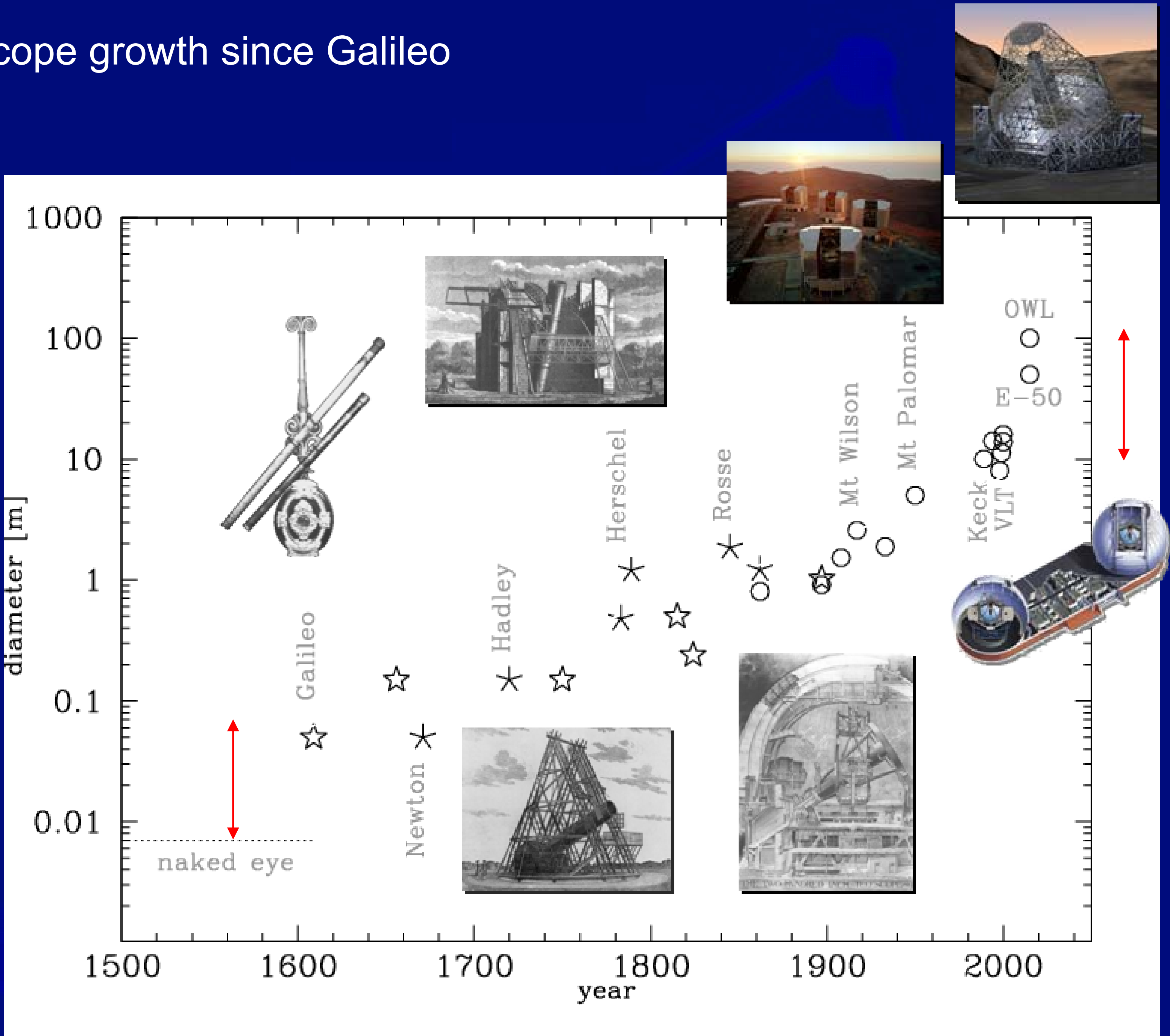
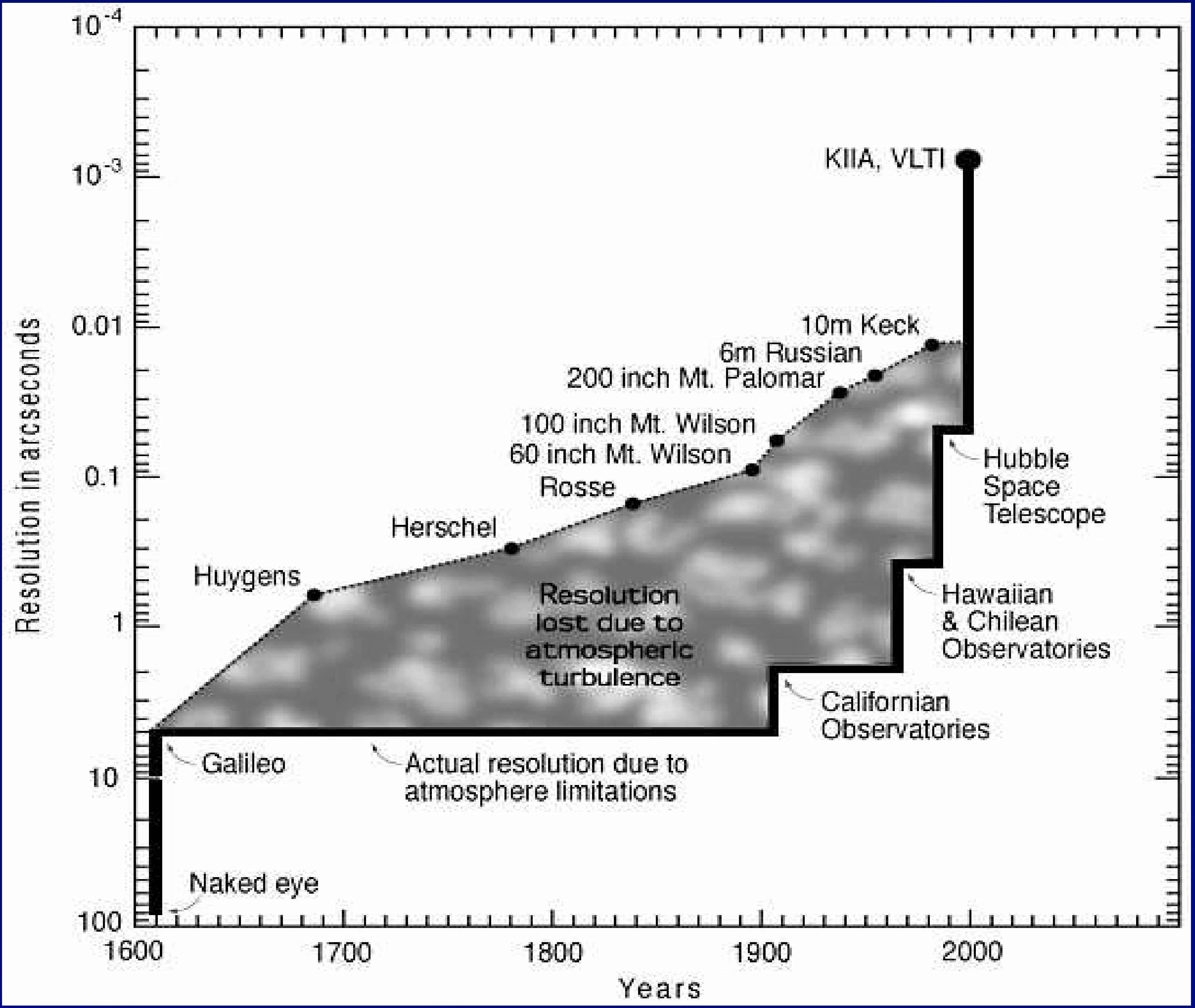
Interferometry : VLTI + ALMA

Massimo Tarenghi
ALMA Director

Santiago 4 December 2006

Telescope growth since Galileo





KIIA, VLTI
10m Keck
6m Russian
200 inch Mt. Palomar
100 inch Mt. Wilson
60 inch Mt. Wilson
Rosse
Herschel
Huygens
Resolution lost due to atmospheric turbulence
Hubble Space Telescope
Hawaiian & Chilean Observatories
Californian Observatories
Galileo
Actual resolution due to atmosphere limitations
Naked eye
Resolution in arcseconds
Years
10^-4
10^-3
0.01
0.1
1
10
100
1600
1700
1800
1900
2000

Principle of Interferometry

Observing the same object with two (or more) telescopes

=> Collecting more photons
but same image quality

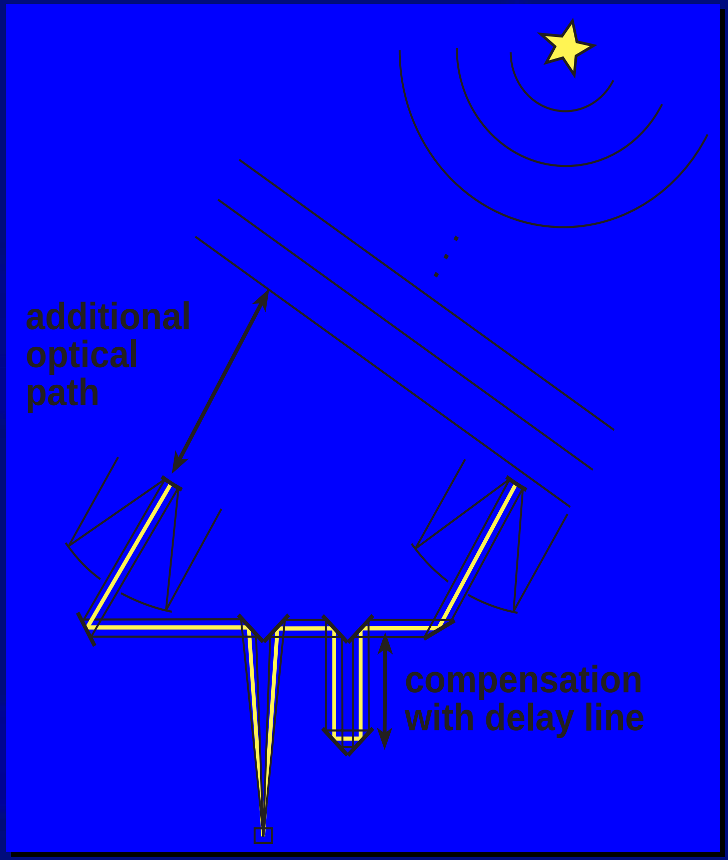
Compensate for optical path difference

=> Interferogram has higher
angular resolution

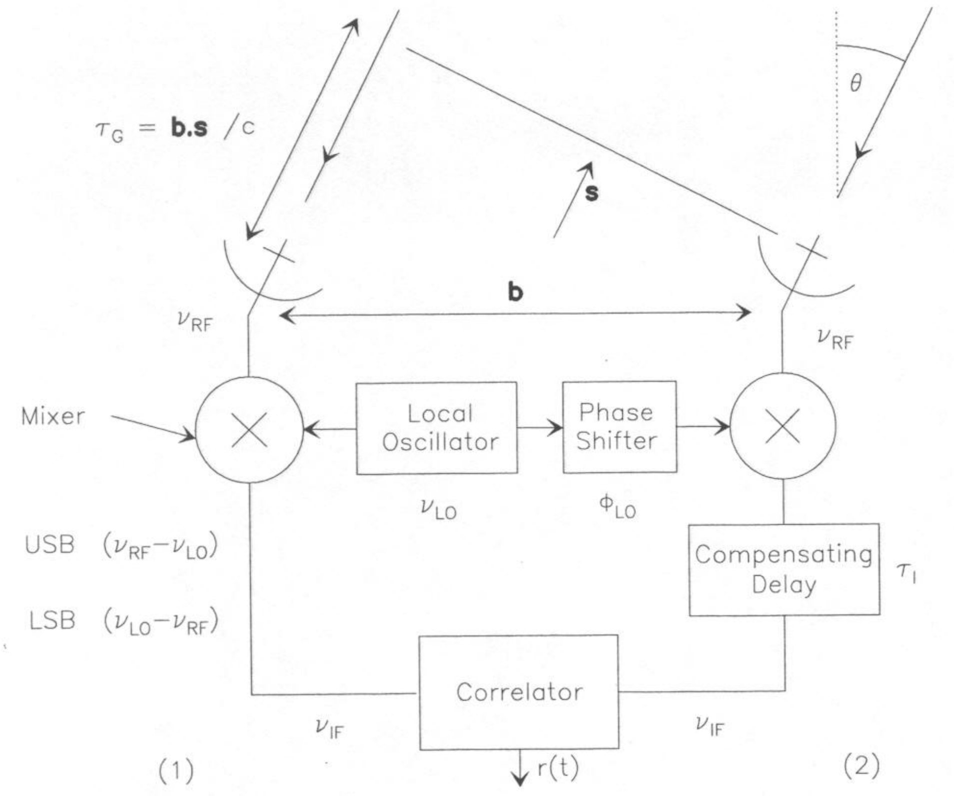
Requirements for Delay Lines

Position accuracy 1μm over 65m of travel

Tip-tilt <1.5 arcsec

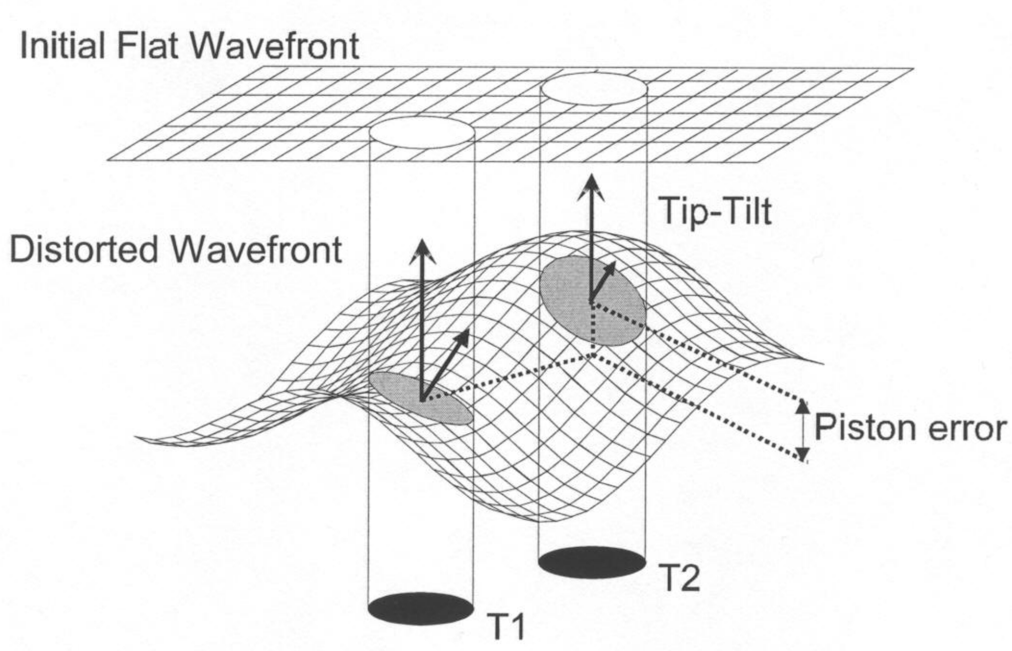


We know it works well in the radio (VLA,VLBI etc). Radio interferometers look exactly the same as O/IR interferometers from the front, so...



Radio vs OI: some similarities, BIG differences

For both, the atmosphere above telescopes/antennas adds a random phase that has to be accounted for (fringe packet moves randomly near ZOPD) ➔ need for calibrating the measured complex visibility with a point source (Transfer Function similar to PSF).



But...

In the radio (10-600 THz):

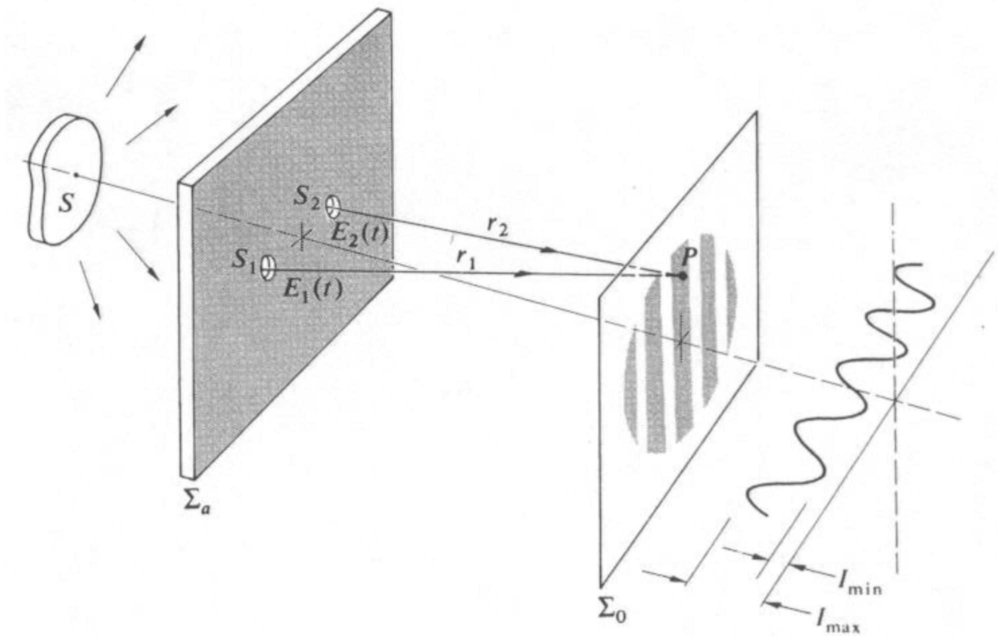
t_0=atmospheric coherence time~20min,

iso-planatic patch~1-2°

In the O/IR:

t_0~10ms, iso-planatic patch~30”

This means that phase referencing in the radio can be done by off-pointing to a calibrator star, in O/IR this is essentially impossible!



S
S_2
$E_2(t)$
S_1
$E_1(t)$
r_2
r_1
P
Σ_a
Σ_0
I_{min}
I_{max}

Why are fringes better?

Small star and large star

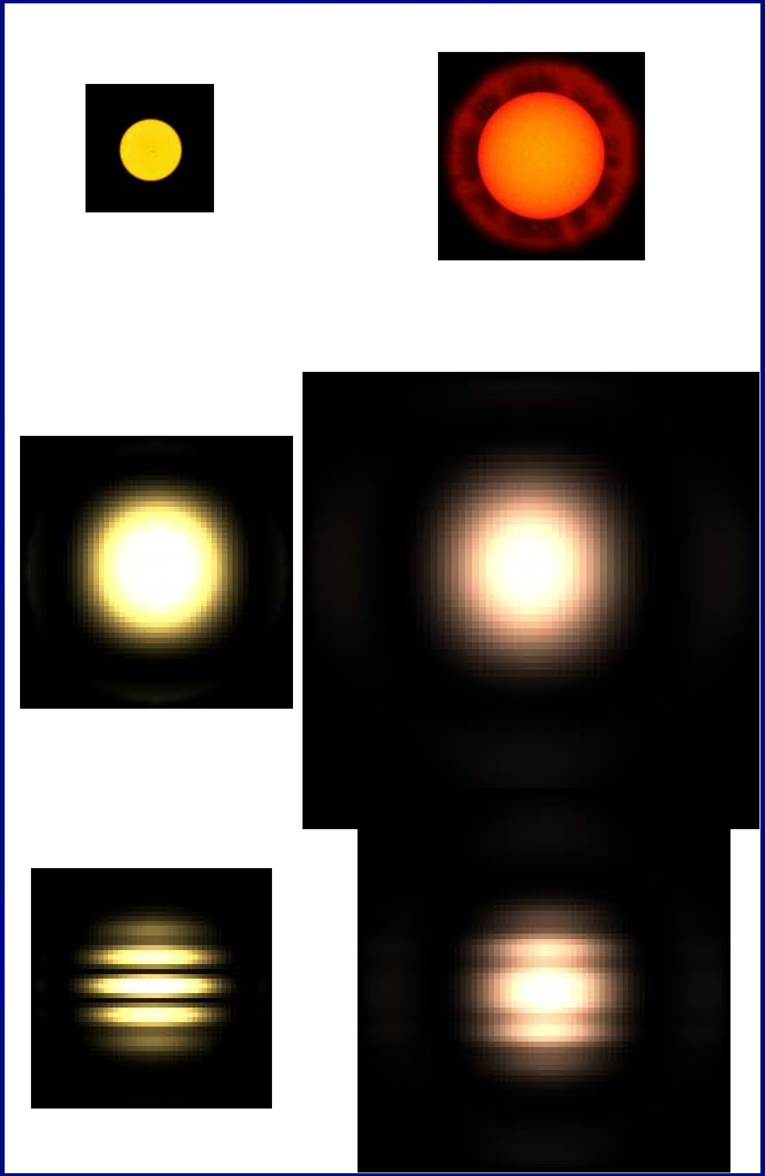
- Angular star diameter varies with size of star and distance

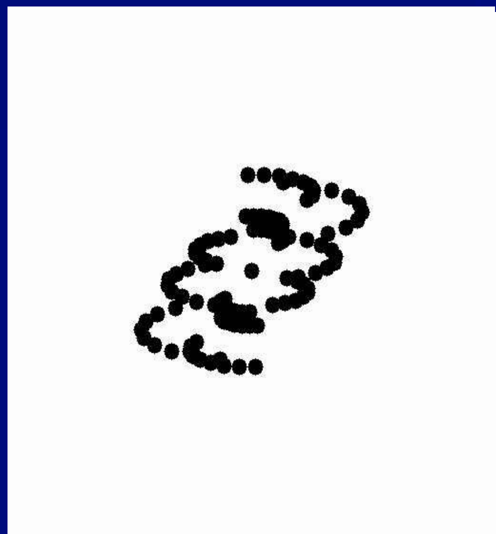
Images have the same size.

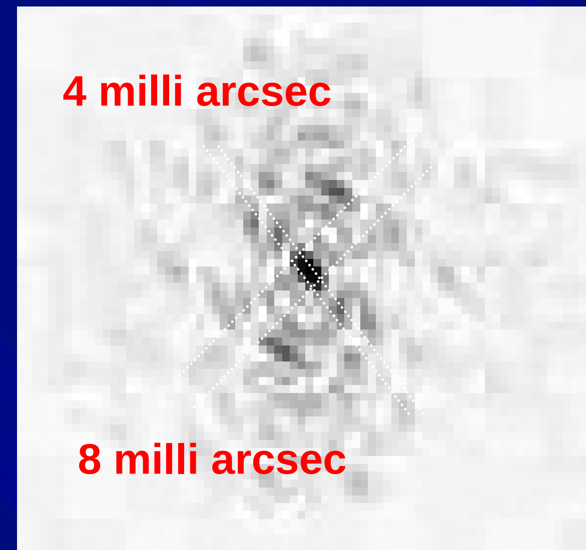
- There is a smallest image size depending on the telescope diameter. Even a point has this image size, called the Point Spread Function (PSF).

