ALMA as a Scientific Instrument

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Bologna, April 29th 2010

Outline

- What is ALMA?
- ALMA as it will be
- ALMA Operations
- Early Science
- Planning an ALMA observation
- Current status

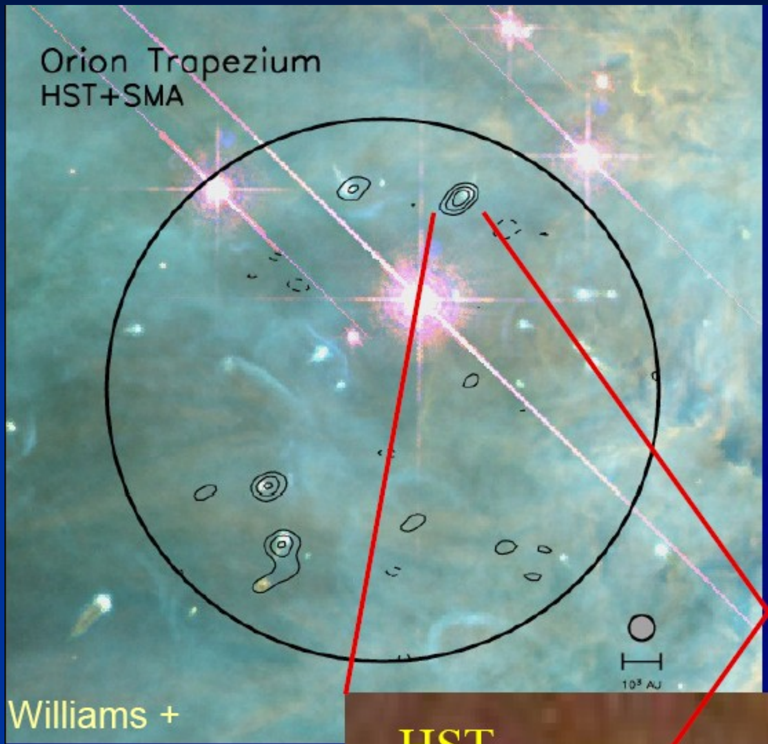
Atacama Large Millimetre/ Sub-Millimetre Array

- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths (1cm - 0.3mm/30 – 950 GHz)
- **H**igh, dry site, Chajnantor Plateau, Chile (5000m)
- 50 dishes with 12m diameter (EU/NA).
- Baselines from ~15m to 14.5km.
- ALMA Compact Array (ACA) provided by Japan
  - 12 7m dishes in compact configurations
    - 4 12m dishes primarily for total-power
- Low-noise, wide-band receivers.
- Digital correlator giving wide range of spectral resolutions.
- Software (dynamic scheduling, imaging, pipelines)

Highest-level science goals

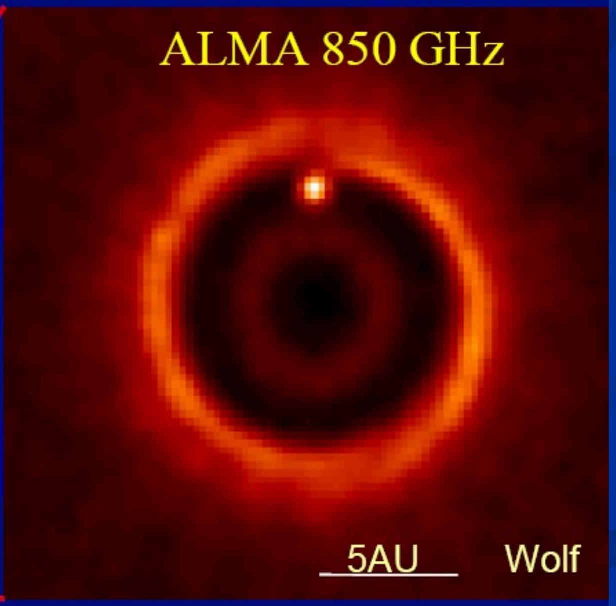
- Image spectral line emission from CO or C+ in a galaxy with similar mass to the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.
- Image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc. Study the physical, chemical, and magnetic field structure of the disk and detect the tidal gaps created by planets undergoing formation.
- Provide precise images at a resolution of 0.1 arcsec.

Formation of planets



Birth of planets

- $M_{planet} / M_{star} = 1.0\ M_{Jup} / .5\ M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus



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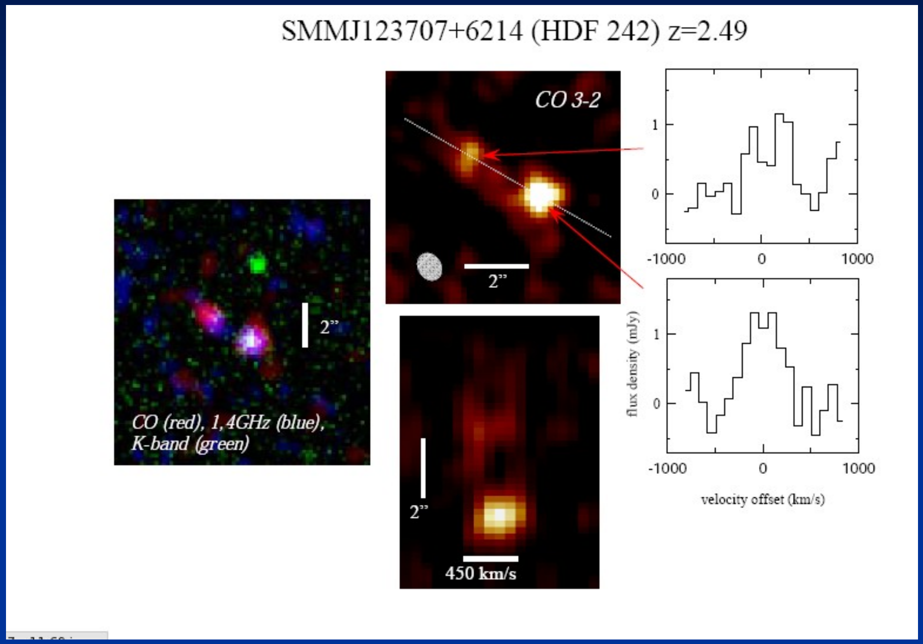
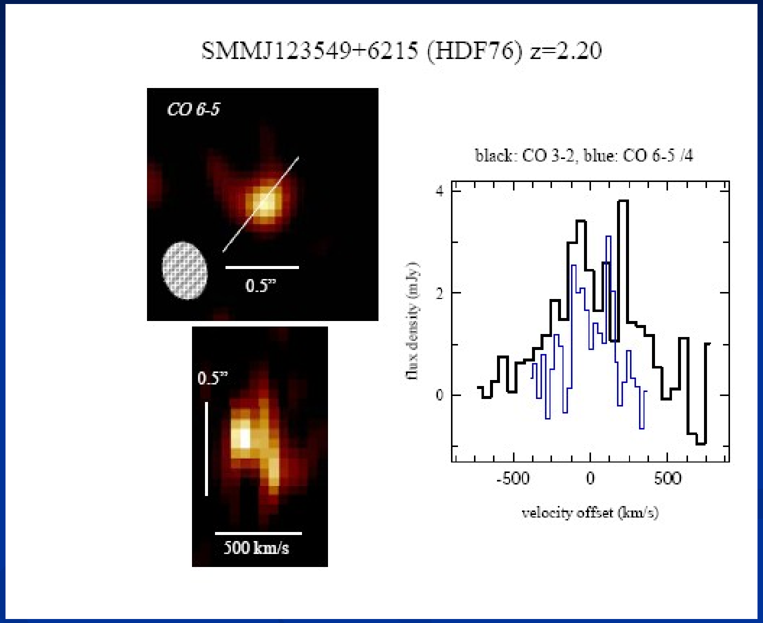
CO in z ≈ 2 sub-mm galaxies

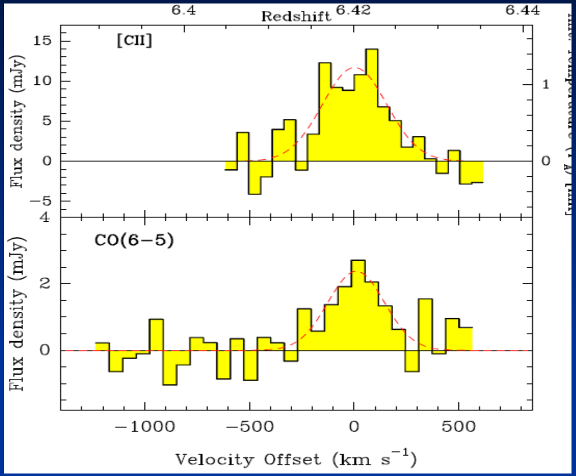




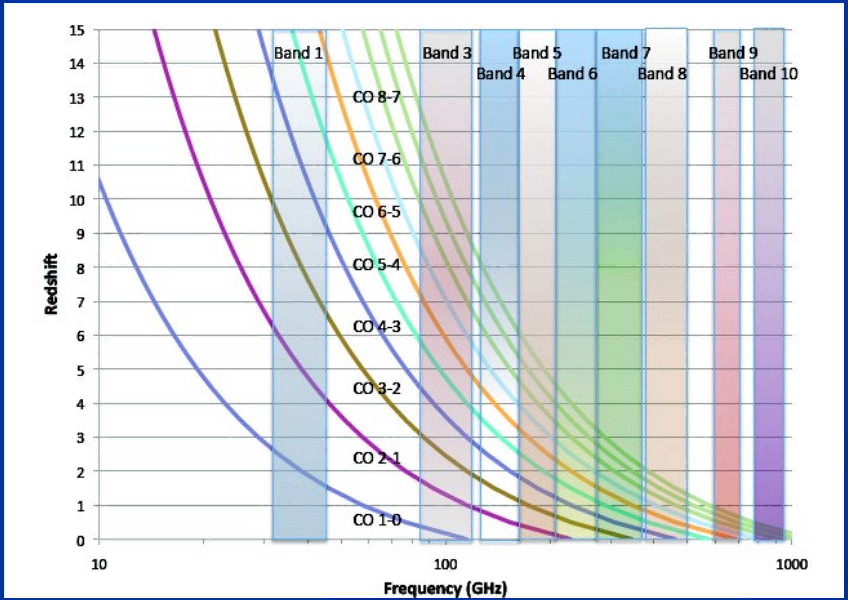
Current observations can resolve only the brightest sub-mm galaxies. These seem to be short-lived examples of maximal star formation in ongoing mergers.

