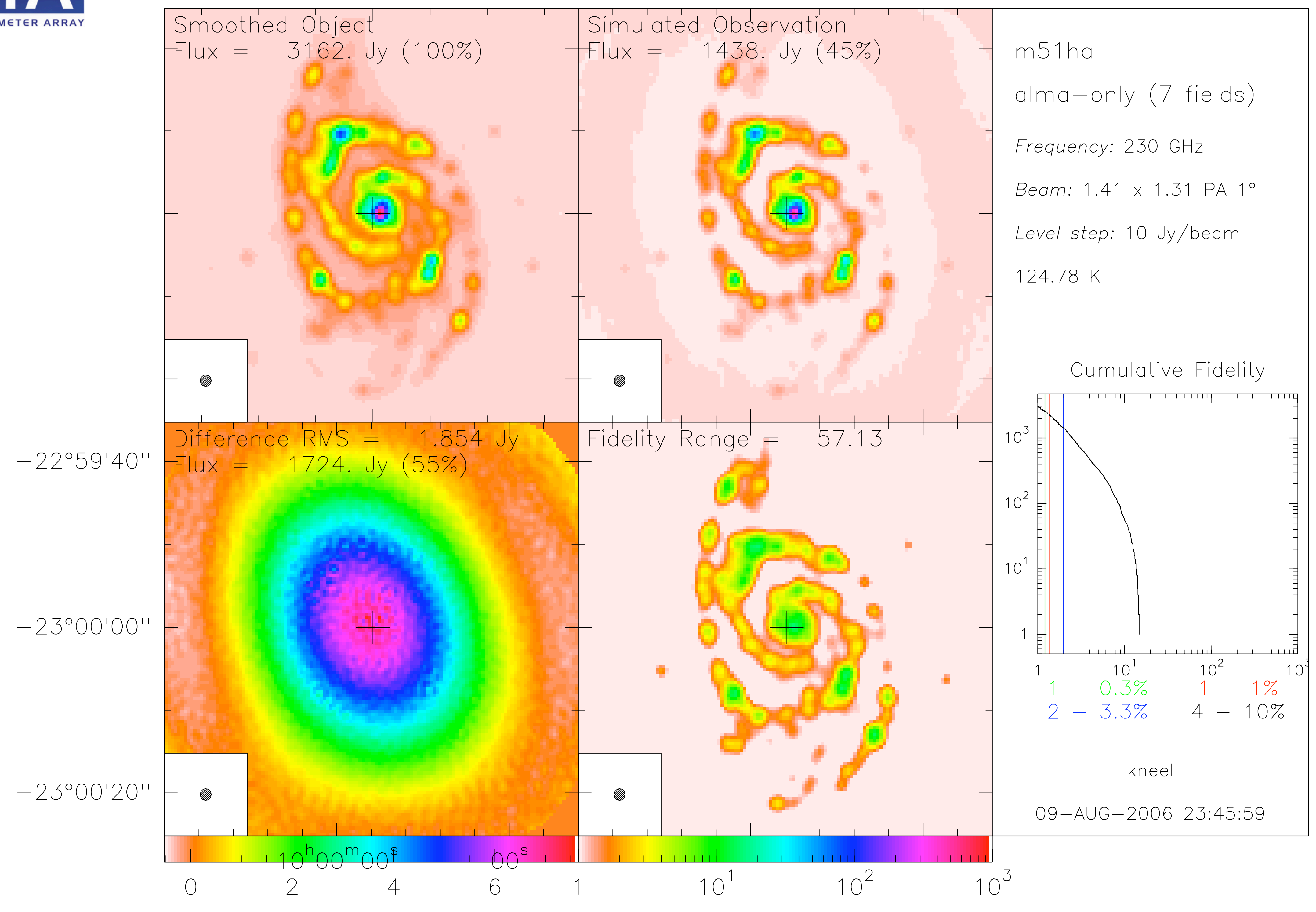
- Grid 3 points per primary beam, 1.2 hour integration time (on+off)