Interferograms are different

- Their equivalent PSF is smaller than that of the individual telescopes.







uv coverage for
object at -15∞
8 hour observation with all UTs

Resulting PSF is the Fourier transform of the visibilities

λ = 2.2μm (K-band)

Magnitude limit K~20

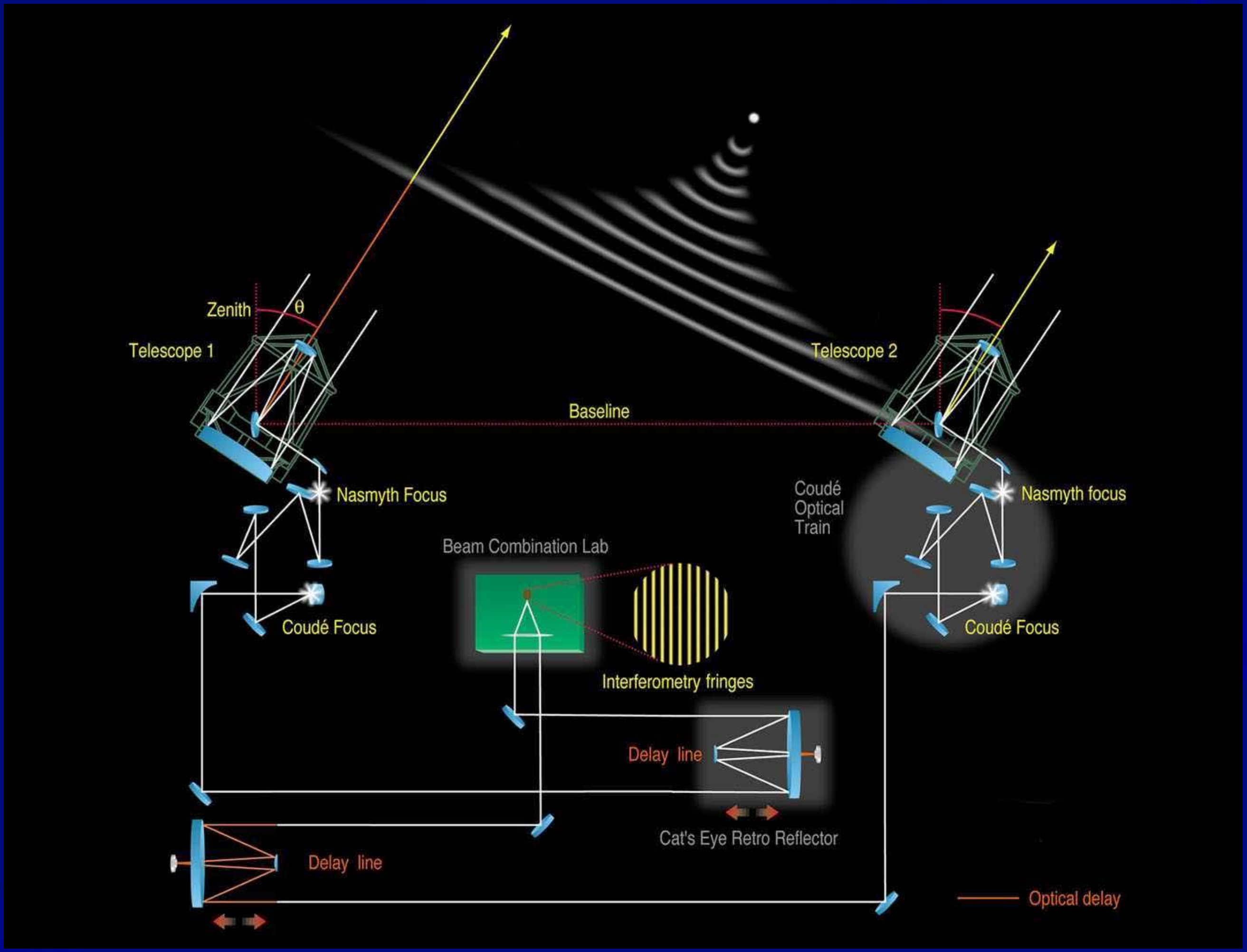
Optical/IR Long Baseline Interferometry: (very) Brief History

- First serious use of OI in astronomy: angular separation of Capella (Anderson, ApJ, 51, 263, 1920); diameter of Betelgeuse (Michelson and Pease, ApJ, 53, 249, 1921) both with the Michelson interferometer on Mt.Wilson
- Routine measurement of stellar diameters (Hanbury-Brown and Twiss, Nature, 177, 27, 1956) with the intensity interferometer at Narrabri, Australia.
- First direct combination of light from 2 telescopes (Labeyrie, ApJ, 196, L71, 1975) at Nice Obs.
- First optical synthesis imaging of Capella with COAST (Baldwin et al., A&A, 306, L13, 1996)
- First combination of very large telescopes (Keck 10m, VLT 8m), 2001
- First 6-way beam combination at NPOI, Flagstaff, 2002

Current situation: large interferometers everywhere!

- VLTI on Paranal (4x8m+3x1.8m, B=200m)
- Keck interferometer on Mauna Kea (2x10m+4x1.8m, B=140m)
- CHARA on Mt. Wilson (6x1m,B=350m)
- LBT on Mt. Graham (2x8.5m, B=23m)
- SUSI, Aus, (3x0.15m, B=640m)
- NPOI, Flagstaff, AZ, (10x0.5m, B=440m)
- SIM, Darwin, TPF in space

VLTI optical schematic

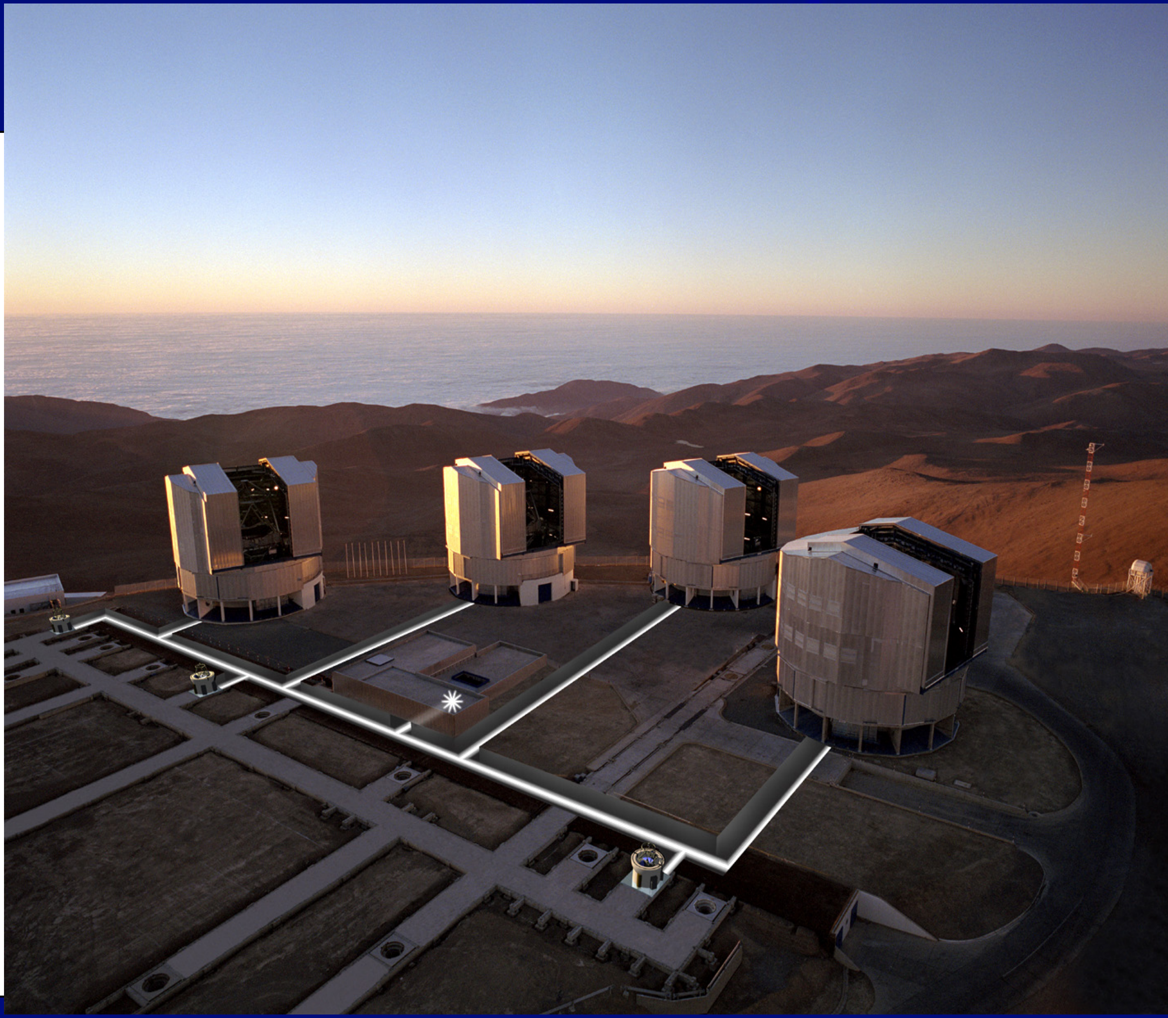


The VLT Interferometer

Four 8-m Unit Telescopes
Max. Baseline 130m
fi angular resolution:
  1.5 – 30 milli arcsec

Four 1.8-m Auxiliary Telescopes
Baselines 8 – 200m
fi angular resolution:
  1 – 20 milli arcsec

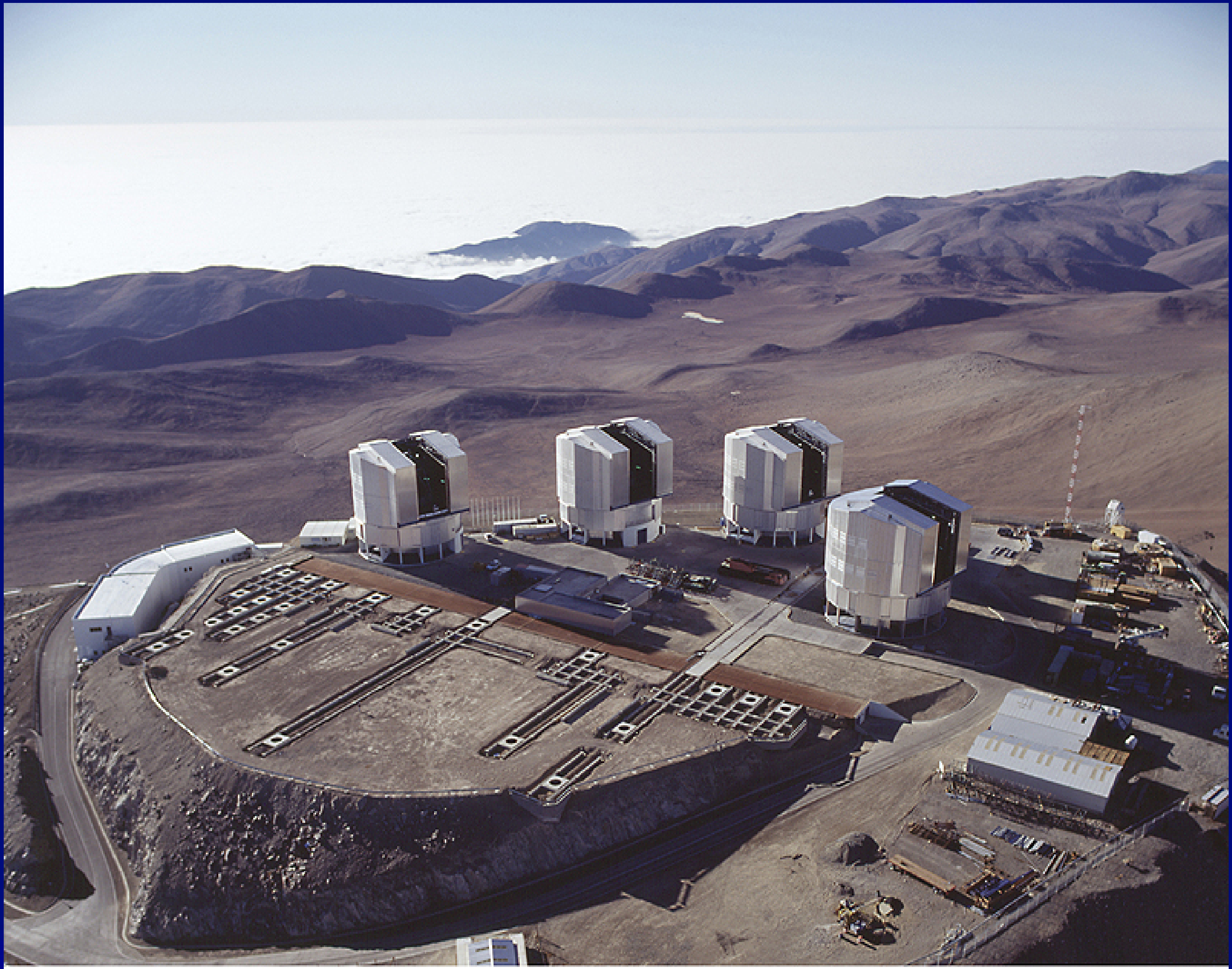
Excellent uv coverage



Paranal

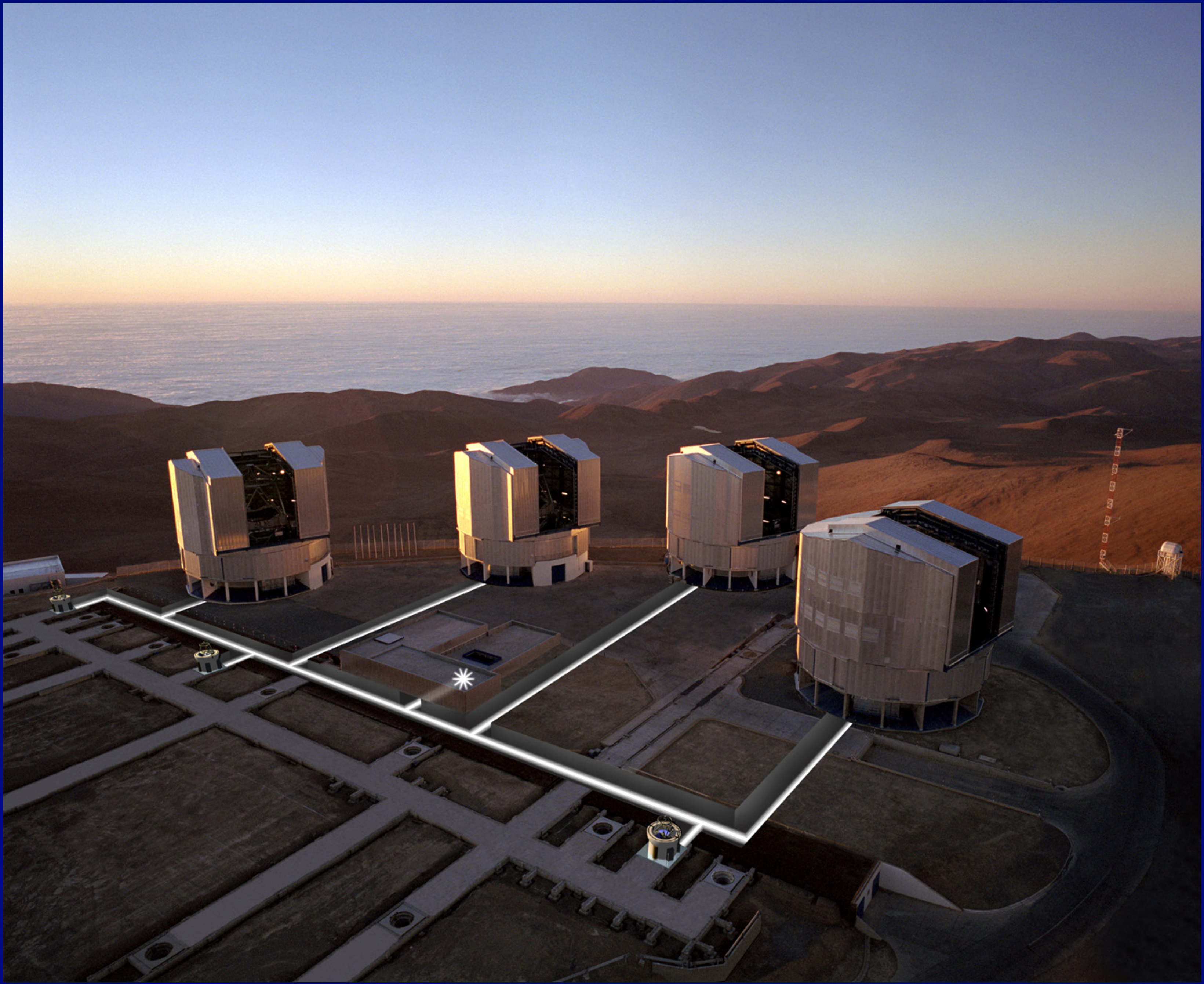

CERRO PARANAL
1991
1994
1999
PARANAL OBSERVATORY
ESO PR PHOTO 36/00 (20 DECEMBER 2000)

Paranal Observatory

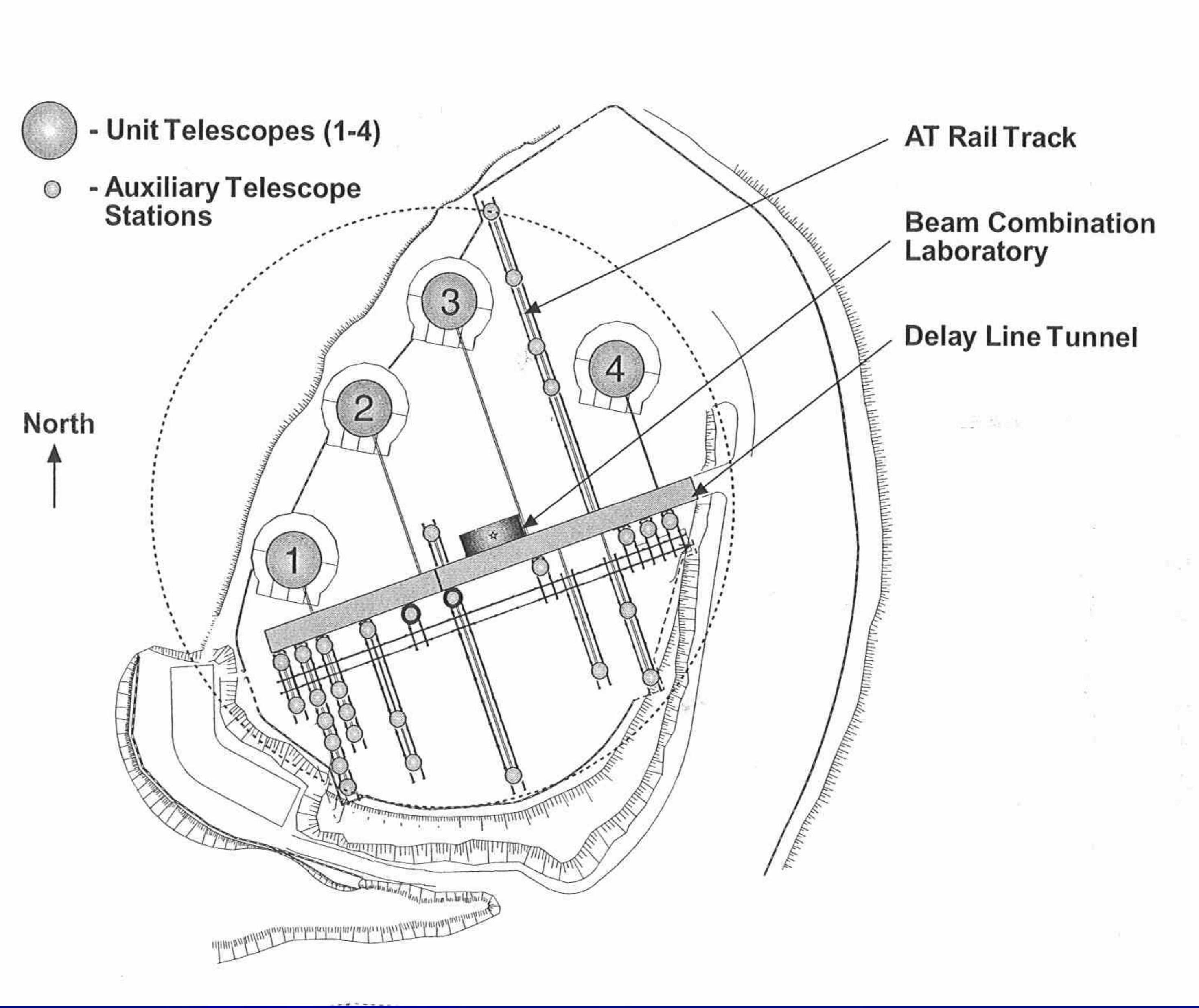


VLT at Paranal

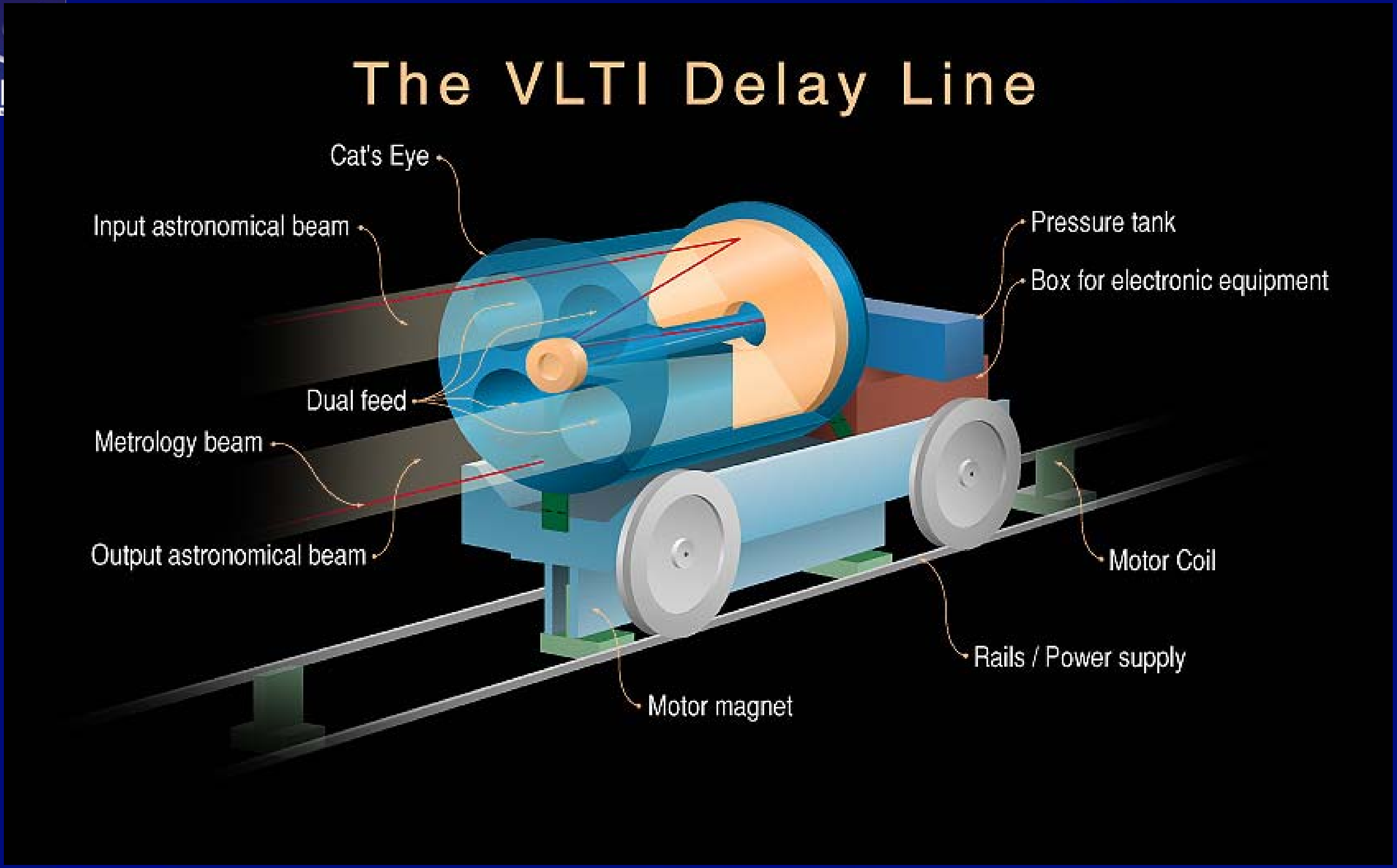
ESO PR Photo 43b/99 (8 December 1999)