Velocity fields disc-like or irregular.

The first galaxies



CII – Main coolant in the Milky Way
Line of choice for EoR studies
Quasar, z = 6.4



CO transitions

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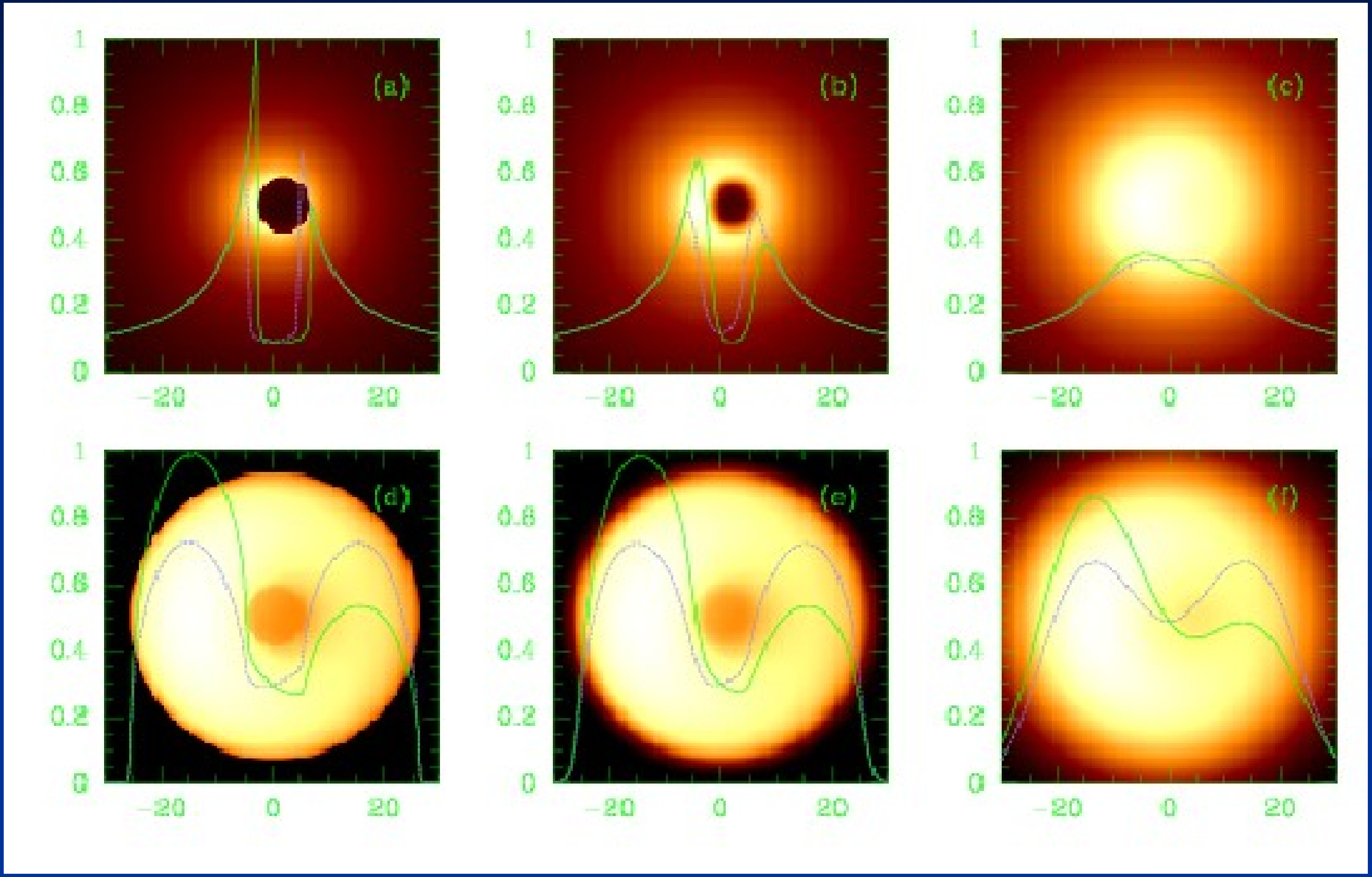
VLBI observations of Sgr A* with phased-up ALMA



Kerr (spinning) black hole

Schwarzschild (non-rotating) black hole

GR ray tracing

0.6mm VLBI

1.3mm VLBI

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More science areas

- Dust emission from star-forming galaxies at z ~ 10
- Blind surveys for CO in star-forming galaxies at all epochs
- Detailed studies of cold gas and dust in nearby galaxies; AGN torus sructure
- Dynamics of molecular gas around the Galactic Centre
- Star formation: physics and chemistry of collapse, accretion, outflows and disks.
- Complex organic (including prebiotic) molecules
- Molecules and dust around evolved stars
- Planetary atmospheres, cometary nuclei, asteroids
- ……………

Physical processes

- Aside from non-thermal emission, most of what ALMA will see comes from elements heavier than H and He (except recombination lines, LiH). Therefore probe stellar products.
- Temperatures are < stellar surface – the "Cold Universe"
- Continuum: thermal emission from dust (scattered emission polarized)
- Lines: molecular rotational transitions + redshifted atomic
- Line polarization: Zeeman, Goldreich-Kylafis
- Heating via stellar UV, cosmic rays, hard photons from AGN – hence the link to star and galaxy formation
- Non-thermal mechanisms include synchrotron (lower frequencies; linearly polarized) and Compton scattering (Sunyayev-Zeldovich).

ALMA as it will be

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Key performance numbers

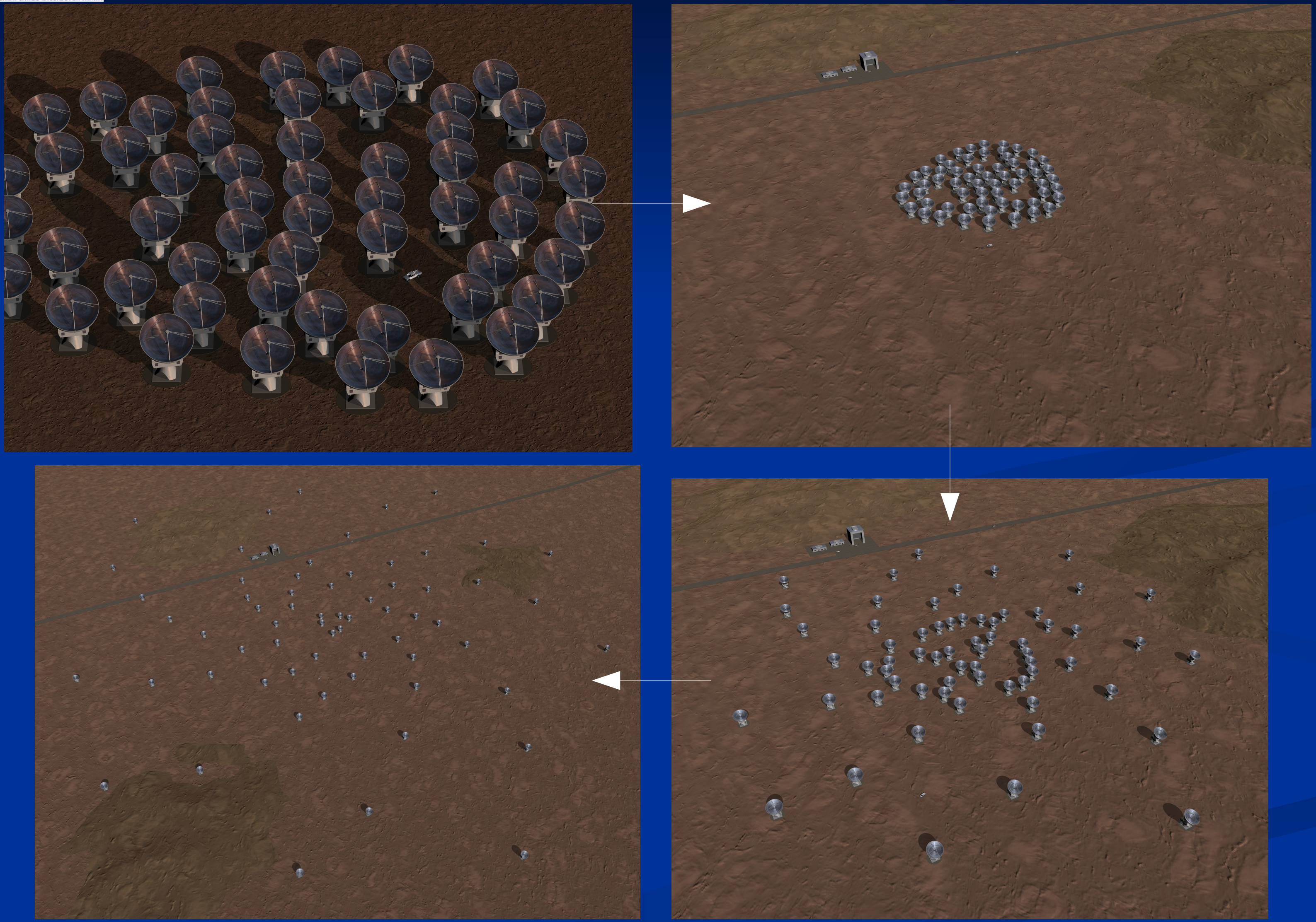
- Baseline range 15m – 14.5 km + ACA + single dish
- Field of view / arcsec ≈ 17 (λ/mm) [12m dish]

