ALMA:
Status and Scientific Capabilities

Richard Hills

ALMA Project Scientist

ALMA STATUS – March 2009

- Main buildings done. Roads & pads on high site underway
- 15 antennas in various stages – 2 conditionally accepted.
- 2 Transporters on site and accepted.
- Two receiver system and 4 sets of electronics on site
- 16-input correlator and first quadrant of 64-input installed
- Mass production underway of almost all other items
- Systems and software testing completed at VLA site
- Some development work still going on in other areas:
  - Band 10 front-ends
  - Calibration Loads
  - Laser Local Oscillator refinements

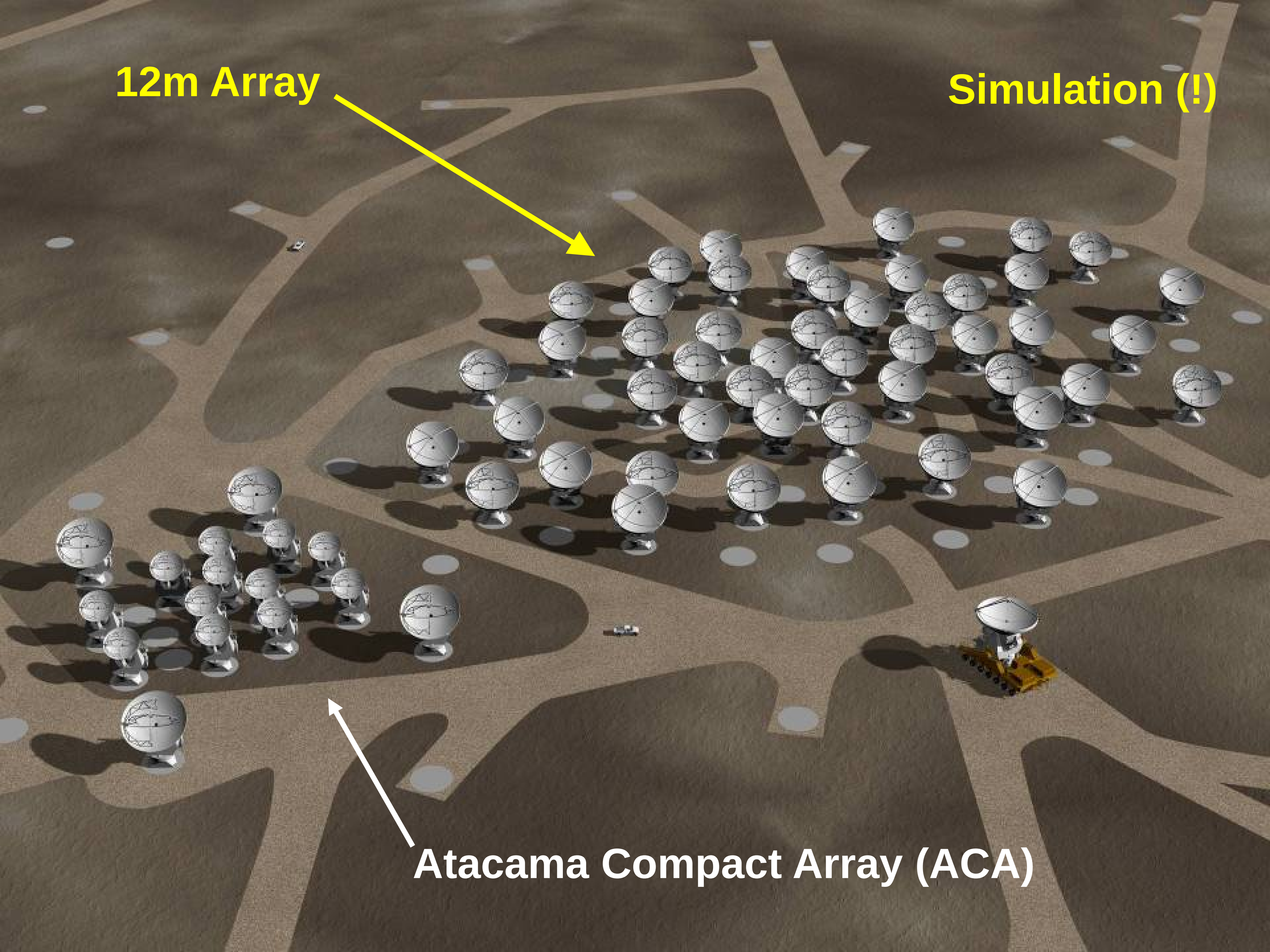
ALMA Site

Paranal

La Serena

Santiago

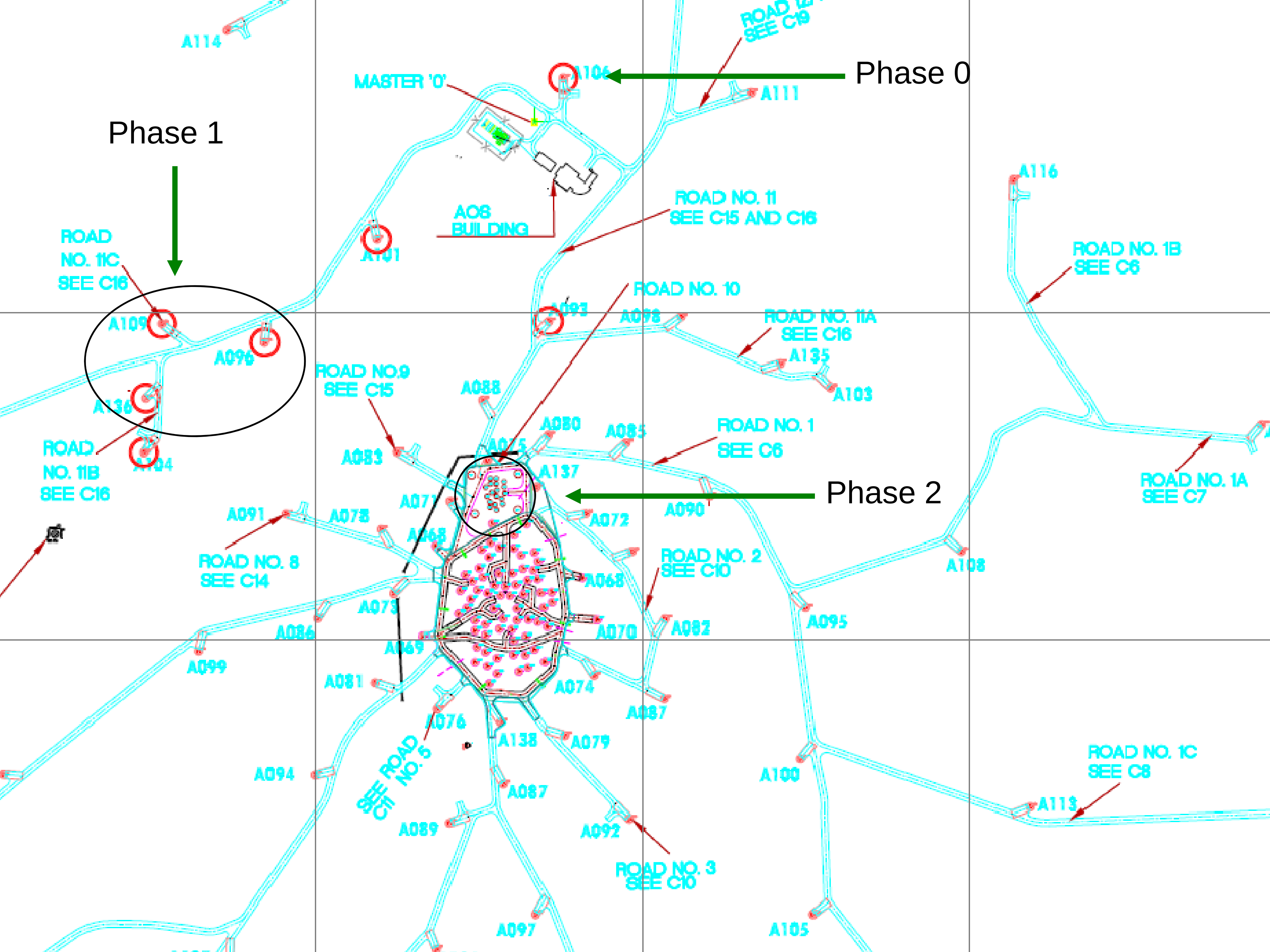
Google-Earth view of site with antennas in the most extended configuration – baselines to 16km


12m Array
Simulation (!)
Atacama Compact Array (ACA)

Foundations for the Compact Array – nearly done.   Power and fibres next.