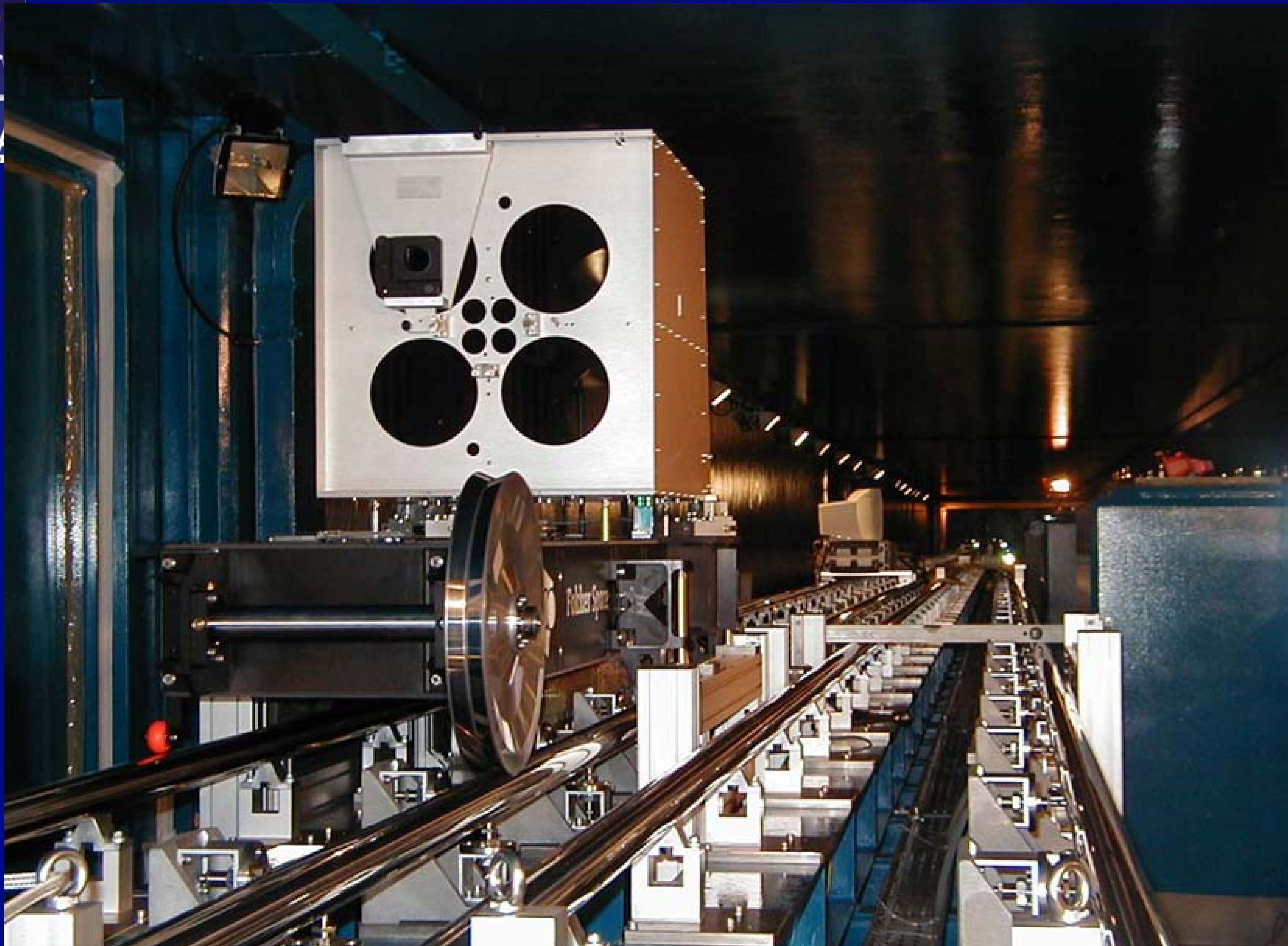
VLTI



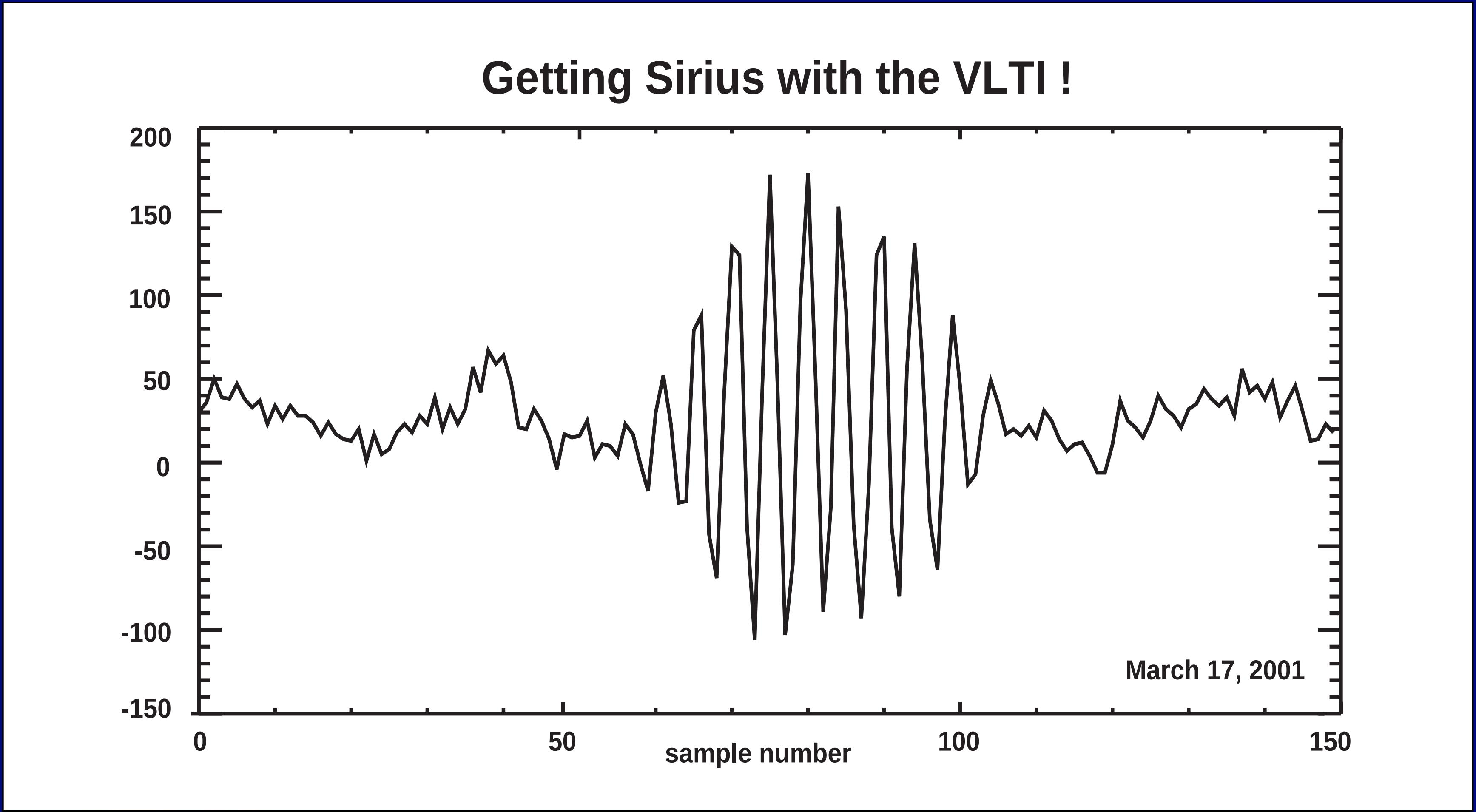
- Unit Telescopes (1-4)
- Auxiliary Telescope Stations
AT Rail Track
Beam Combination Laboratory
Delay Line Tunnel
North
1
2
3
4


The VLTI Delay Line
Cat's Eye
Input astronomical beam
Pressure tank
Box for electronic equipment
Dual feed
Metrology beam
Output astronomical beam
Motor Coil
Rails / Power supply
Motor magnet

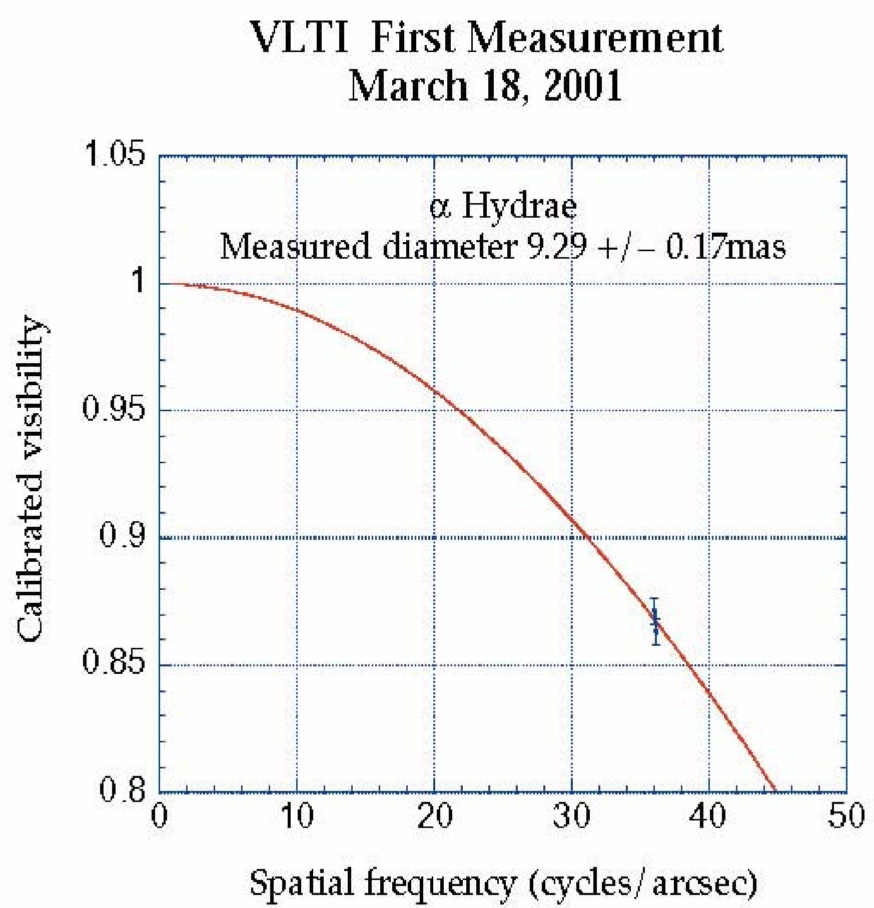
ALMA



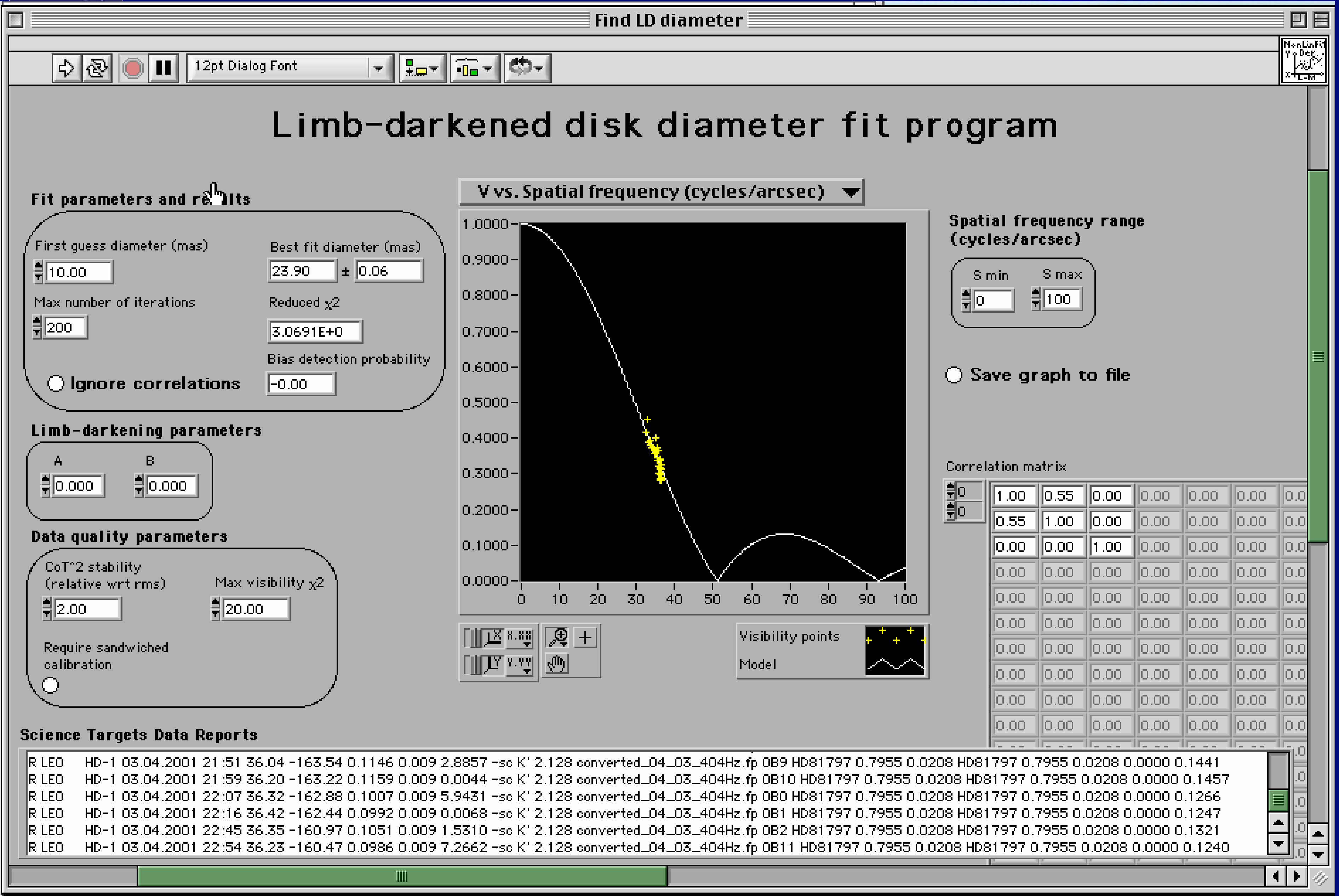
First Fringes with VINCI and Siderostats



