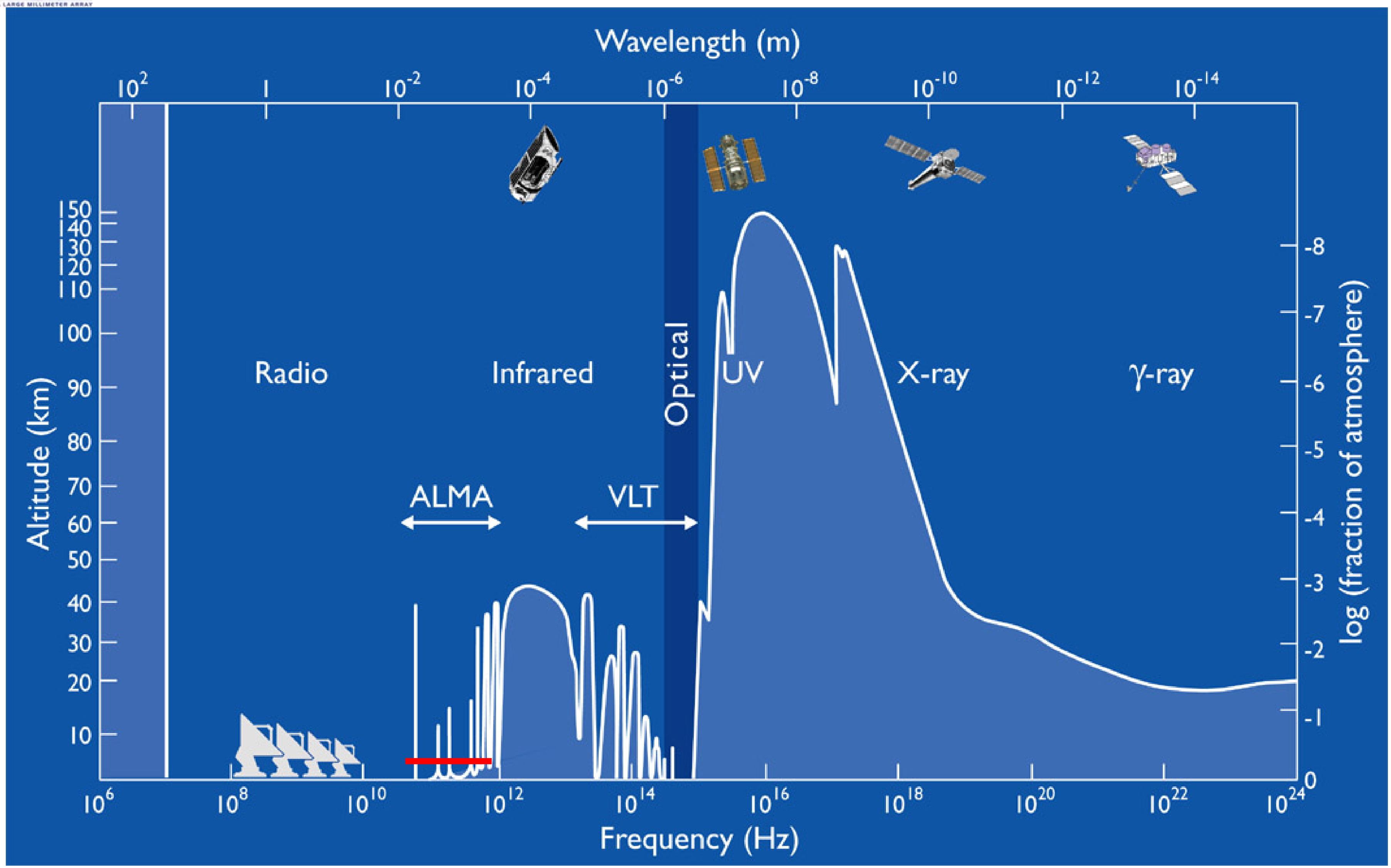
Global International Project:
The Atacama Large Millimiter/submillimiter Array

Massimo Tarenghi
ALMA Director

Opacity of the Atmosphere



Brief History of ALMA

ALMA is the merger of three projects conceived in the 1980’s and 90’s

- MMA (US; 1982)
- LMSA (Japan; 1983)
- LSA (Europe; 1995)

Discussions of collaboration since mid-1990’s

Represents 1.3B$ investment (construction) by ALMA partners,

Plus 70 M$x30 years=2.1B$ in operations

The 1980s Roots of ALMA

LSA

(1988)

MMA

(1982)

LMA

(1983)

ALMA

ATACAMA LARGE MILLIMETER ARRAY

A Next Generation Millimeter Telescope

A major step in astronomy → a mm/submm equivalent of VLT, HST, JWST, EVLA

- Capable of seeing star-forming galaxies across the Universe
- Capable of seeing star-forming regions across the Galaxy

These Objectives Require:

- An angular resolution of 0.1” at 3 mm
- A collecting area of >5,600 sq m
- An array of antennas
- A site which is high, dry, large, flat - a high Andean plateau is ideal

1997 June: Meeting with NRAO in Charlottesville, and signing of an ESO-NRAO Resolution to work towards a common project.

Convergence of objectives:

Europe: interest also in submm → high-altitude site, compromise on smaller antenna size and total area

U.S.: interest also in large collecting area → compromise on larger antenna size

Issues:

Feasibility of large submm-quality antennas, homogeneous vs. heterogeneous array, Organizational structure, Europe-US and Chile

RESOLUTION

Whereas the development of millimeter-wavelength astronomy has shown the potential of large millimeter interferometric arrays for revealing the origin and evolution of stars and planetary systems, of galaxies, and of the Universe itself; the communities in the United States and Europe have proposed the construction of the Millimeter Array (MMA) and the Large Southern Array (LSA), respectively; and there is an opportunity through cooperation to achieve more than either community planned; we, as the observatories responsible for these projects and with the support of our communities, resolve to organize a partnership that will explore the union of the LSA and MMA into a single, common project to be located in Chile. Specifically, this partnership will study the technical, logistical, and operational aspects of a joint project. Of particular importance, the two antenna concepts currently under consideration will be studied to identify the best antenna size and design or combination of sizes to address the scientific goals of the two research communities. In doing so we will work through our observatories, utilizing the expertise in millimeter astronomy resident in research groups and institutions in our communities. Finally, we recognize that there are similar goals for millimeter astronomy in Japan, and cooperative activities with that project will continue.

R. Giacconi — P. Vanden Bout

European Southern Observatory — National Radio Astronomy Observatory

26 June 1997

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, Japan and North America in cooperation with the Republic of Chile.

ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere , in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC).

ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

ALMA project

- ALMA project
  - Europe (ESO) + North America (NRAO+Canada) + Chile
  - Up to 64 12-m antennas at 5000-m in the Atacama desert in Chile
  - antenna baselines = 150 m to 10 km (reconfigurable)
  - 4 receiver bands around 100, 250, 325, and 650 GHz (first light)
    - DSB/2SB receivers
    - Dual polarization
    - Wide band IF (4-12 GHz)
    - Cryogenic temperatures
  - possibility to expand to 10 bands over 30 GHz to 1 THz
  - Wide band IF (4-12 GHz) 6 Mb/s average data rates (60 Mb/s peak)
- After Japan has joined in 2004
  - additional 4 12-m + 12 7-m antennas (compact array)
  - additional correlator
  - receiver bands around 150 and 450 GHz (+ possibly 850 GHz)

1300 M$ (2006)

ALMA Science Requirements

High Fidelity Imaging.

Precise Imaging at 0.1” Resolution.

Routine Sub-mJy Continuum Sensitivity.

Routine mK Spectral Sensitivity.

Wideband Frequency Coverage.

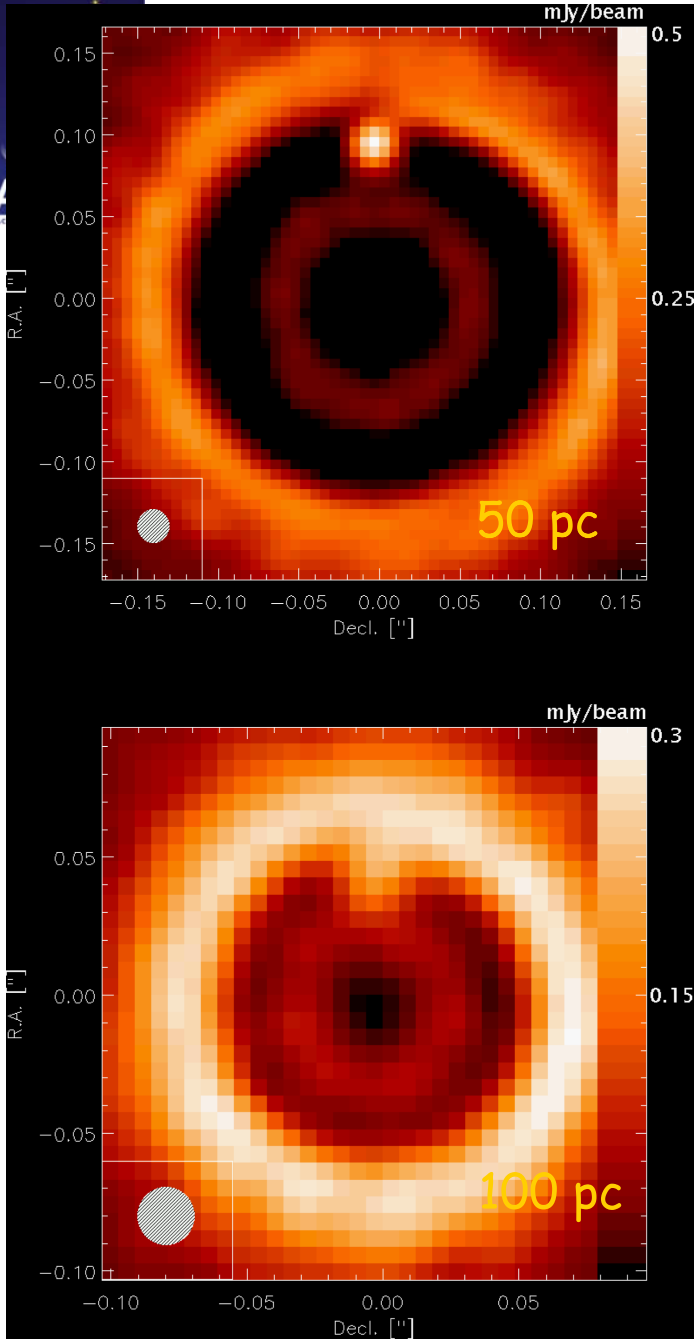
Wide Field Imaging Mosaicking.

Submillimeter Receiver System.

Full Polarization Capability.

System Flexibility.

ALMA Key science 1: Planetary regions, nearby disks



$M_{planet} / M_{star} = 0.5\ M_{Jup} / 1\ M_{sun}$

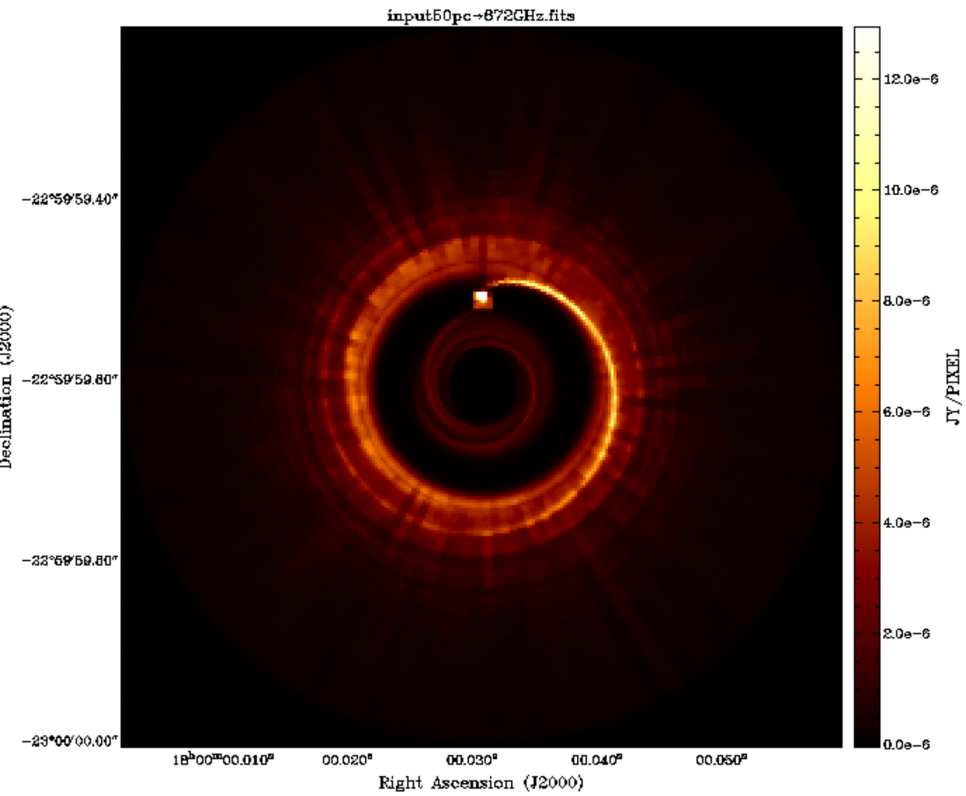
Orbital radius: 5 AU

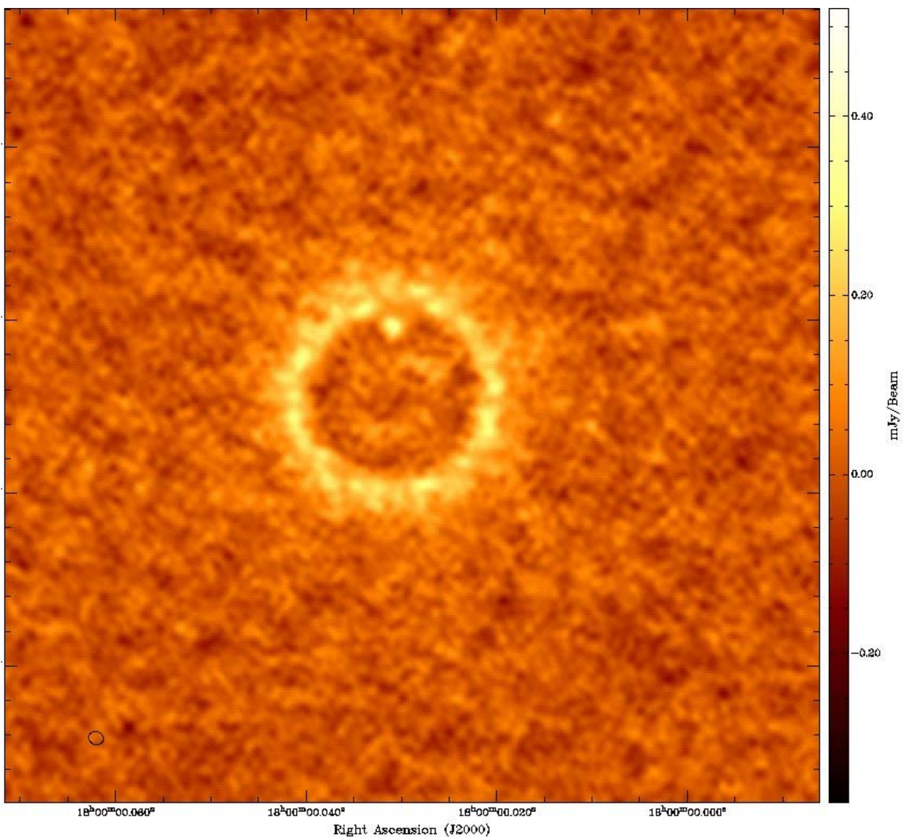
Disk mass as in the circumstellar disk around the Butterfly Star in Taurus

ALMA: 10km, t_{int}=8h, 30º phase noise)
Wolf & D'Angelo (2005)
astro-ph / 0410064

Wolf Disk Simulation, (preliminary CASA)

R. Reid





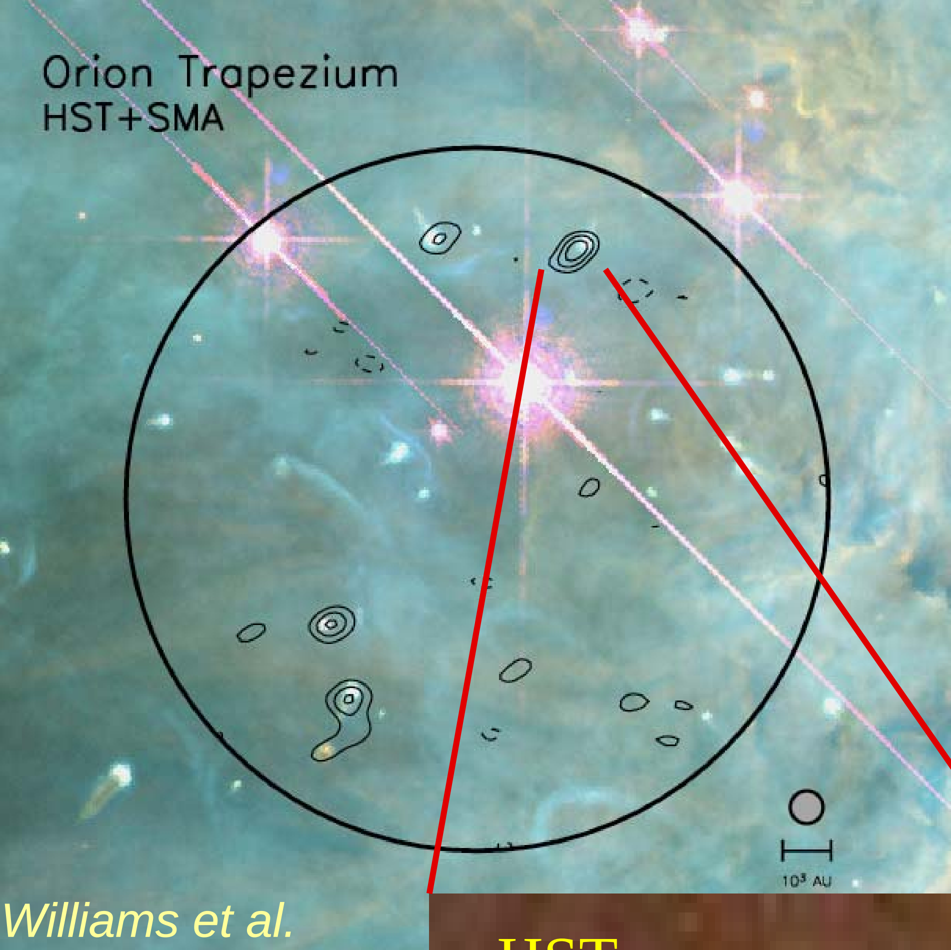
Left-Original model

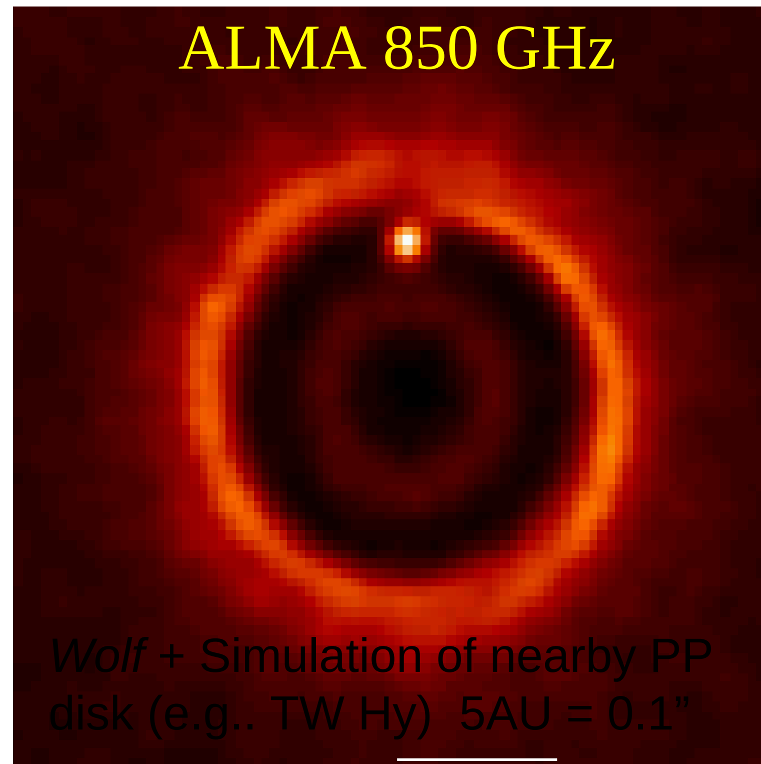
Right-simulated phase correction (Memo 521).