  29 (λ/mm) [7m dish]
- Resolution/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

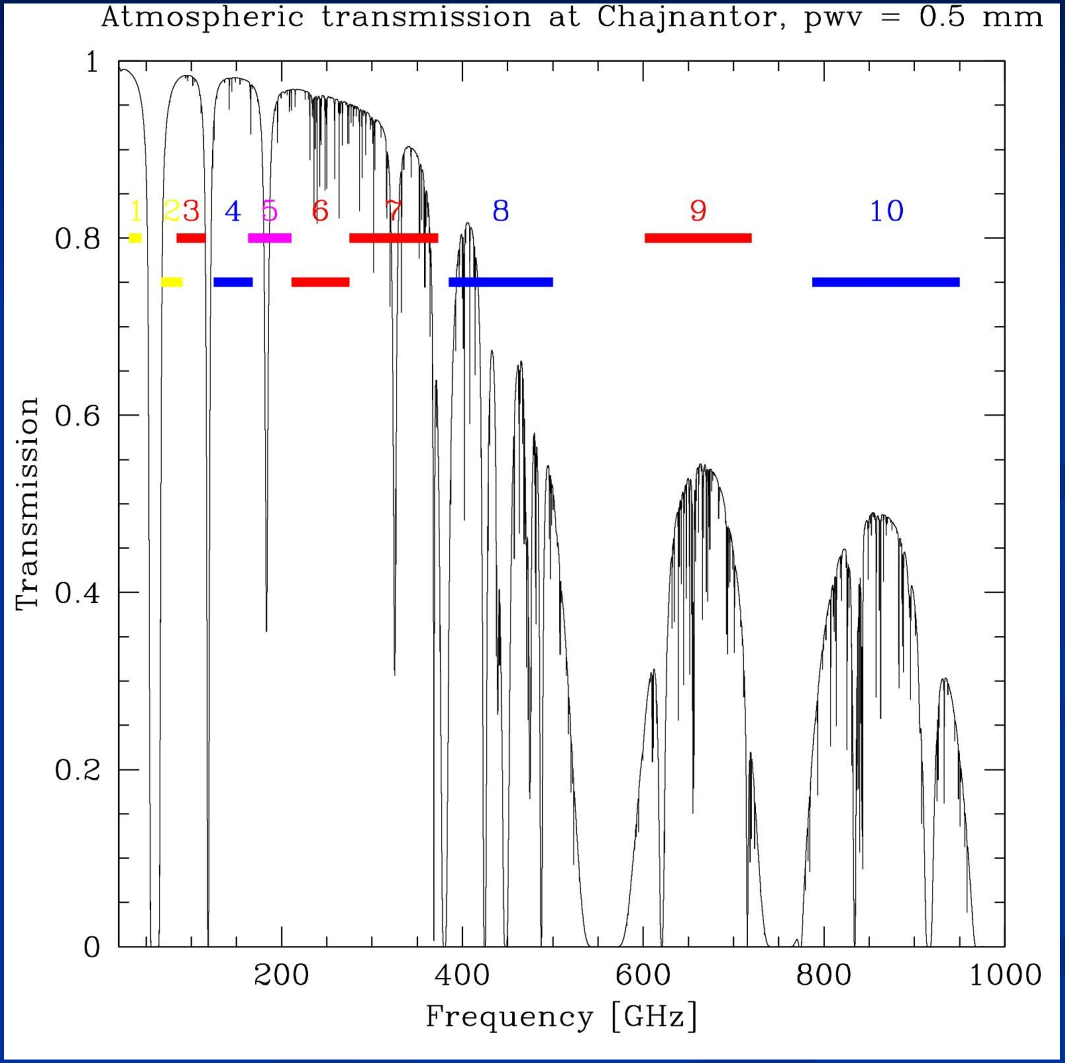
  0.04 arcsec at 100 GHz, 14.5 km baseline

  0.005 arcsec at 900 GHz, 14.5 km baseline
- Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … → sub-mJy continuum sensitivity and wide spectral coverage
- Full polarization

Continuous reconfiguration



Transparent site allows full spectral coverage



Basic numbers

					Compact		Most Extended	
Band	Frequency	Primary Beam (FOV; ")	Largest Scale (")	Continuum Sensitivity (mJy)	Angular Resolution (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
Band 1	31.3 - 45 GHz							
Band 2	67 -90 GHz							
Band 3	84 - 116 GHz	56	37	0.05	3.18	0.07	0.038	482
Band 4	125 - 163 GHz	48	32	0.06	2.5	0.071	0.03	495
Band 5	163 - 211 GHz	35	23					
Band 6	211 - 275 GHz	27	18	0.10	1.52	0.104	0.018	709
Band 7	275 - 373 GHz	18	12	0.20	1.01	0.167	0.012	1128
Band 8	385 - 500 GHz	12	9	0.40	0.86	0.234	0.01	1569
Band 9	602 - 720 GHz	9	6	0.69	0.52	0.641	0.006	4305
Band 10	787 - 950 GHz	7	5	1.1	0.38	0.940	0.005	

Continuum sensitivities for 8 GHz bandwidth,
Lines 1 km/s; 2 polarizations, 50 antennas, 60s

To be developed in the future. Available for early science.

Spectral modes

- Channel bandwidth 31.25 MHz – 2 GHz (x4 baseband channels)
- Maximum 4096 x (4/N) x (2/P) spectral points/channel, where N = 1, 2 or 4 is the number of channels and P=2 for full polarization; 1 for parallel hands only.
- Maximum spectral resolution 3.8 kHz.
- Tunable FIR filter bank to subdivide 2 GHz baseband into 32 (possibly overlapping) sub-channels, each 62.5 or 31.25 MHz wide
- Flexible combinations of centre frequency and resolution

Correlator modes

Number of sub-channel filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity resolution at 230 GHz	Correlation	Sample Factor	Minimum dump time*	Sensitivity**
32	2 GHz	2048	976 kHz	1.28 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
16	1 GHz	2048	488 kHz	0.64 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
16	1 GHz	1024	976 kHz	1.28 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
8	500 MHz	2048	244 kHz	0.32 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
8	500 MHz	1024	488 kHz	0.64 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
8	500 MHz	512	976 kHz	1.28 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
4	250 MHz	2048	122 kHz	0.16 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
4	250 MHz	1024	244 kHz	0.32 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
4	250 MHz	512	488 kHz	0.64 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
4	250 MHz	256	976 kHz	1.28 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
2	125 MHz	2048	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
2	125 MHz	1024	122 kHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
2	125 MHz	512	244 kHz	0.32 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
2	125 MHz	256	488 kHz	0.64 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
1	62.5 MHz	2048	30 kHz	0.04 km/s	2-bit x 2-bit	Nyquist	512 msec	0.88
1	62.5 MHz	1024	61 kHz	0.08 km/s	2-bit x 2-bit	Twice Nyquist	256 msec	0.94
1	62.5 MHz	512	122 kHz	0.16 km/s	4-bit x 4-bit	Nyquist	128 msec	0.99
1	62.5 MHz	256	244 kHz	0.32 km/s	4-bit x 4-bit	Twice Nyquist	64 msec	0.99
1	31.25 MHz	2048	15 kHz	0.02 km/s	2-bit x 2-bit	Twice Nyquist	512 msec	0.94
1	31.25 MHz	512	61 kHz	0.08 km/s	4-bit x 4-bit	Twice Nyquist	128 msec	0.99
Time Division Mode	2 GHz	64	31.25 MHz	40.8 km/s	2-bit x 2-bit	Nyquist	16 msec	0.88

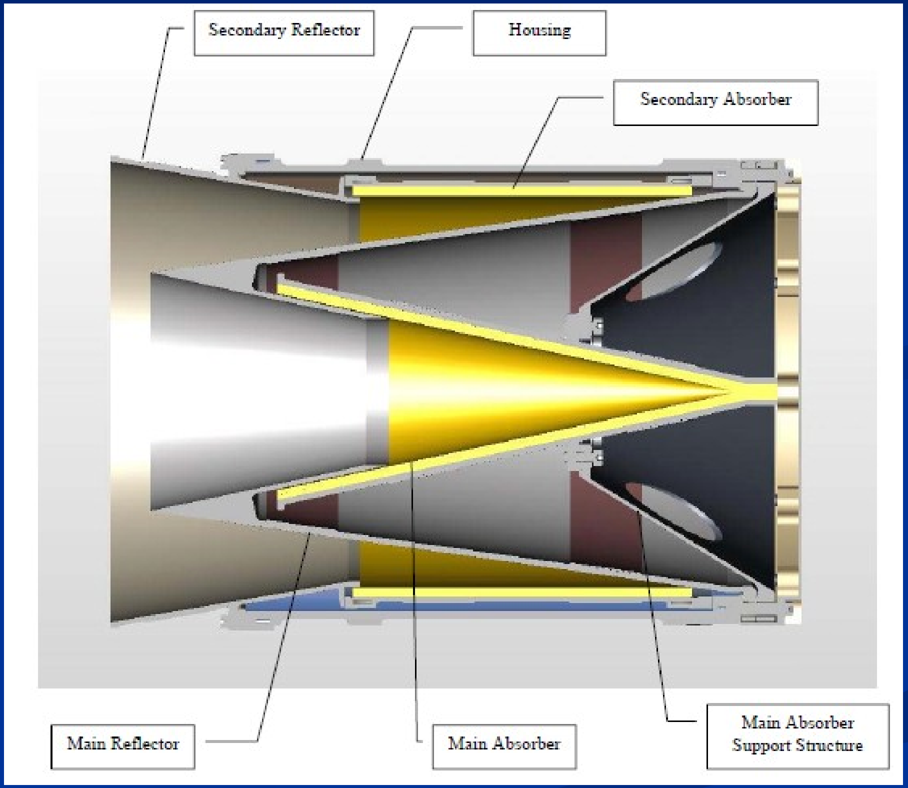
Mode table for 4 polarizations. Single polarization allows 4 times higher spectral resolution.