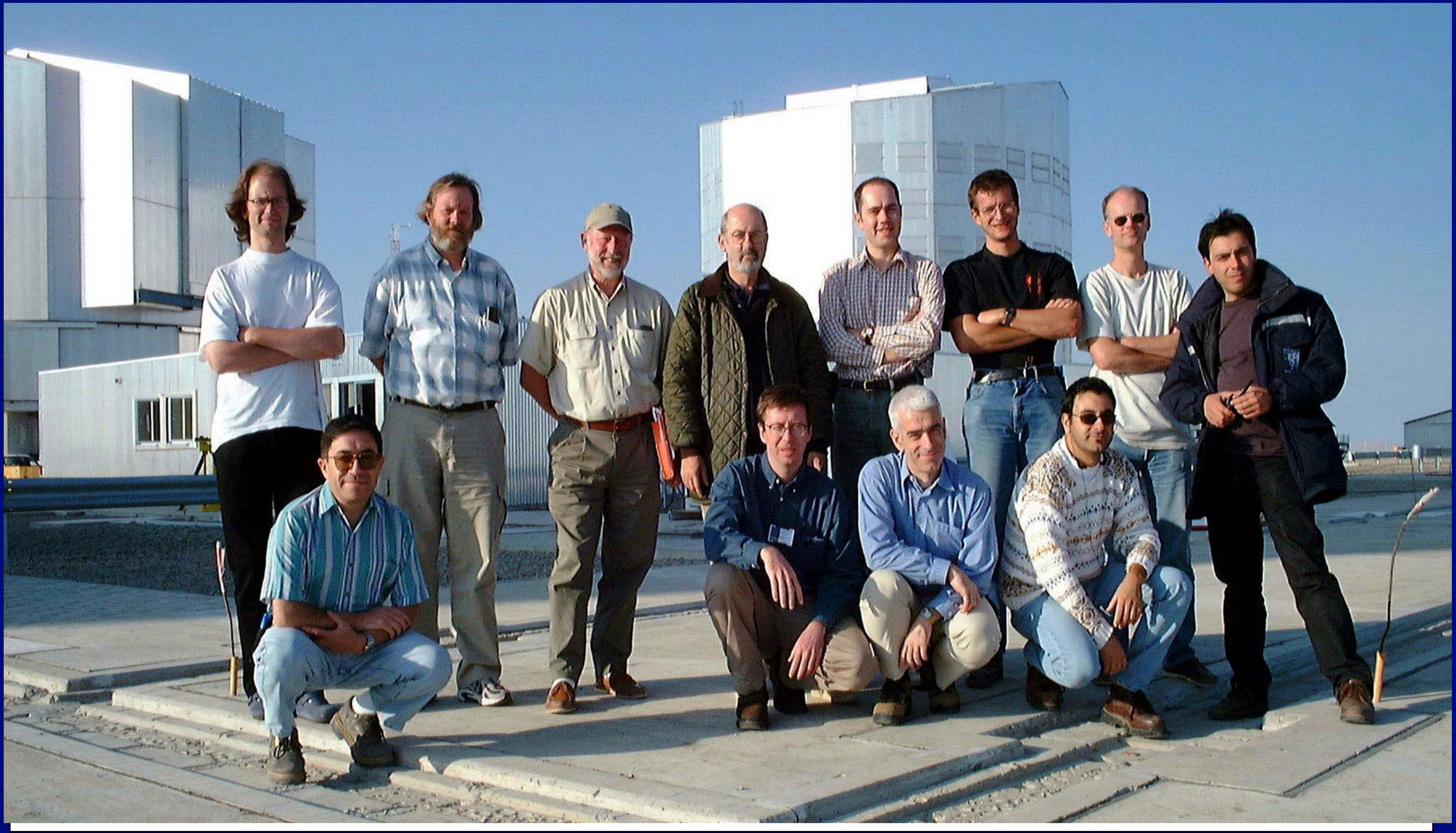
First star diameter



Full set of data on R Leo



The First Fringe Team at Paranal

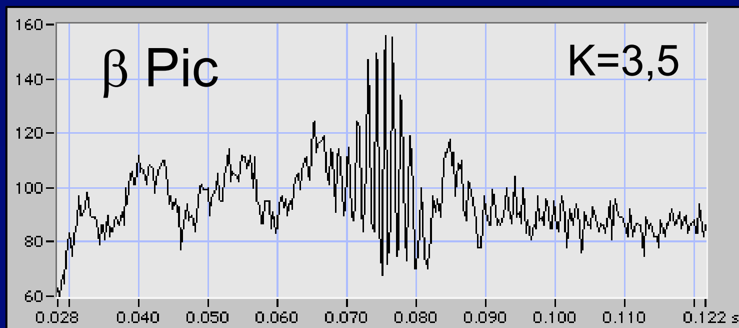


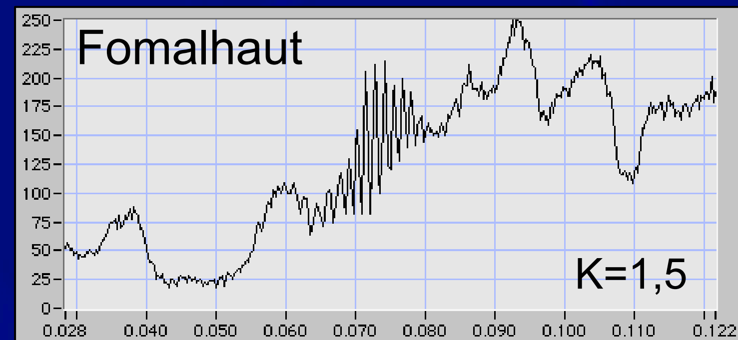
March 18, 2001

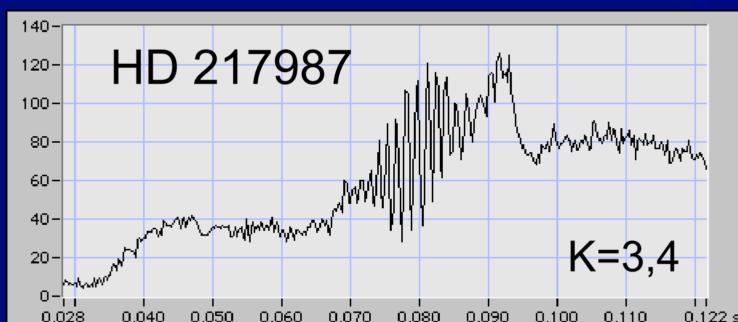
The VLTI team in Garching

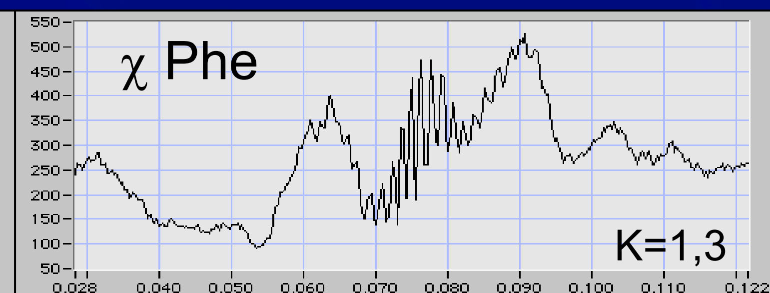
March 19, 2001

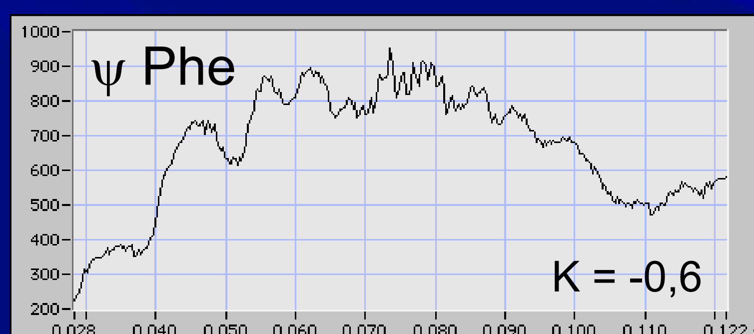
A few examples





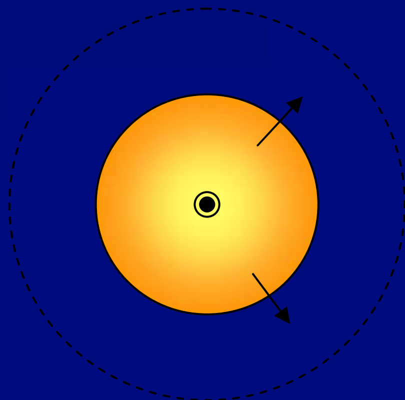


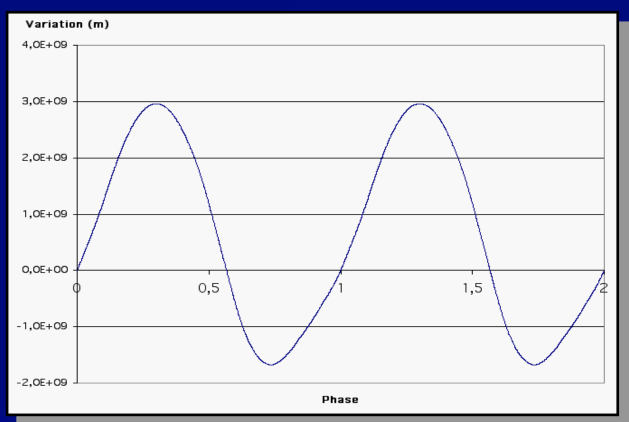




Precise distance determinations using Cepheids

Radial velocity

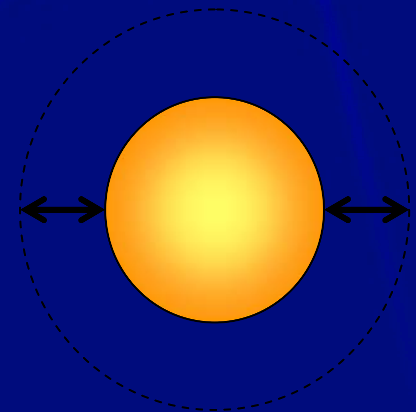


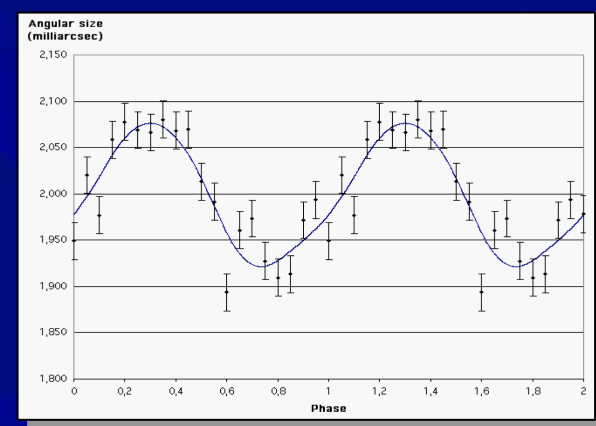


Orthogonal to the plane of the sky

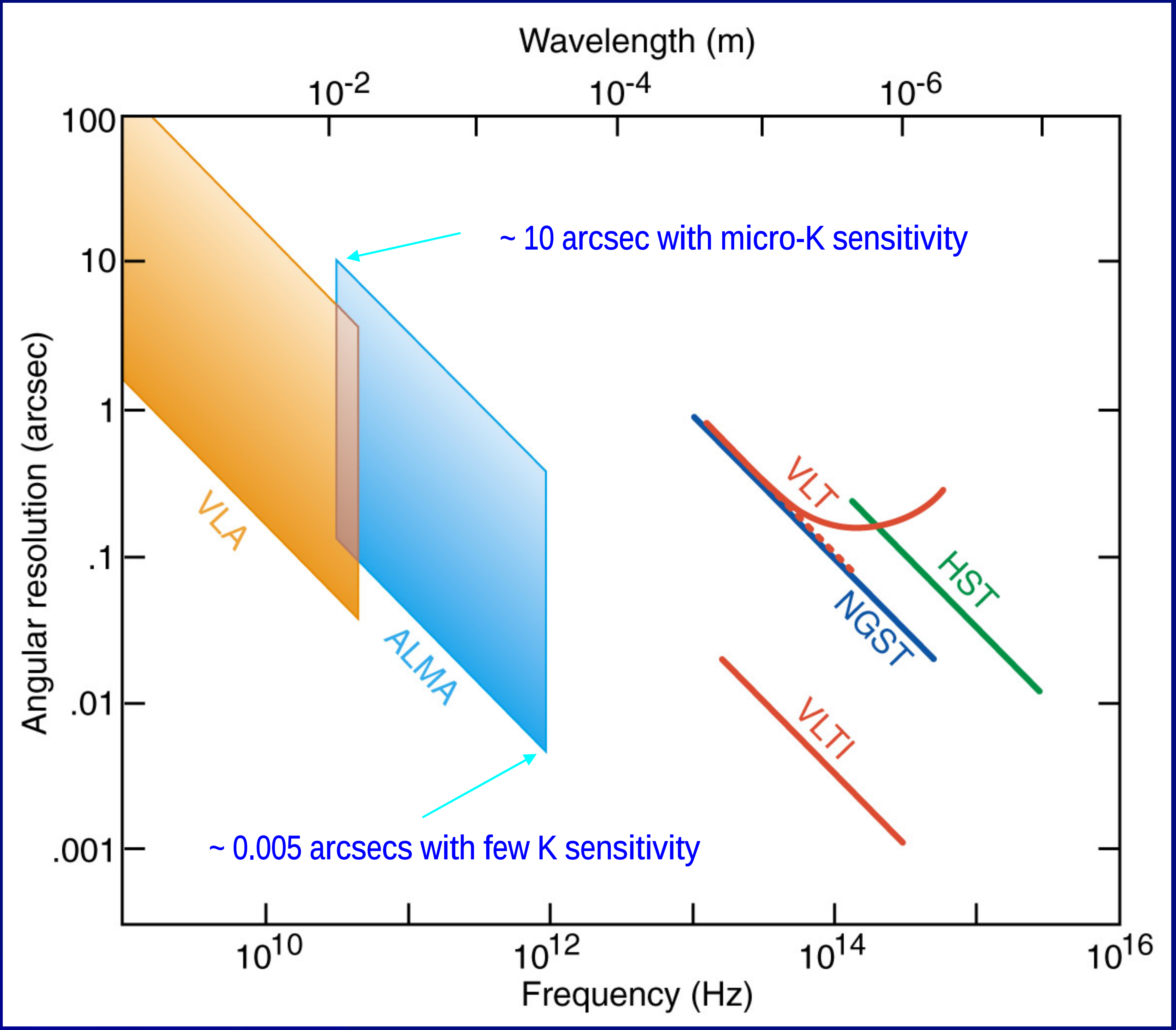
Distance

Interferometry





In the plane of the sky



Wavelength (m)
10-2
10-4
10-6
100
10
1
.1
.01
.001
Angular resolution (arcsec)
~ 10 arcsec with micro-K sensitivity
VLA
ALMA
VLT
HST
NGST
VLTI
~ 0.005 arcsecs with few K sensitivity
1010
1012
1014
1016
Frequency (Hz)

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
European Southern Observatory

P. Vanden Bout
National Radio Astronomy Observatory

26 June 1997

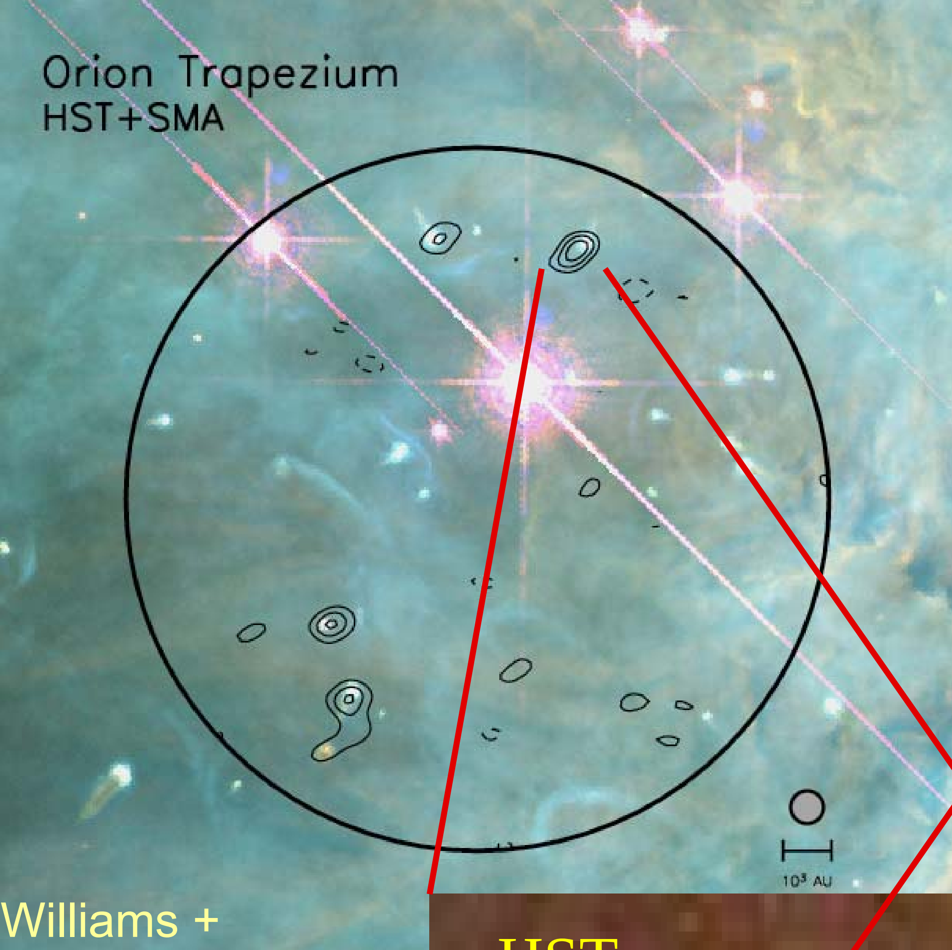
- The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of Europe, Japan and North America in cooperation with the Republic of Chile.
- ALMA is funded in Europe by the European Organisation for Astronomical Research in the Southern Hemisphere and Spain, 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).

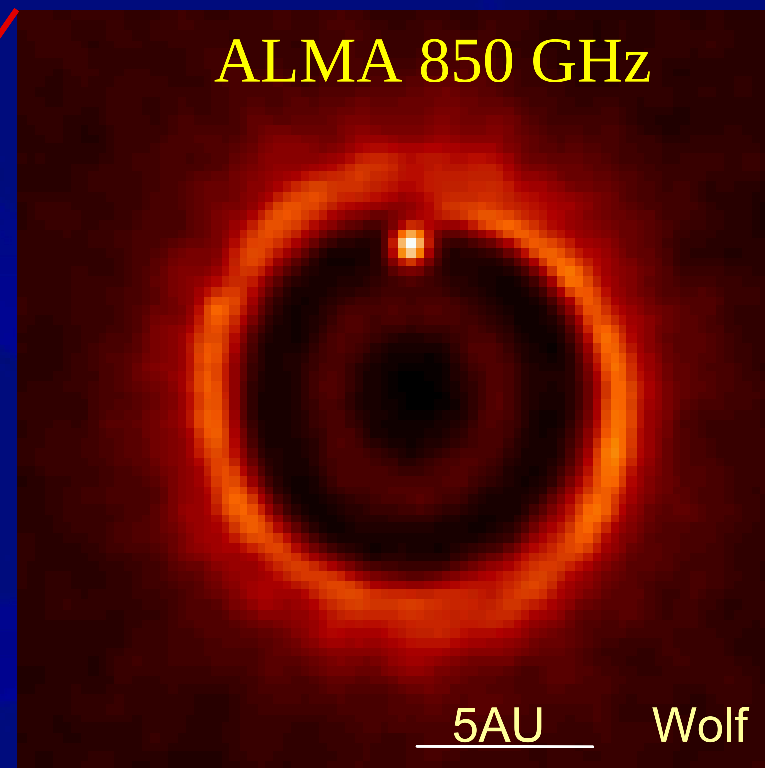
What is ALMA?

- Baselines from 15m to 15km
- 5000m site in Atacama desert
- Receivers: low-noise, wide-band (8GHz), dual-polarisation, SSB
- Digital correlator, >=8192 spectral channels, 4 Stokes
- Sensitive, precision imaging between 30 and 950 GHz
  - 350 GHz continuum sensitivity: about 1.4mJy in one second
  - Angular resolution will reach ~40 mas at 100 GHz (5mas at 900GHz)
  - First light system has 6 bands: 100, 230, 345 and 650GHz
  - Japan will provide 140, 460 and 900GHz
- *10-100 times more sensitive and 10-100 times better angular resolution compared to current mm/submm telescopes*

Birth of planets

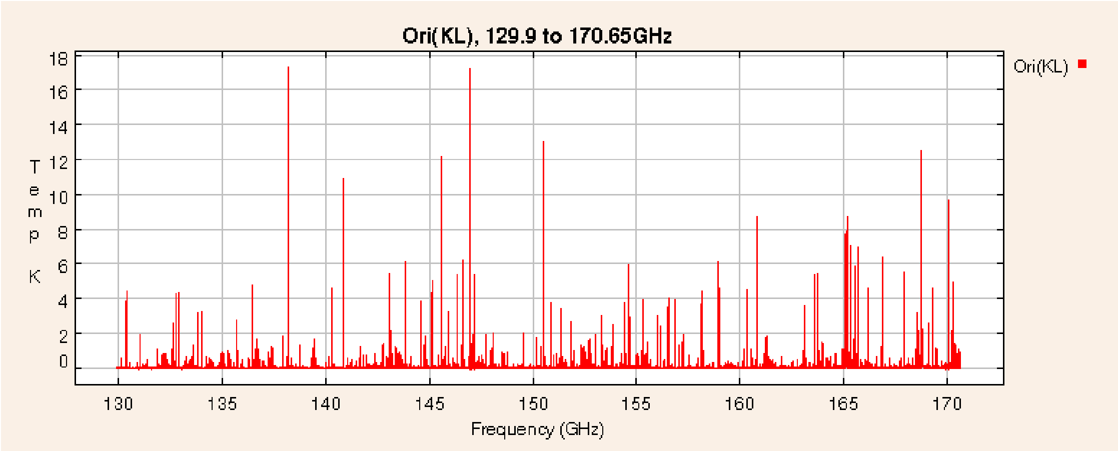
- $M_{planet} / M_{star} = 1.0\ M_{Jup} / .5\ M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus





ALMA Key Science 2: Astrochemistry

Spectrum courtesy B. Turner (NRAO)

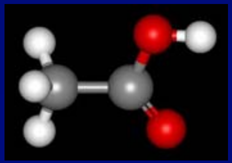


Millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.

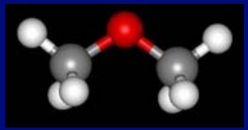
Most of the observed transitions of the 125 known interstellar molecules lie in the mm/submm spectral region—here some 17,000 lines are seen in a small portion of the spectrum at 2mm.