Birth of planets

$M_{planet} / M_{star} \;=\; 1.0\, M_{Jup} / .5\, M_{sun}$

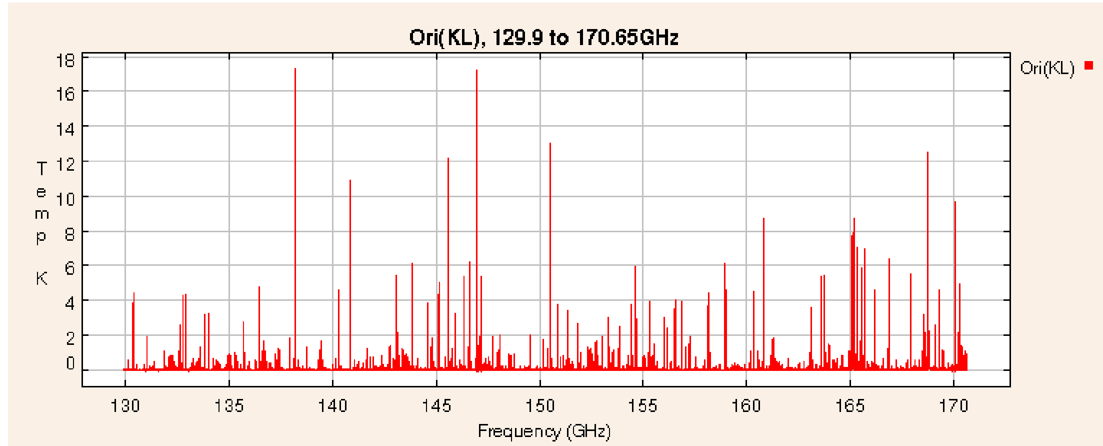
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus





ALMA Key Science 2: Astrochemistry

Spectrum courtesy B. Turner (NRAO



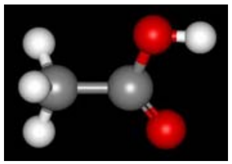
Millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.

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.

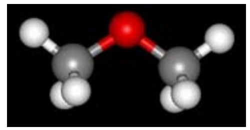
Detected interstellar molecules

H_2	HD	H_3+	H_2D+				
CH	CH^+	C_2	CH_2	C_2H	*C_3		
CH_3	C_2H_2	C_3H(lin)	c-C_3H	*CH_4	C_4		
c-C_3H_2	H_2CCC(lin)		C_4H	*C_5	*C_2H_4	C_5H	
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	H_2C_6		
*C_7H	CH_3C_4H	C_8H	*C_6H_6				
OH	CO	CO+	H_2O	HCO	HCO+		
HOC+	C_2O	CO_2	H_3O+	HOCO+	H_2CO		
C_3O	CH_2CO	HCOOH	H_2COH+	CH_3OH	CH_2CHO		
CH_2CHOH	CH_2CHCHO		HC_2CHO	C_5O	CH_3CHO	c-C_2H_4O	
CH_3OCHO	CH_2OHCHO		CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO	
$(CH_3)_2CO$	$HOCH_2CH_2OH$		$C_2H_5OCH_3$	$(CH_2OH)_2CO$			
NH	CN	N_2	NH_2	HCN	HNC		
N_2H^+	NH_3	$HCNH^+$	H_2CN	HCCN	C_3N		
CH_2CN	CH_2NH	HC_2CN	HC_2NC	NH_2CN	C_3NH		
CH_3CN	CH_3NC	HC_3NH^+	*HC_4N	C_5N	CH_3NH_2		
CH_2CHCN	HC_5N	CH_3C_3N	CH_3CH_2CN	HC_7N	CH_3C_5N?	HC_9N	$HC_{11}N$
NO	HNO	N2O	HNCO	NH2CHO			
SH	CS	SO	SO+	NS	SiH		
*SiC	SiN	SiO	SiS	HCl	*NaCl		
*AlCl	*KCl	HF	*AlF	*CP	PN		
H_2S	C_2S	SO_2	OCS	HCS+	c-SiC_2		
*SiCN	*SiNC	*NaCN	*MgCN	*MgNC	*AlNC		
H_2CS	HNCS	C_3S	c-SiC_3	*SiH_4	*SiC_4		
CH_3SH	C_5S	FeO					

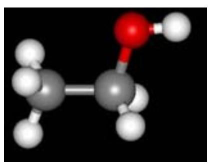
Detected



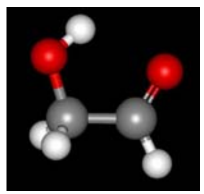
Acetic acid



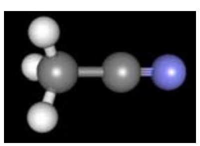
Di-methyl ether



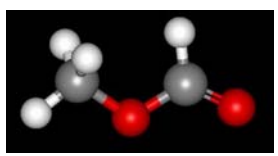
Ethanol



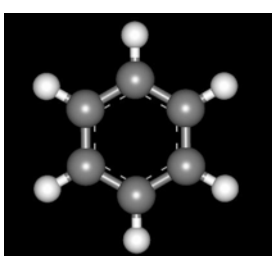
Sugar



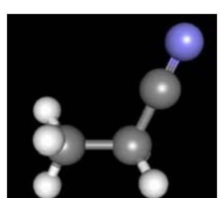
Methyl cyanide



Methyl formate

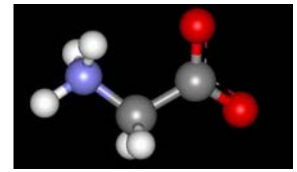


Benzene

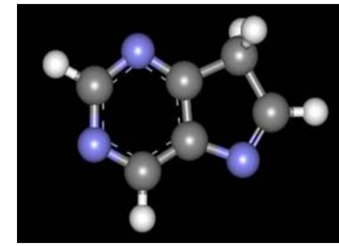


Ethyl cyanide

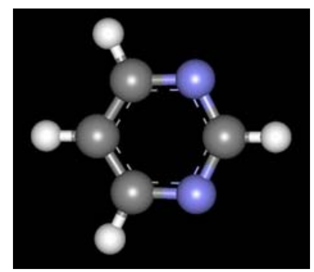
Not (yet) detected



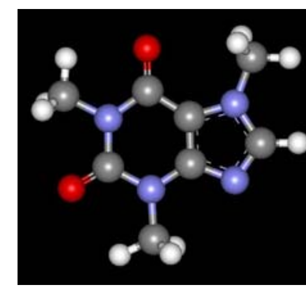
Glycine



Purine



Pyrimidine

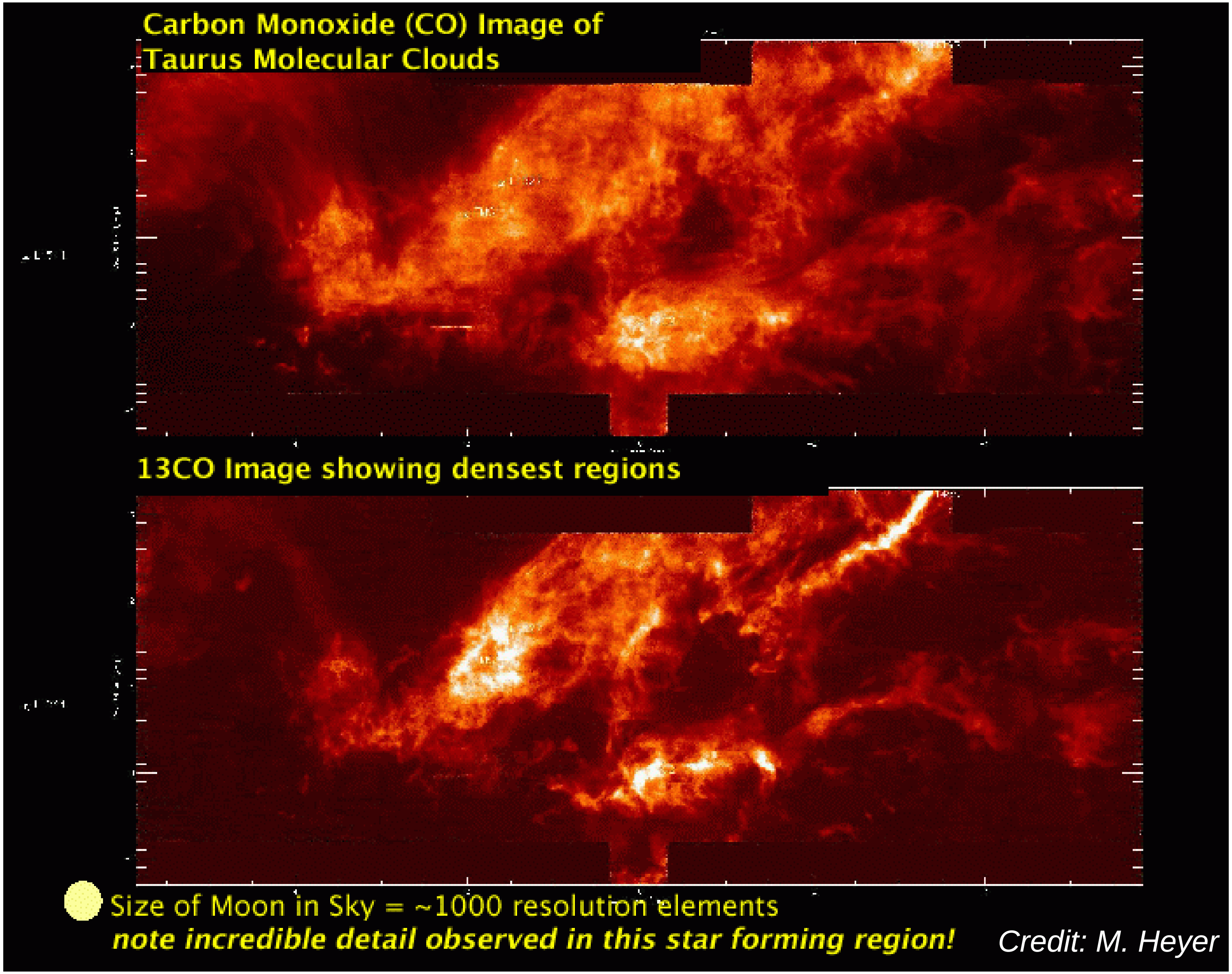


Caffeine

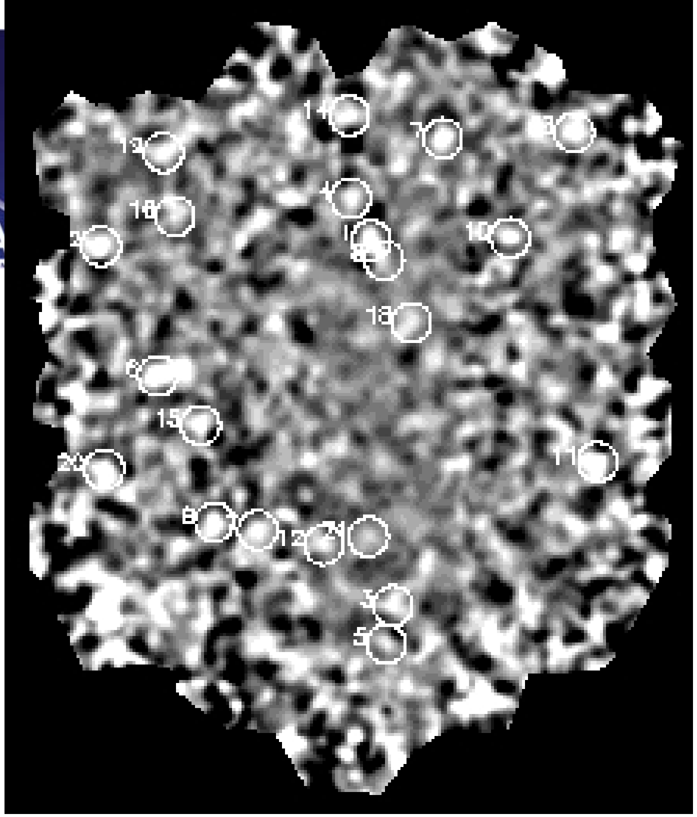
Q13: how far does chemical complexity go? Can we find pre-biotic molecules?

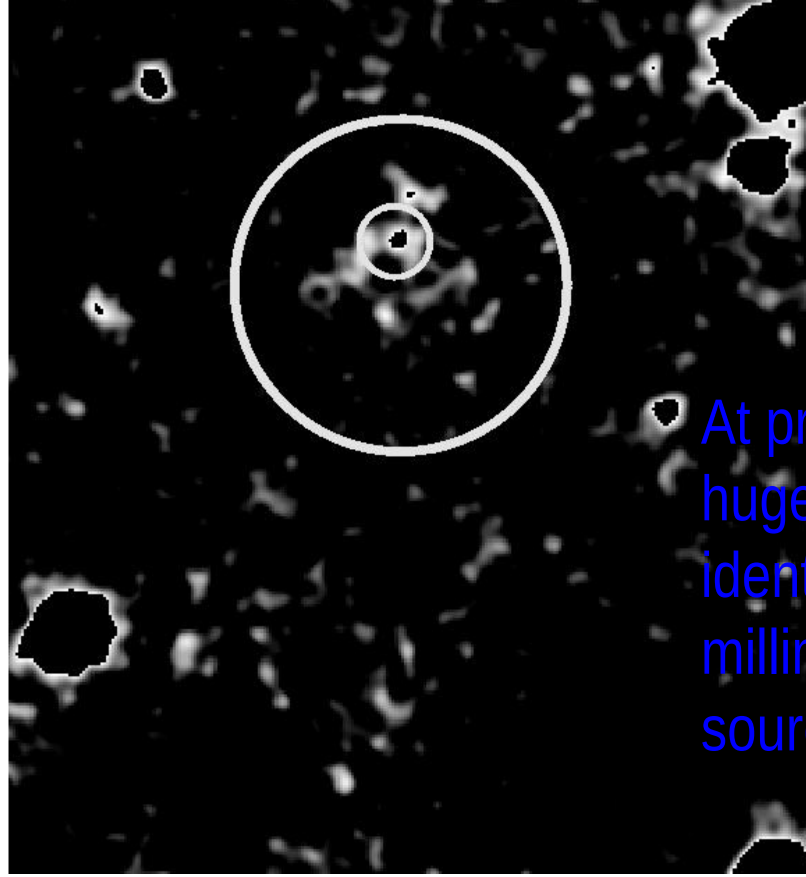
Based on Ehrenfreund 2003

ALMA Key science 3: Interstellar Medium

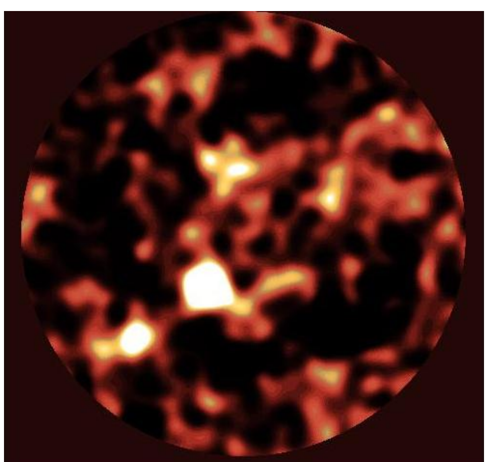


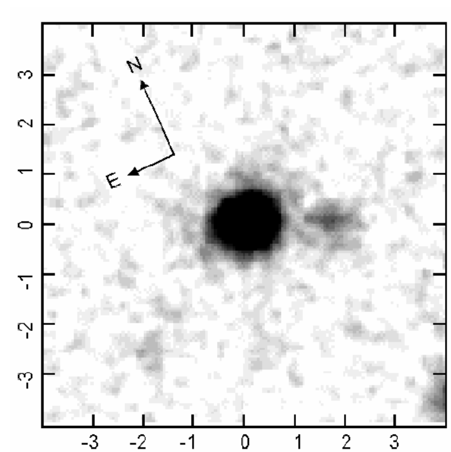
Credit: M. Heyer

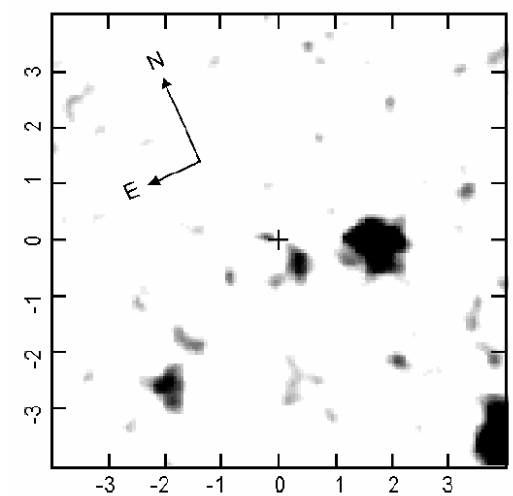


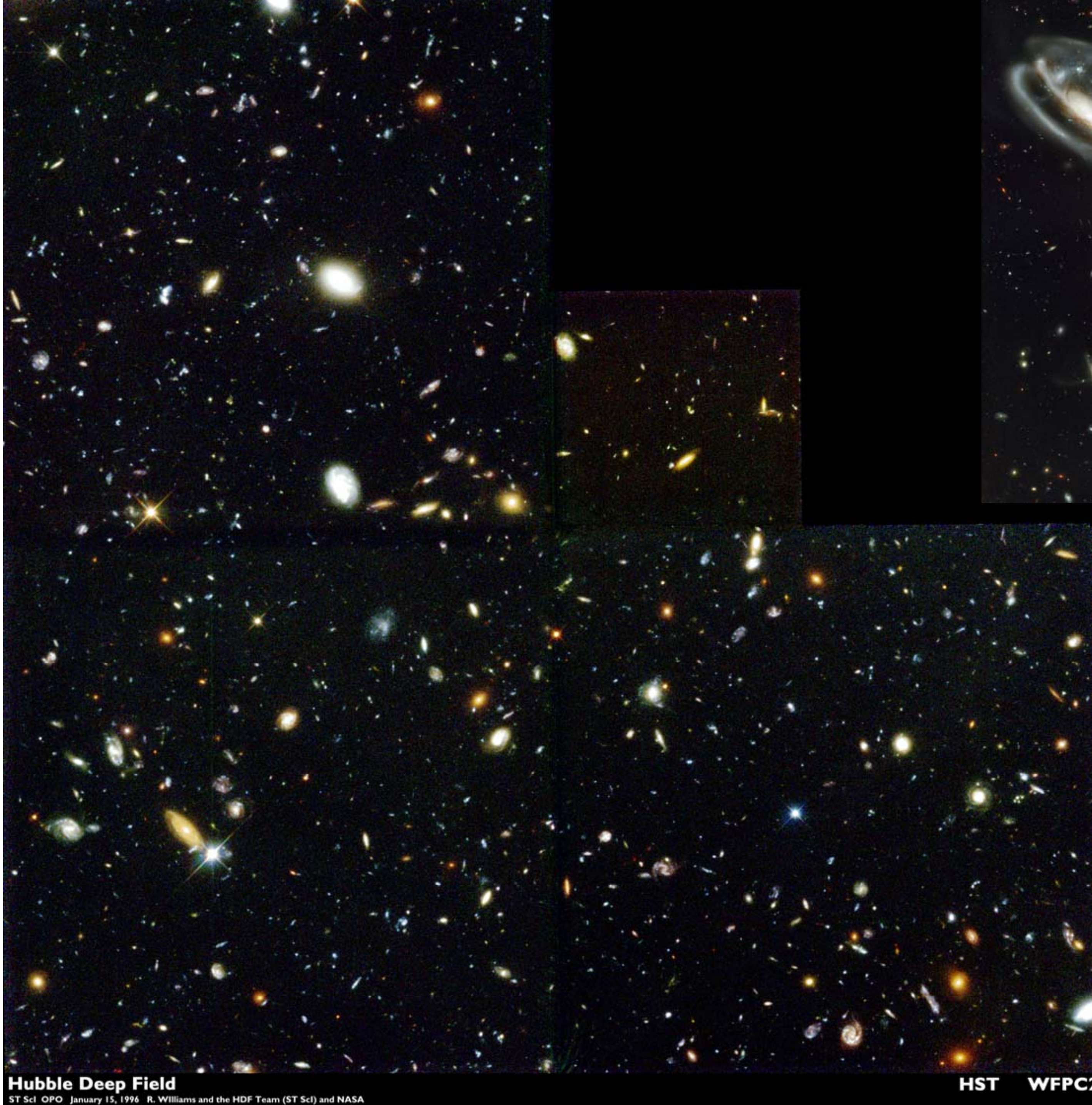


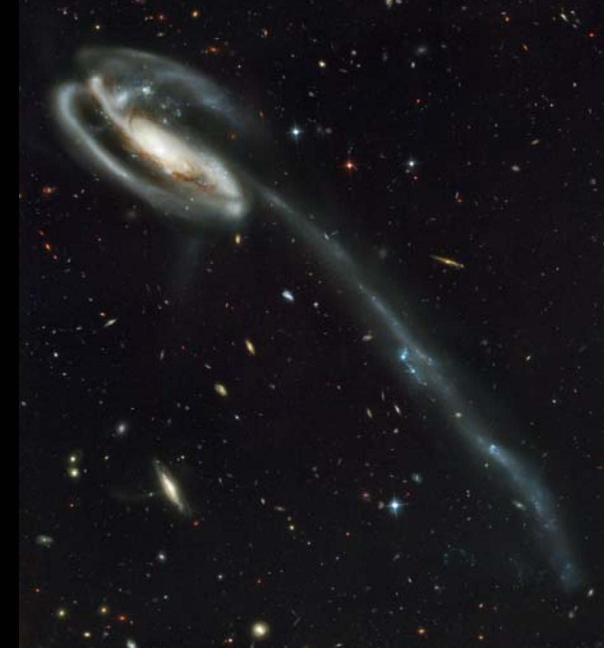
At present it's a huge struggle to identify millimetre-wave sources