Compare various combinations of the data sets for image fidelity

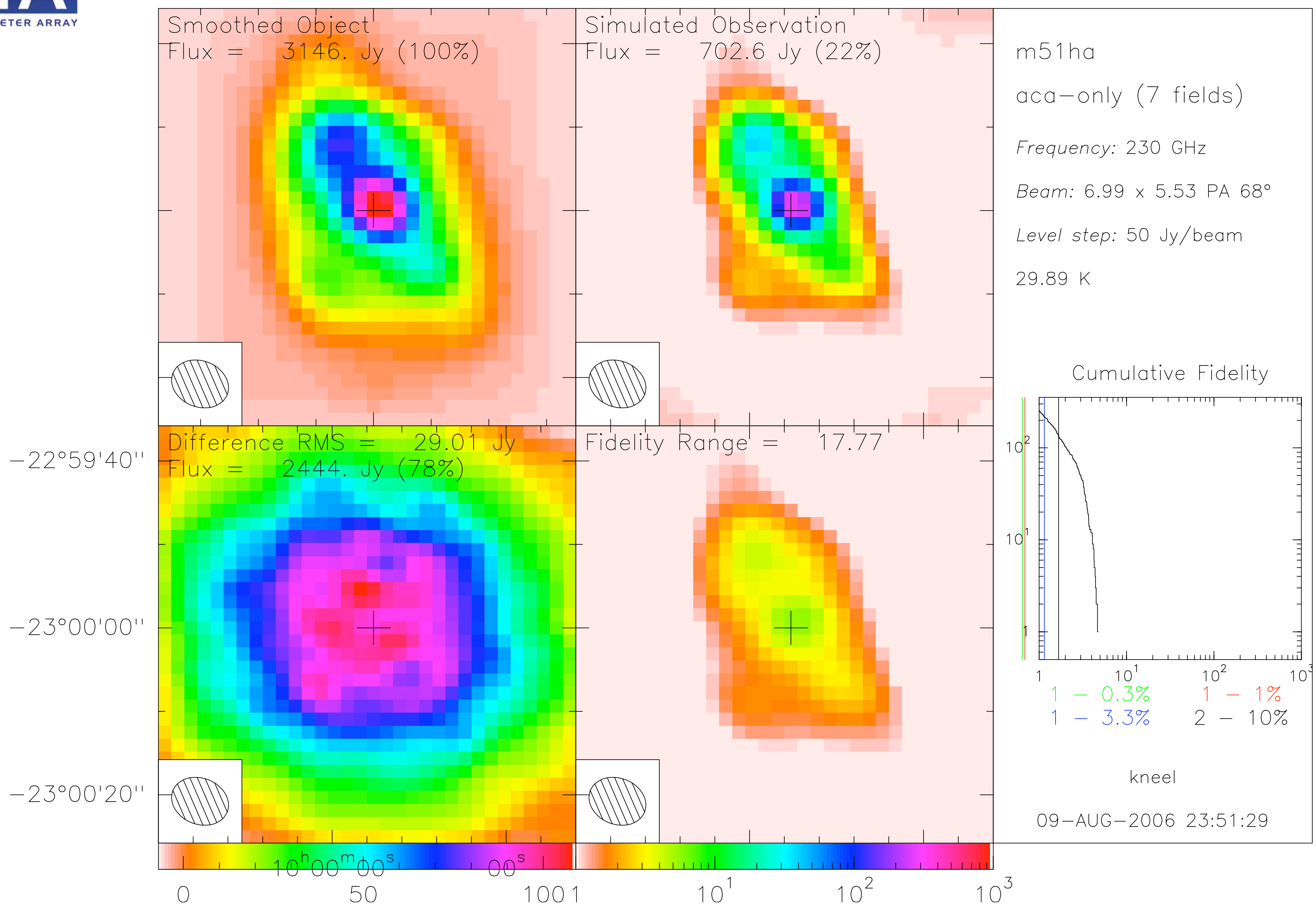
# ALMA Field Arrangement



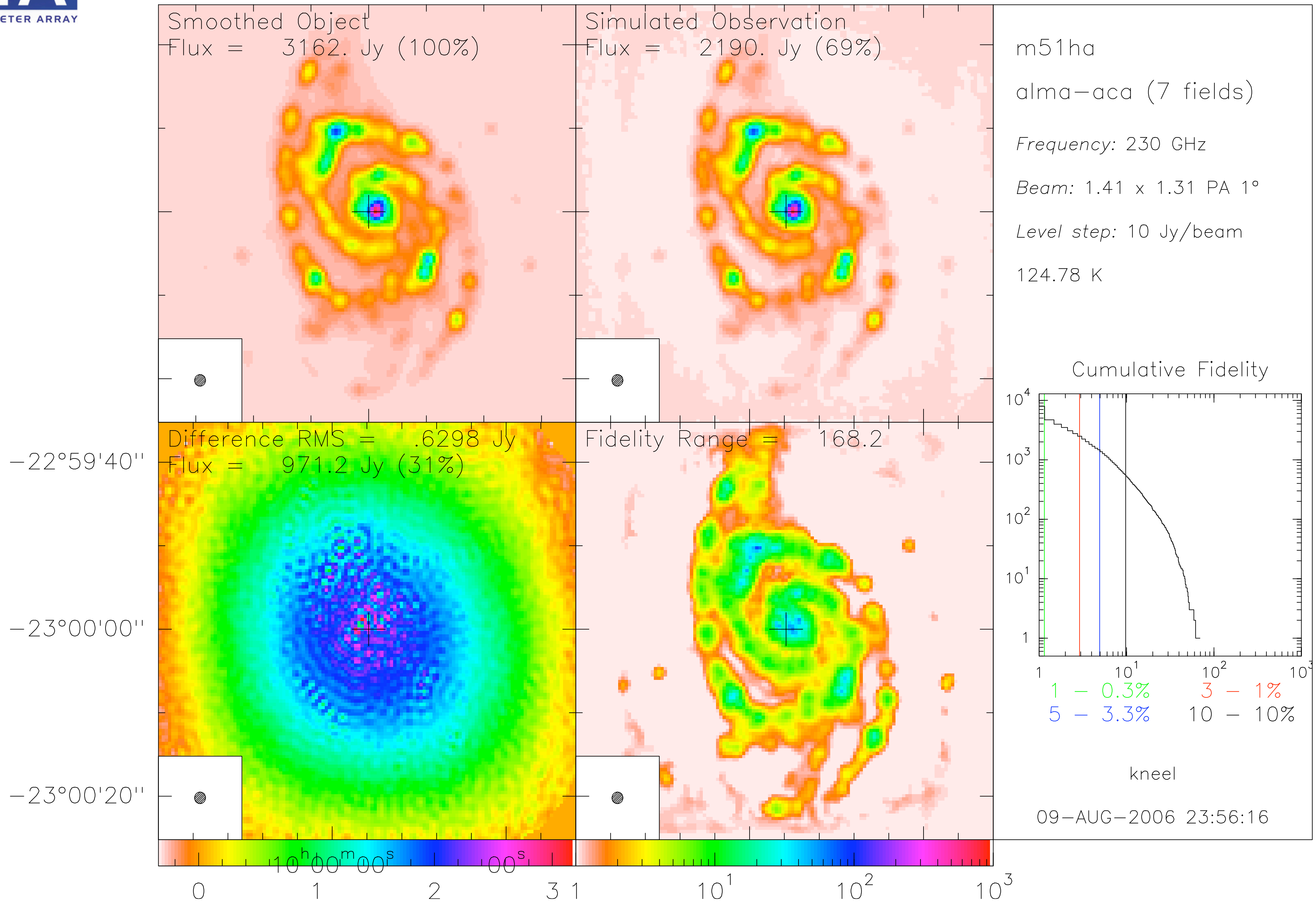
# ALMA Observations



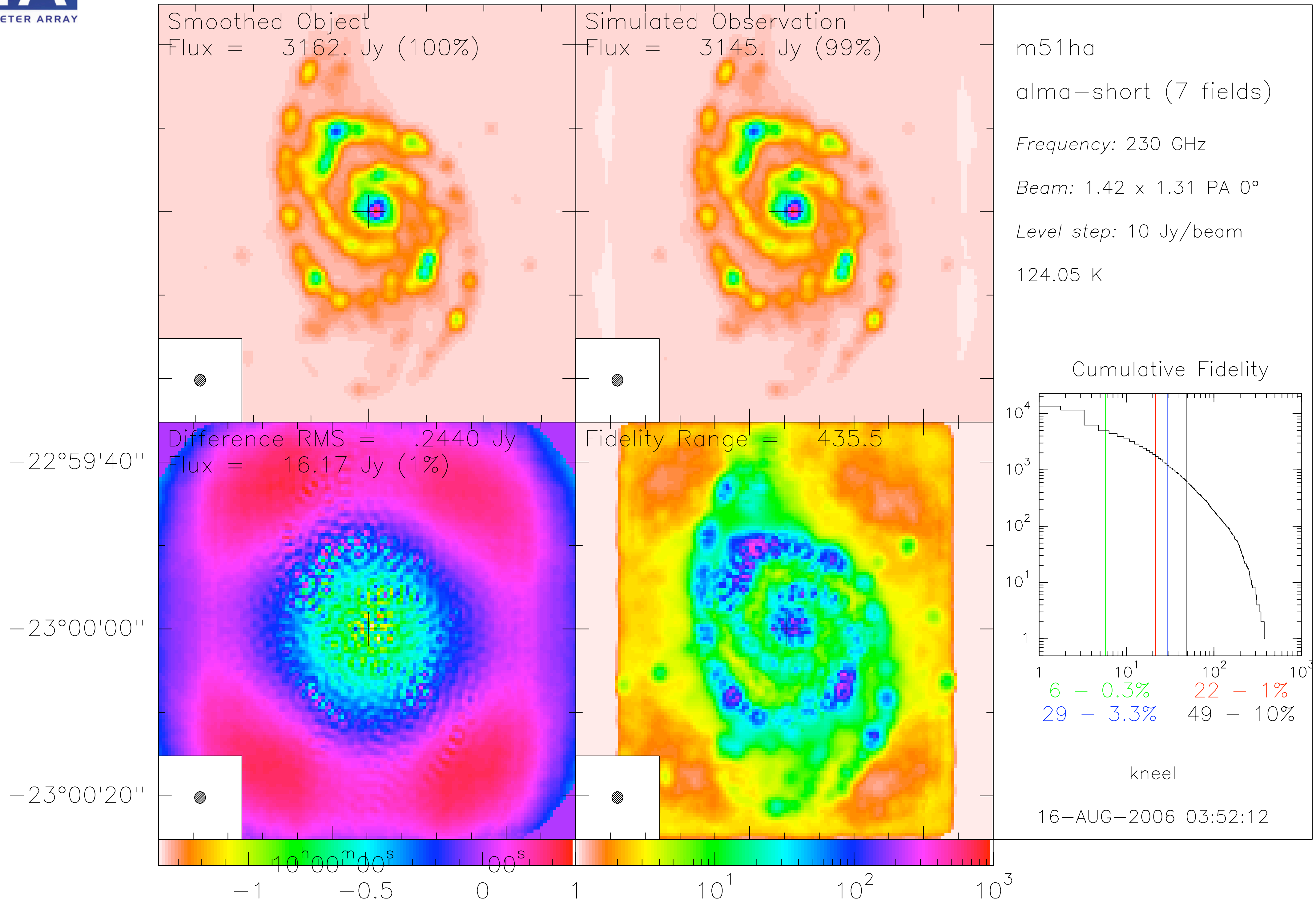
# ACA 7-m Observations



# ALMA + ACA 7-m

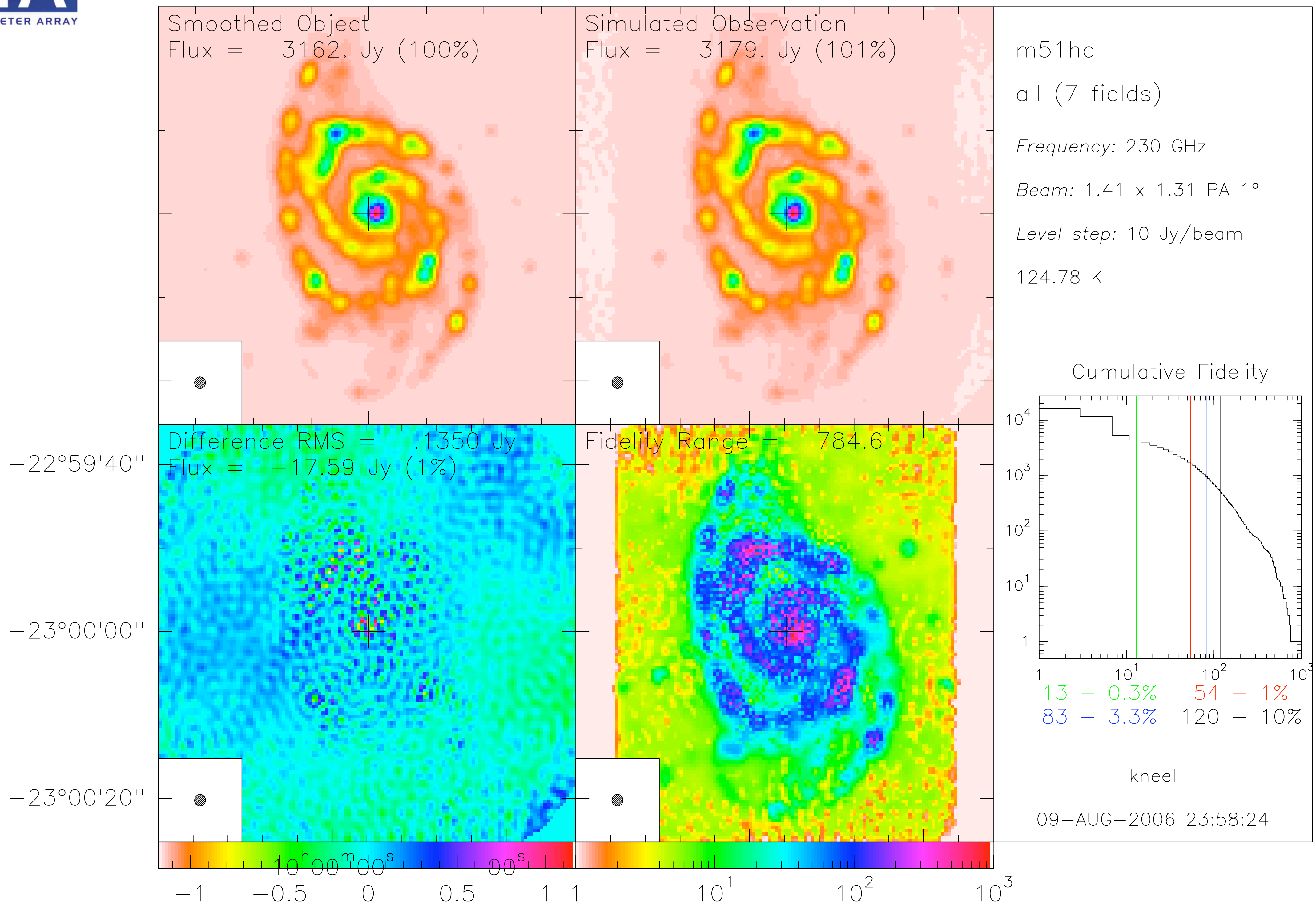

Smoothed Object
Flux = 3162. Jy (100%)
Simulated Observation
Flux = 2190. Jy (69%)
m51ha
alma−aca (7 fields)
Frequency: 230 GHz
Beam: 1.41 x 1.31 PA 1°
Level step: 10 Jy/beam
124.78 K
Difference RMS = .6298 Jy