Some complex organic molecules

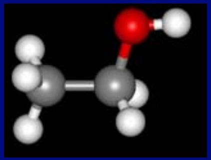
Detected



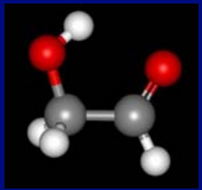
Acetic acid



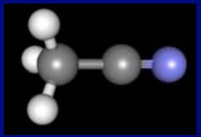
Di-methyl ether



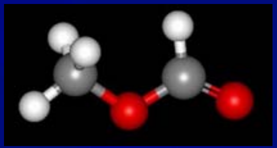
Ethanol



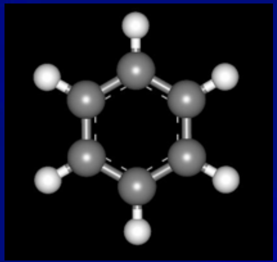
Sugar



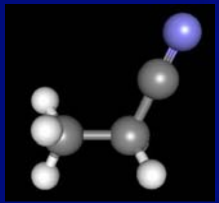
Methyl cyanide



Methyl formate

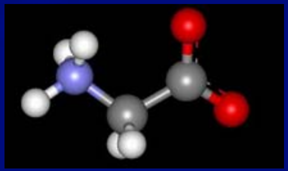


Benzene

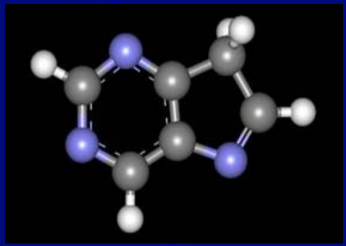


Ethyl cyanide

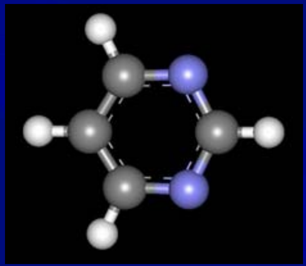
Not (yet) detected



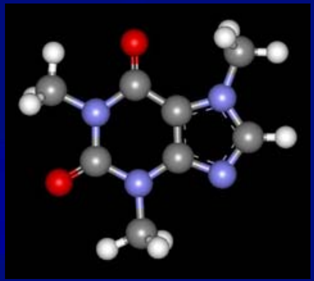
Glycine



Purine



Pyrimidine

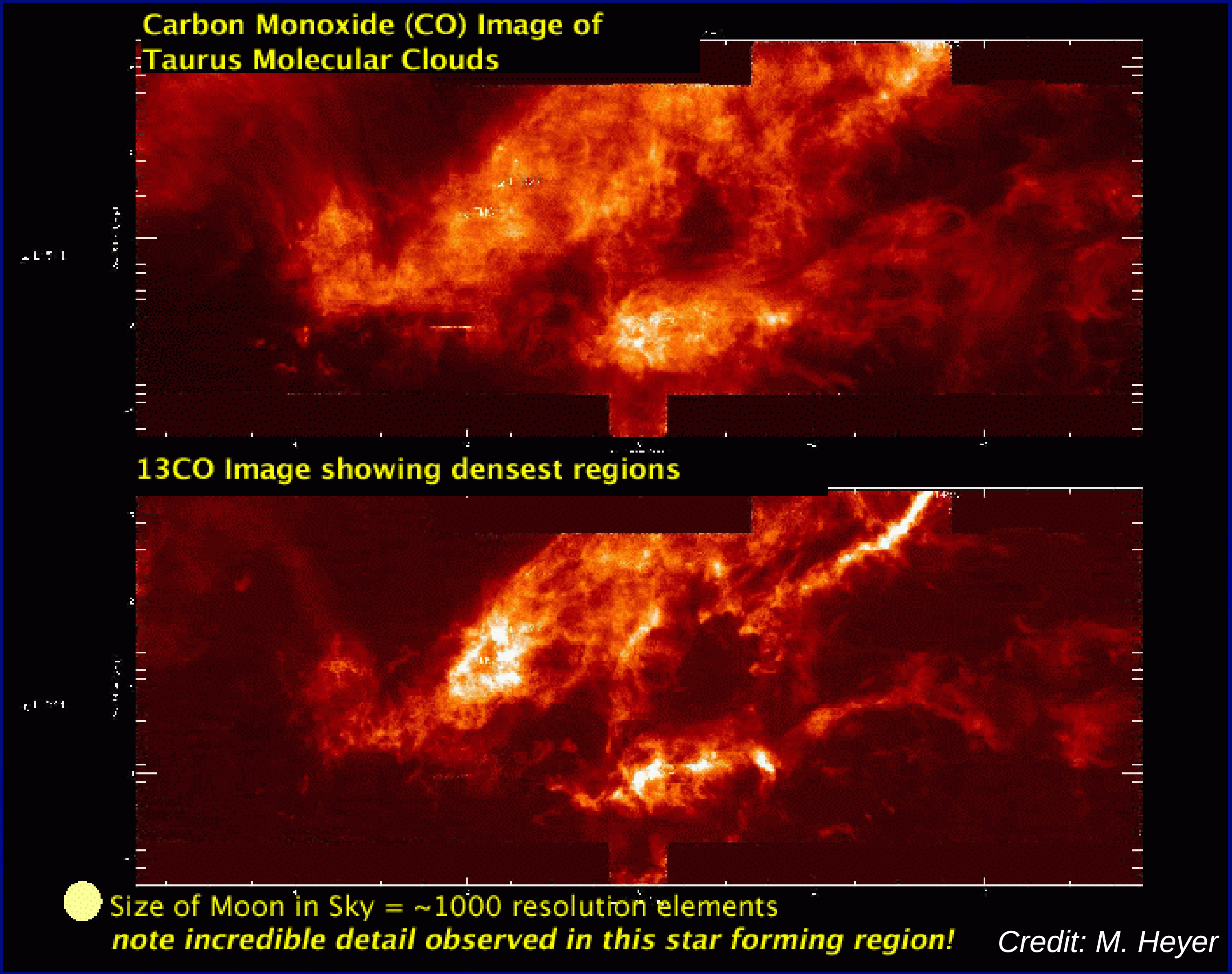


Caffeine

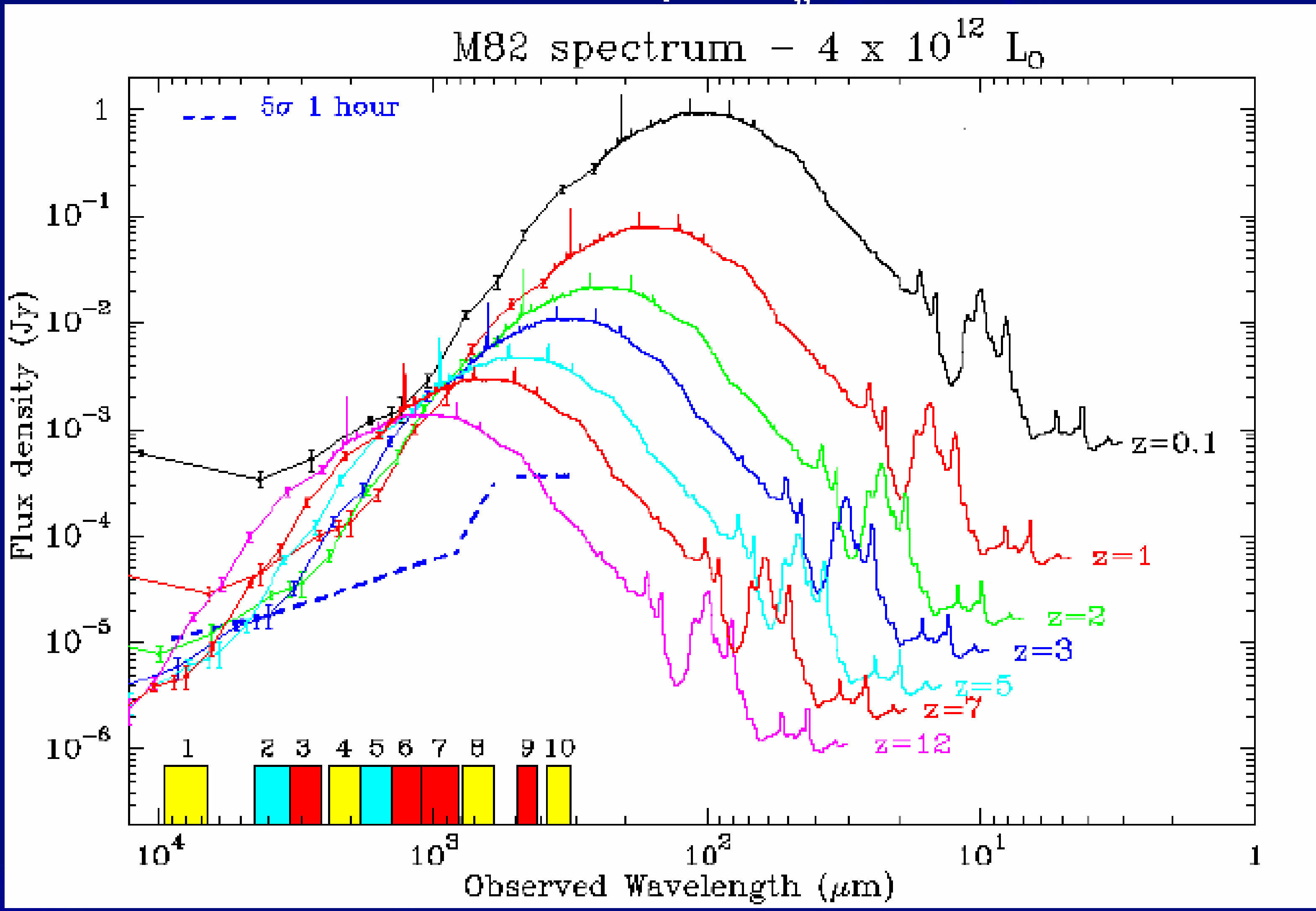
Q13: how far does chemical complexity go? Can we find pre-biotic molecules?

Based on Ehrenfreund 2003

ALMA Key science 3: Interstellar Medium

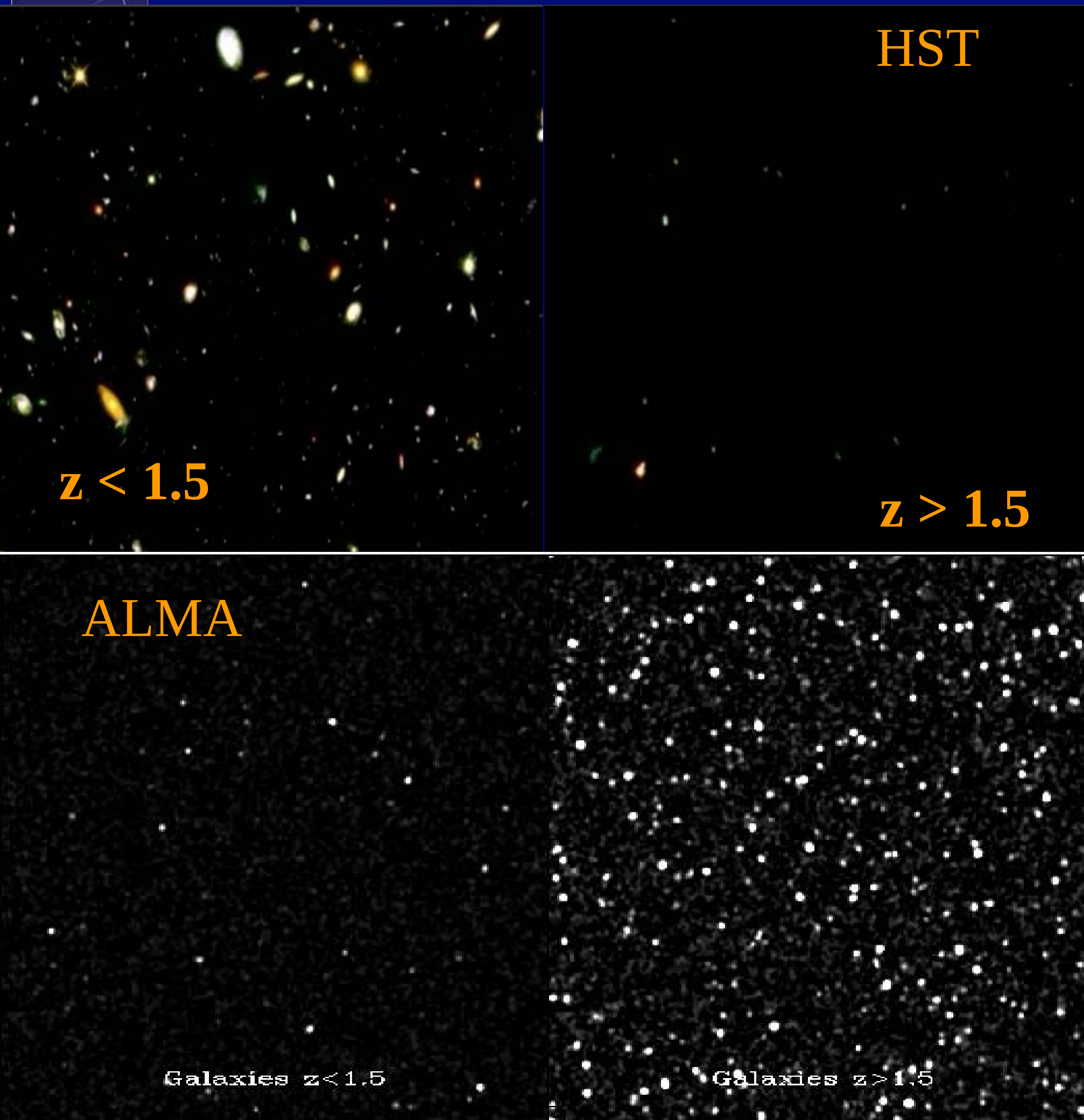


Credit: M. Heyer



M82 spectrum - 4 x 10^12 L_o
5σ 1 hour
Flux density (Jy)
Observed Wavelength (μm)
z=0.1
z=1
z=2
z=3
z=5
z=7
z=12
1 2 3 4 5 6 7 8 9 10

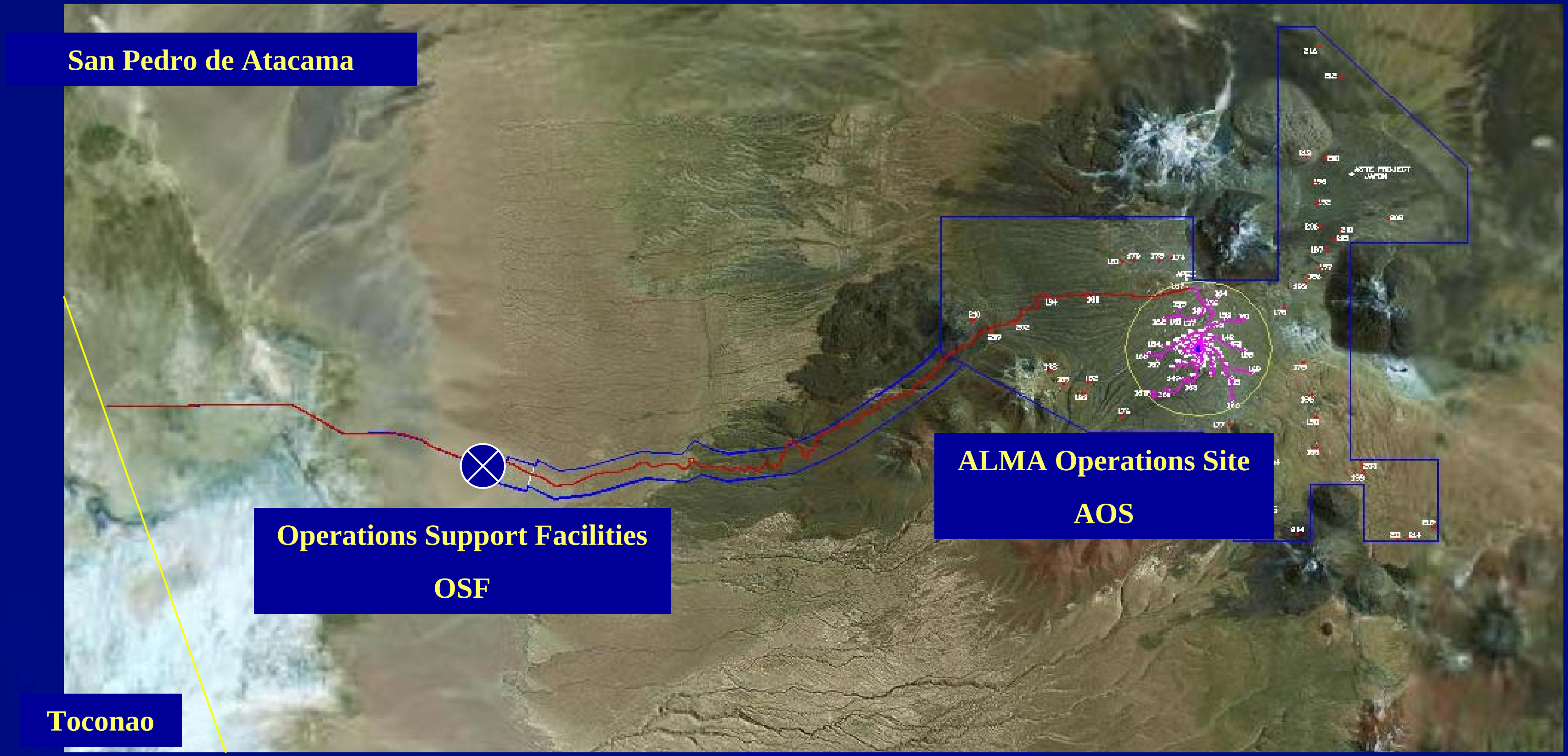
ALMA Deep field: ‘normal’ galaxies at high z



- Detect current submm gal in seconds!
- ALMA deep survey: 3days, **0.1 mJy (5σ),** 4’
- HST: few 1000 Gal, most at $z<1.5$
- ALMA: few 100 Gal, 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


N
W
E
S
©2005 Google

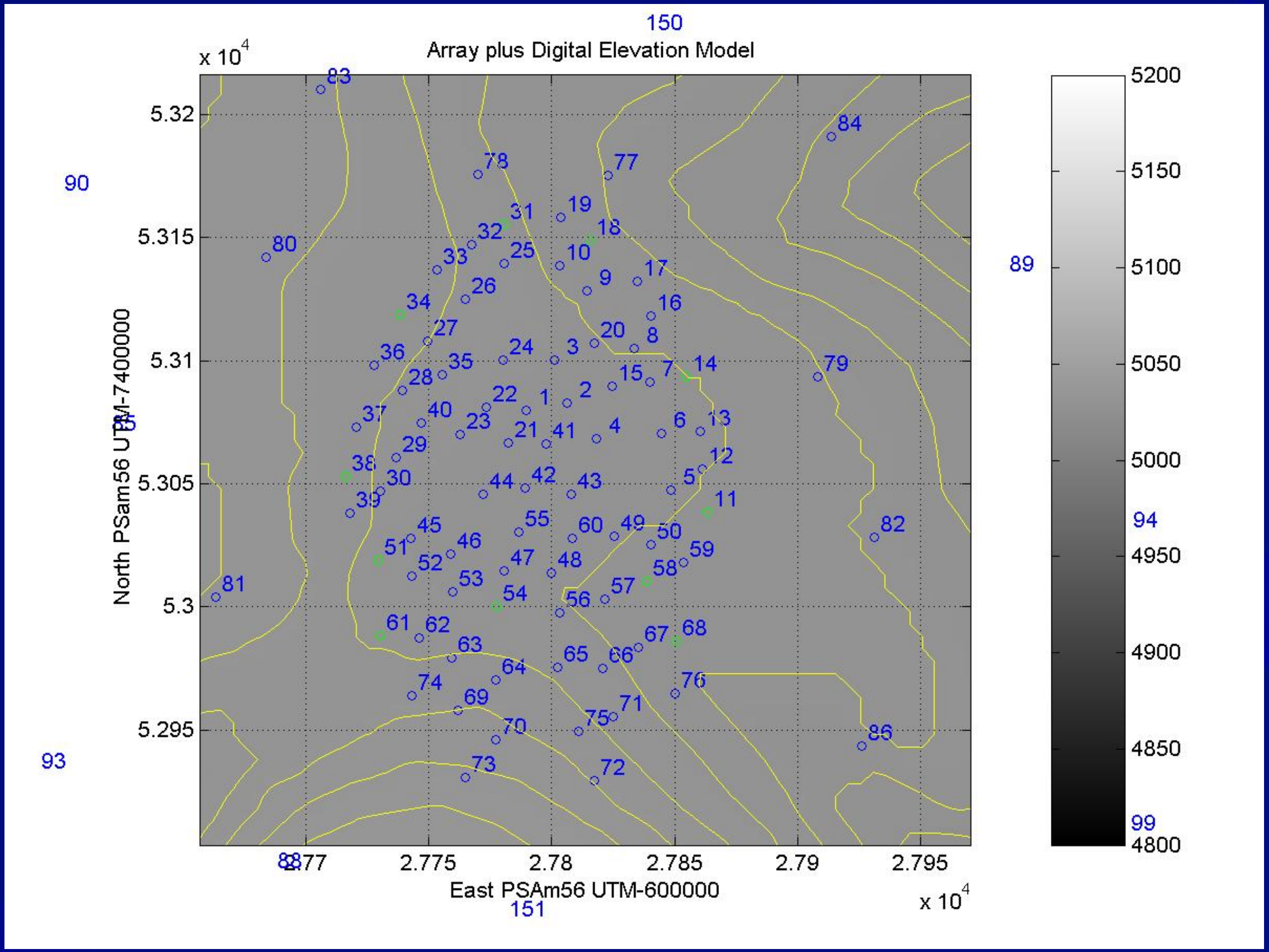
ALMA Site


San Pedro de Atacama
Operations Support Facilities
OSF
ALMA Operations Site
AOS
Toconao

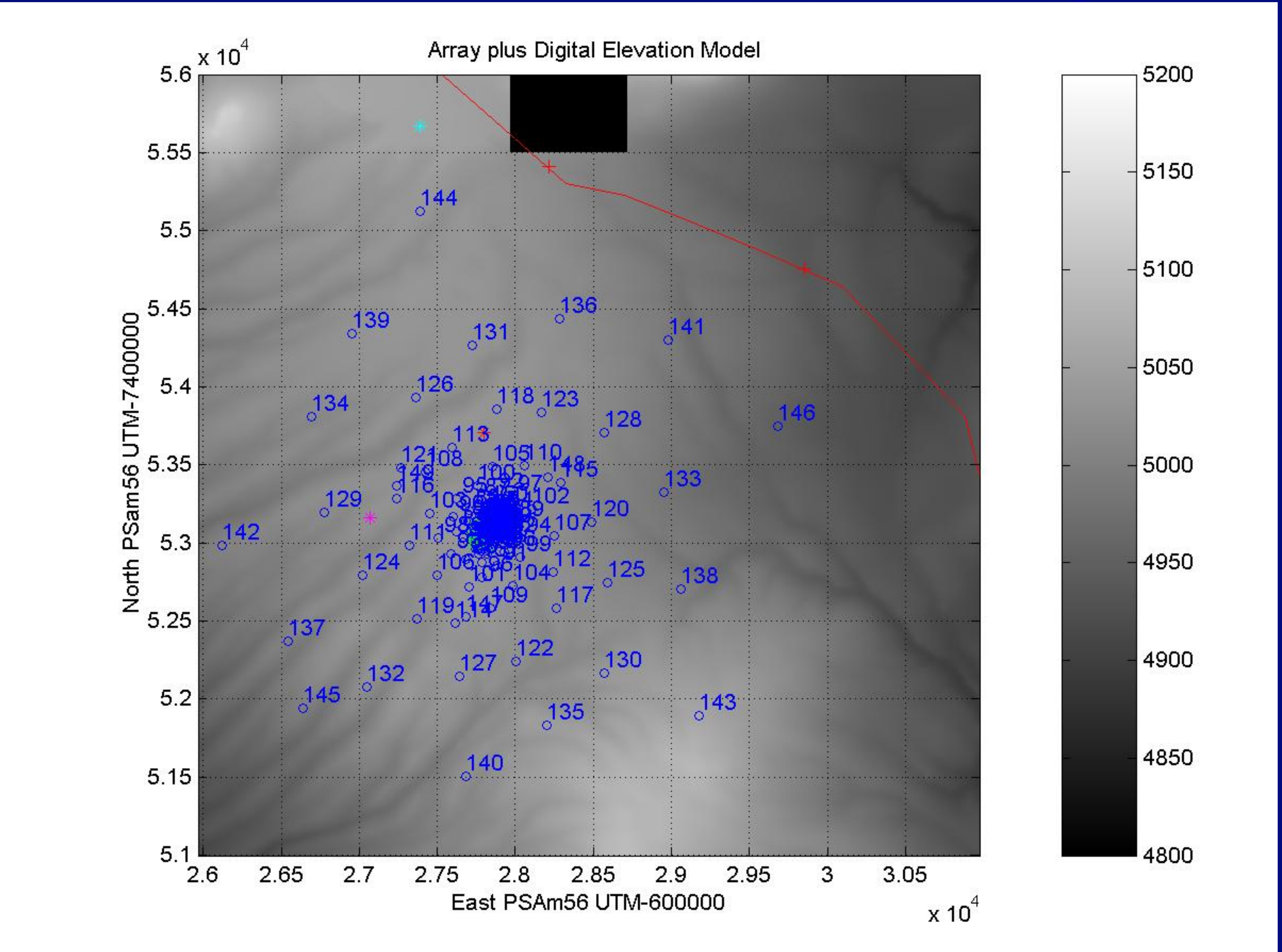
ALMA
ATACAMA LARGE MILLIMETER ARRAY

Central part of the array.