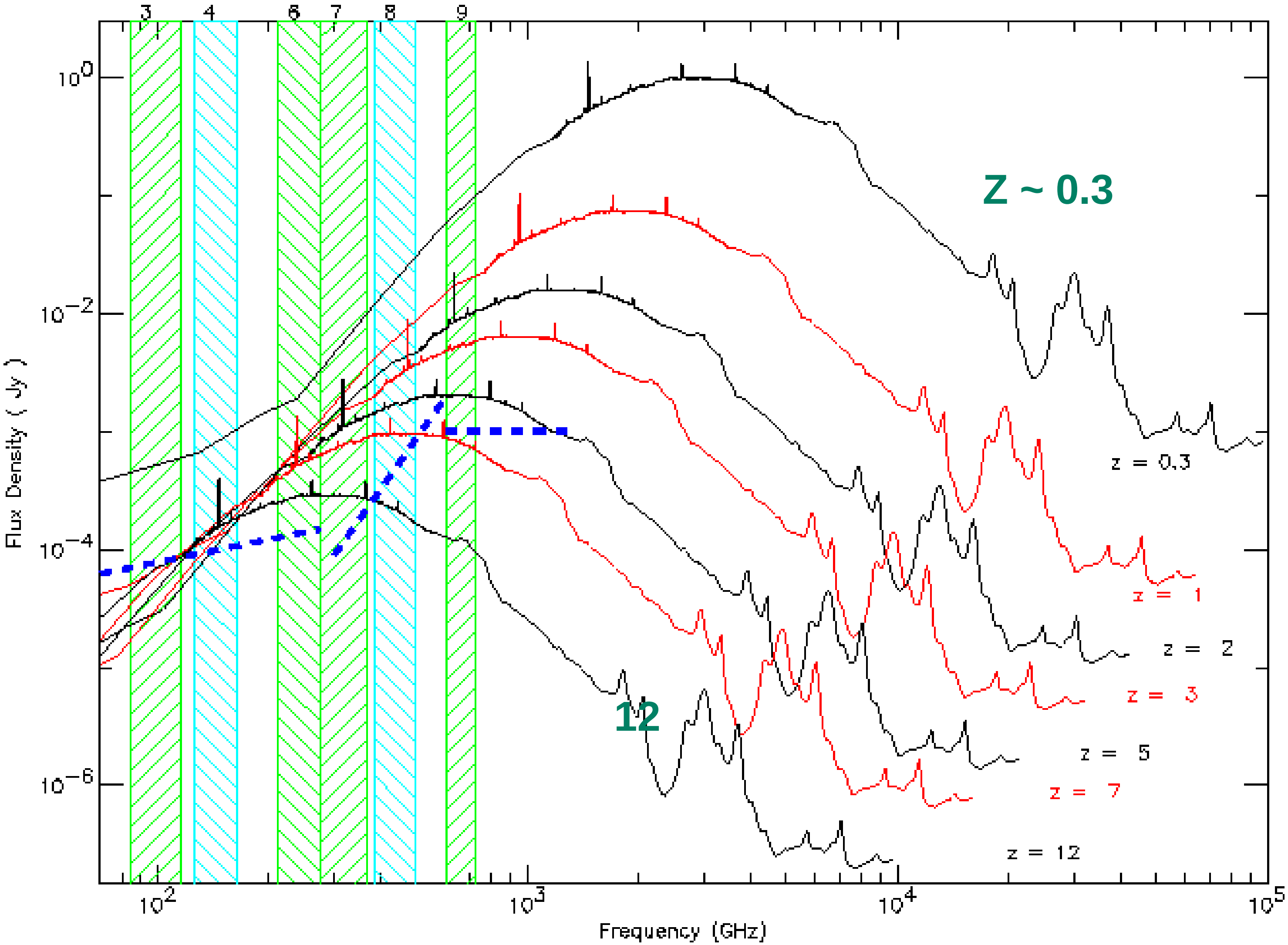




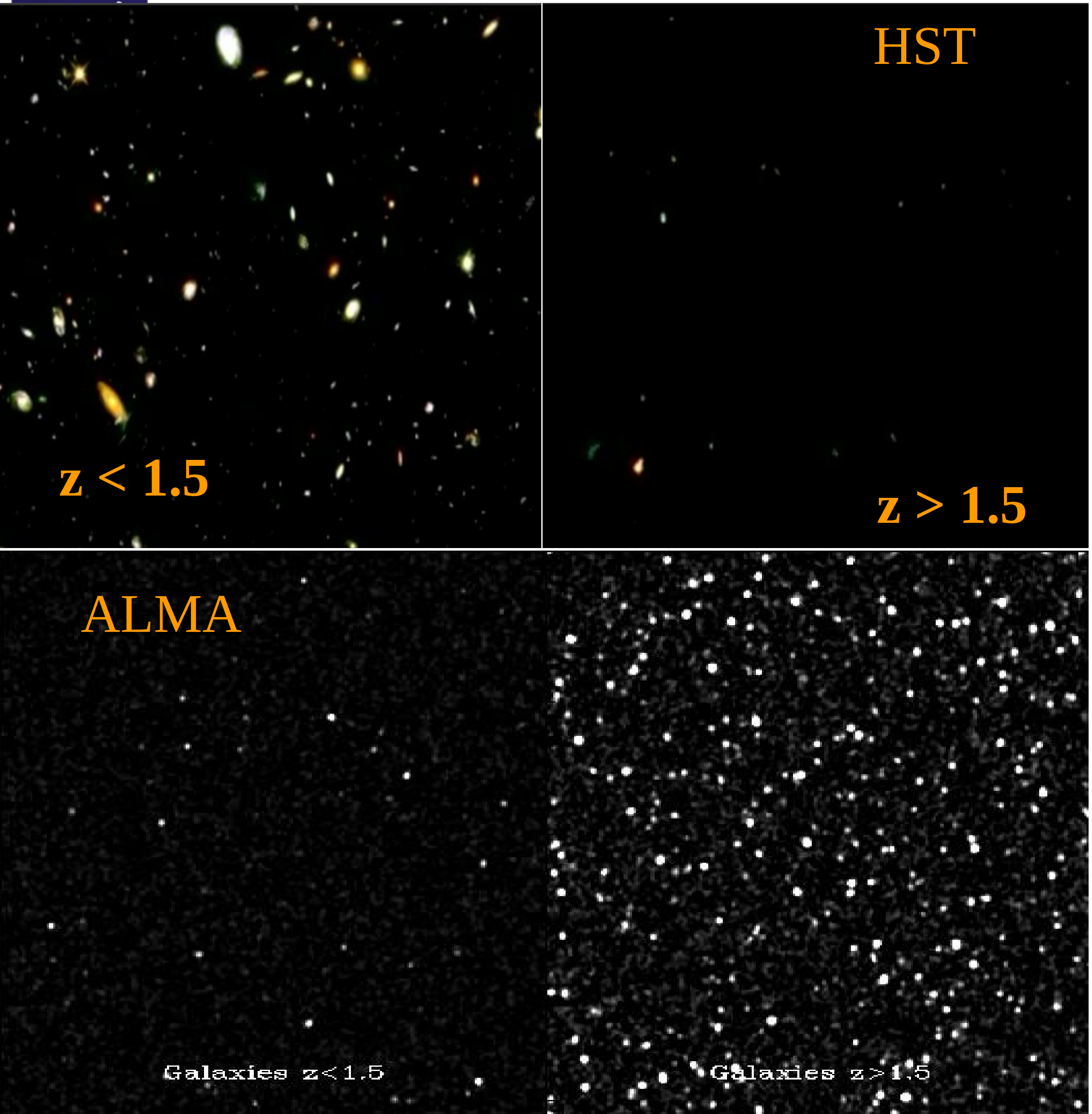


Remember:
this is what
~0.1 arcsec
resolution
looks like!

ALMA Key science 4: High redshift deep fields



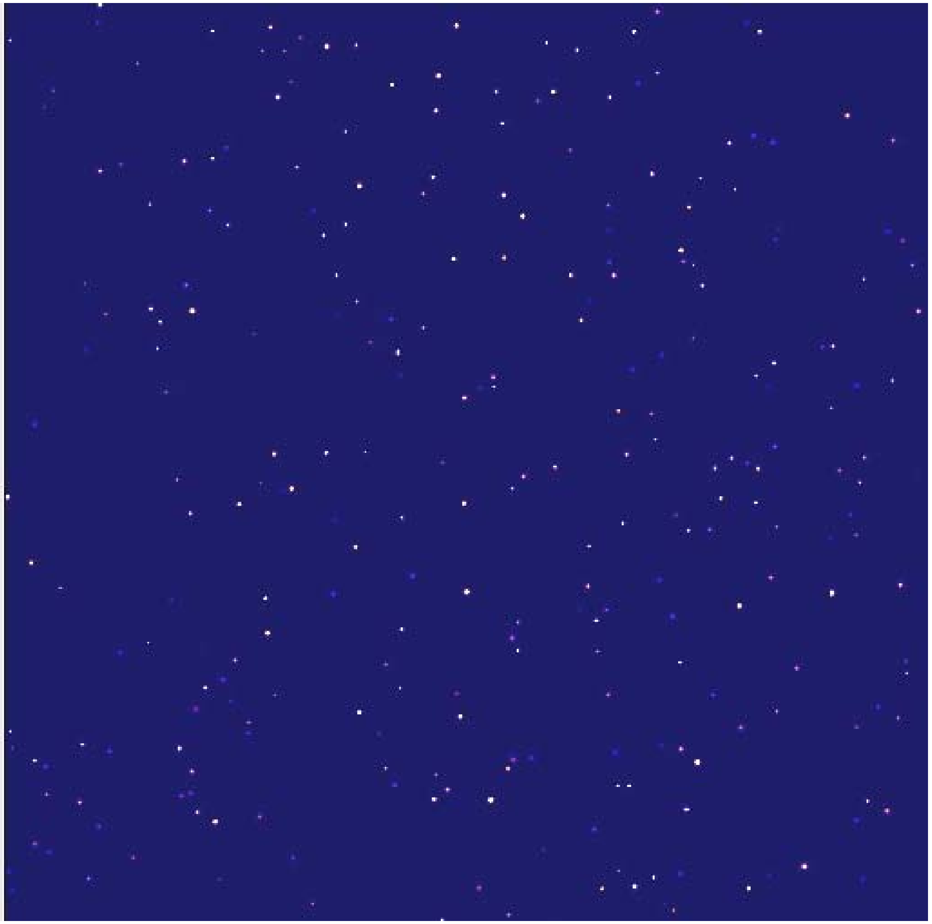
ALMA Deep field: ‘normal’ galaxies at high z



- Detect current submm gal in seconds!
- ALMA deep survey: 3days, **0.1 mJy (5s),** 4’
- HST: a few thousand Gals, most at z<1.5
- ALMA: a few hundred Gals, most at z>1.5
- Parallel spectroscopic surveys, 100 and 200 GHz: CO/other lines in majority of sources
- Redshifts, dust, gas masses, plus high res. images of gas dynamics, star formation

Cosmological Source Surveys

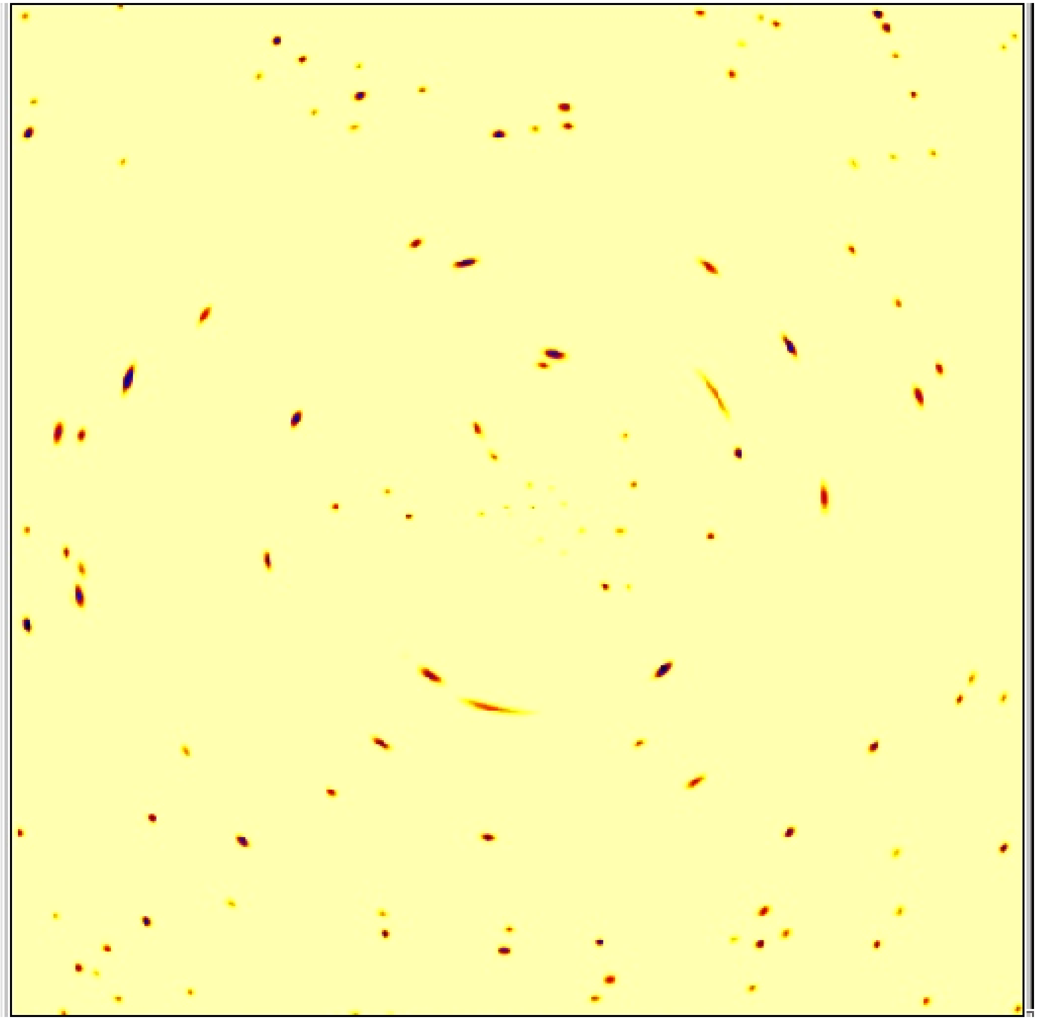
- Simulation of 100 hr survey. 9 arc minute field of view.
- High angular resolution means that confusion is not a problem.
- Redshift distribution is almost flat from z = 1 to 6 !



Clusters

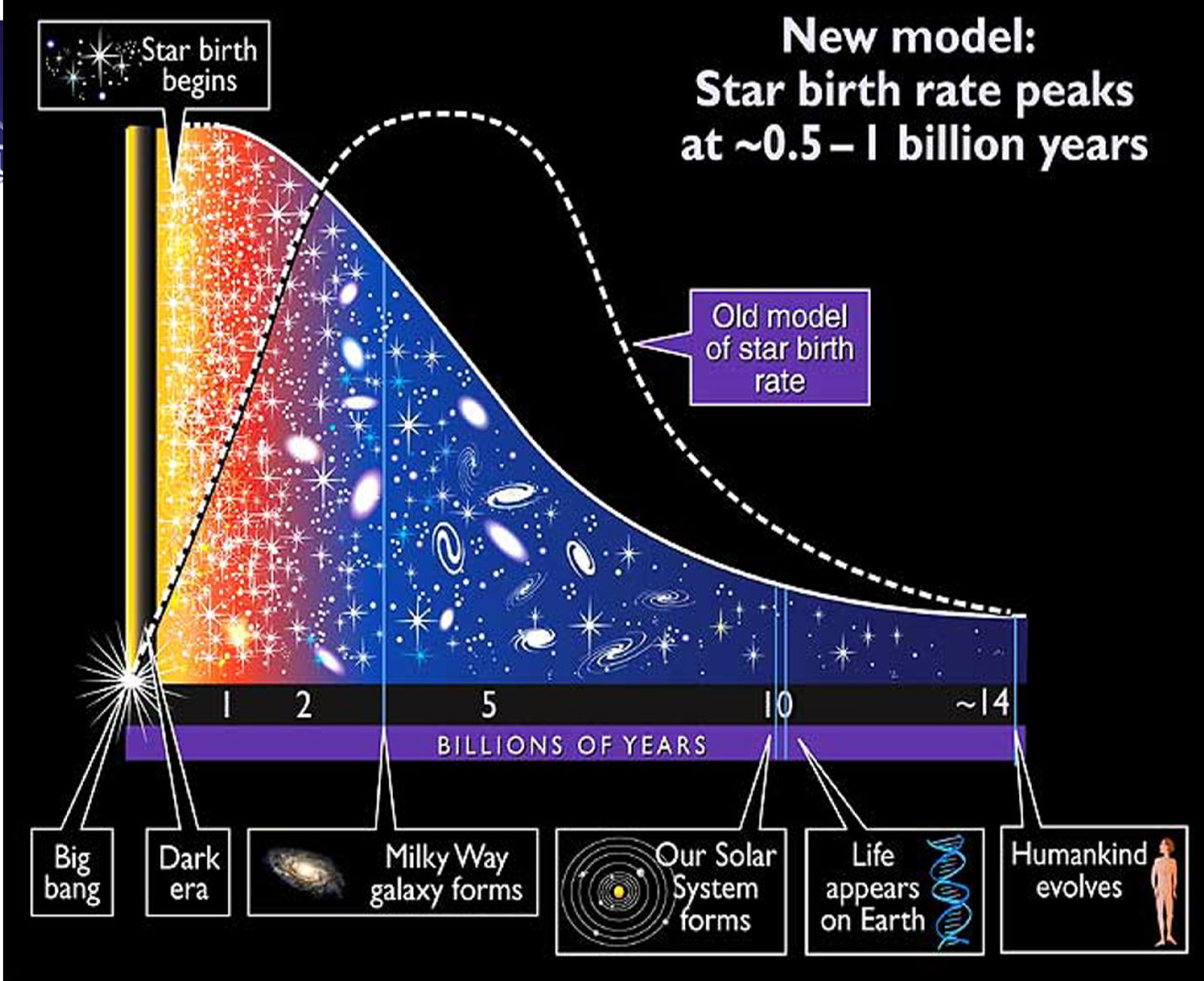
Lensing – on right is same survey as previous but with a z=0.3 cluster in foreground.