Phase calibration

- **Requirements**
  - Reduce atmospheric and electronic phase fluctuations to as low a level as possible
  - Required by imaging and flux scale (decorrelation)
- **Techniques**
  - Fast switching (interleave with observations of a nearby calibrator, perhaps at a lower frequency). 20 – 300s cycle times. Requires calibrator within ~2^{o}.
  - Water-vapour radiometry (measure emission from 183 GHz atmospheric line; deduce phase fluctuations on 1s timescales).
  - Self-calibration

Amplitude calibration

- Correcting for atmospheric attenuation
  - Dual-load calibration device
- Primary amplitude calibrators
  - Mars: models good, but large
  - Galilean satellites
  - Asteroids
  - Stars
  - Compact HII regions
- Cross-calibration
  - Planck
  - Herschel



ALMA Operations

- Basic concepts
  - Service mode, scheduled dynamically (weather)
  - All observations executed as scheduling blocks, which contain all of the information required to schedule and run the observations (calibration)
  - Primary data products are image cube; raw, calibrated visibility data also available.
  - Everything is archived.
- Support
  - Software for proposal preparation, reduction, pipeline
  - Documentation
  - Face-to-face support

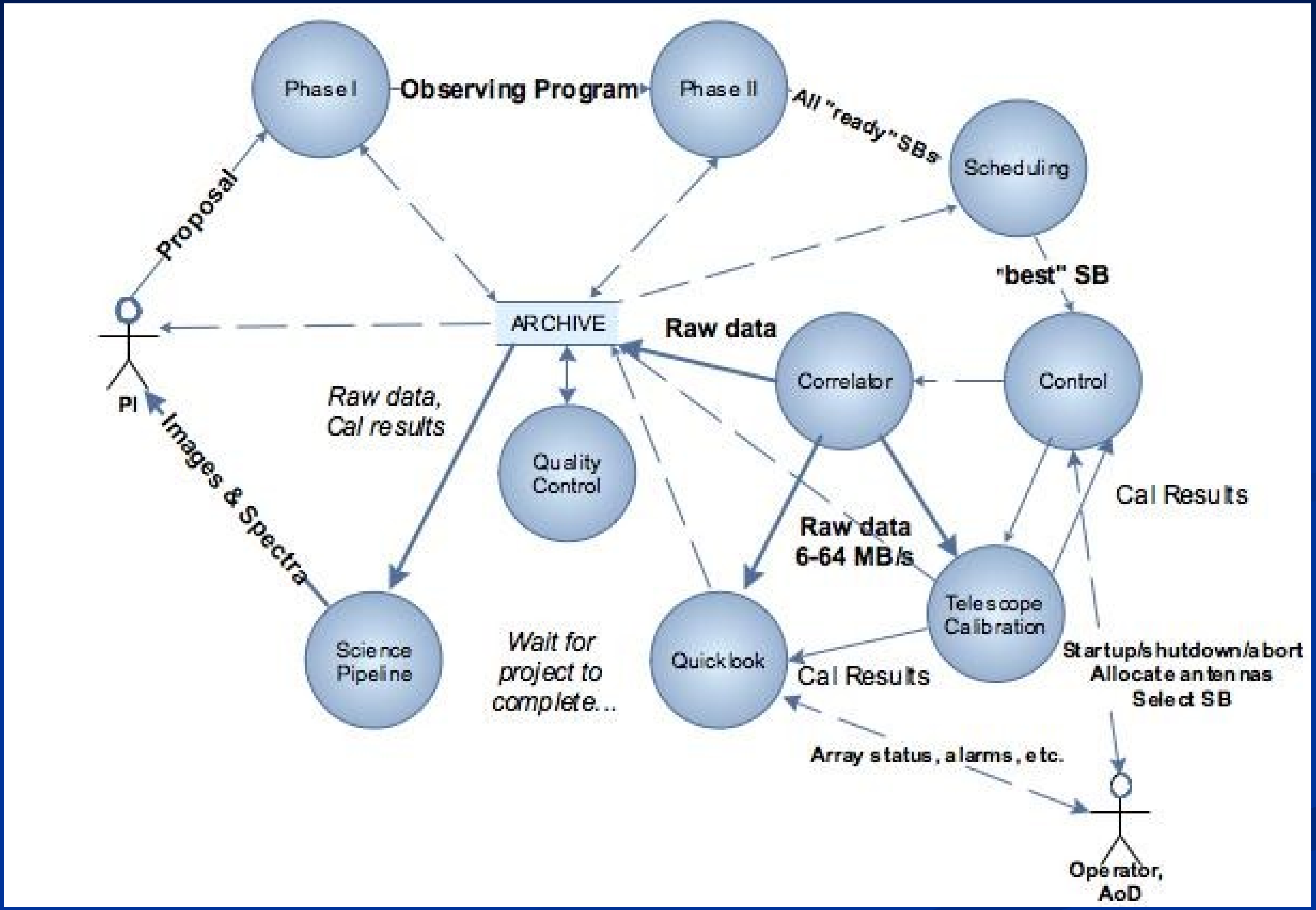
ALMA Projects

- Phase I
  - Submit proposal using the Observing Tool (OT)
  - Review
- Phase II
  - Submit observing project, again using the OT
  - Preparation of scheduling blocks
- Observations
  - Select from queue (weather, priority)
  - Accumulate data until goals are met
  - Pipeline reduction, quality assurance
- Data distribution
  - PI
  - Public after proprietary period

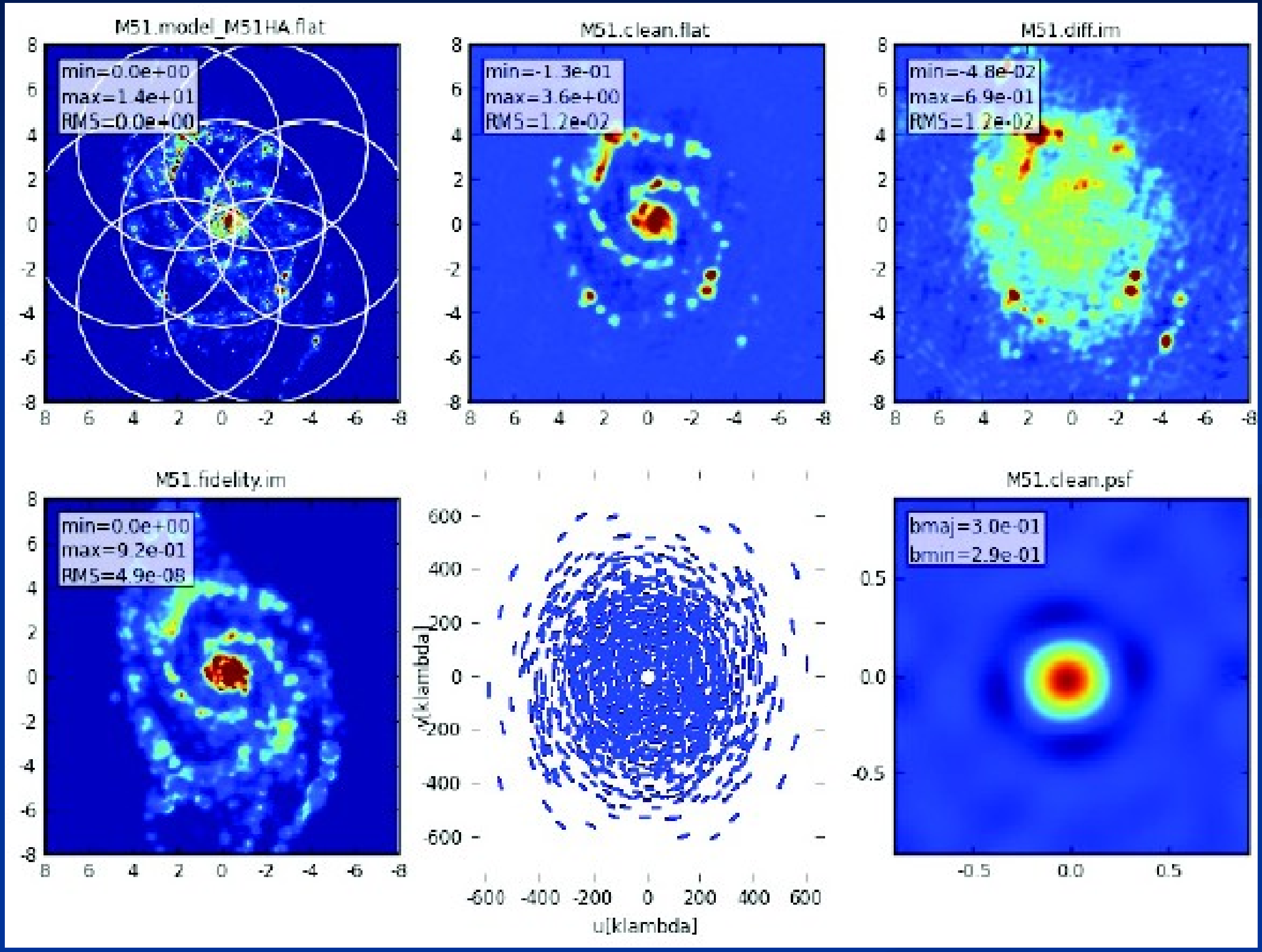
Dataflow

Data-cubes will be primary product

uv data also archived



Simulation and Data Reduction



CASA offline package – go to school

Includes simulation capability

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ALMA Regional Centres

- Three ALMA Regional Centres
  - Europe
  - North America
  - East Asia
- Primary interfaces to their respective user communities
  - Assist users in proposal/programme preparation and data reduction
  - Manage the time allocation process
  - Run archive mirrors and deliver data
  - Provide AOD and commissioning personnel

The European ARC

- Central Node at ESO
  - Archive and data delivery
  - Proposals
  - e-mail helpdesk
  - VLT support model
  - Funded by ESO/ALMA
- Regional nodes
  - Face-to-face user support
  - Regional users
  - Specialised expertise
  - Local/EU funds

IRAM (France, Spain, MPG)
Jodrell Bank (UK)
Leiden (Netherlands)
Bonn/Koeln/Bochum (Germany)
Onsala (Nordic countries)
IRA Bologna (Italy)

What is Early Science?