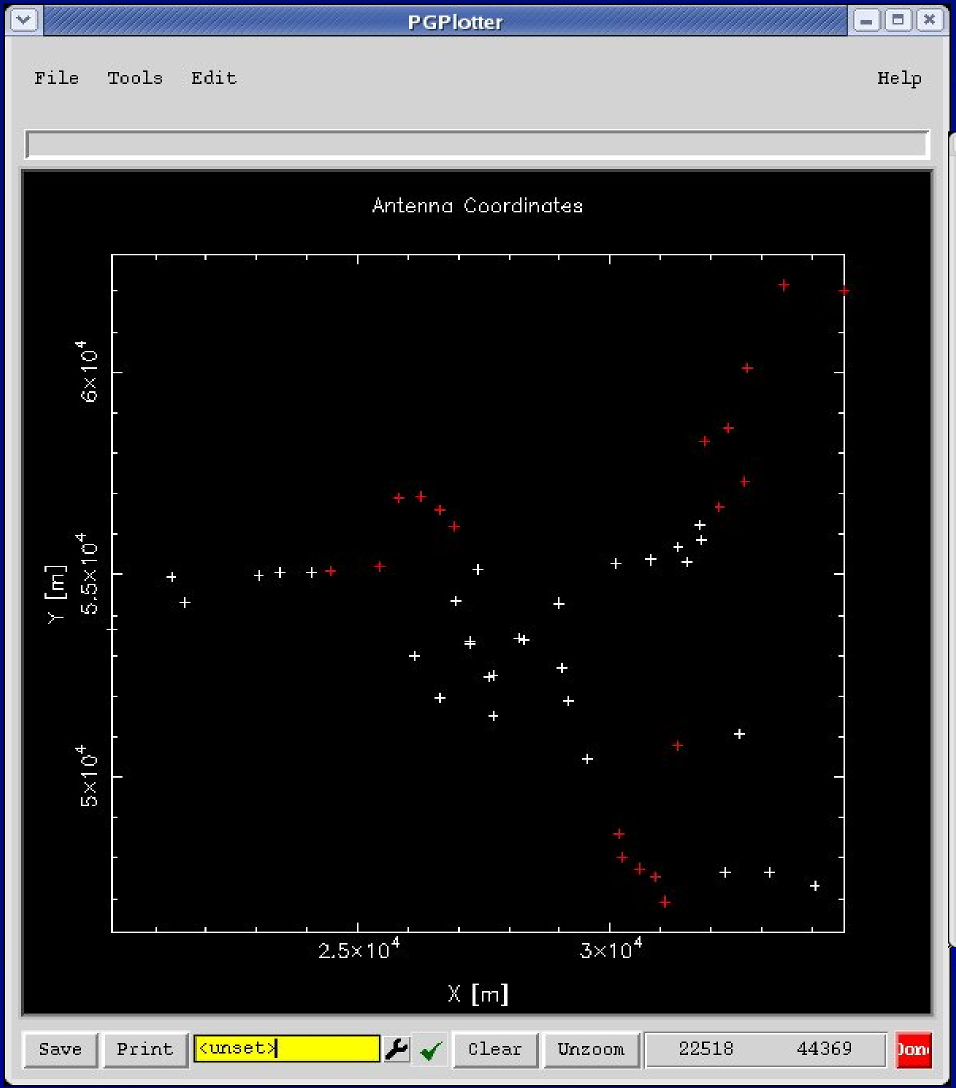
Contours shown are at 1m intervals.

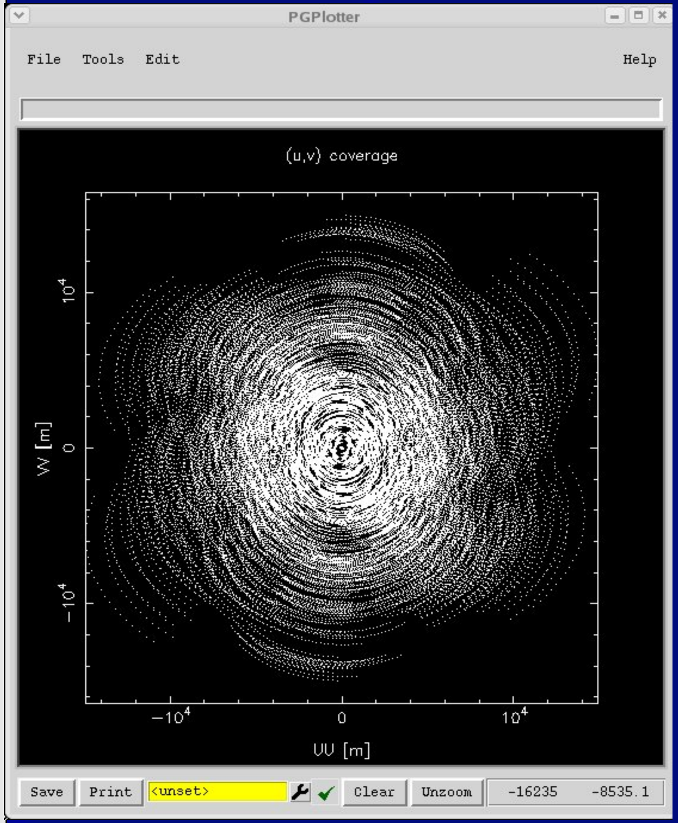


The pad positions overlaid on a grayscale showing Elevation (Black 4800m – White 5200m)

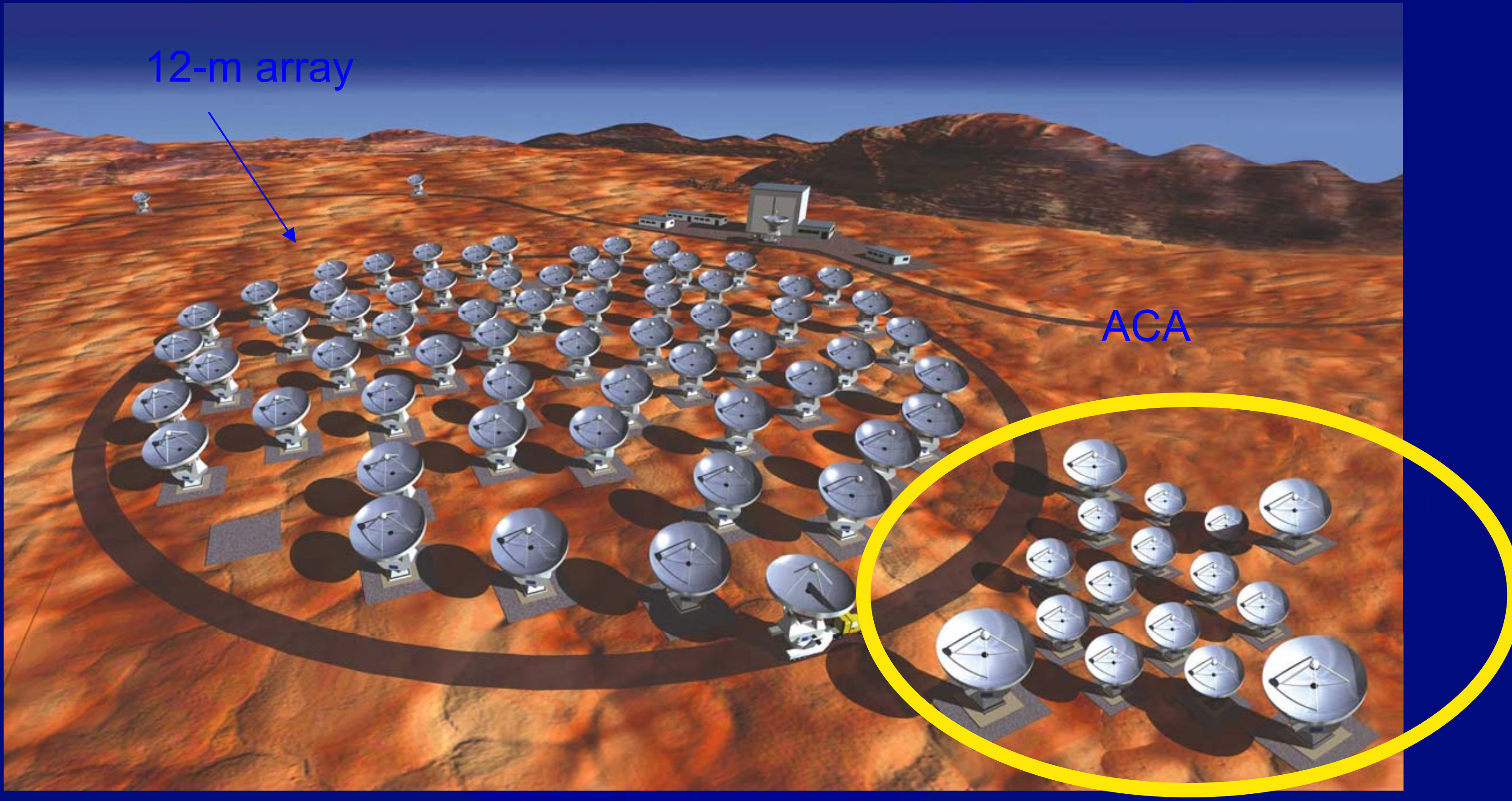


Strawman


PGPlotter
File Tools Edit Help
Antenna Coordinates
6×10^4
5.5×10^4
5×10^4
Y [m]
2.5×10^4
3×10^4
X [m]
Save Print <unset> Clear Unzoom 22518 44369


PGPlotter
File Tools Edit Help
(u,v) coverage
10^4
0
−10^4
VV [m]
UU [m]
Save Print <unset> Clear Unzoom -16235 -8535.1

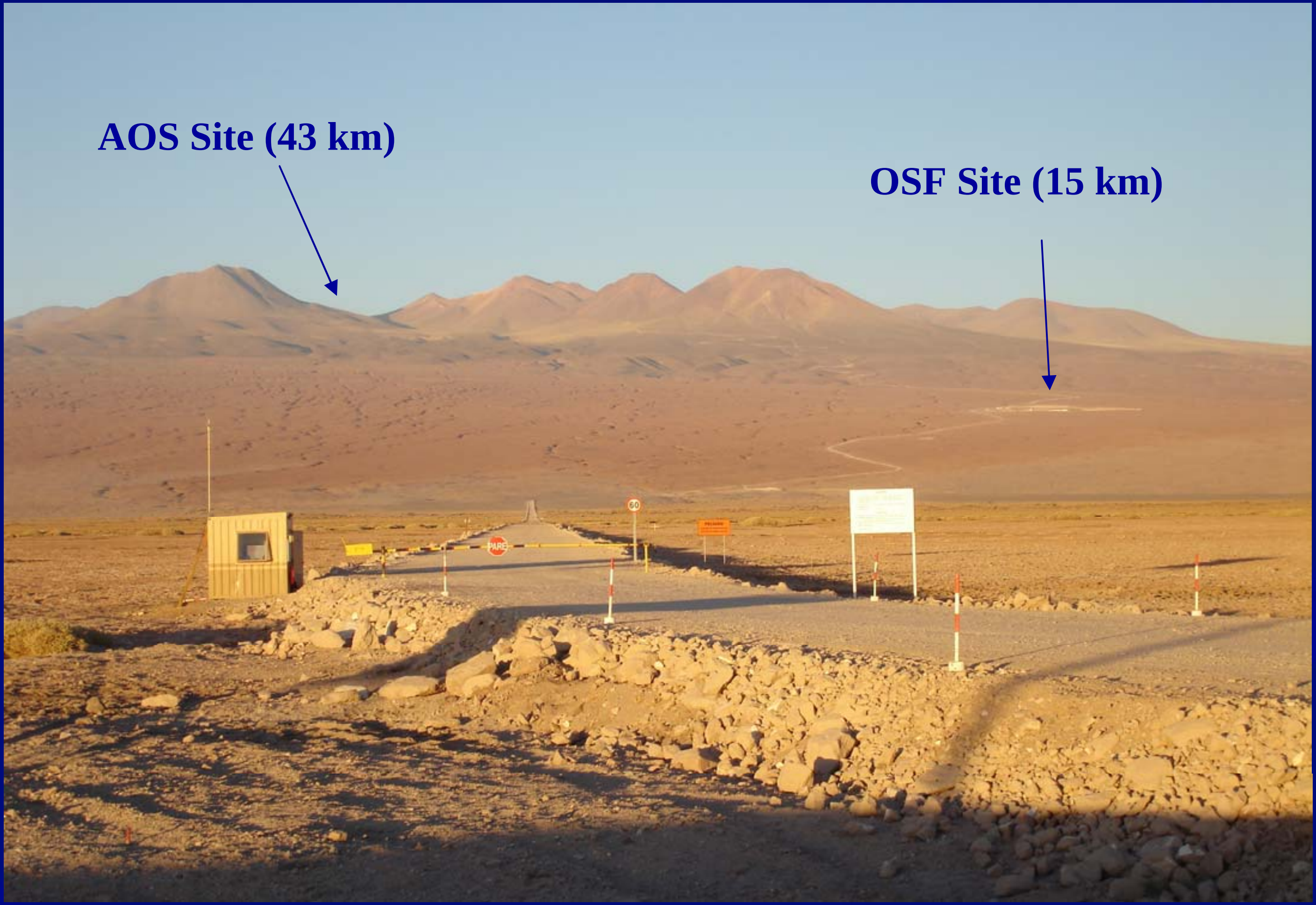
Array Configuration of Enhanced ALMA



The ACA System :

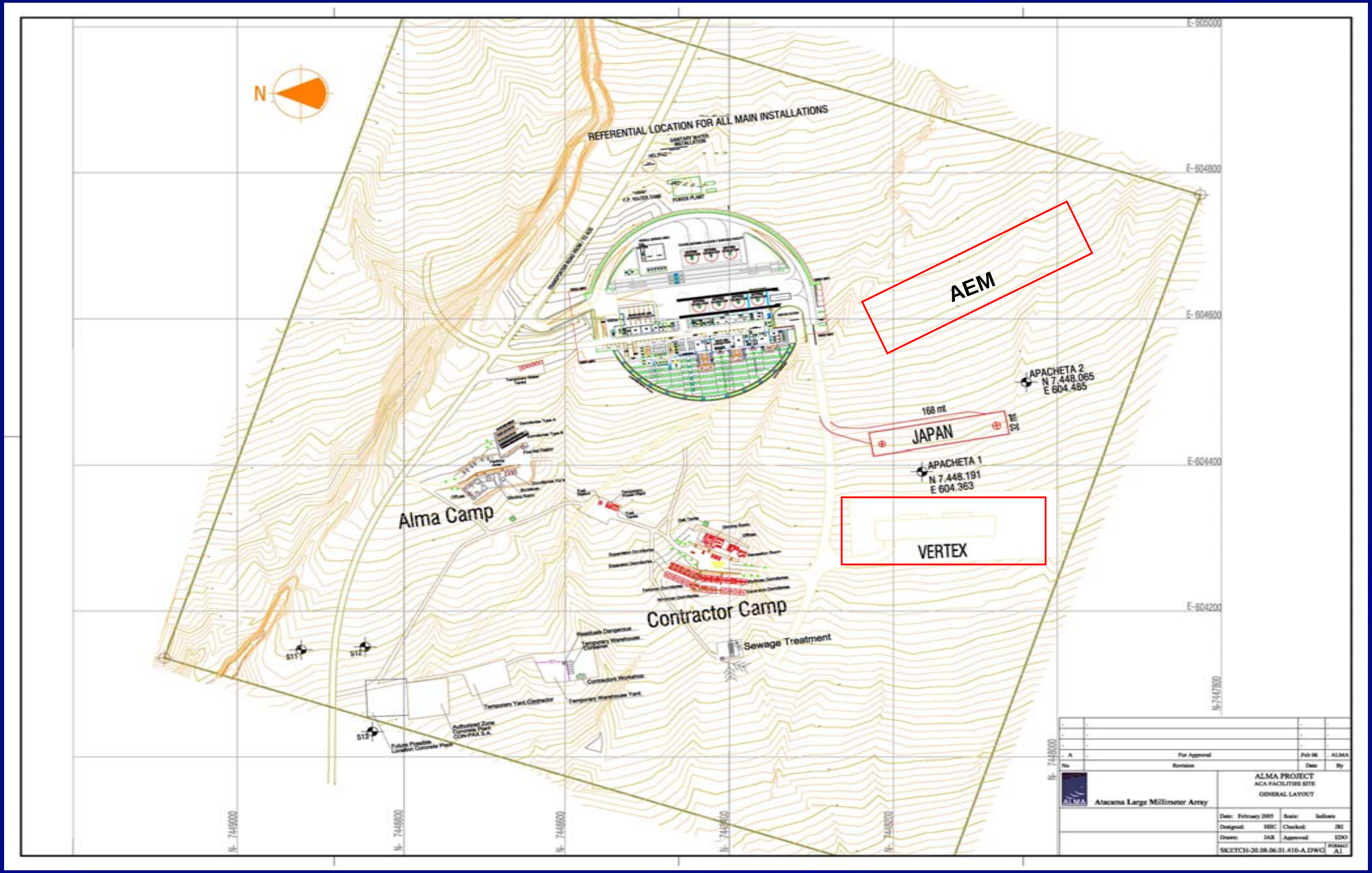
Twelve (12) 7-meter diameter antennas (18 stations)
Four (4) 12-meter diameter antennas (4 stations)
ACA Correlator in AOS building

Road to AOS



Completed up to AOS – 43 km

The Operations Support Facilities - Area



General Layout Including Camps and Antenna Assembly Areas

OSF – Vertex Assembly Area

ALMA OSF – Technical Facilities

ESO signed construction contact beginning of August 2006

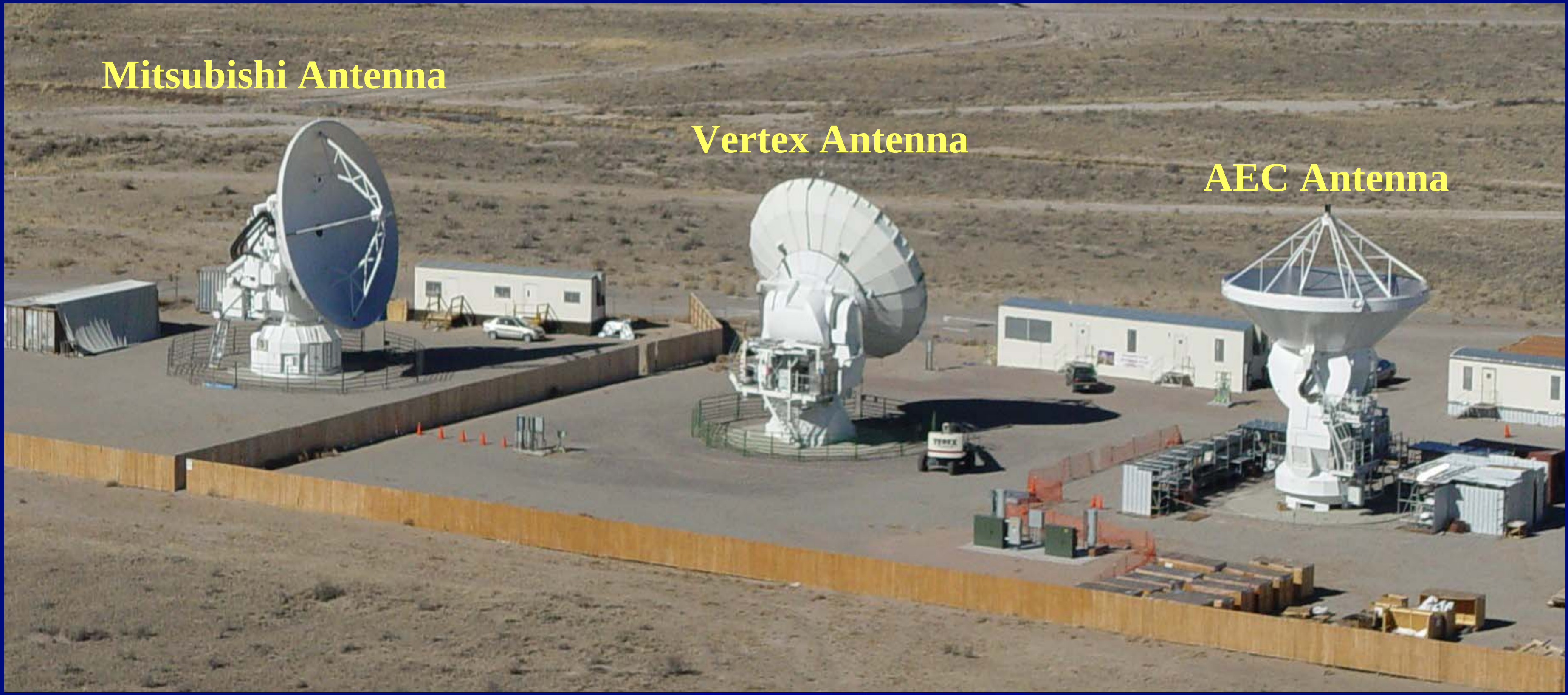
About 6000 m^2 net surface - Ready Q1/2008

Road to AOS

Width of road: 14 to 19 meters

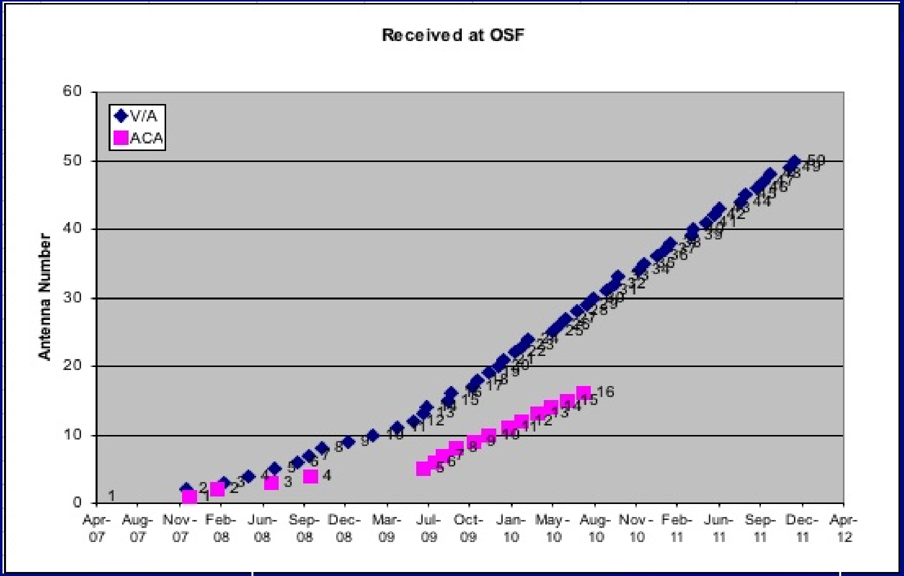
Array Operations Site– Technical Building

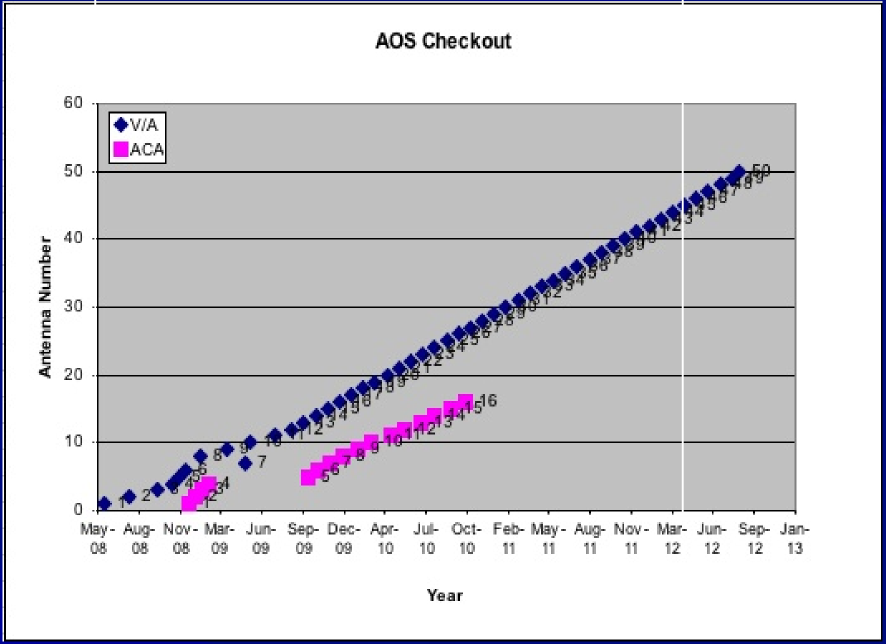
The Three ALMA Prototype Antennas at the ATF