Plus SZ effect in both emission and absorption – fine structure in intergalactic medium

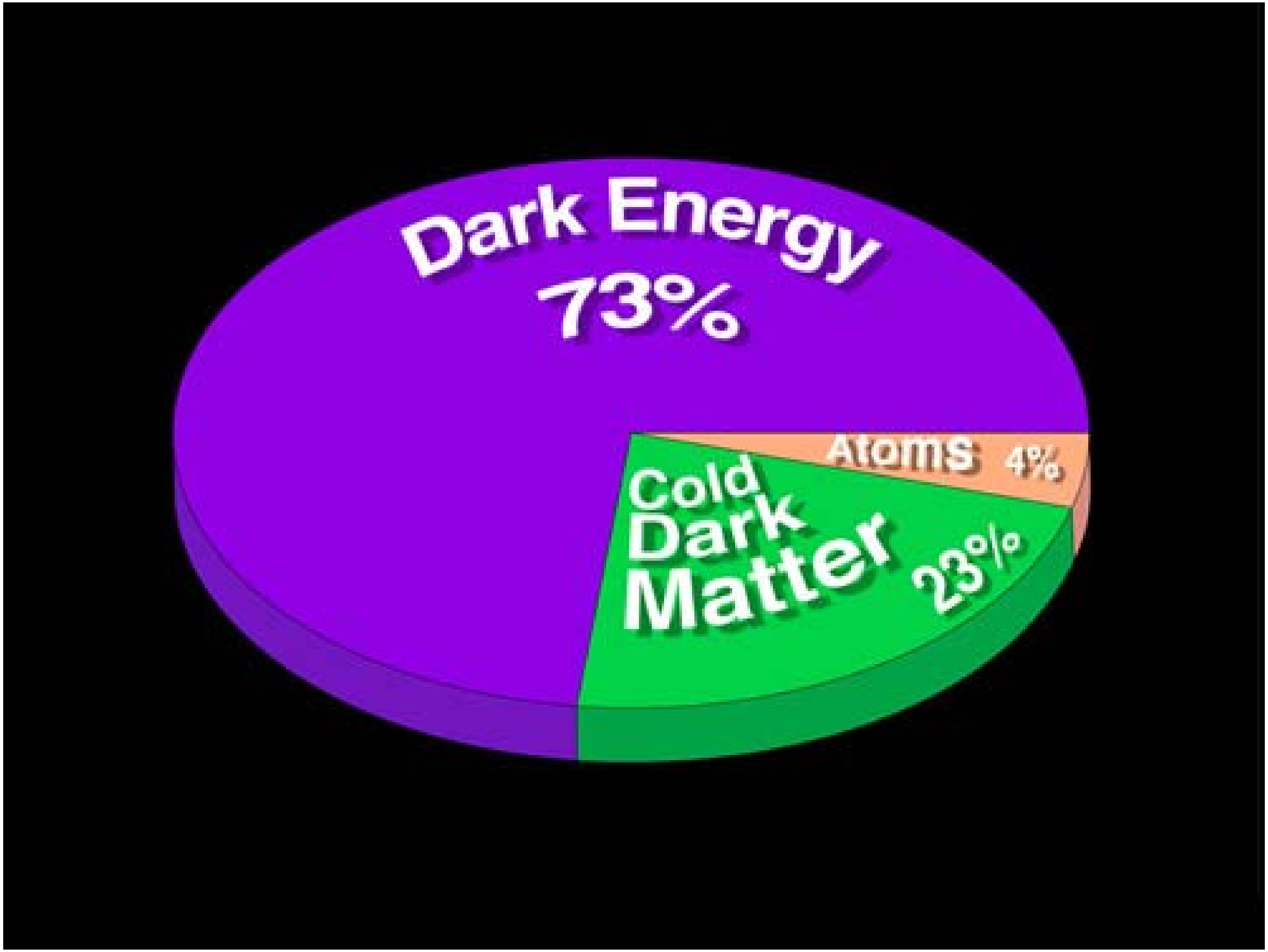


Further Science drivers

- Extended sources
  - Mosaicing (multiple pointings)
  - High fidelity imaging, merge in single-dish + additional short spacings (compact array – one of the Japanese contributions)
- Magnetic fields in ISM, protostars, merging galaxies
  - Full polarisation capability down to ~0.1% level
- Multi-waveband projects
  - Excellent calibration, goal is 1% for mm-band and 3% at submm
- Solar observations
  - Dishes can point at the Sun
  - Time resolution down to ~0.02 seconds


New model:
Star birth rate peaks
at ~0.5 – 1 billion years
Star birth begins
Old model of star birth rate
1
2
5
10
~14
BILLIONS OF YEARS
Big bang
Dark era
Milky Way galaxy forms
Our Solar System forms
Life appears on Earth
Humankind evolves

Our Universe…?



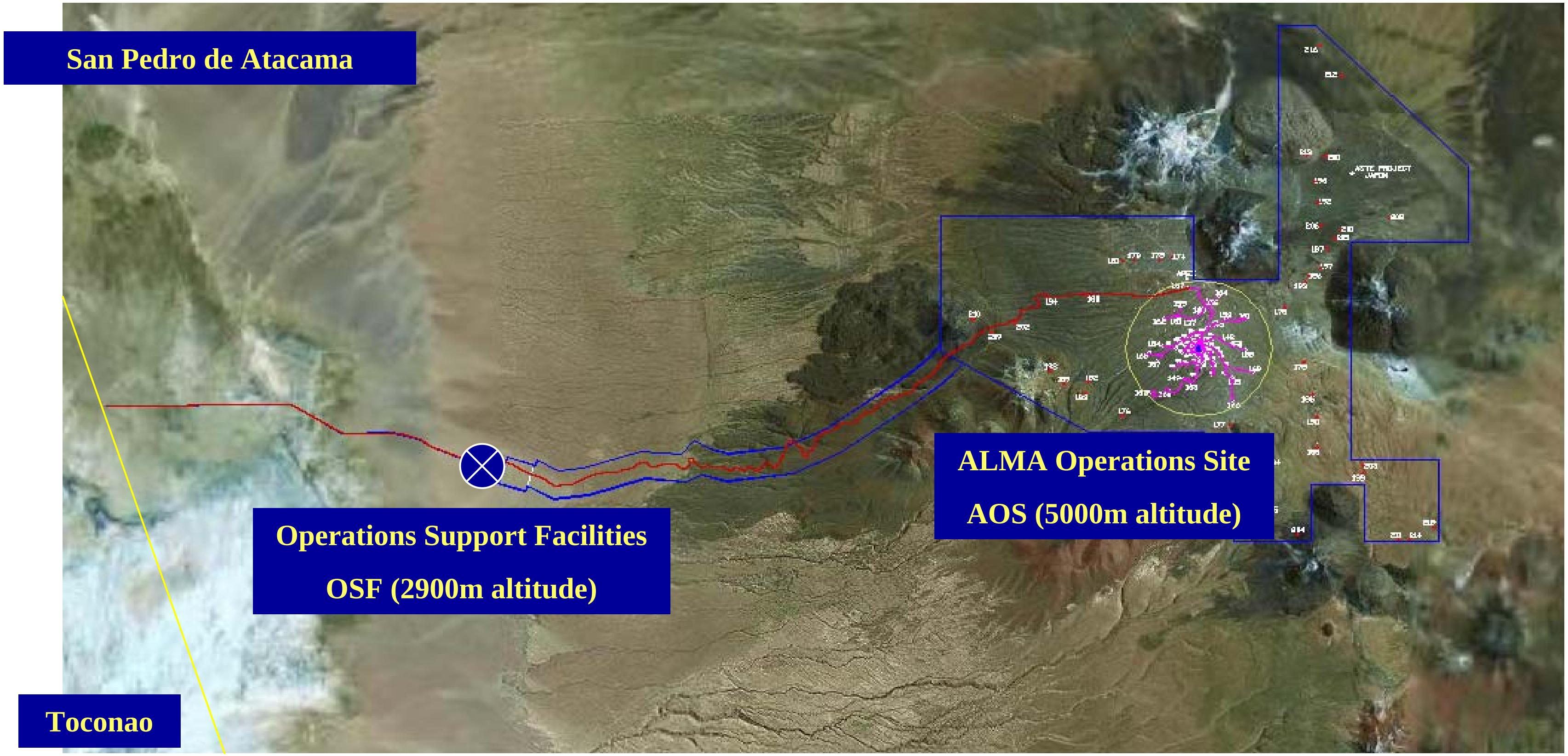
ALMA location

ALMA Site

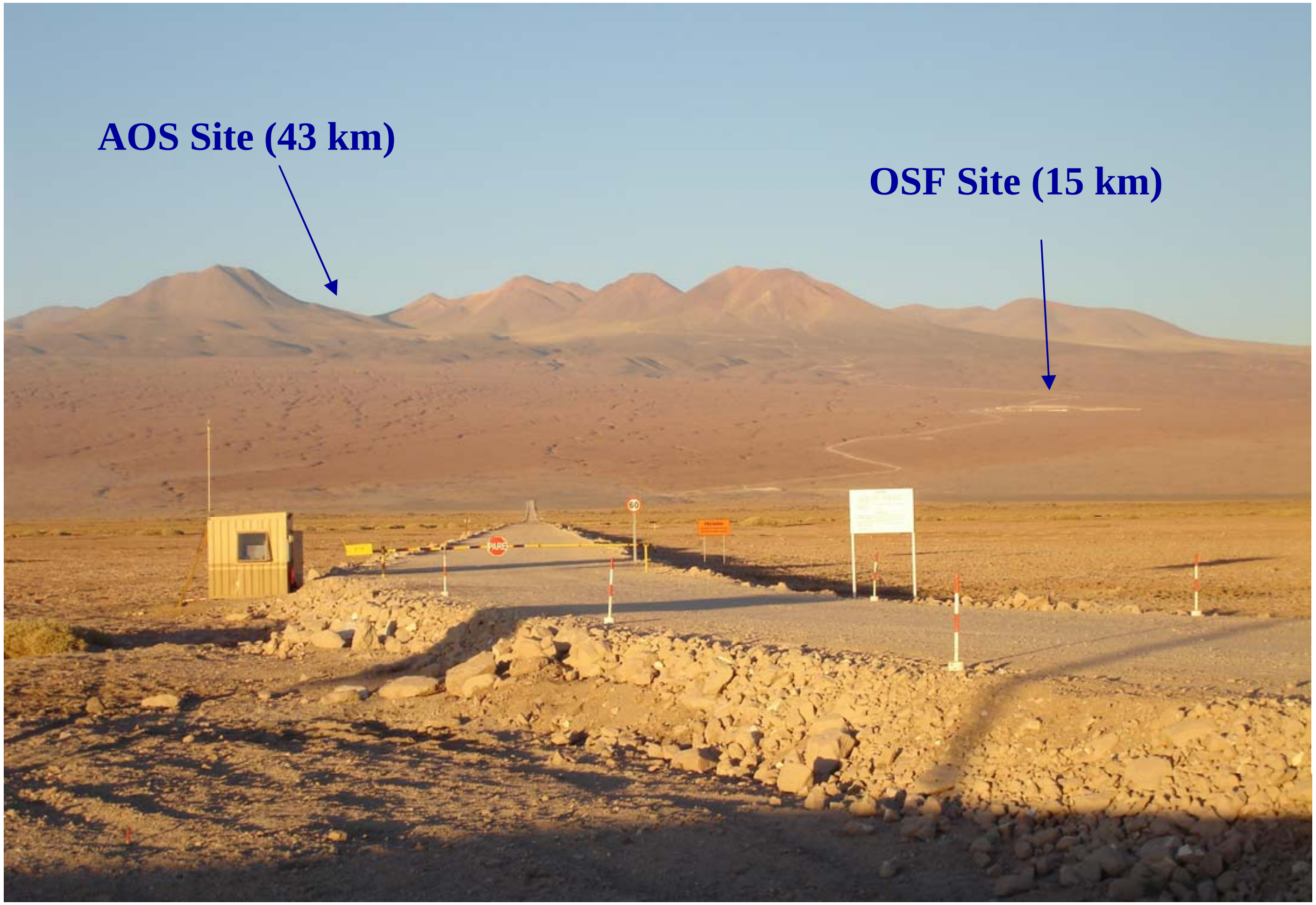

ALMA
Paranal
La Serena
Santiago
Chile
Peru
Bolivia
La Paz
Sucre
ALMA
Pacific Ocean
Santiago
Argentina
Atlantic Ocean


Tocopilla
Chuquicamata
Calama
Geiser
del Tatio
BOLIVIA
San Pedro de Atacama
ALMA
Toconao
Mejillones
Baquedano
Salar
de
Atacama
Antofagasta
Peine
Mina
Escondida
Paranal
ARGENTINA
Taltal
22º
23º
24º
25º
24
24
23
25
5
1
1
5
1

ALMA Site


San Pedro de Atacama
ALMA Operations Site
AOS (5000m altitude)
Operations Support Facilities
OSF (2900m altitude)
Toconao

Road to AOS

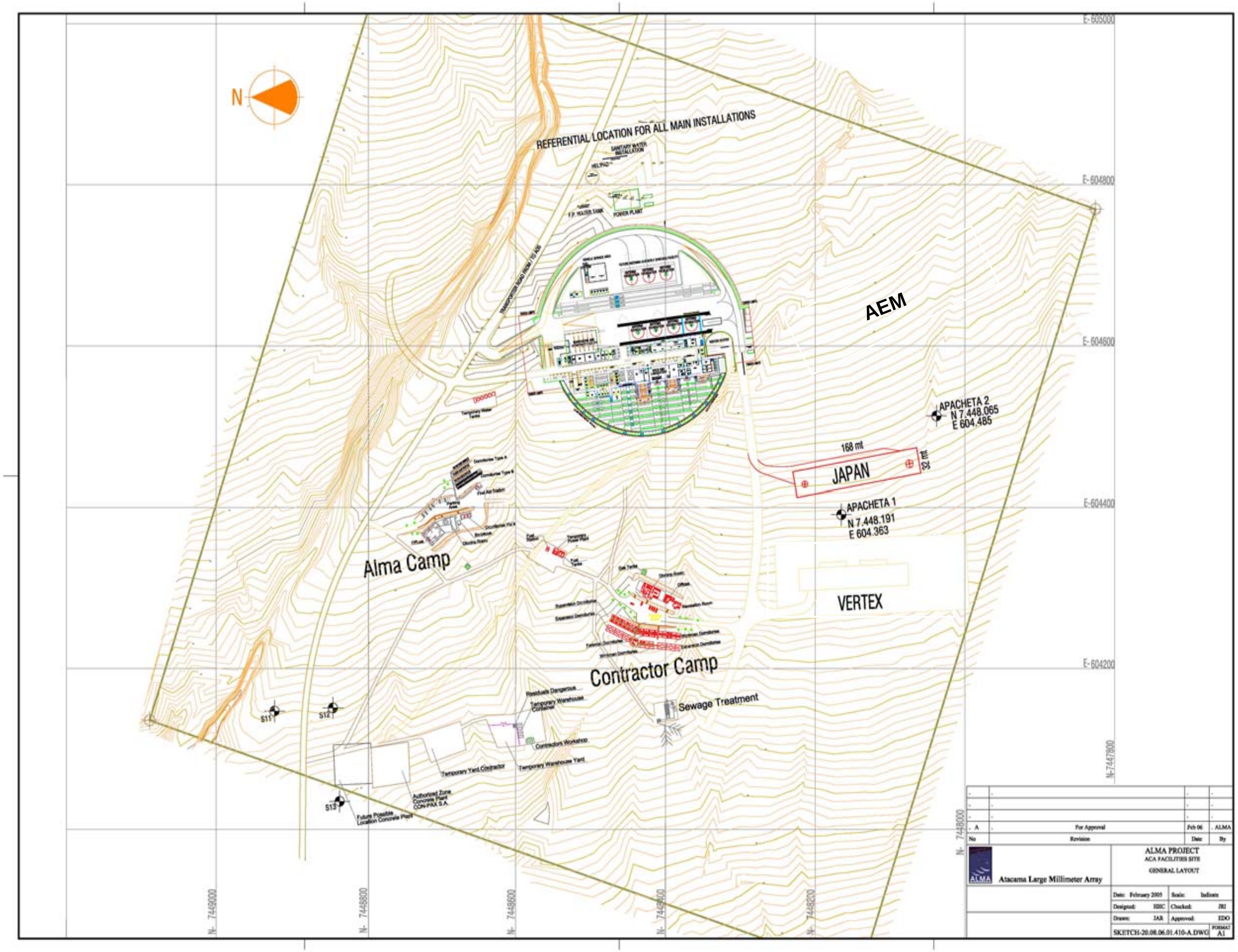


Completed up to AOS – 43 km

Road to AOS

Width of road: 14 to 19 meters over 43 km

The Operations Support Facilities - Area



General Layout Including Camps and Antenna Assembly Areas

Site

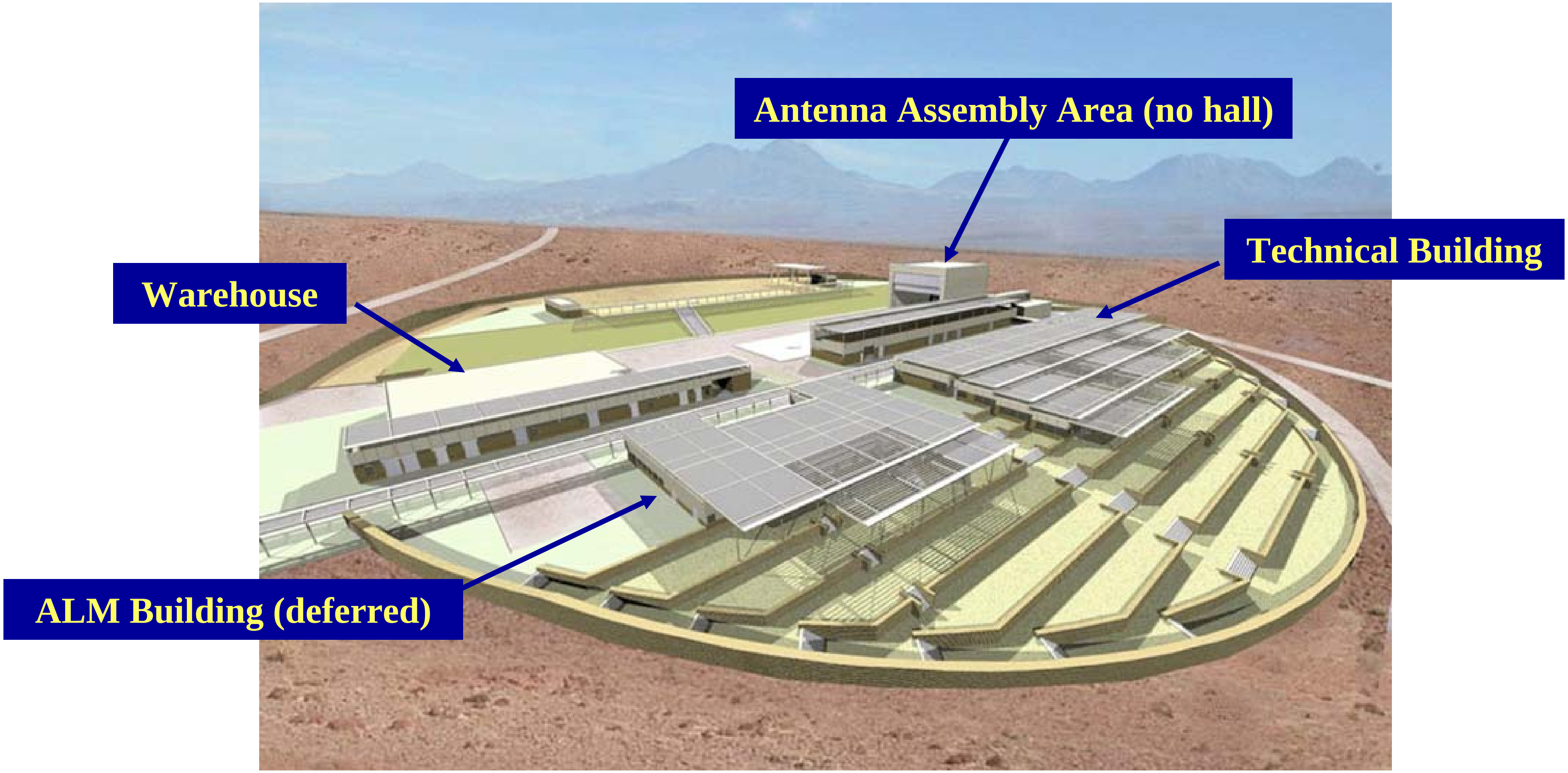
OSF

- AIV building done
- OSF building on schedule (Jan 2008 finish)
- VxRSI SEF building essentially done
- Camp Expansion underway
- First antenna being assembled

AOS

- AOS TB completion May, 14 June dedication
- Antenna foundation construction under bid
- Road, fiber network design complete

ALMA OSF – Technical Facilities



ESO signed construction contact beginning of August 2006
About 6000 m^2 net surface - Ready Q1/2008

Operations Support Facility

TB Roofing ceremony held 10 March

Holography Tower providing photography vantage point.