- Minimum
  - 16 antennas with at least 3 bands out of 3, 6, 7, 9
  - Single-field synthesis imaging
  - Antenna stations to provide good coverage out to 250m
  - Calibration equivalent to current mm arrays (loads + WVR)
  - Software
  - At least 33% of time available (1 year scheduling period)
- Goals
  - Bands 3, 6, 7 and 9 on all antennas; 4 and 8 on some
  - Pointed mosaics
  - Baselines out to at least 1 km
  - Linear and circular polarization
  - Single-dish mapping (including OTF)
  - Calibration better than existing arrays

Priority correlator configurations

Mode	Pol	Sub-Chan	Band-width	Spectral points	Spectral Resolution (kHz)	Corre-lation (bits)	Sample Factor (Nyquist)	Sensitivity
13	Full	1	2GHz	2048	976	2x2	1	0.88
18	Full	1	62.5MHz	2048	30	2x2	1	0.88
36	Full	1	62.5MHz	1024	61	4x4	2	0.94
52	Full	1	62.5MHz	512	122	4x4	1	0.95
66	Full	1	62.5MHz	256	244	4x4	2	0.95
70*	Full		2GHz	64	31.25	2x2	1	0.88
7	Par	32	2GHz	4096	488	2x2	1	0.88
12	Par	1	62.5MHz	4096	15	2x2	1	0.88
30	Par	1	62.5MHz	2048	30	2x2	2	0.94
48	Par	1	62.5MHz	1024	61	4x4	1	0.95
62	Par	1	62.5MHz	512	122	4x4	2	0.95
69*	Par		2GHz	128	15.6	2x2	1	0.88

* Time division mode

Planning an ALMA observation

- Frequency: value(s), bandwidth(s), resolution(s)
- Spatial resolution
- Field(s) of view → mosaic
- Largest scale of structure → need for ACA, single dish
- Total intensity, linear and circular polarization
- Sensitivity (integration time/rms noise)
- Structural complexity and image fidelity
- Effect of atmospheric conditions (absorption, phase errors)
- Astrometry, amplitude calibration, scheduling with other observations, ...

What frequency?

- Continuum: emission mechanism (e.g. synchrotron $\nu^{-\alpha}$, thermal ν^2, dust ν^3, ...), bearing in mind that system noise increases with ν, and phase errors get worse.
- Resolution effects scale with frequency: for detection experiments, you may not want to resolve the target.
- Lines: one or more? Line + continuum? Velocity resolution?

Units and conversions

- Velocity and spectral resolution: $\Delta\nu = (\Delta v/c)\nu$
- Brightness temperature and surface brightness. B_ν is in units of $Wm^{-2}\ s^{-1}\ Hz^{-1}\ sr^{-1}$ (convert to Jy/beam). Remember: resolved source + small beam = low signal. Beware of the difference between Planck and Rayleigh-Jeans brightness temperatures.

$$T_B = \frac{h\nu}{k * \ln(2h\nu^3/c^2 B_\nu + 1)} \quad \text{(Planck formula)}$$

$$T_B = \frac{\lambda^2}{2k} B_\nu \quad \text{(Rayleigh} - \text{Jean approximation)}$$

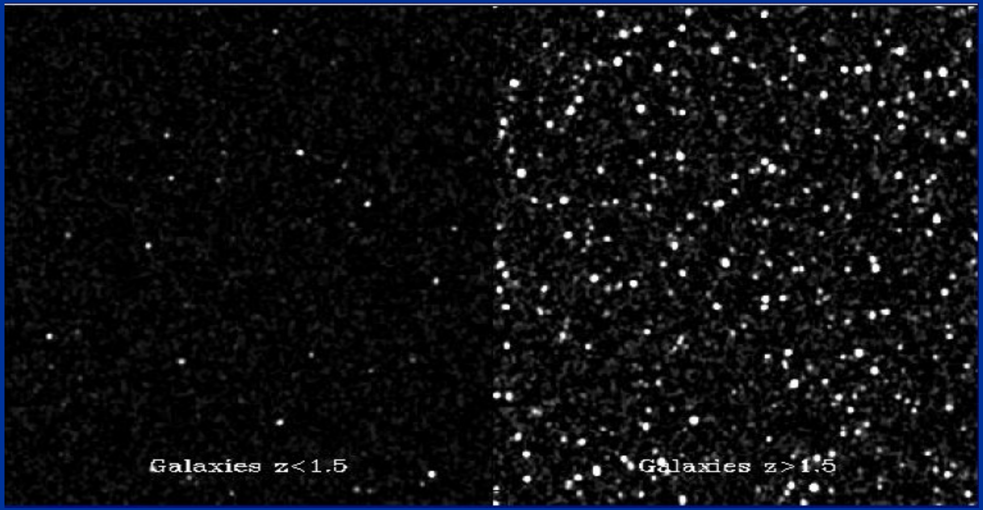
T_B = brightness temperature (K)

$$\Delta S \propto \frac{T_{sys}}{D^2 \left[n_p \, N(N-1) \, \Delta\nu \, \Delta t \right]^{1/2}}$$

ΔS = rms noise
n_p = number of polarizations
$\Delta\nu$ = bandwidth
Δt = integration time
N antennas

Deep Survey

HDF optical



ALMA simulation

$z < 1.5$ $z > 1.5$

Deep redshift survey 1

- Band 3: sensitive continuum + CO lines at all redshifts except z = 0.4 – 1 and 1.7 – 2. Maximises field size for a single pointing.
- Angular resolution: high enough to avoid confusion, but try not to resolve targets → 3 arcsec → compact configuration. No need for ACA or single dish.
- Line widths expected to be ~a few hundred kms^{-1}. Velocity resolution 50 kms^{-1} → 15 MHz channels at 90 GHz → can use full 8 GHz bandwidth, 512 channels, and get maximum continuum sensitivity. 4 tunings will cover 84 – 116 GHz.

Deep survey 2

- Brightest known sub-mm galaxies have ~10 mJy in 50 kms^{-1} channel. Suppose we want a factor of 10 fainter with S/N = 10 → 0.1 mJy rms in 1 channel. We get 0.05 mJy rms in 8 GHz, so integration time ~ 2 hr.
- In that time, the continuum rms is 4 µJy, and we can combine 4 tunings to get a deep image with rms 2 µJy.
- Number counts suggest that there will be ~10 sources/primary beam, so to get a decent sample of 100 galaxies, we need a mosaic of 10 pointings, ~20 hr on-source + overheads.

Magnetic-field geometry in protostellar envelopes 1

- Thermal emission from dust, polarized by scattering from dust grains aligned with the magnetic field. Aim is to test ambipolar diffusion models.
- Band 7 (highest sensitivity to polarized dust emission)
- Resolution 1 arcsec (200 AU at 200 pc compared with total size of 4000 AU)
- Field size 20 arcsec. FWHM of primary beam is 18 arcsec, so need separation ~7.5 arcsec to get uniform sensitivity→ 7-point mosaic.
- ACA to sample scales 10 – 20 arcsec.

Dust polarization 2

- Inner envelope > a few 10's of μK; 3% polarization, 5σ detection → 100 μK rms
- This corresponds to 3.65 x 10^{-21} $Wm^{-2}Hz^{-1}sr^{-1}$
- Beam is (π/4 ln2)(1 arcsec/rad)^2 = 2.7 x 10^{-11} sr
- rms ~10 μJy / beam, cf. 0.2 mJy/beam in 60s
- 7 hr / field x 7 pointings ~ 50 hr + overheads + ACA

Early Science Proposals: what's different?

- Number of antennas
  - Point-source sensitivity is a factor of ~3 lower with 16 compared with 50 antennas
  - Image fidelity is worse (simulate)
- Baselines up to 1km → resolution limited (factor of 14.5)
- Receiver bands
  - Bands 3, 6, 7, 9 (mostly)
- Restricted range of correlator configurations
- Mosaic/single-dish combination limited; no ACA
- Calibration accuracy

What's best for Early Science?