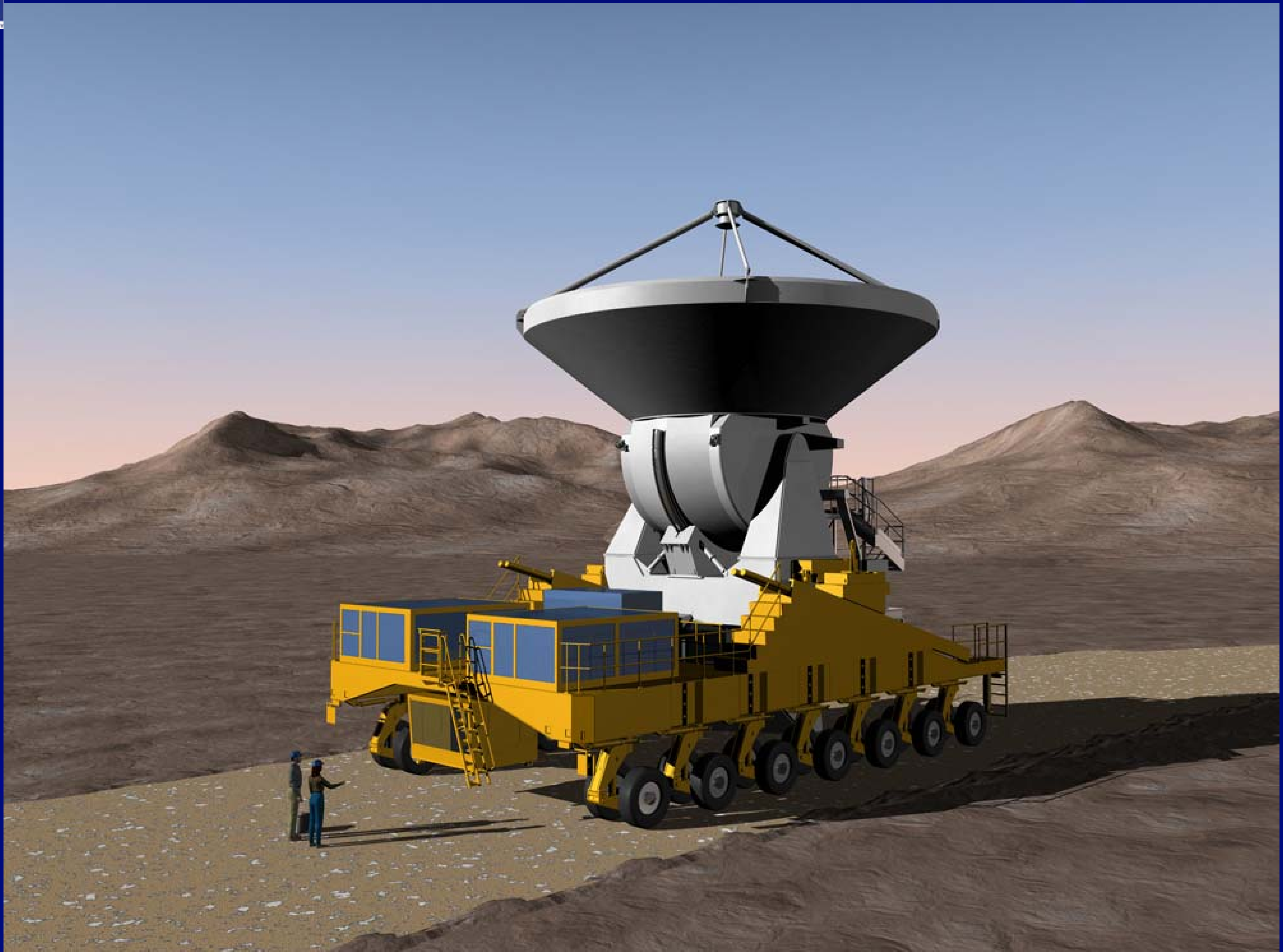
12 Meter Diameter, Carbon Fiber Support Structures

Telescope Checkout Schedule



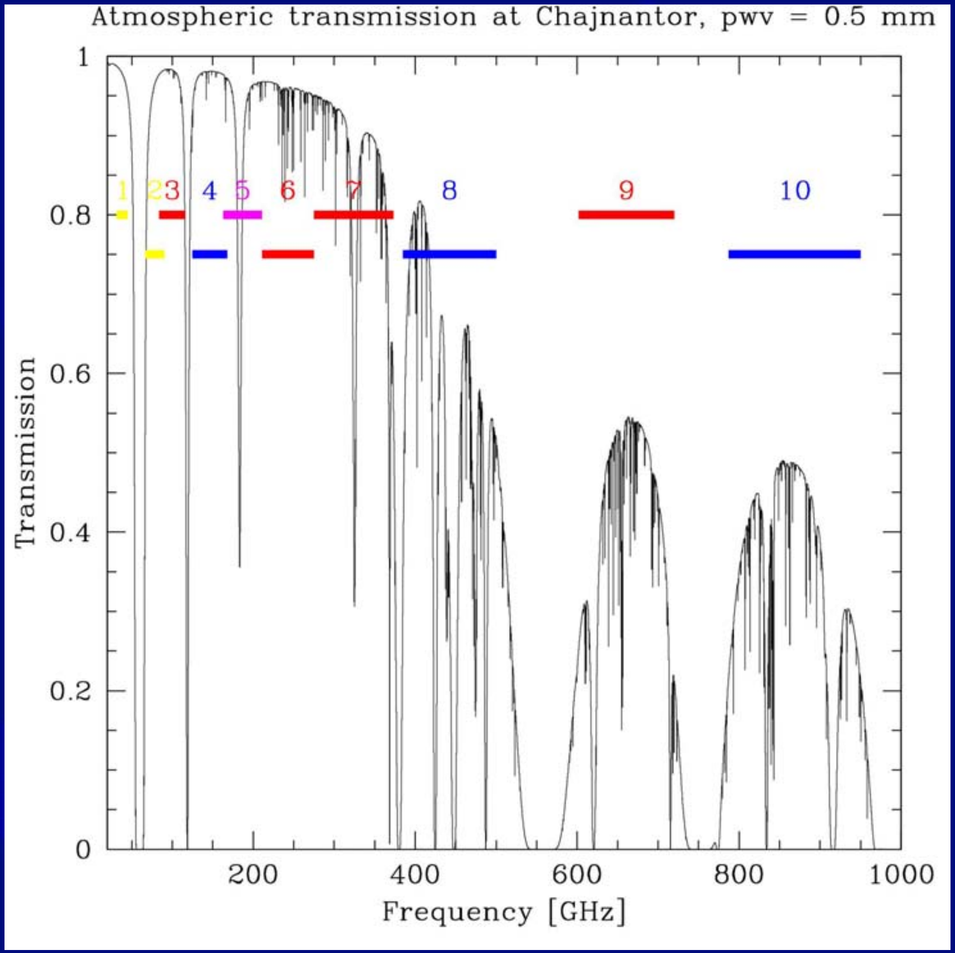


ALMA **Transporters**



Transparent Site Allows Complete Spectral Coverage

❖10 Frequency bands coincident with atmospheric windows have been defined.
❖Bands 3 (3mm), 6 (1mm), 7 (.85mm) and 9 (.45mm) will be available from the start.
❖Bands 4 (2mm), 8 (.65mm) and, later, some 10 (.35mm), built by Japan, also available.
❖Some Band 5 (1.5mm) receivers built with EU funding.
❖All process 16 GHz of data
  - ❖2polzns x 8 GHz (1.3mm=B6)
  - ❖2 polzns x 2SBs x 4 GHz (3mm=B3, 2mm=B4, .8mm=B7, 1.5mm=B5)
  - ❖2 polzns x DSB x 8 GHz (.6mm=B8, .45mm=B9, .35mm=B10)



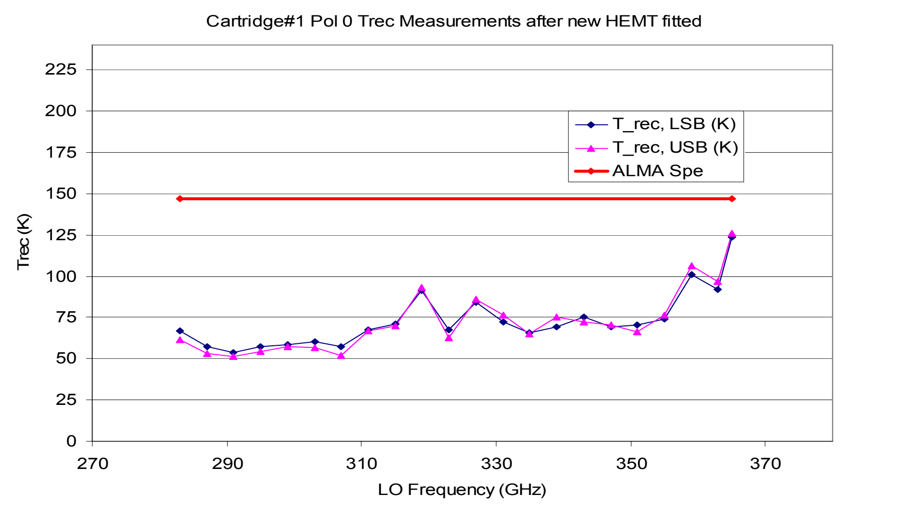
Front End Cryostats

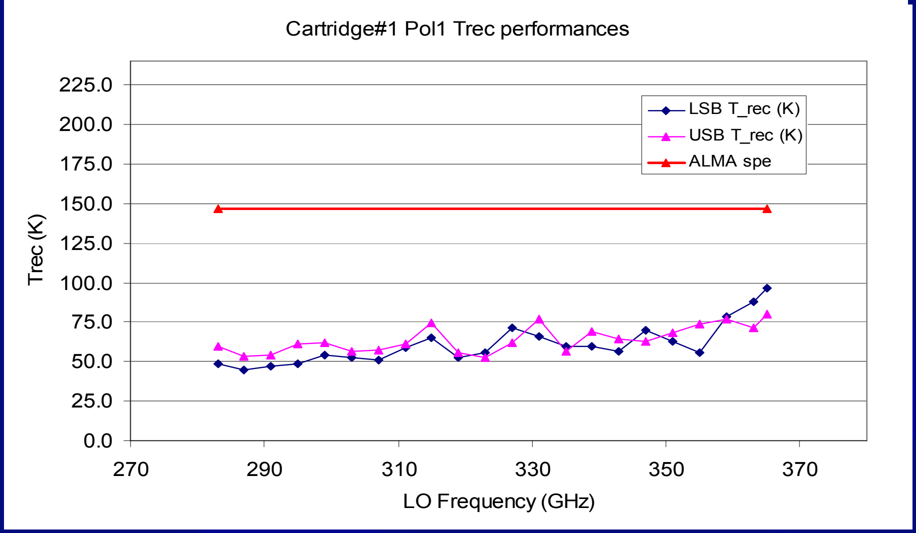
All cryostats will be assembled at RAL and shipped to the three Front End Integration Centres. First four cryostats accepted.

Cartridge Production

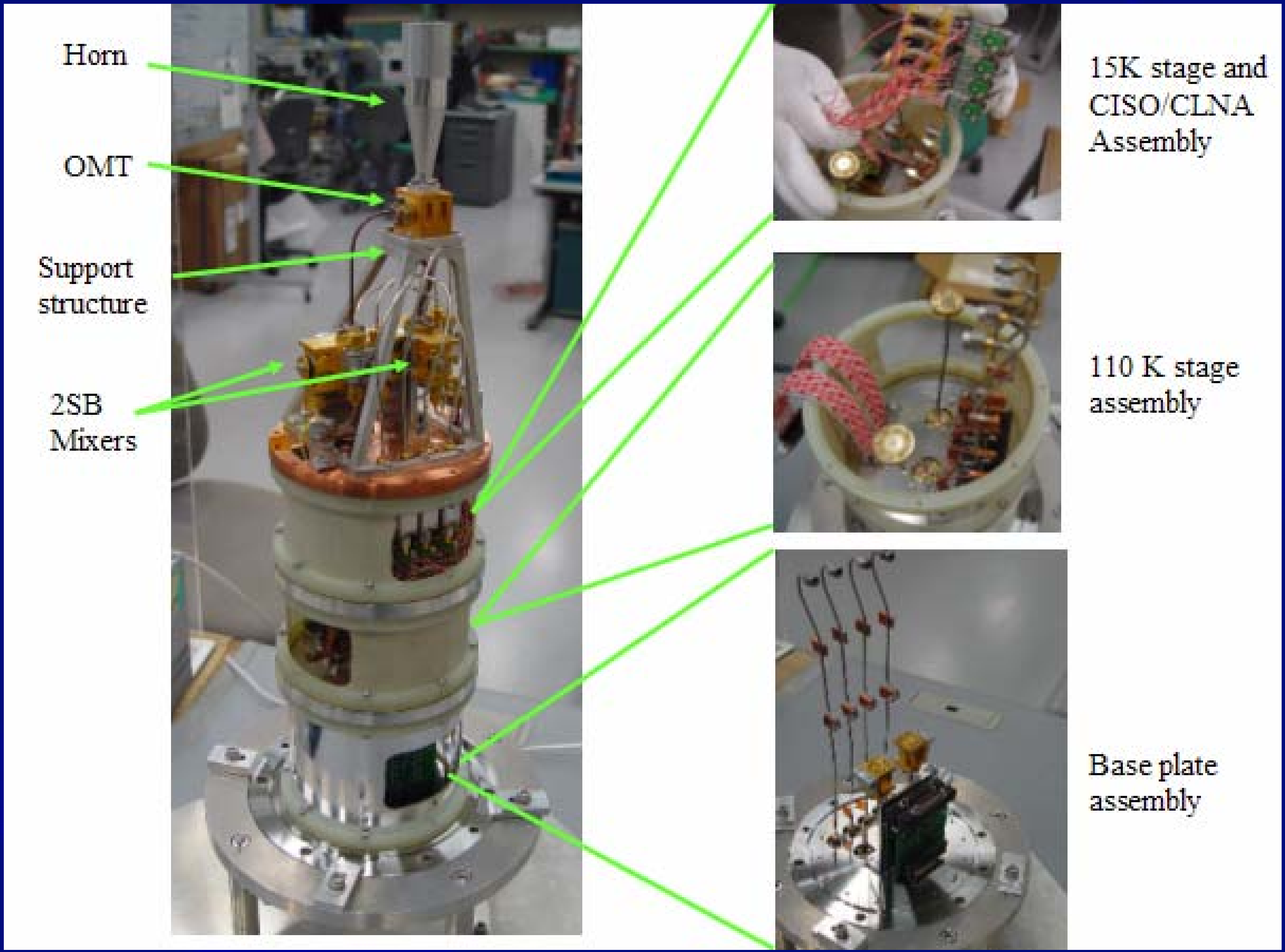
- Band 3 (HIA, Canada):
  - Assembly of third cartridge in progres
- Band 6 (NRAO, USA):
  - Three cartridges assembled.
- Band 7 (IRAM, France):
  - Five cartridges assembled. First cartridge accepted at NA FEIC.
- Band 9 (SRON, The Netherlands):
  - First cartridge assembled.

Band 7 Noise Performance

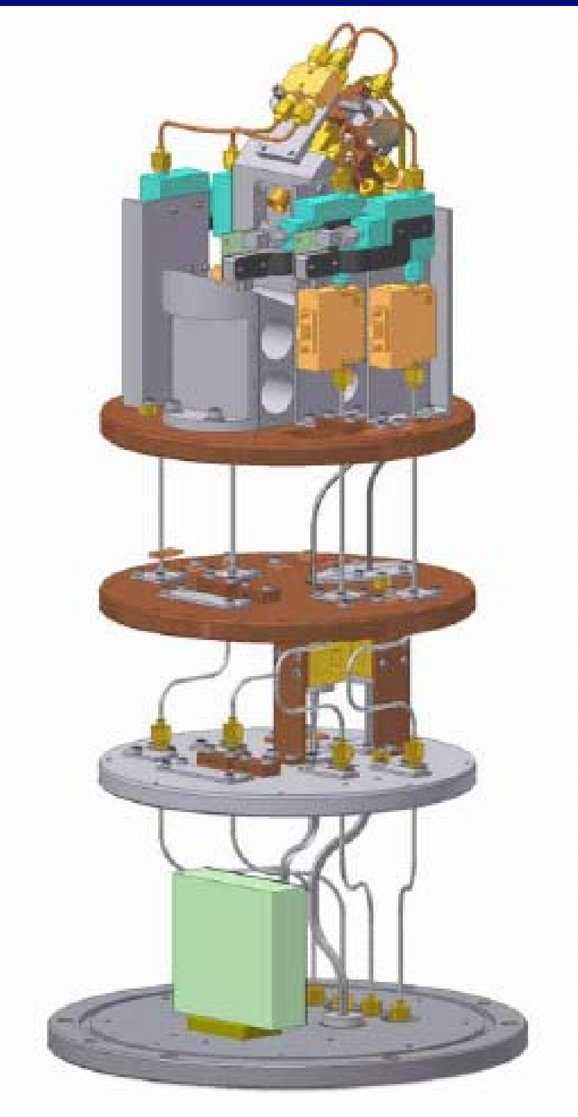


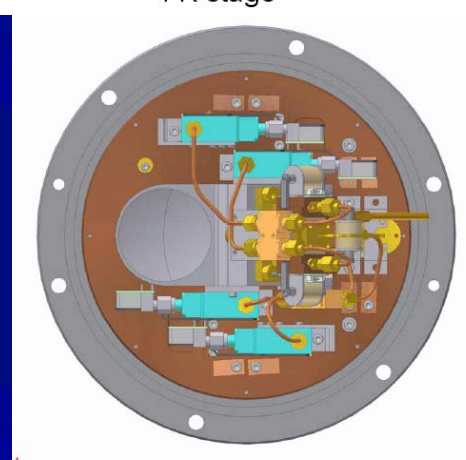


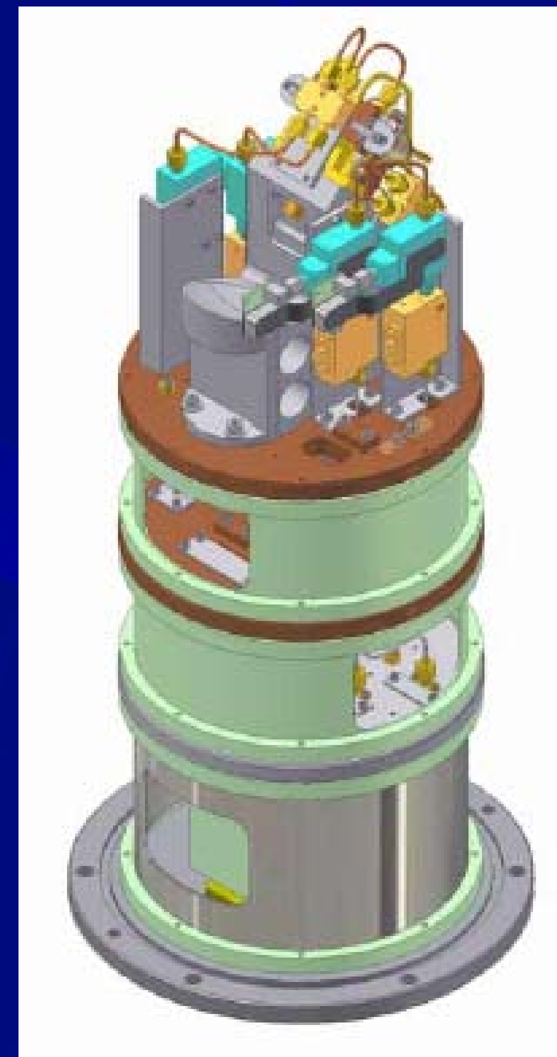
Assembled Band 4 Pre-Production Cartridge