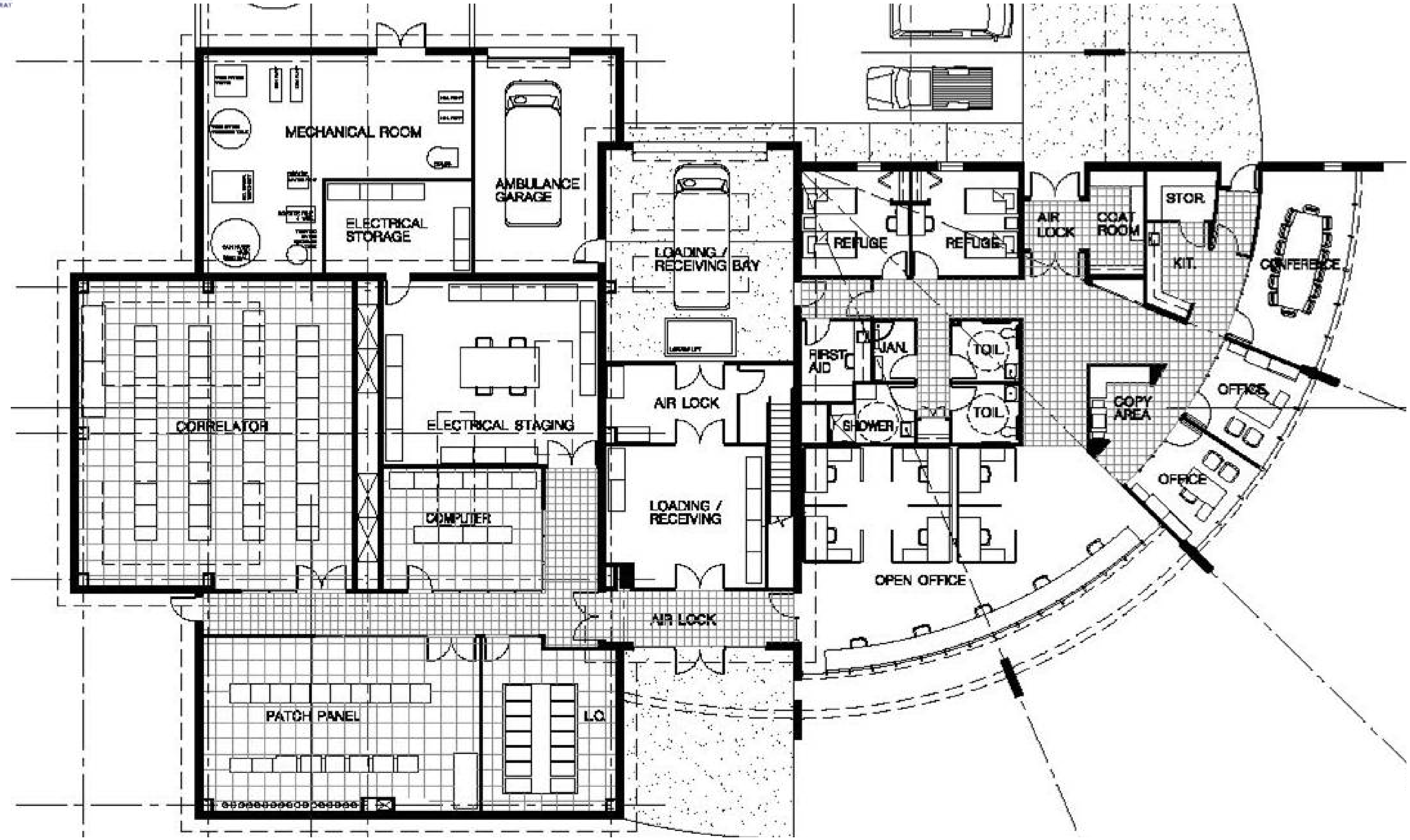
Operations Support Facility

Contractor's Camp holds ~440 persons

ALMA Camp full with 30, being expanded

AOS Technical Building: Nearly Complete

ALMA AOS – Array Operations Site Layout



AOS – the High Site of ALMA (5000 meters): Data Transmission, Computers, Correlator

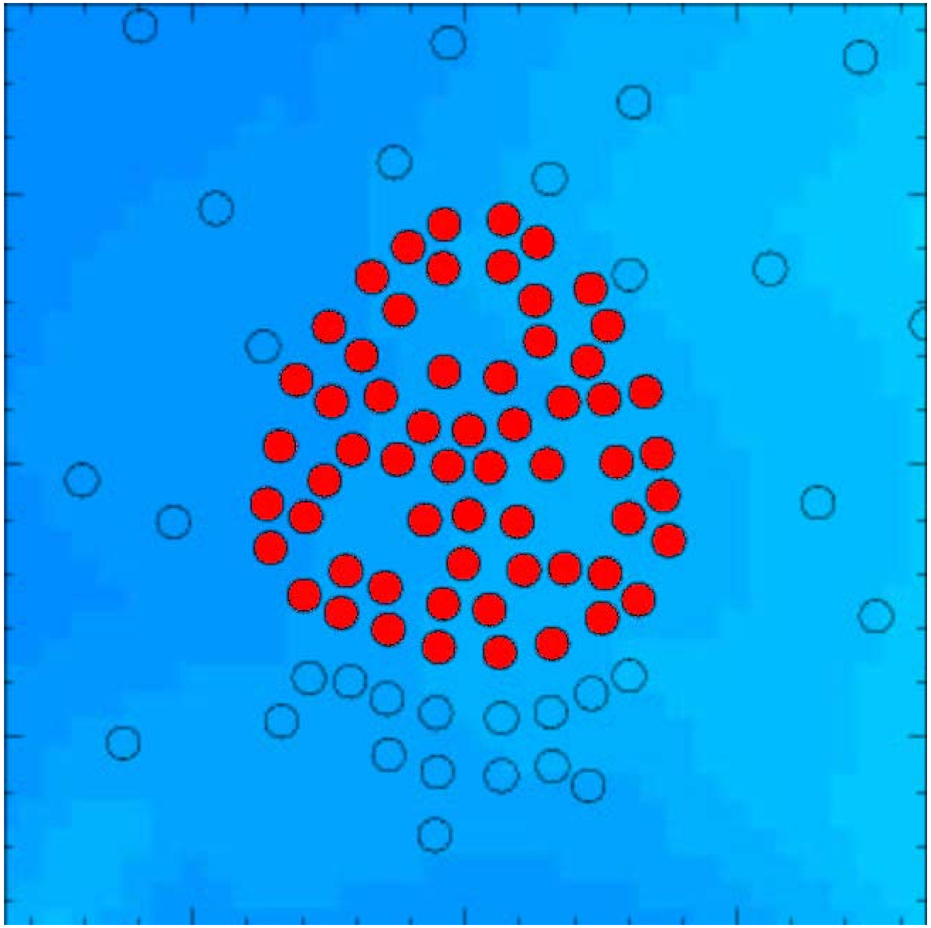
Configuration

The outer array design is complete, 8 configurations.

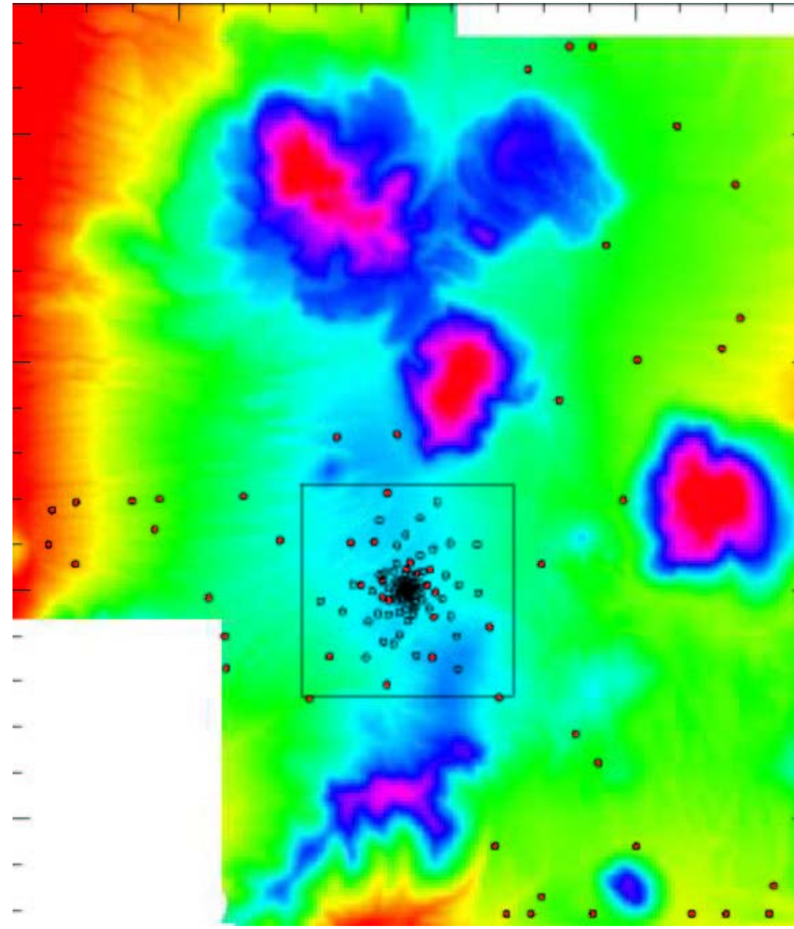
- Measures of merit are:
  - max inner sidelobe: 7.7% (largest configuration: 6%)
  - max mid sidelobes: 5.5% (largest: 6%)
  - max outer sidelobes: 2.3% (largest: 3%)
  - at dec = -48 deg:
  - resolution at 300 GHz: 16 mas
  - Bmaj/Bmin = 1.06
- Simulations with Casa begun (ongoing at NA ARC)
- Configuration works well on baselines to other nearby telescopes
- Example follows.