- Keep it simple: single fields, sources well within the primary beam
- Limited resolution
- Sensitivity will already be good

Current Status
Antennas and Transporter

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First European Antenna assembled

Foundations

Central cluster ↑

← West 207

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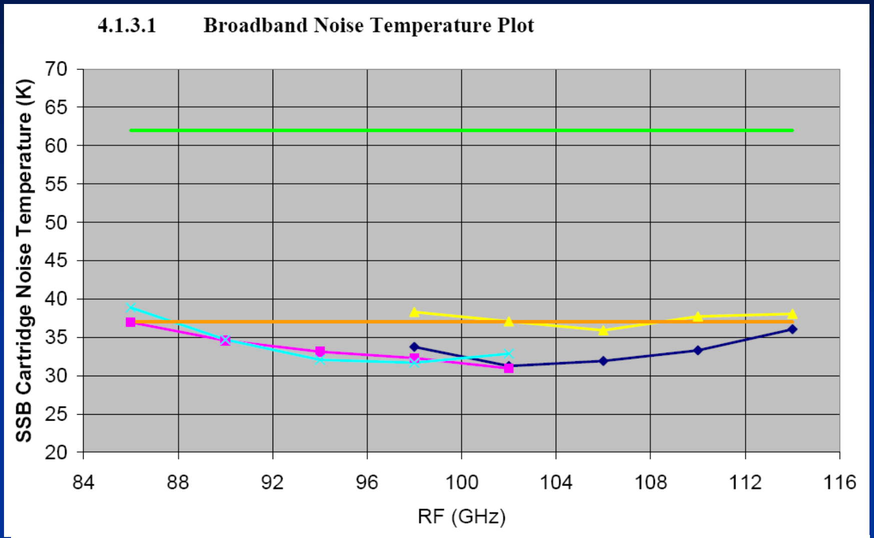
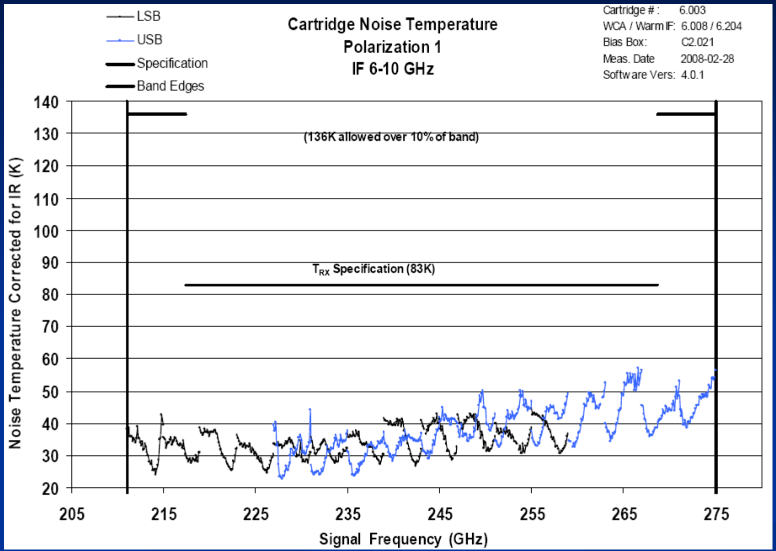
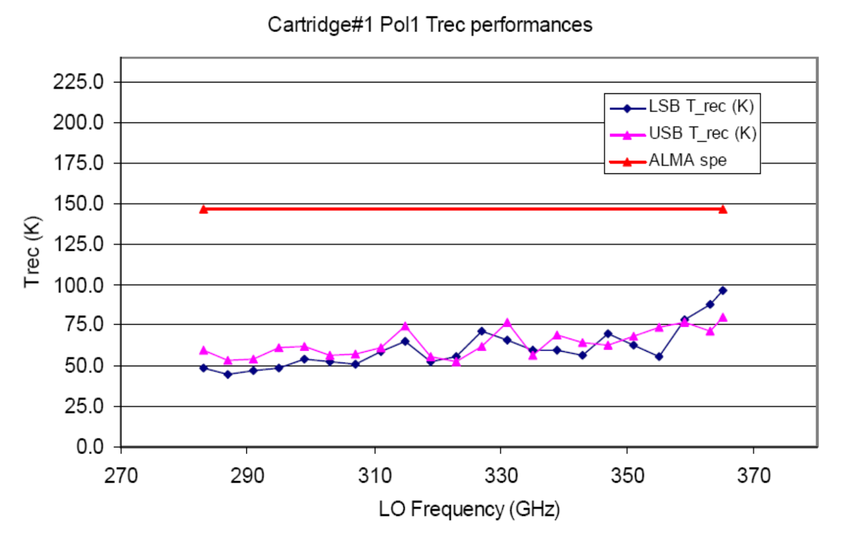
Buildings and Correlator