Flux = 971.2 Jy (31%)
Fidelity Range = 168.2
−22°59'40''
−23°00'00''
−23°00'20''
10h00m00s
00s
0
1
2
3
1
10^1
10^2
10^3
Cumulative Fidelity
1 − 0.3%
3 − 1%
5 − 3.3%
10 − 10%
kneel
09−AUG−2006 23:56:16

# ALMA + ACA 12-m



Smoothed Object
Flux = 3162. Jy (100%)
Simulated Observation
Flux = 3145. Jy (99%)
Difference RMS = .2440 Jy
Flux = 16.17 Jy (1%)
Fidelity Range = 435.5
m51ha
alma–short (7 fields)
Frequency: 230 GHz
Beam: 1.42 x 1.31 PA 0°
Level step: 10 Jy/beam
124.05 K
Cumulative Fidelity
6 – 0.3%
22 – 1%
29 – 3.3%
49 – 10%
kneel
16–AUG–2006 03:52:12
–22°59'40''
–23°00'00''
–23°00'20''
10h00m00s
00s
–1
–0.5
0
1

# ALMA + ACA 7-m + ACA 12-m



# Comparison Results

| Data Set | Flux Recovered | Fidelity above 1% of peak | Fidelity above 10% of peak |
|---|---|---|---|
| ACA 7-m | 22% | 1 | 2 |
| ALMA | 45% | 1 | 4 |
| ALMA + ACA 7-m | 69% | 3 | 10 |
| ALMA + ACA 12-m | 99% | 22 | 49 |
| All | 101% | 54 | 120 |

Extensive simulations show value of ACA 7-m

- Robust imaging under wide range of conditions
- More resistant to pointing errors and primary beam “errors”

This simulation had no errors

- Probably do not fairly represent ACA 7-m

# Demo of the ALMA OT

ALMA will be a service observing facility

- Dynamical scheduling
- Configuration
- Weather

Phase I - Phase II process

- ALMA Observing Tool

ALMA should be easy to use - not just for the black-belts

OT design reflects needs of non-experts and experts alike

“Science View” and “System View” modes

NRC·CNRC
Herzberg Institute of Astrophysics

ALMA
ATACAMA LARGE MILLIMETER ARRAY

# www.alma.info

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