Interferometer configurations

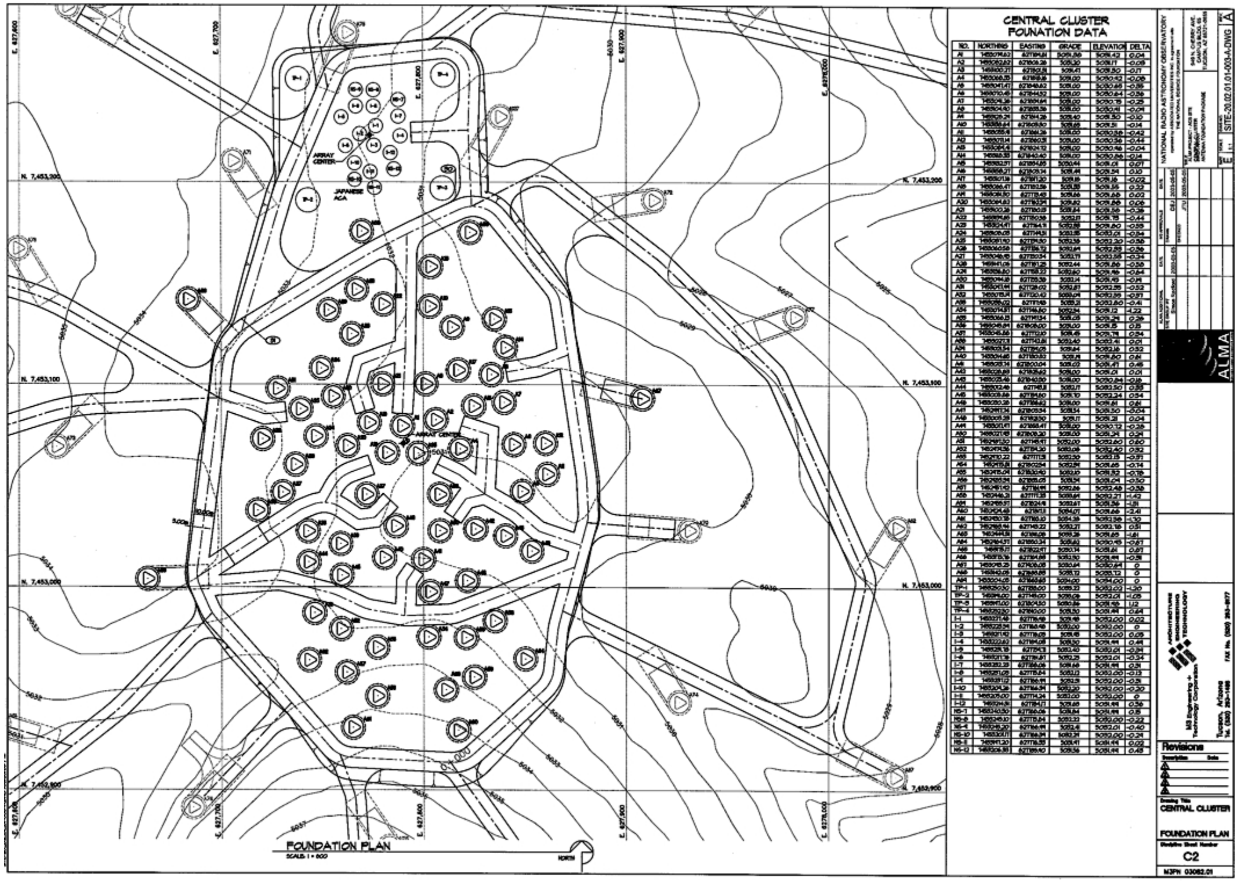
150 m maximum baseline



18 km maximum baseline

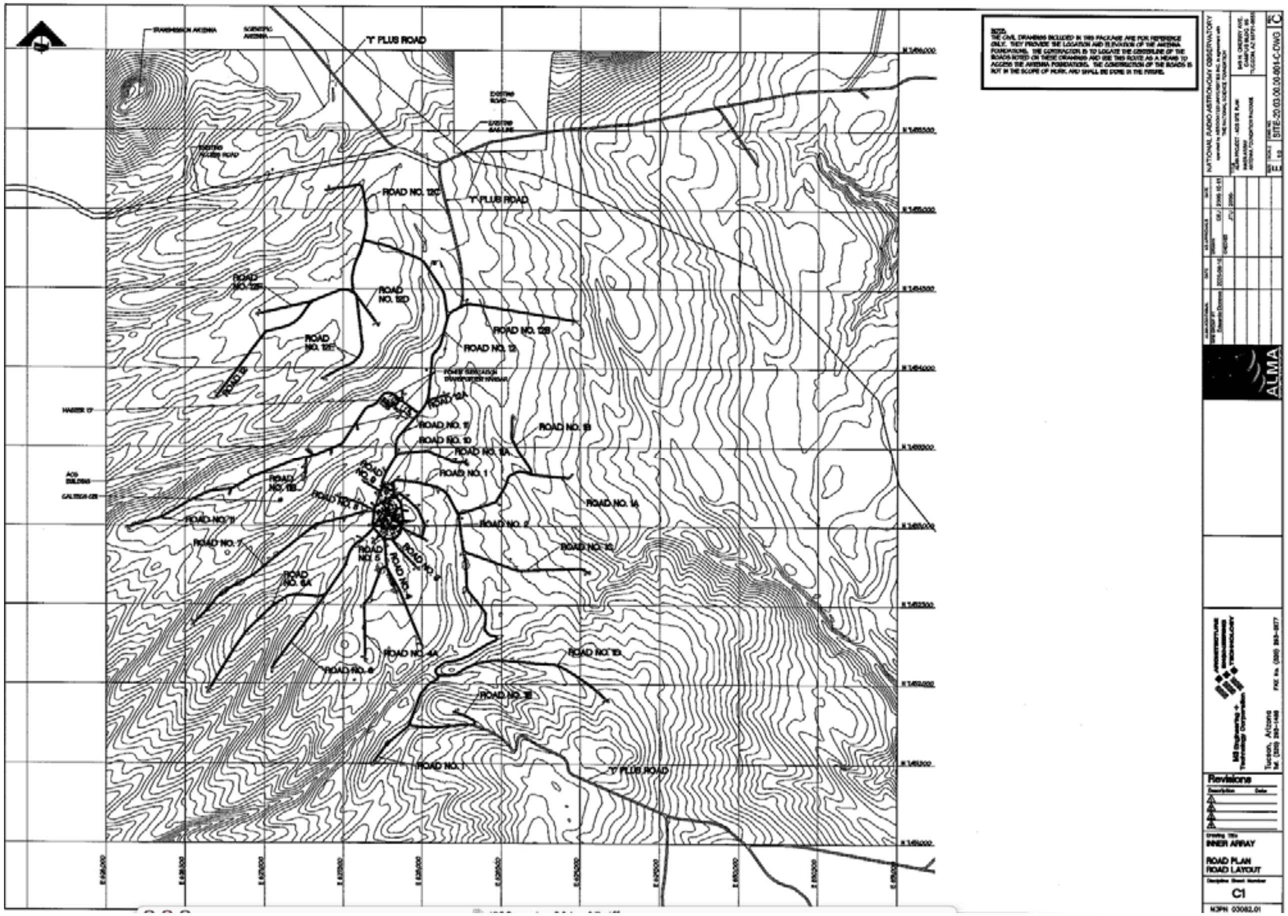


Central Cluster

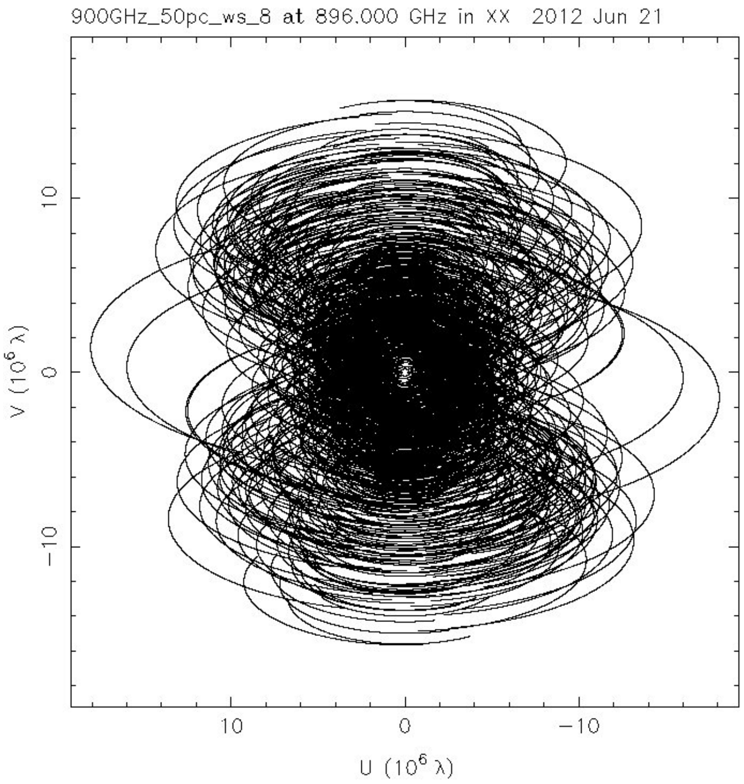


‘150m’ configuration, ACA

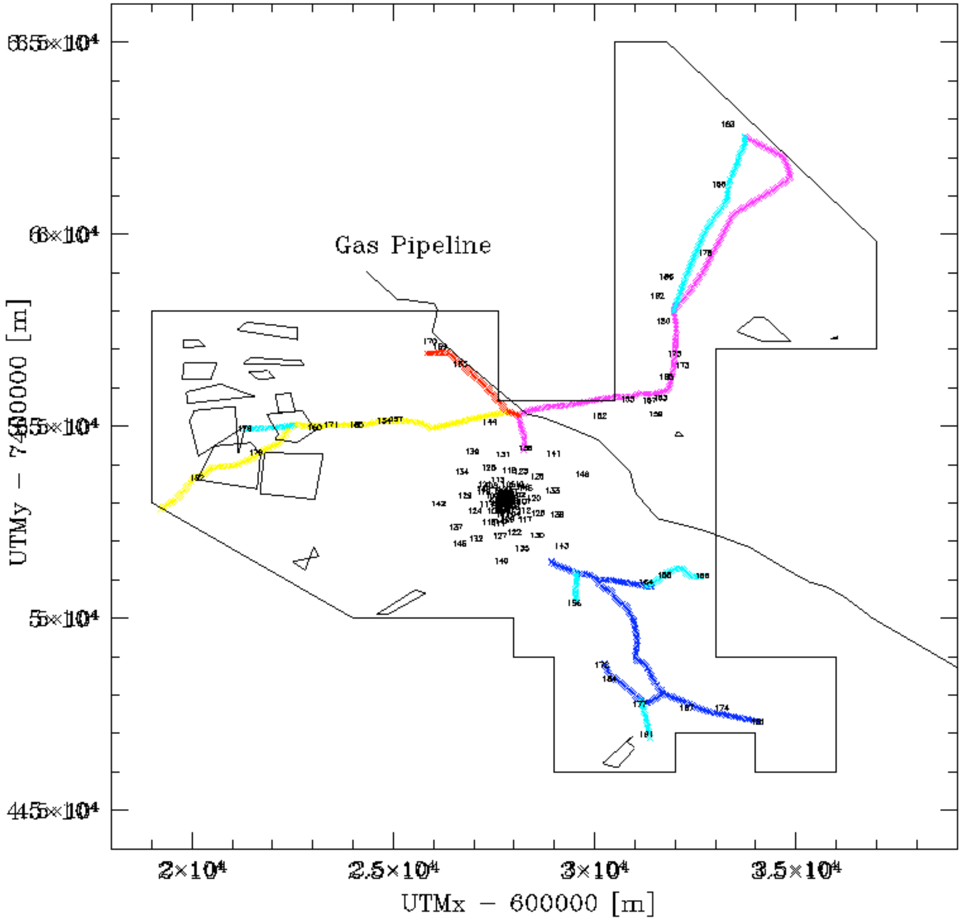
Inner Array



Out to few km road, fiber, pad system

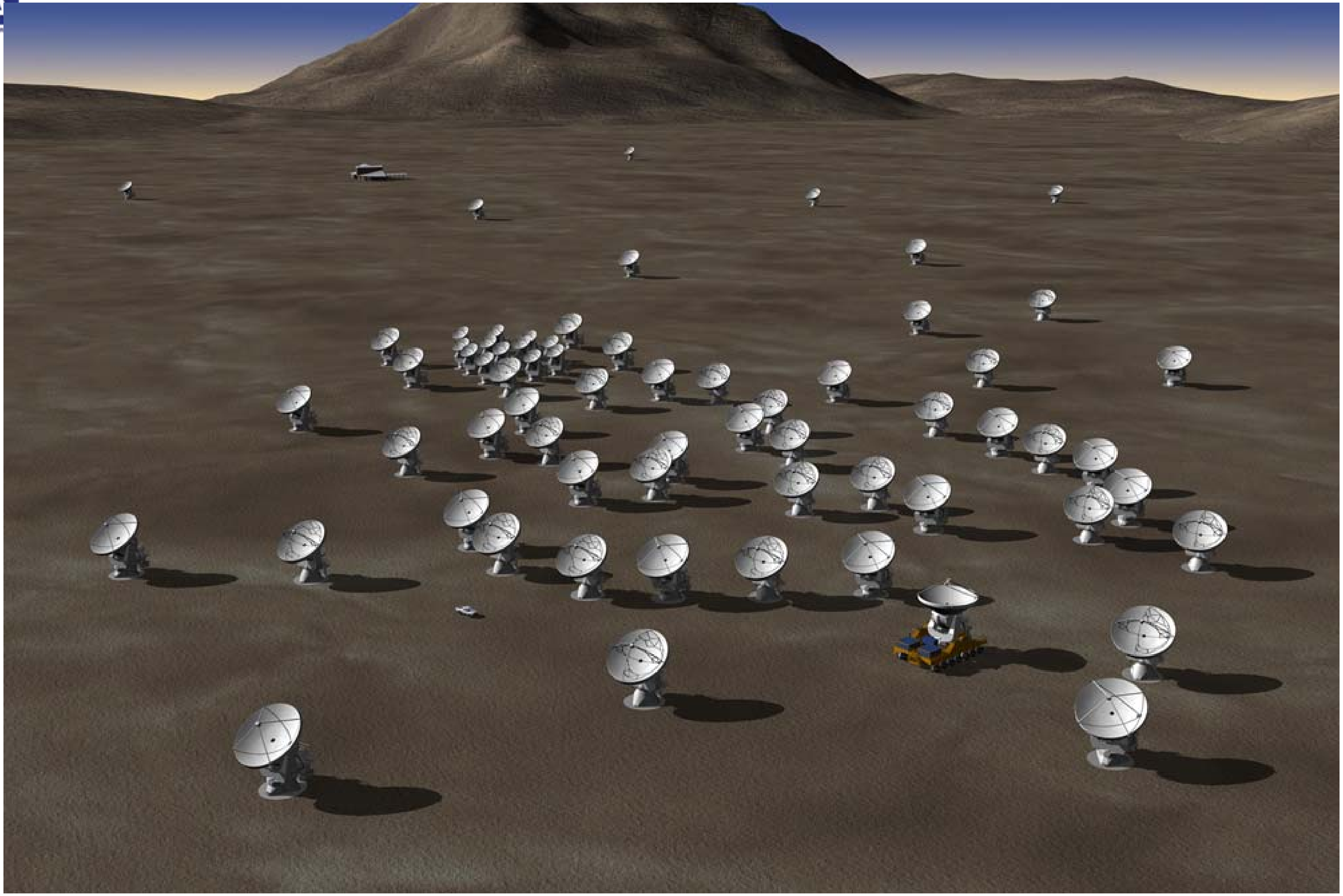


Uv tracks, from Casa



Extended configurations

ALMA



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:

86-119 GHz	"3"
211-275 GHz	"6"
275-370 GHz	"7"
602-720 GHz	"9"

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 60-150 MB/s.

All data archived (raw + images), pipeline processing

ALMA Antennas

Demanding ALMA antenna specifications:

Surface accuracy (25 µm)

Absolute and offset pointing accuracy (2 arcsec absolute, 0.6 arcsec offset)

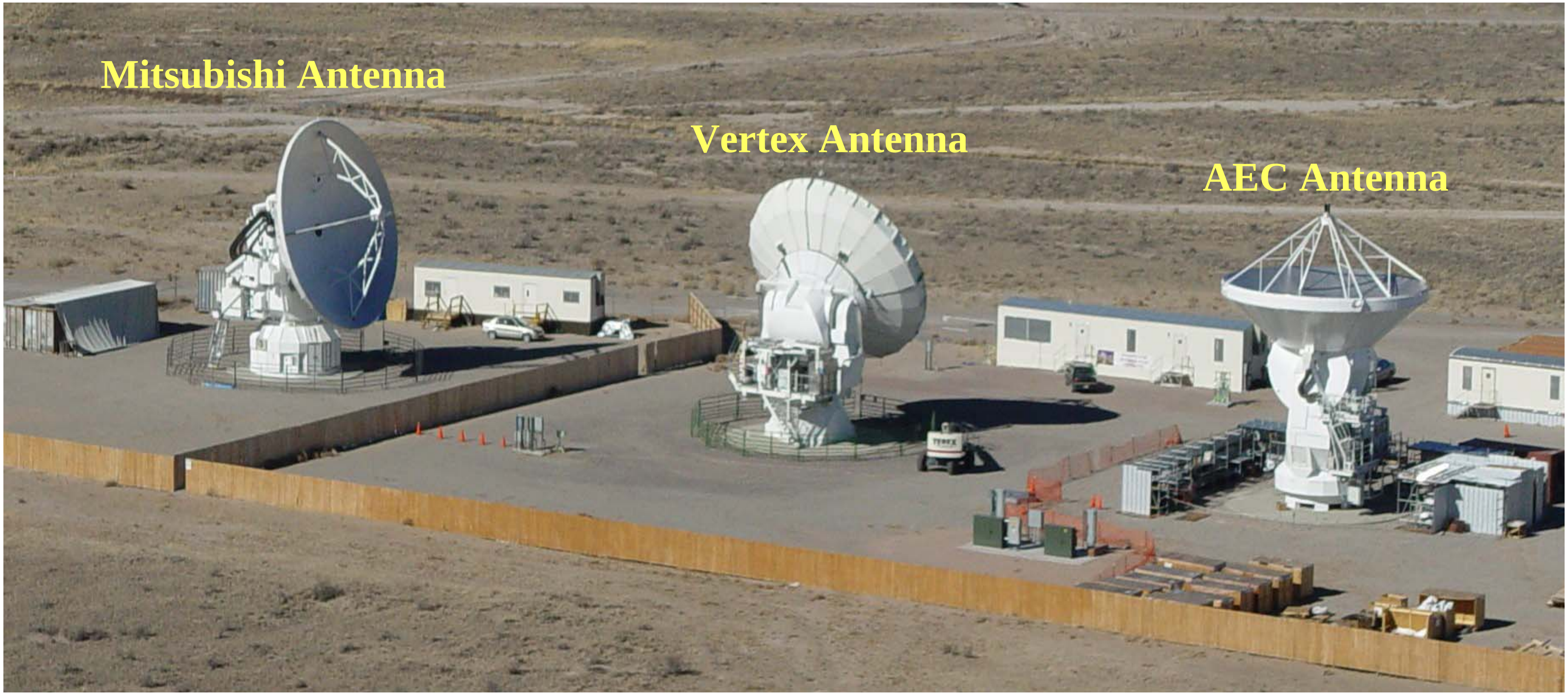
Path length (15 µm non-repeatable, 20 µm repeatable)

To validate these specifications: three prototype antennas built and evaluated at ATF (VLA site).

Vertex Prototype Antenna at the ATF

AEC Prototype Antenna at the ATF

The Three ALMA Prototype Antennas at the ATF



12 Meter Diameter, Carbon Fiber Support Structures

Antenna Procurement

North America – AUI : 25 antennas (12 m):

Contract: General Dynamics / Vertex RSI

First antenna: Q3/2007, last antenna Q4/2011.

Europe - ESO: 25 antennas (12 m):

Contract: AEM Consortium

(Alcatel Alenia Space, European Industrial Engineering, MT Aerospace)

First antenna: Q3/2008, last antenna Q4/2011.

Japan - NAOJ: 4 antennas (12 m) + 12 antennas (7 m):

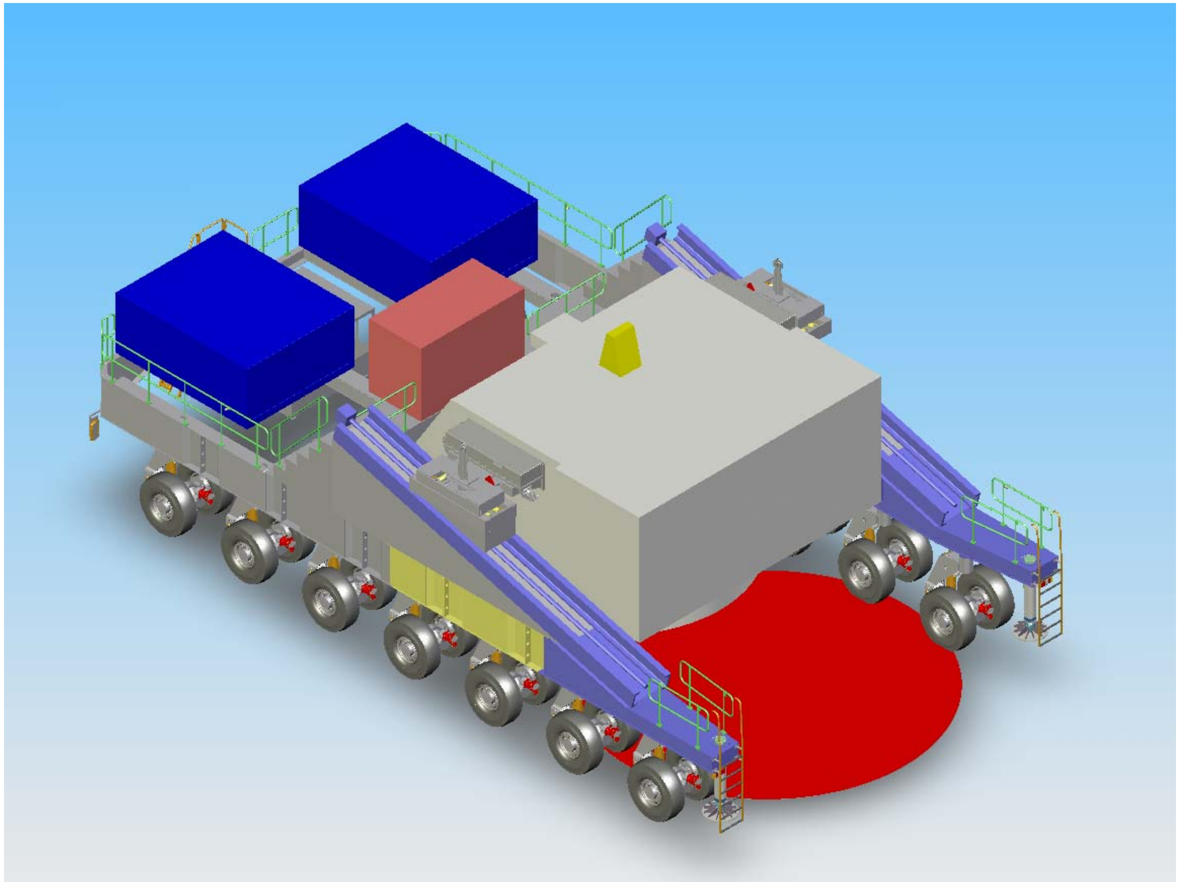
Contract for 12 m: Mitsubishi Electric Corporation (MELCO)

First antenna: Q4/2007, last antenna Q3/2008.

Call for Tender planned for 2007 for 7 m:

First antenna: Q2/2009, last antenna Q3/2010.

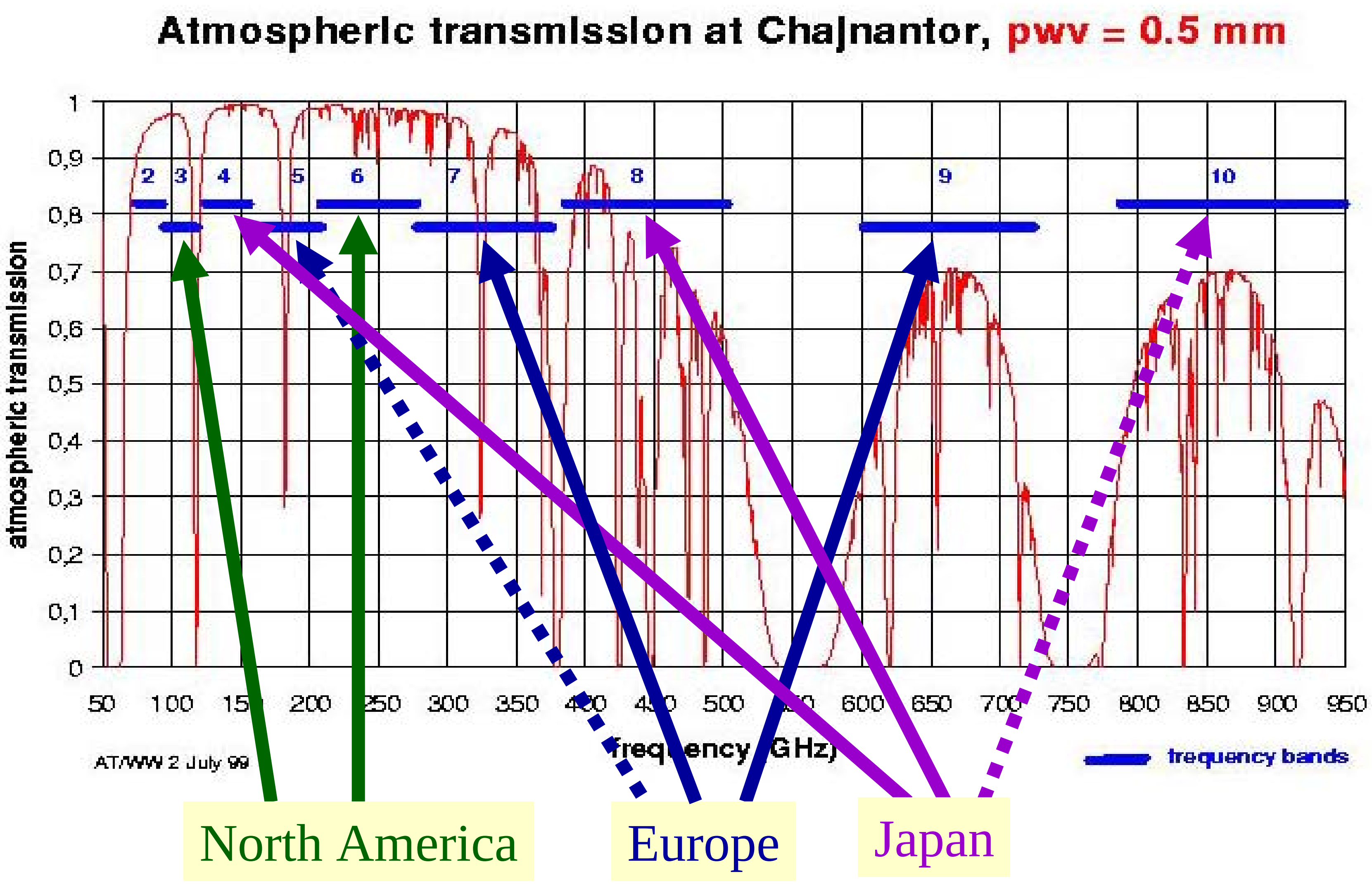
Antenna Transporters



Two transporters:
FDR held in January 2007, delivery Q3/2007 and Q1/2008

ALMA Transporter

Frequency Bands Covered by ALMA



Receivers/Front Ends

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

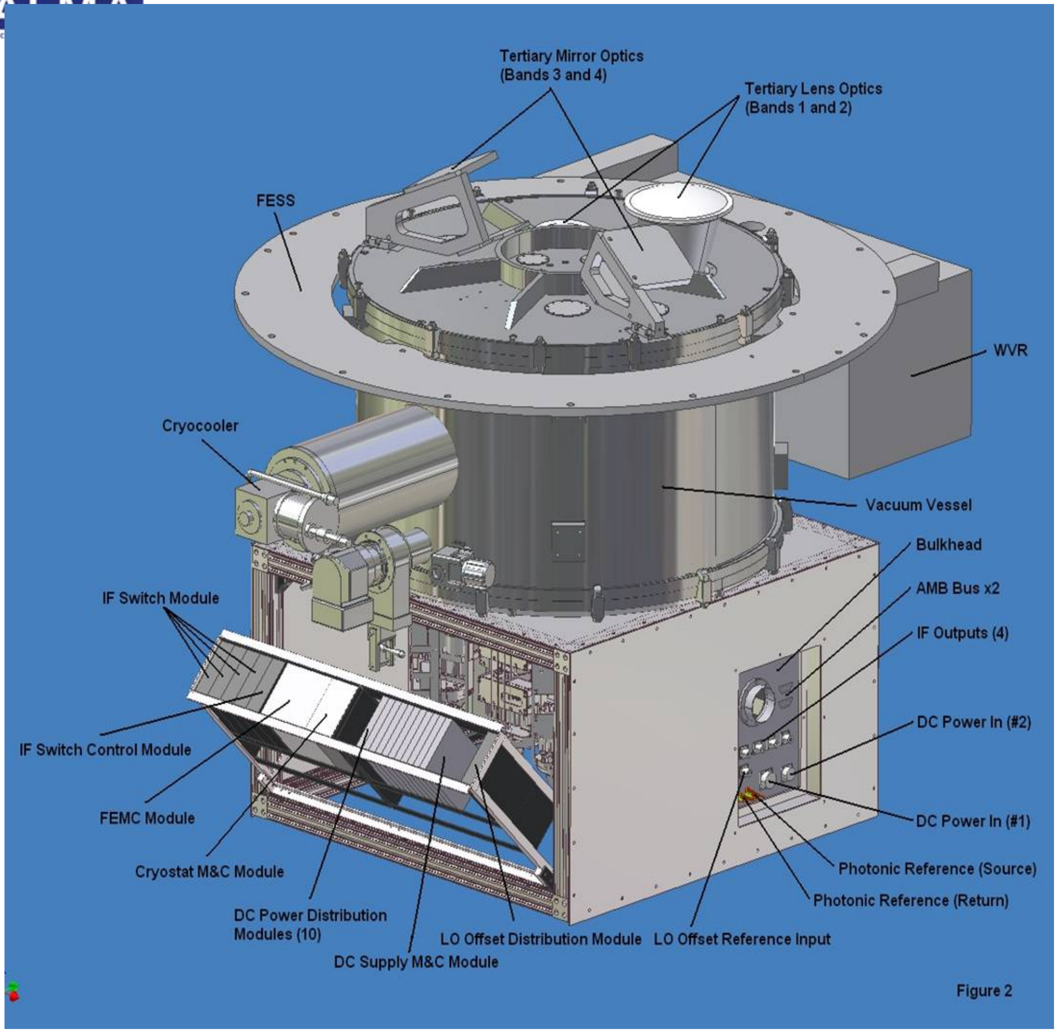
Dual, linear polarization channels:

- **Increased sensitivity**
- **Measurement of 4 Stokes parameters**

183 GHz water vapour radiometer:

- **Used for atmospheric path length correction**

Front-end, layout



Front End Cryostats

All cryostats will be assembled at RAL and shipped to the three Front End Integration Centres.

First seven cryostats assembled and verified.

Cartridge Production

Band 3 (HIA, Canada):

Four cartridges assembled.

Two delivered and accepted by NA FEIC.

Band 9

Band 6 (NRAO, USA):

Three cartridges assembled and delivered to NA FEIC.

Band 7 (IRAM, France):

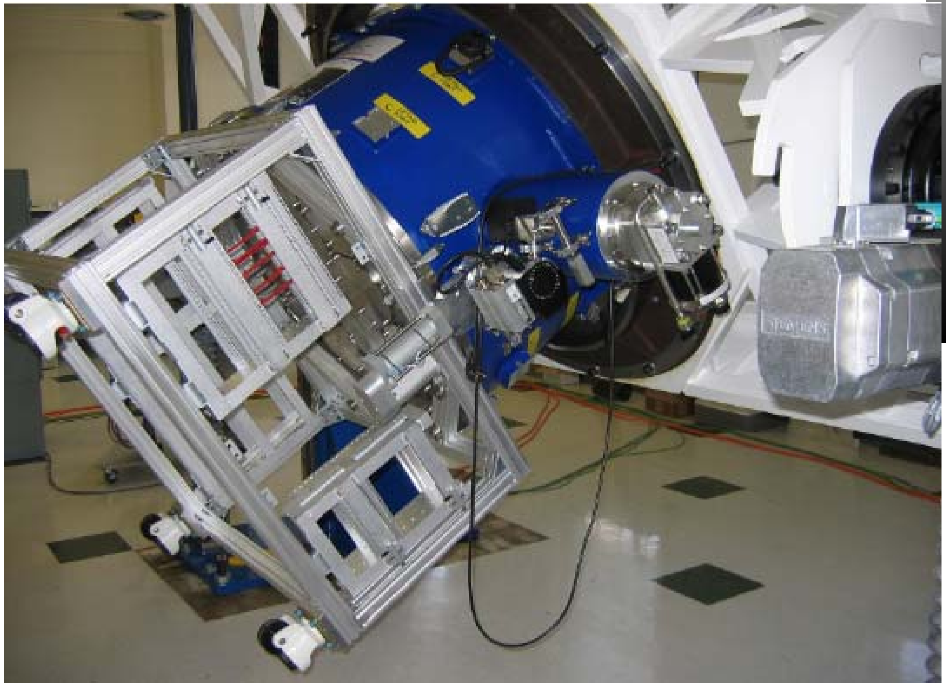
Five cartridges assembled. Two accepted by and four delivered to NA FEIC.