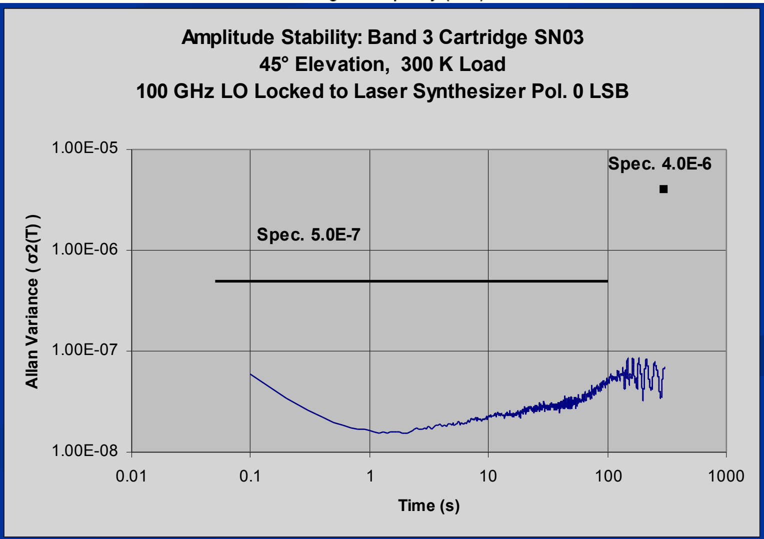
5 receivers, each with 4 bands

Excellent receiver performance

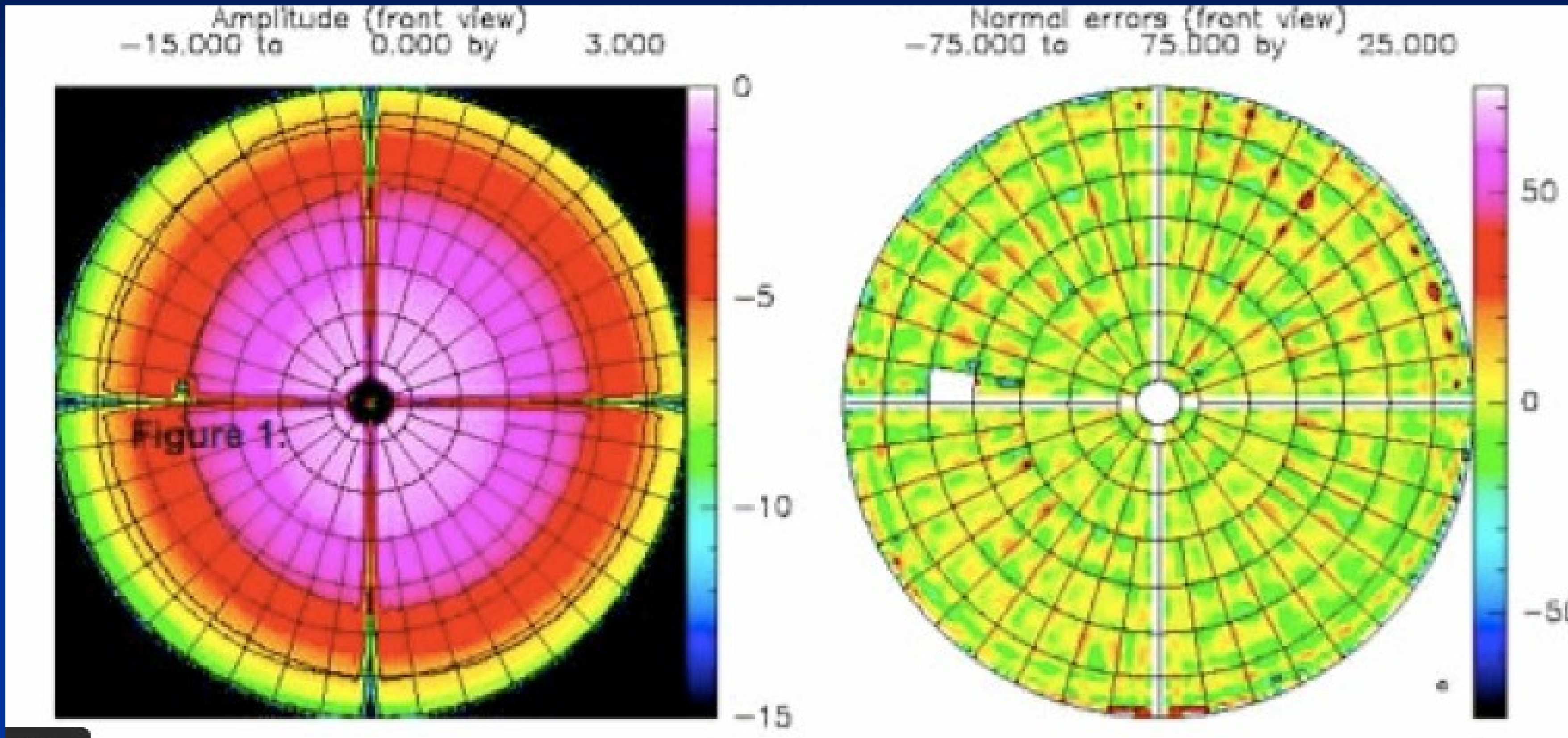






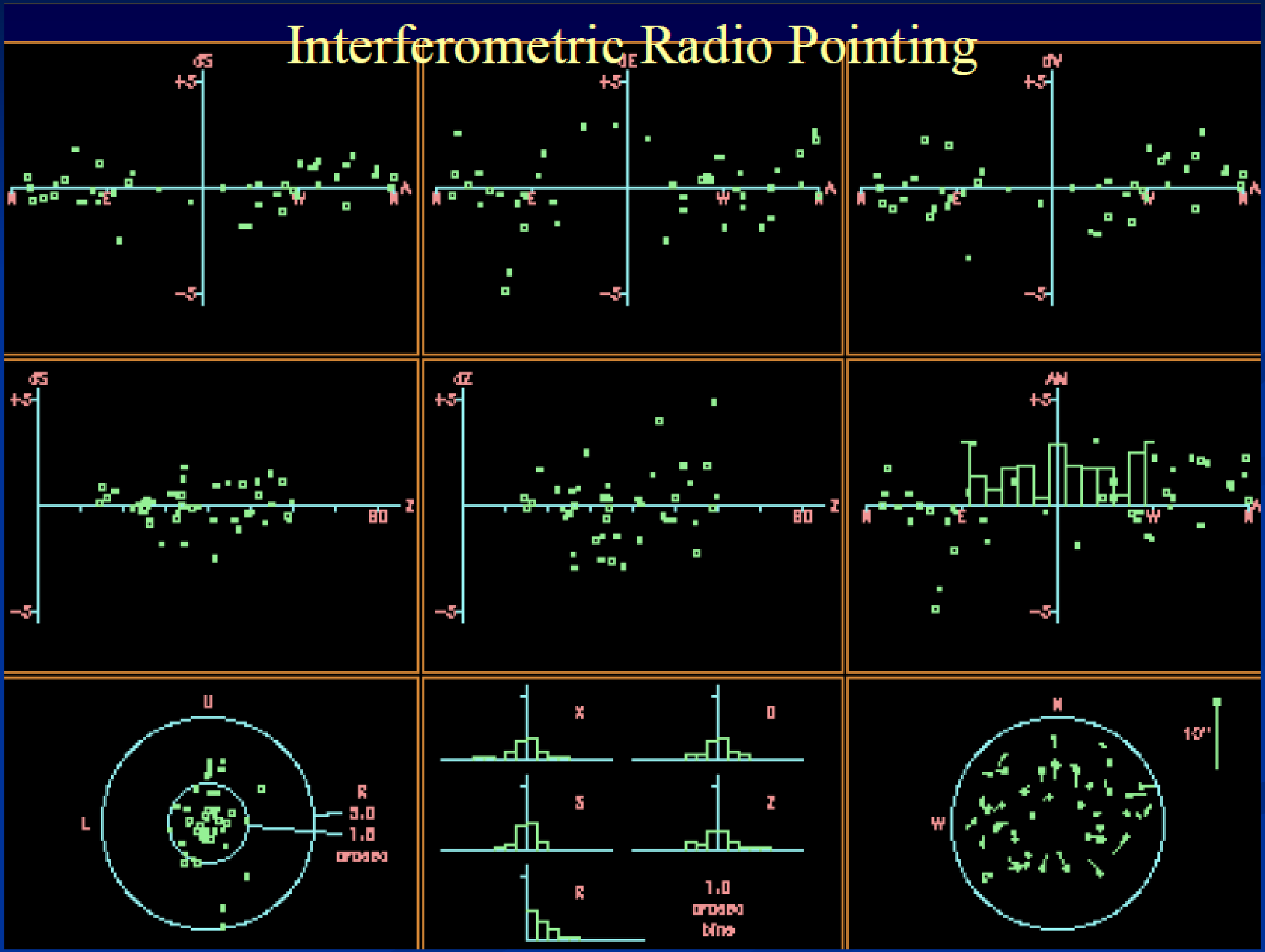


Antenna surface



Primary reflector best yet: rms 7.7μm

Pointing



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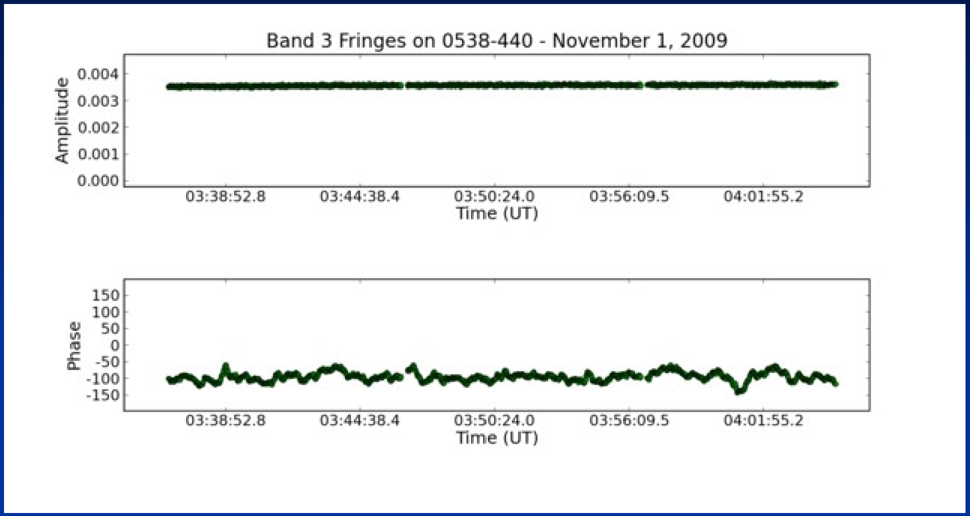
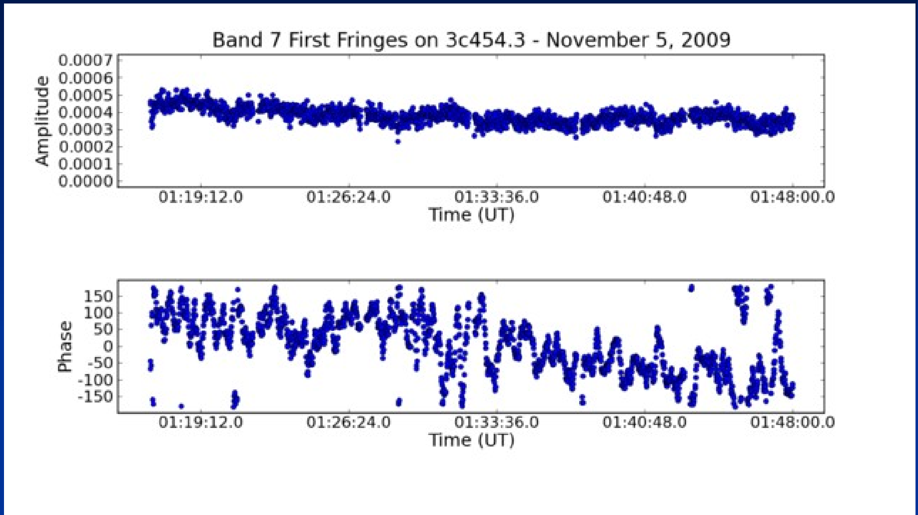
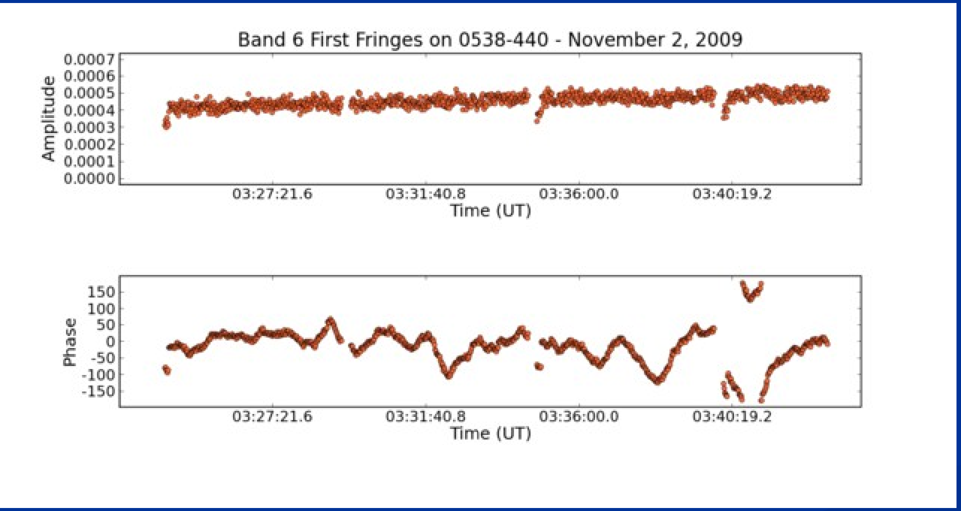
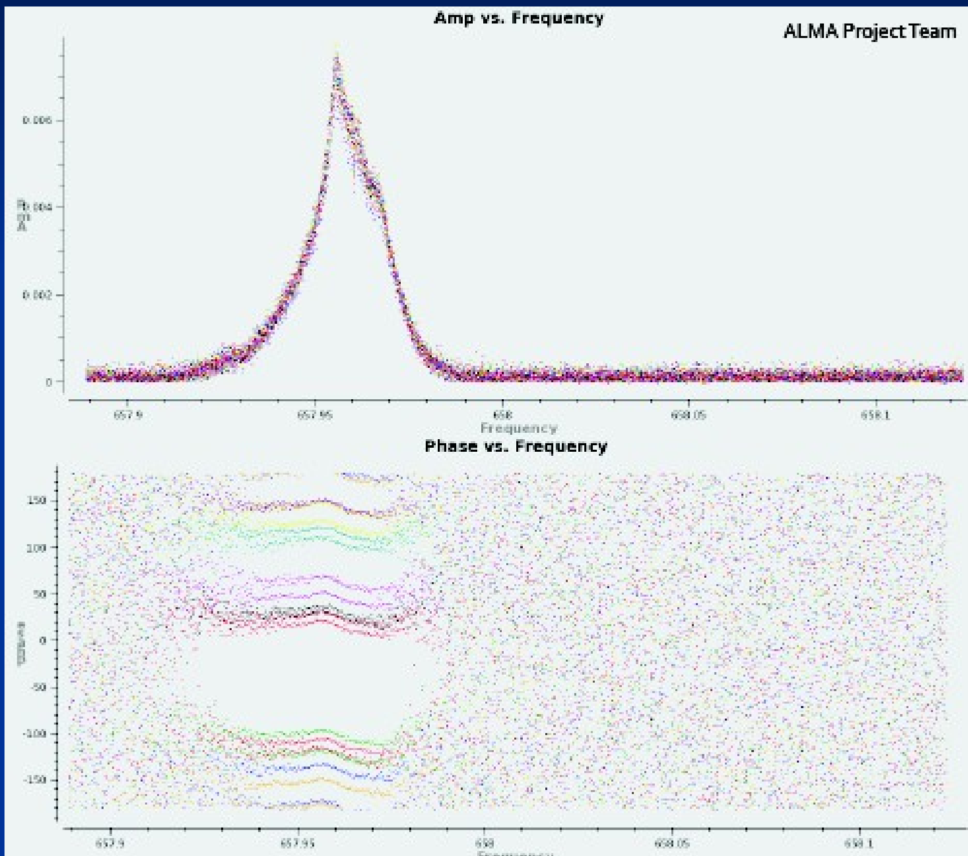
First fringes at AOS - broad-band