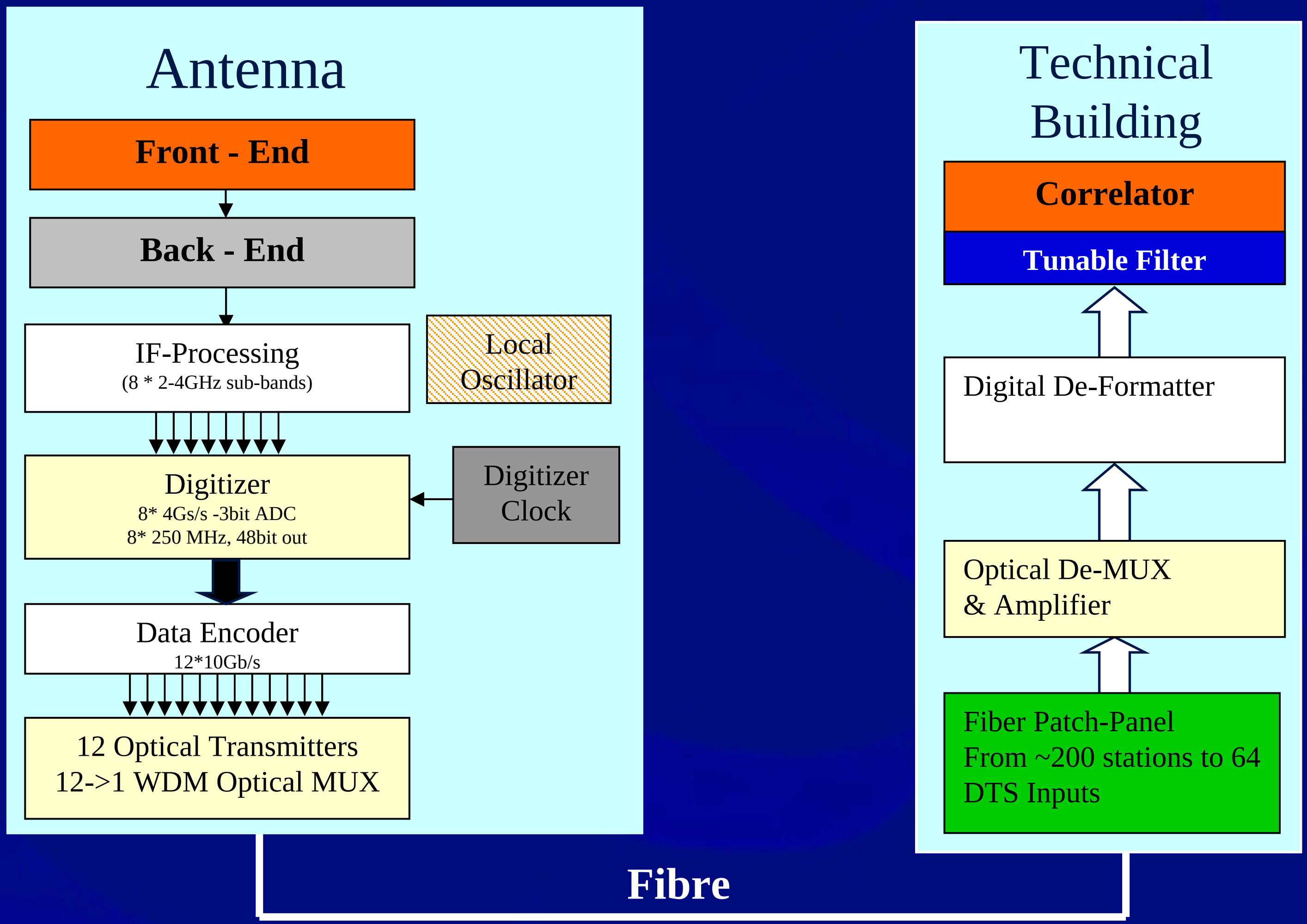
Band 8 Pre-Production Cartridge Design



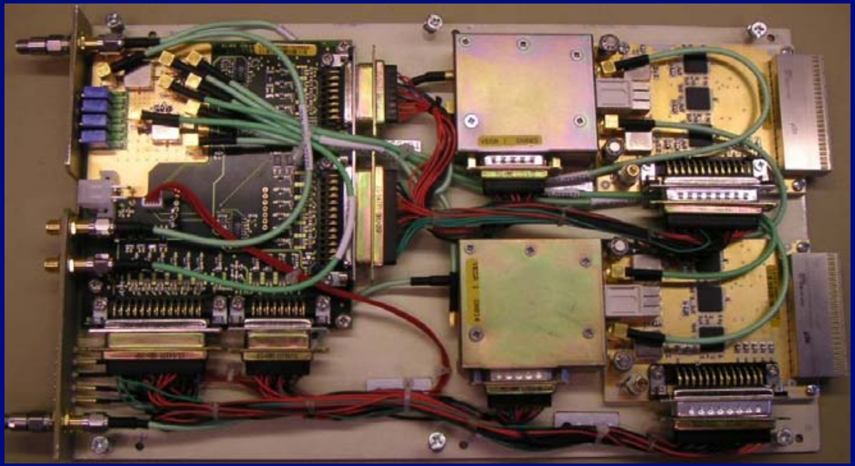




Data Transmission: Front – End to Correlator



Back End – 4 GHz Digitizer



Prototype Digitizer

Production Digitizer

- **Status:**
  - Layout was optimized to reduce number of parts and assembly costs.
  - Improved performance and reliability.
  - The first four digitizer units tested at University of Bordeaux. Already shipped to NRAO to replace prototypes and to be used at ATF.
  - New features (more diagnostics and remote operation) under evaluation.

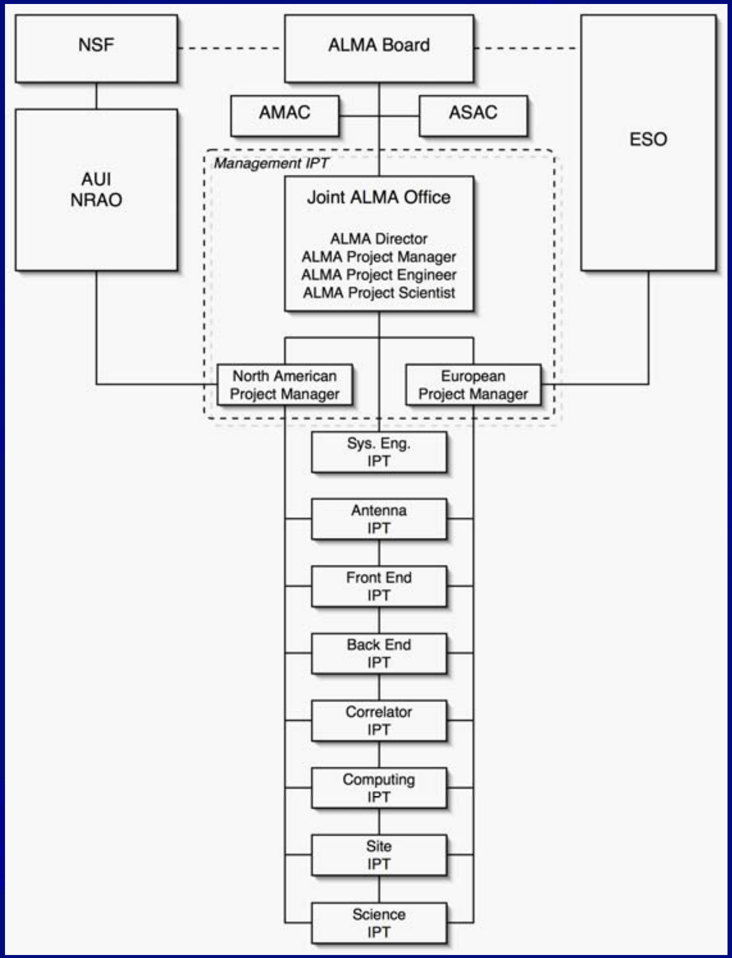
The Correlator

First of four Correlators at NRAO

- 2912 printed circuit boards
- 5200 interface cables
- More than 20 million solder joints
- First quadrant completed Q3/2007

ALMA Project Organization

- Director:
  M. Tarenghi
- Project Manager:
  T. Beasley
- Project Engineer:
  R. Murowinski
- Project Scientist:
  ....
- Project Manager (NA)
  A. Russell
- Project Manager (EU) H. Rykaczweski



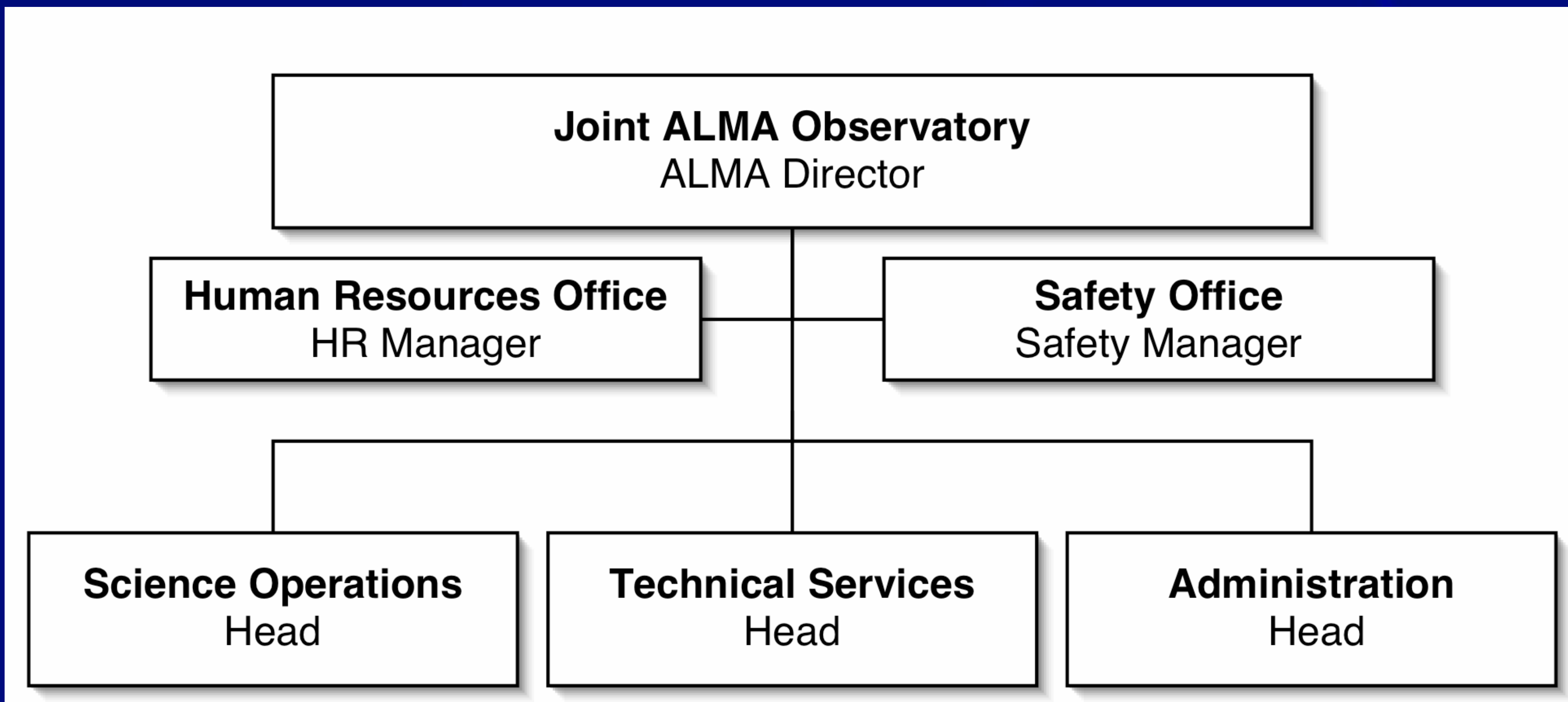
Guidelines for ALMA Operations

- 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 Centers (ARCs), including proposal handling and support for data reduction and archival research.
- Maintenance, Repair and Development work on hardware and software is contracted to the Executives.

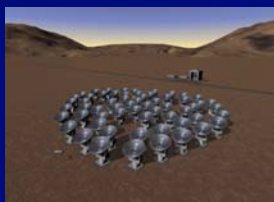
ALMA Operations

- **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

ALMA Observatory Top-Level



ALMA Sites in Chile



Antenna Operations Site (AOS)

40 MB/s (peak)

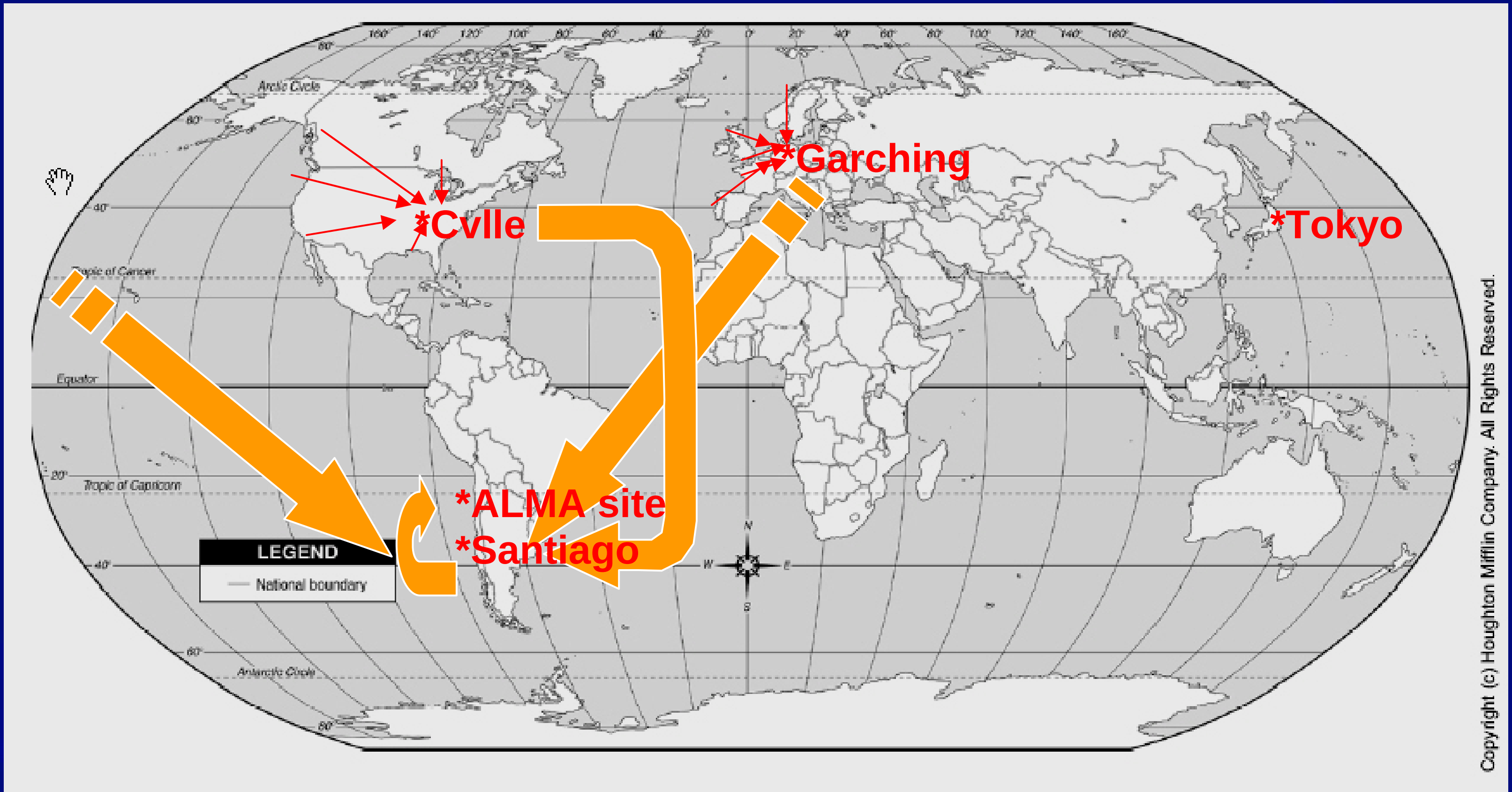
Operation Support Facility (OSF)

6 MB/s (average)

Santiago Central Office (SCO)

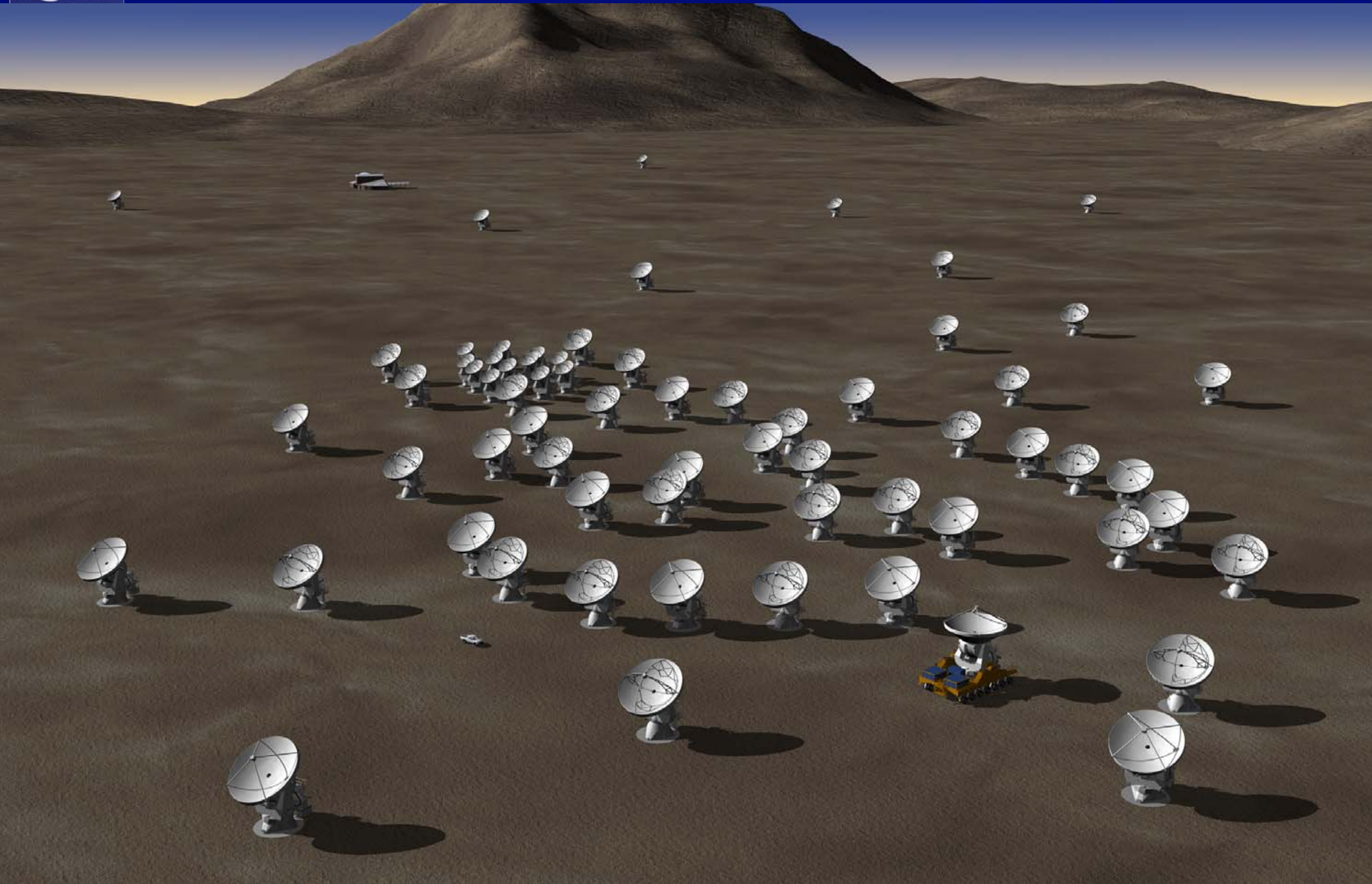
ALMA Regional Centers

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



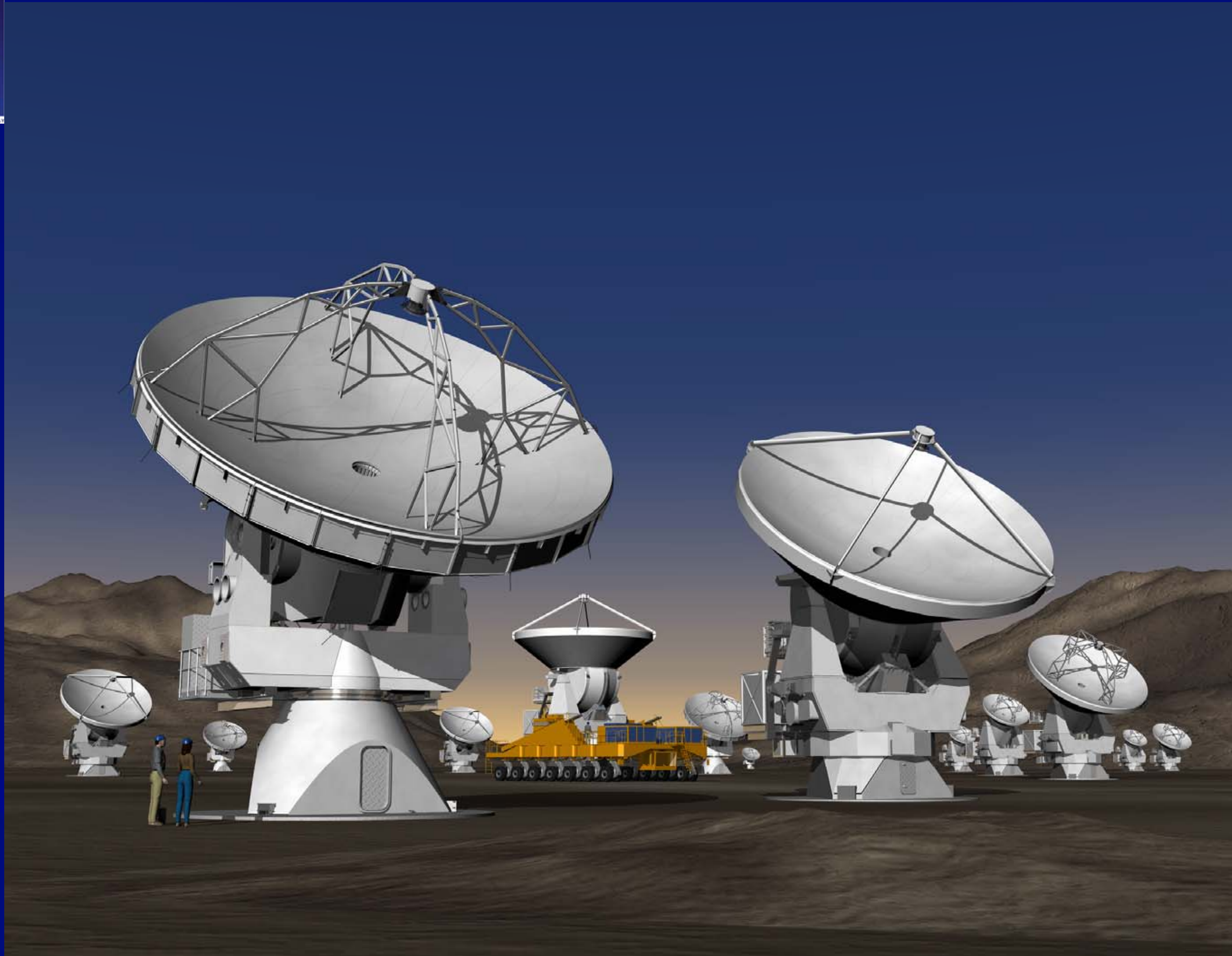
ALMA – Schedule

▪ Completion of OSF, AOS Facilities:	Q1/2008
▪ Antenna Acceptance at the OSF:	Q2/2007 - Q4/2011
▪ First Interferometry at AOS:	2009
▪ Call for Proposals and Early Science:	2010
▪ Full Operations:	2012



ALMA

ATACAMA LARGE MILLIMETER ARRAY



ALMA

ATACAMA LARGE MILLIMETER ARRAY