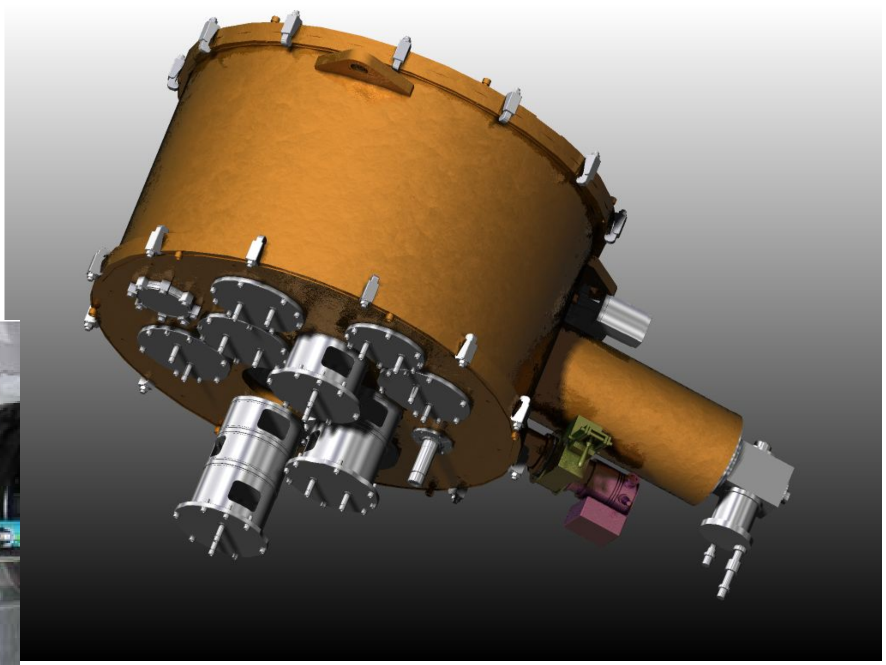
Band 9 (NOVA, The Netherlands):

Four cartridges assembled. Two accepted by NA FEIC.

Front-end

First cryostat in integration center



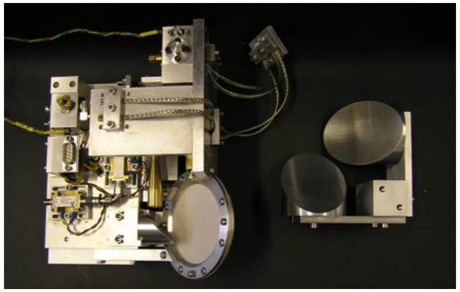


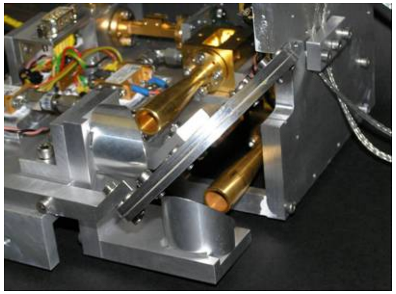
Receiver cartridge concept

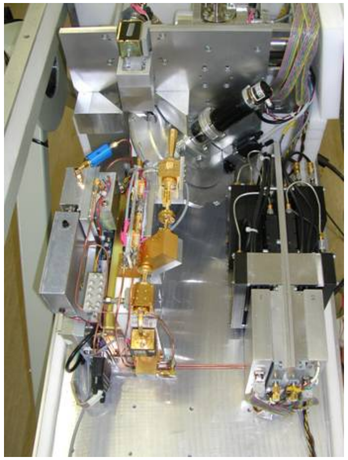
Water Vapor Radiometer

Development status

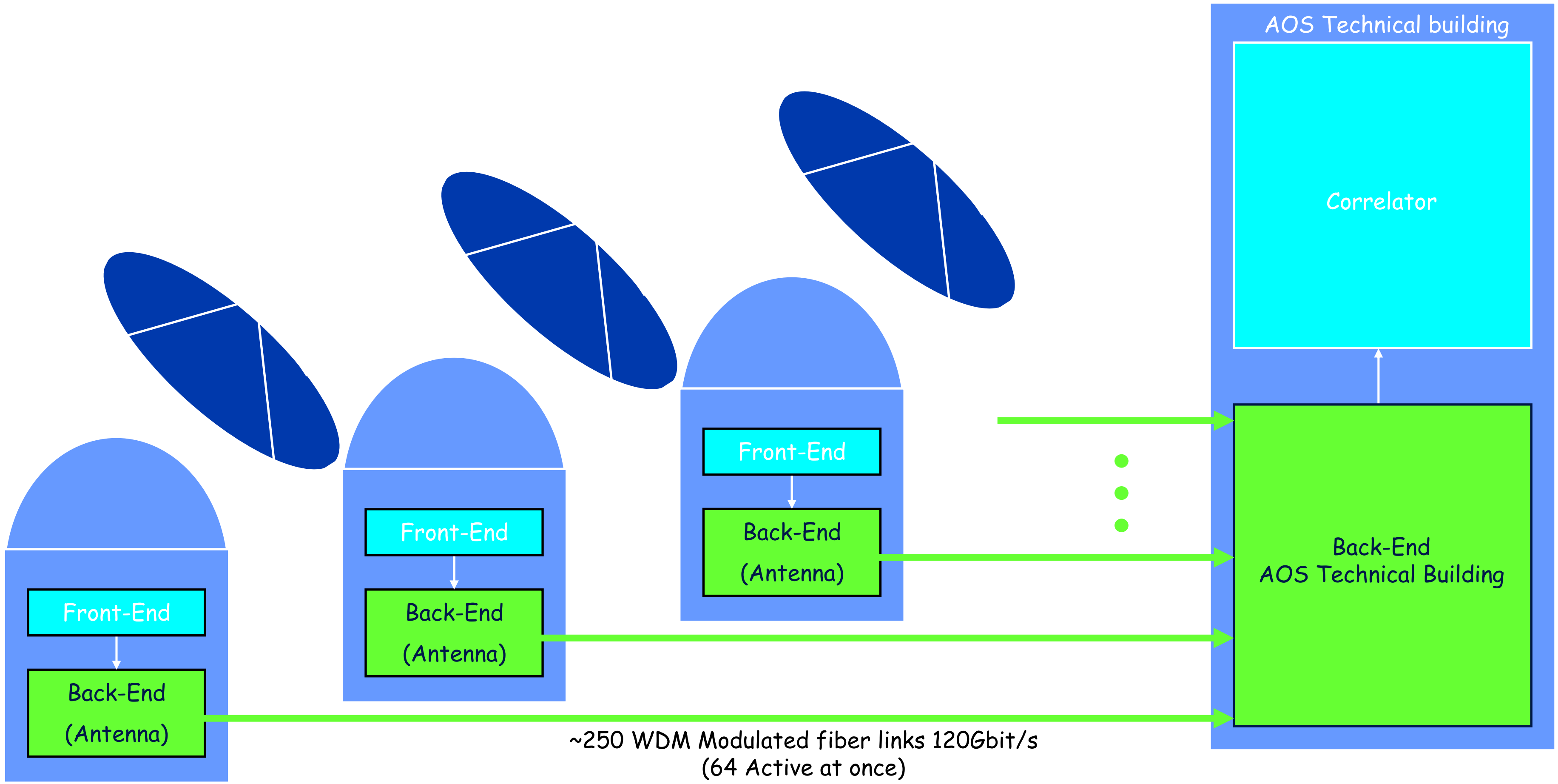
- Two prototype WVRs (Cambridge and Onsala) have been completed and fully tested
- Key performance of both prototypes is in agreement with requirements
- Testing underway at SMA



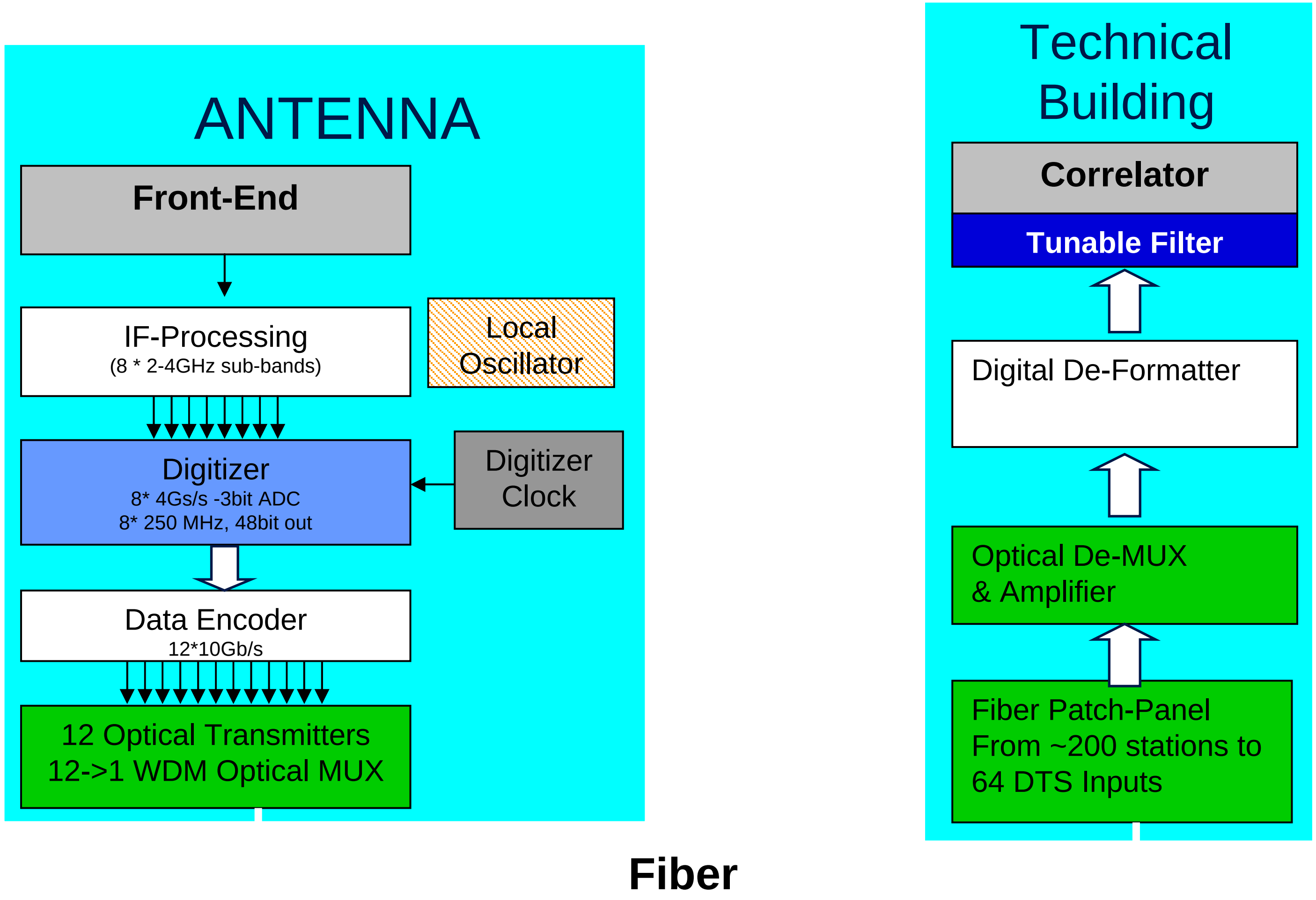




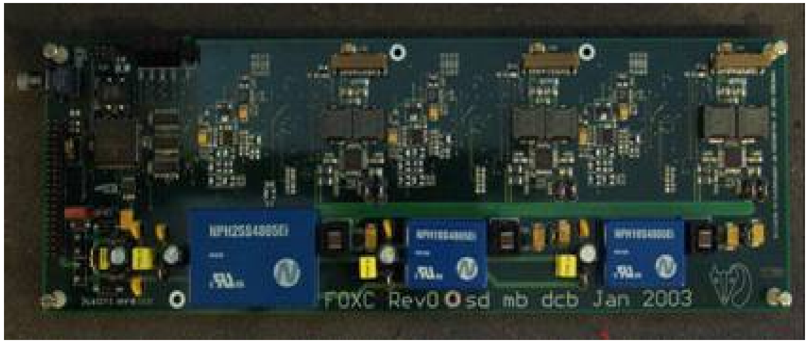
Location of Back End and Correlator



Back End → Correlator

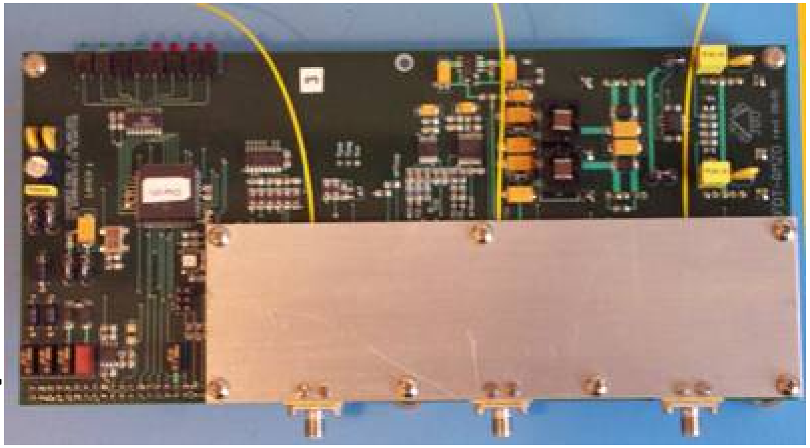


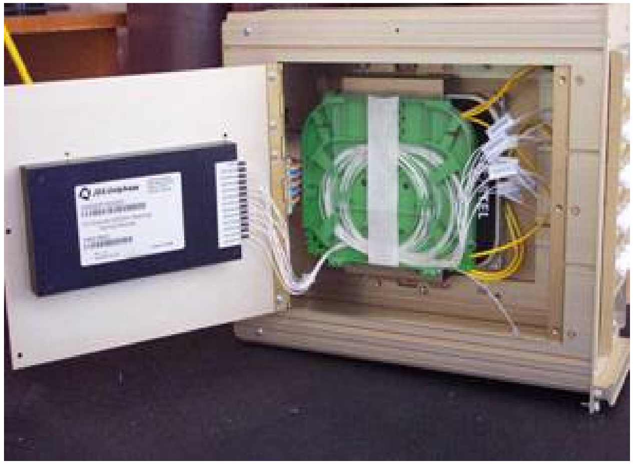
Back End – Optical DTS



Optical Transmitter

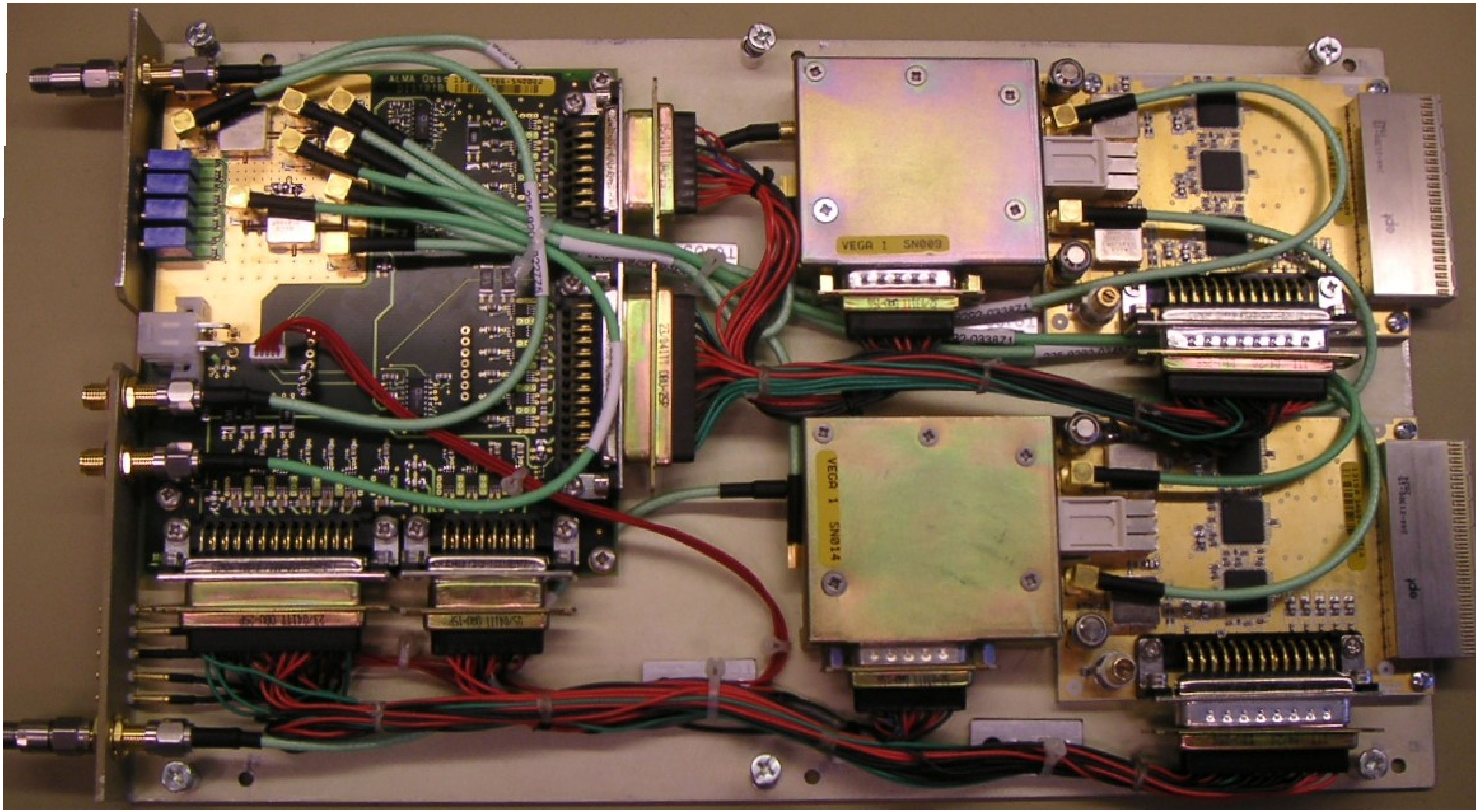
Optical Receiver >





< Optical Amplifier Demux

4 Gsa/sec UB Digitizer Assembly



Correlator Specifications

Number of antennas	64
Number of IF pairs per antenna	4
Max. sampling rate per IF pair	2 x 4 GHz
Digitizing format	3 bit, 8 level
Correlating format	2 bit, 4 level
Max. delay range	30 km
Channels per IF pair	4096
Autocorrelation channels per baseline	1024
Polarization	Full stokes (4 products)

First quadrant of correlator completed August 2007

The Correlator

First of four Correlators at NRAO

2912 printed circuit boards

5200 interface cables

More than 20 million solder joints

$34*10^9$ Millions of op. per second

Computing

The fundamental output of the CIPT will be a ~2M SLOC “end to end” software system running on over 200 computers on 4 continents.