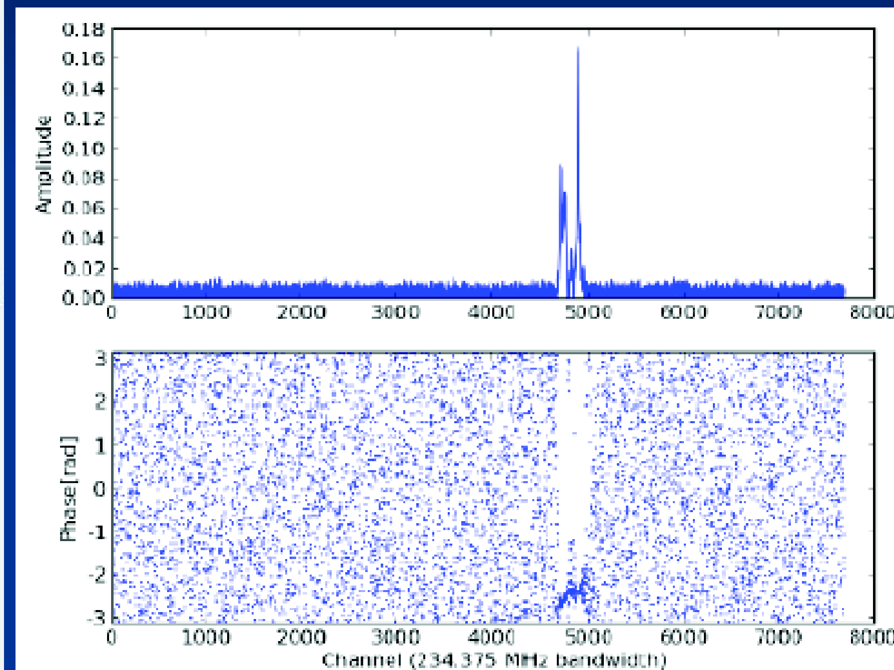






Sub-mm fringes and higher spectral resolution





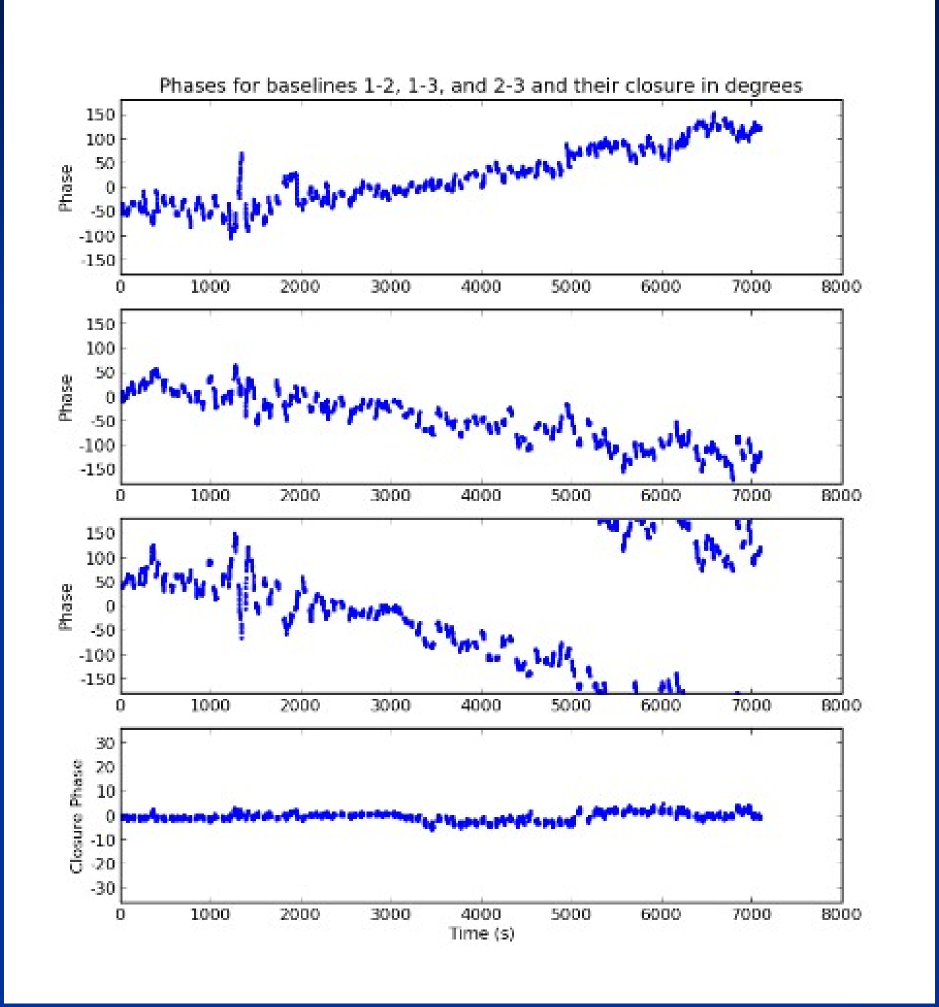
658 GHx VY CMa water maser spectrum

86GHz SiO maser in Orion

3-antenna interferometry at AOS

Current configuration (close-packed)

Closure phase



Closure phase for antennas 1, 2, 3

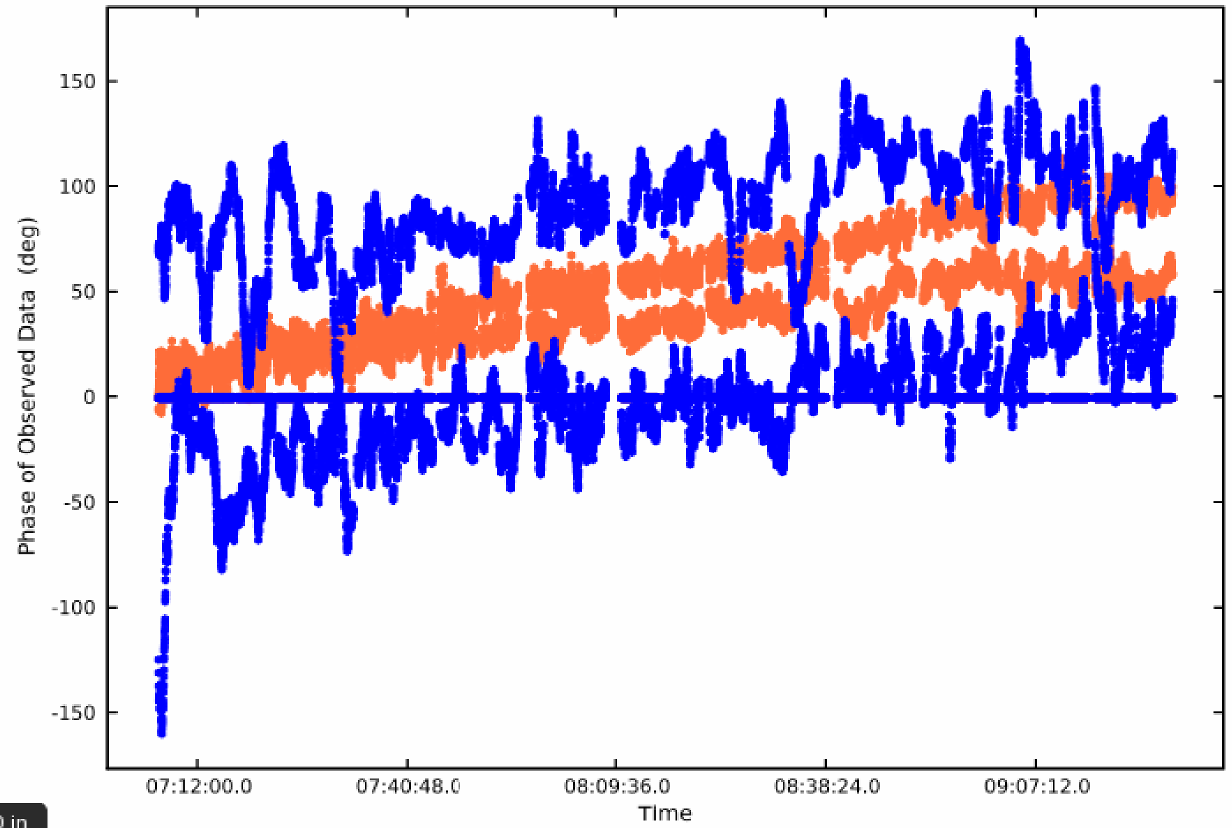
$= \varphi_{12} + \varphi_{23} + \varphi_{31}$

Why is it important?

Provided that the phase closes, the number of unknown phases to be calibrated for N antennas is N – 1. If not, then each baseline needs separate calibration, so there are N(N-1)/2 – 1 unknowns.

WVR correction in action

WVR phase correction in CASA– Blue raw (2 baselines) Orange Corrected



Current Schedule

- First fringes at AOS June – July 2009

Achieved 2009 April 30

- Three antennas at high site, closure phase, end 2009

Achieved 2009 November 26

- Start of Commissioning and Science Verification Jan 2010

Achieved 2010 January 22

- Early Science Decision Point and First call for proposals late 2010
- Proposal deadline early 2011
- Start of Early Science with 16+ antennas Autumn 2011
- Full operation early 2013

Outlook

- No show-stoppers
  - All main subsystems basically work
  - Key technical risks (phase correction, local oscillator distribution) addressed
  - Construction budget adequate for completion
- Schedule
  - Still very tight (especially front ends)
  - EU antennas
- Reliability and efficiency
  - Much work needed to make system fully reliable (e.g. receiver tuning)
  - Sofware test and optimization

Not without problems

... but ALMA is coming soon