Difficult distributed development – software engineering practices, travel

Using aips++ (CASA) as offline system

Current Projected Timeline

2006 Continue Prototype System Testing, Socorro

Early 2007 First antenna arrival and testing at ALMA site

Early 2009 Commissioning Begins with 3-element array

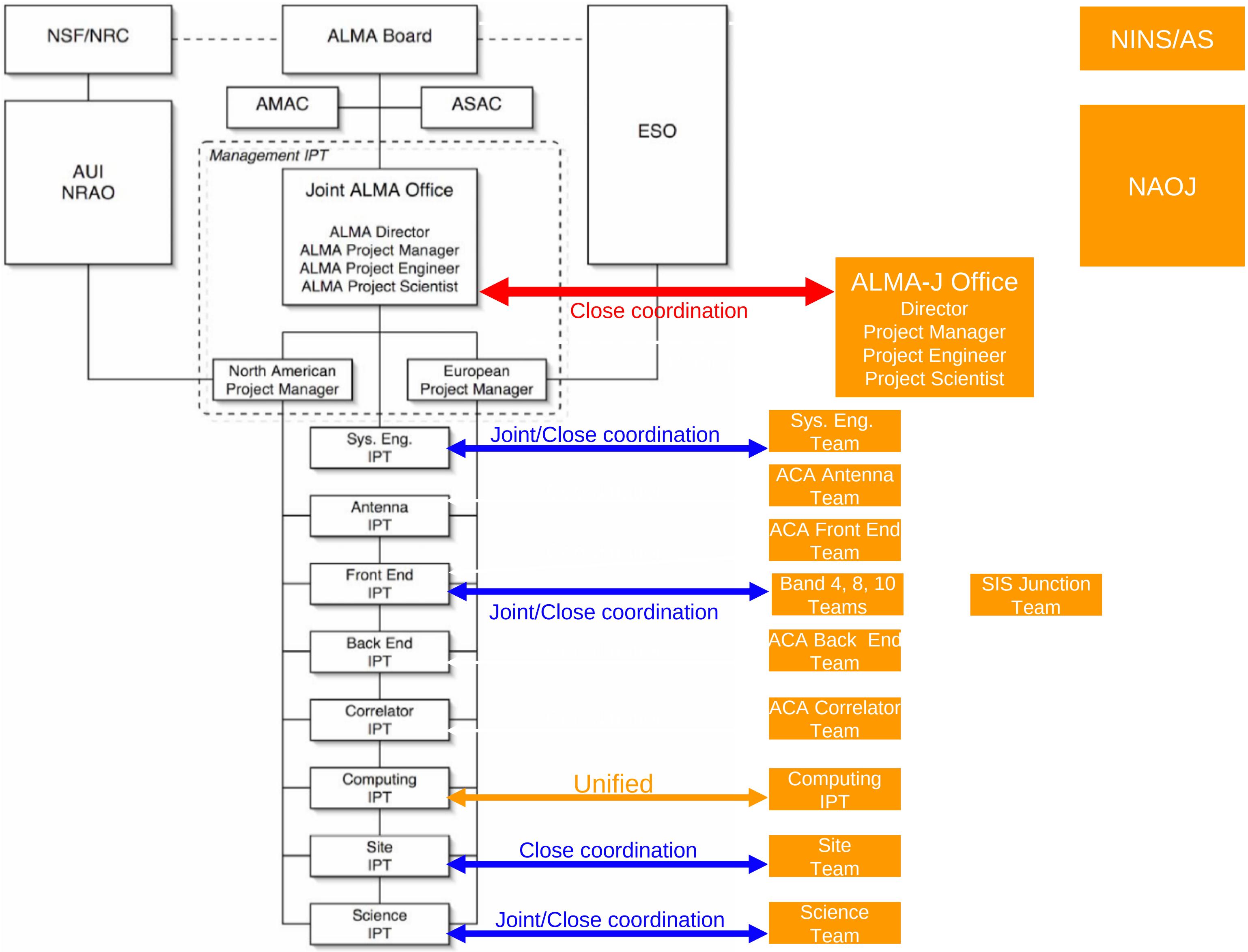
Late 2009 Call for Shared Risk Proposals

- 6+ antennas, 2+ bands, continuum & spectral line, 1km baselines
- Off line data reduction

2012 Pipeline images for standard modes

2012 Baseline ALMA Construction Complete

Management Interaction in Construction



JAO Office

El Golf 40 Piso 18

Santiago

Guidelines for ALMA Operations

ALMA is a service observing facility, for which the scientific demand will be very high. The astronomer is not normally required to be present when his/her observations are executed.

ALMA operational activities in Chile are limited to what is required to acquire, certify and archive the scientific data of the scientific teams proposing observations; this includes certain business functions and other activities requiring proximity to the array. For safety reasons, the number of ALMA staff working at the array site at 5000 meters elevation must be kept to an absolute minimum.

The main interface between the user communities and ALMA is through the Regional Support Centers, including proposal handling and support for data reduction and archival research.

Development work on hardware and software is contracted to the Executives.

ALMA – Major Elements

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

ALMA Operations

"The Joint ALMA Observatory (JAO) is primarily a service organization for conducting the activities in Chile that are required to acquire, certify, and archive the scientific data for the User communities. The interface to ALMA for each of these communities is an ALMA regional center (ARC)."

Array Operations Site (AOS), Chajnantor: ALMA array reconfiguration, site security, correlator – modular design to mitigate high-site maintenance

Operations Support Facility (OSF), San Pedro: Operate array, select schedule blocks, ensure adequate calibration, quick-look data monitoring, Quality Assurance 0 (AoD), basic module repair, standard antenna maintenance, safety, administration

Central Office (Santiago): Pipeline, QA1, Archive, Business, Science office

ALMA regional Centers (ARCs), C'ville, ESO, Tokyo: Proposal functions, sched block preparation, basic user support and feedback, archive copy and research, QA2, module maintenance & repair, software M&R, OSF staffing (AoD), H/W + S/W development, advance science support and development

Reminder

ALMA Operations is not funded as part of the ALMA construction project.

ALMA Operations will have separate, independent, funding that overlaps in time with the construction project.

Baseline plan for the relation of Operations to Construction

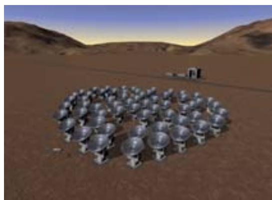
From the ALMA Project Plan (§1.3)

Hardware delivered will be integrated, verified, and commissioned subsystem module-by-subsystem module. Once commissioned, each subsystem module will be placed into service in the operating array

The initial complement of the ALMA operations team must be in place at the OSF and on the array site at the time the first array subsystem modules are commissioned.

The details of the scientific operations plan need to be refined and implemented at the time the first few antennas arrive on site.

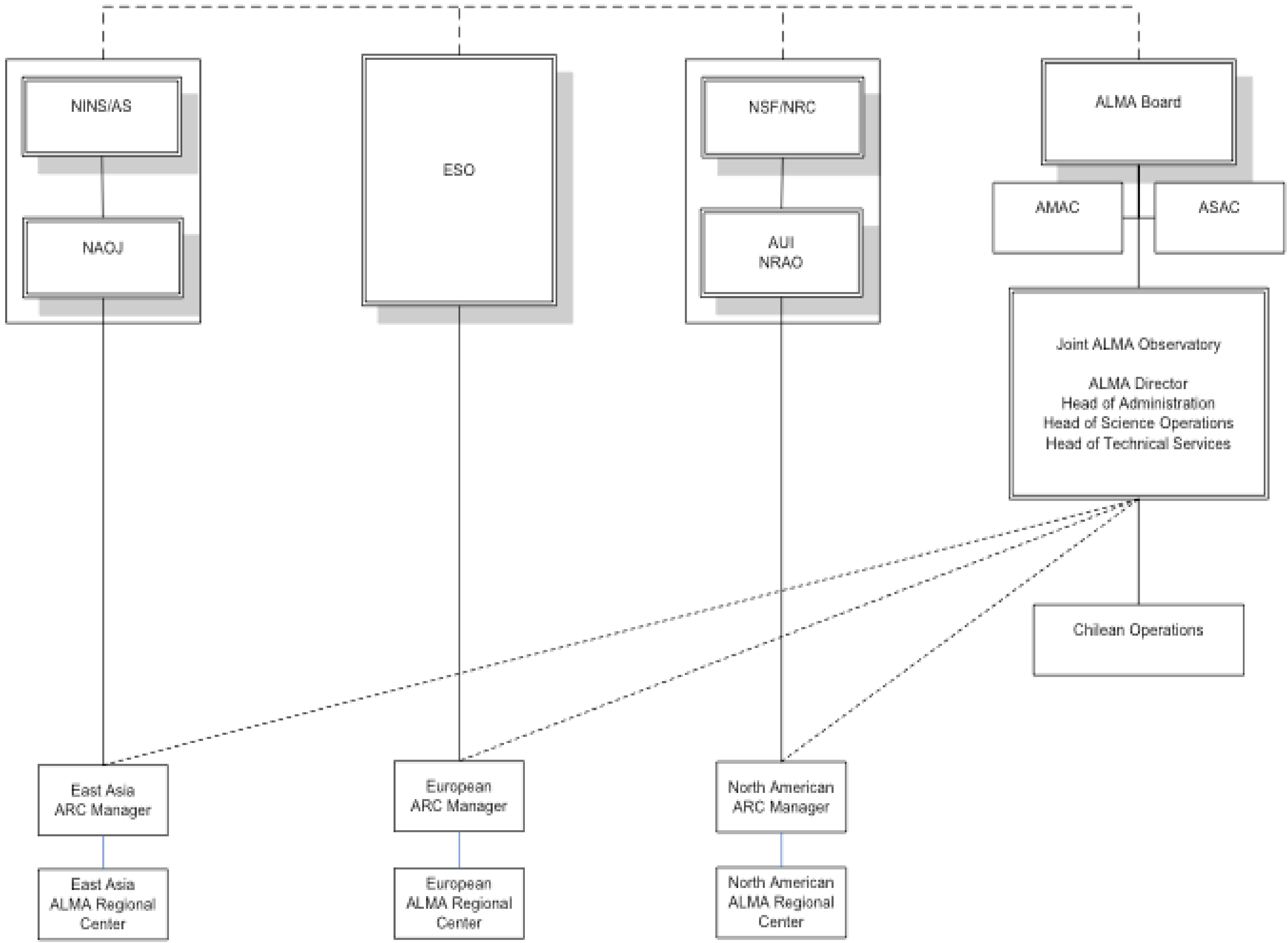
ALMA Sites in Chile



Antenna Operations Site (AOS)

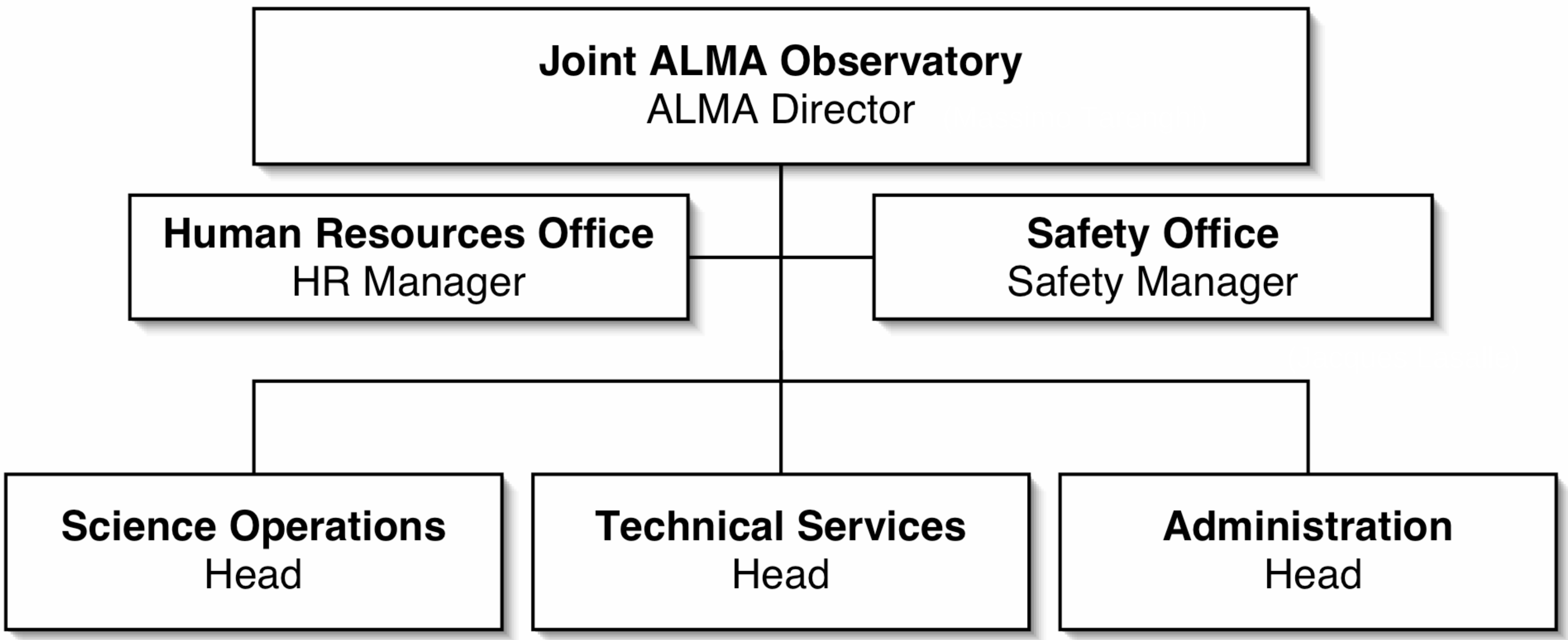
Operation Support Facility (OSF)

Santiago Central Office (SCO)



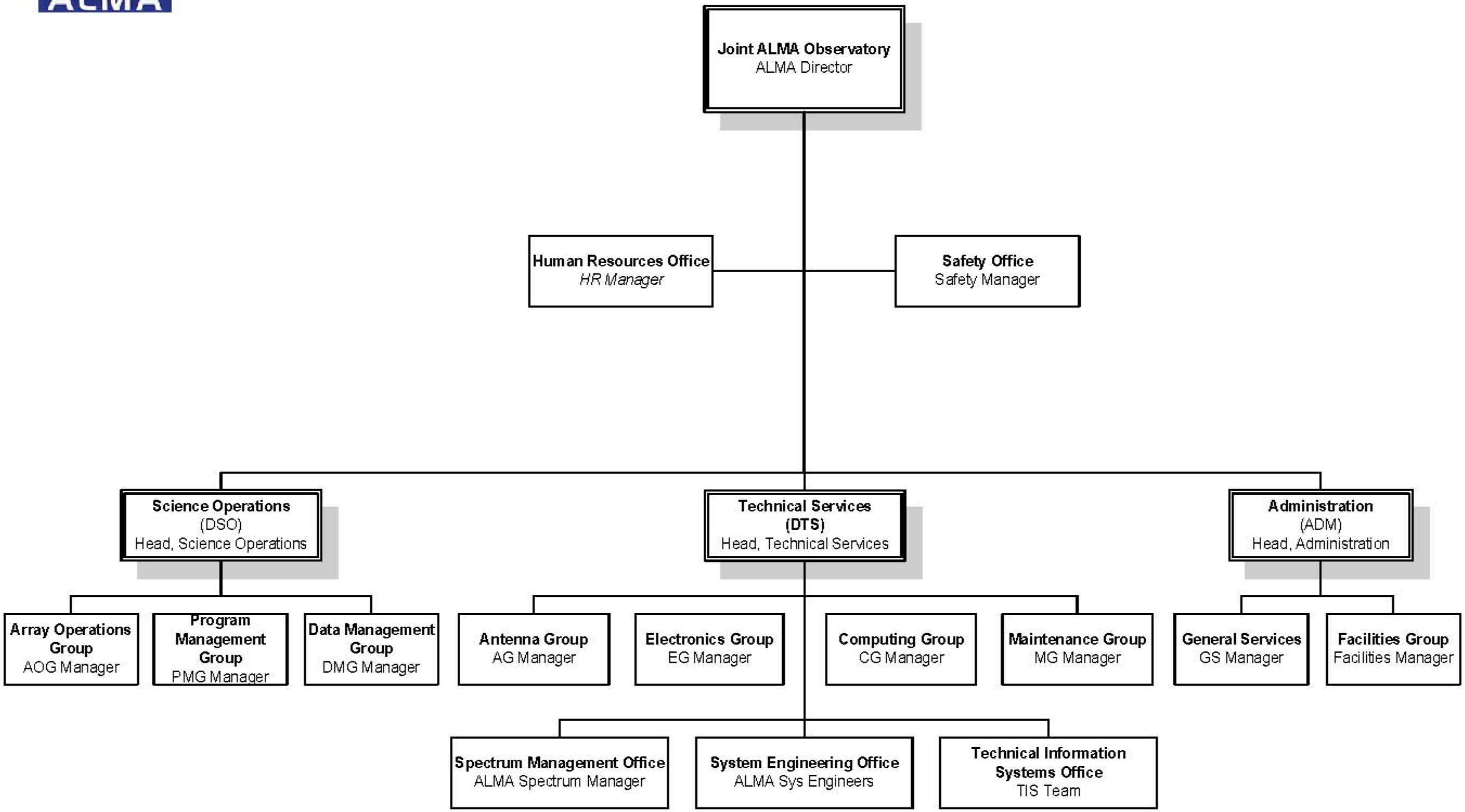
NINS/AS
NAOJ
ESO
NSF/NRC
AUI
NRAO
ALMA Board
AMAC
ASAC
Joint ALMA Observatory
ALMA Director
Head of Administration
Head of Science Operations
Head of Technical Services
Chilean Operations
East Asia
ARC Manager
European
ARC Manager
North American
ARC Manager
East Asia
ALMA Regional
Center
European
ALMA Regional
Center
North American
ALMA Regional
Center

Joint ALMA Observatory



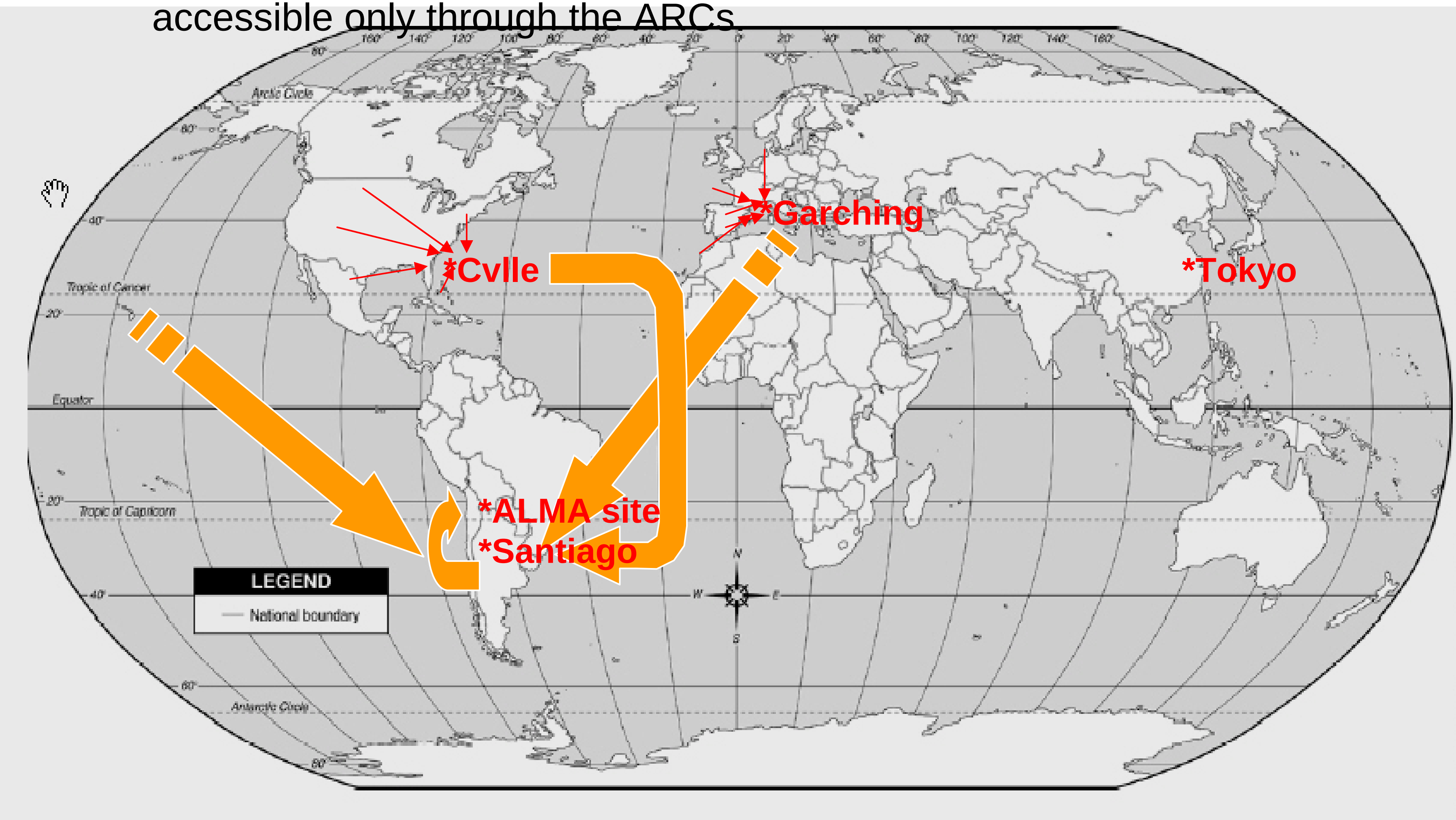
February 2007

Joint ALMA Observatory



ALMA Regional Centers

To the user community, the Joint ALMA Observatory will be remote and accessible only through the ARCs.



ALMA
ATACAMA LARGE MILLIMETER ARRAY