New Plan for Occupation of Antenna Stations

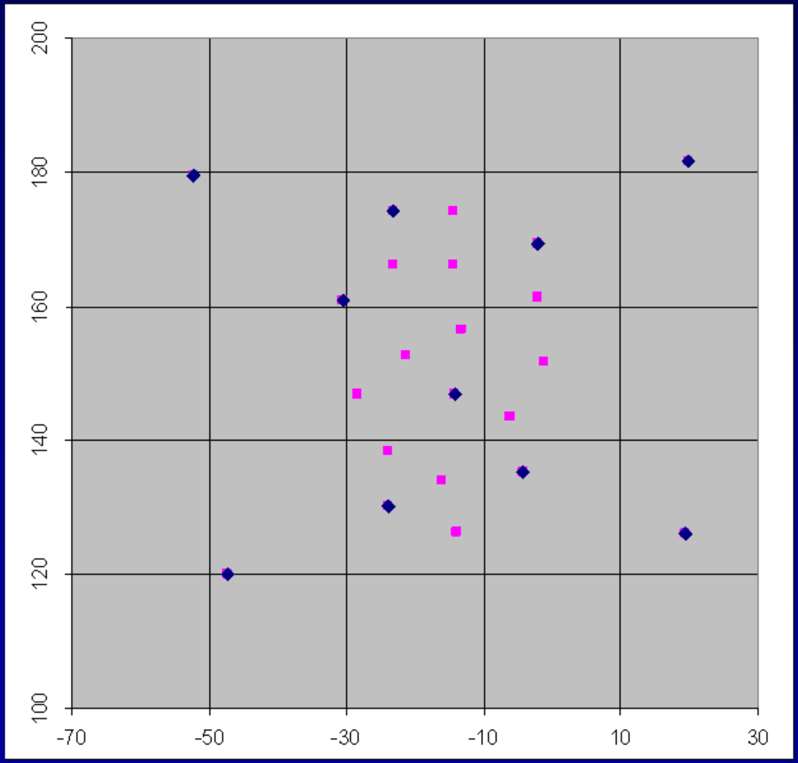
- Phase 0   Jun ’09 1 pad for antenna checkout
- Phase 1   Sep ’09 3 pads for first fringes / closure
- Phase 2   Jan ’10 10 ACA pads - initial commissioning
- Phase 3   July ’10 add 6 inner array pads
- Phase 4   Mar ’11 for Early Science - central cluster
  plus 20 inner array pads
- Phase 5   Oct ’11 high resolution – baselines to ~ 4km
- Phase 6   Apr ‘12 goal for completion of outer array



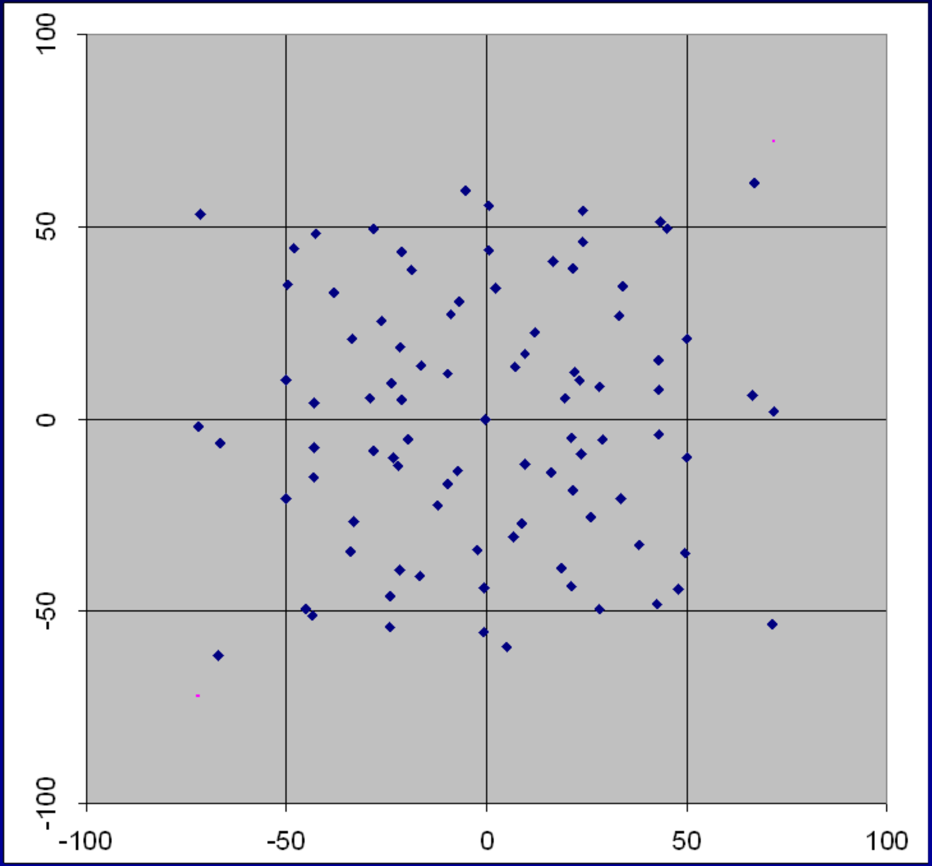
Phase 0
Phase 1
Phase 2
MASTER '0'
A08 BUILDING
ROAD NO. 11 SEE C15 AND C16
ROAD NO. 11C SEE C16
ROAD NO. 11B SEE C16
ROAD NO. 10
ROAD NO. 11A SEE C16
ROAD NO. 1B SEE C6
ROAD NO.9 SEE C15
ROAD NO. 1 SEE C6
ROAD NO. 1A SEE C7
ROAD NO. 8 SEE C14
ROAD NO. 2 SEE C10
ROAD NO. 1C SEE C8
ROAD NO. 3 SEE C10
SEE ROAD NO. 5 C11
A114
A106
A111
A116
A101
A109
A096
A136
A104
A098
A135
A103
A088
A080
A085
A083
A137
A077
A072
A090
A091
A078
A068
A108
A073
A070
A082
A095
A086
A069
A099
A081
A074
A087
A076
A138
A079
A094
A100
A113
A089
A092
A097
A105

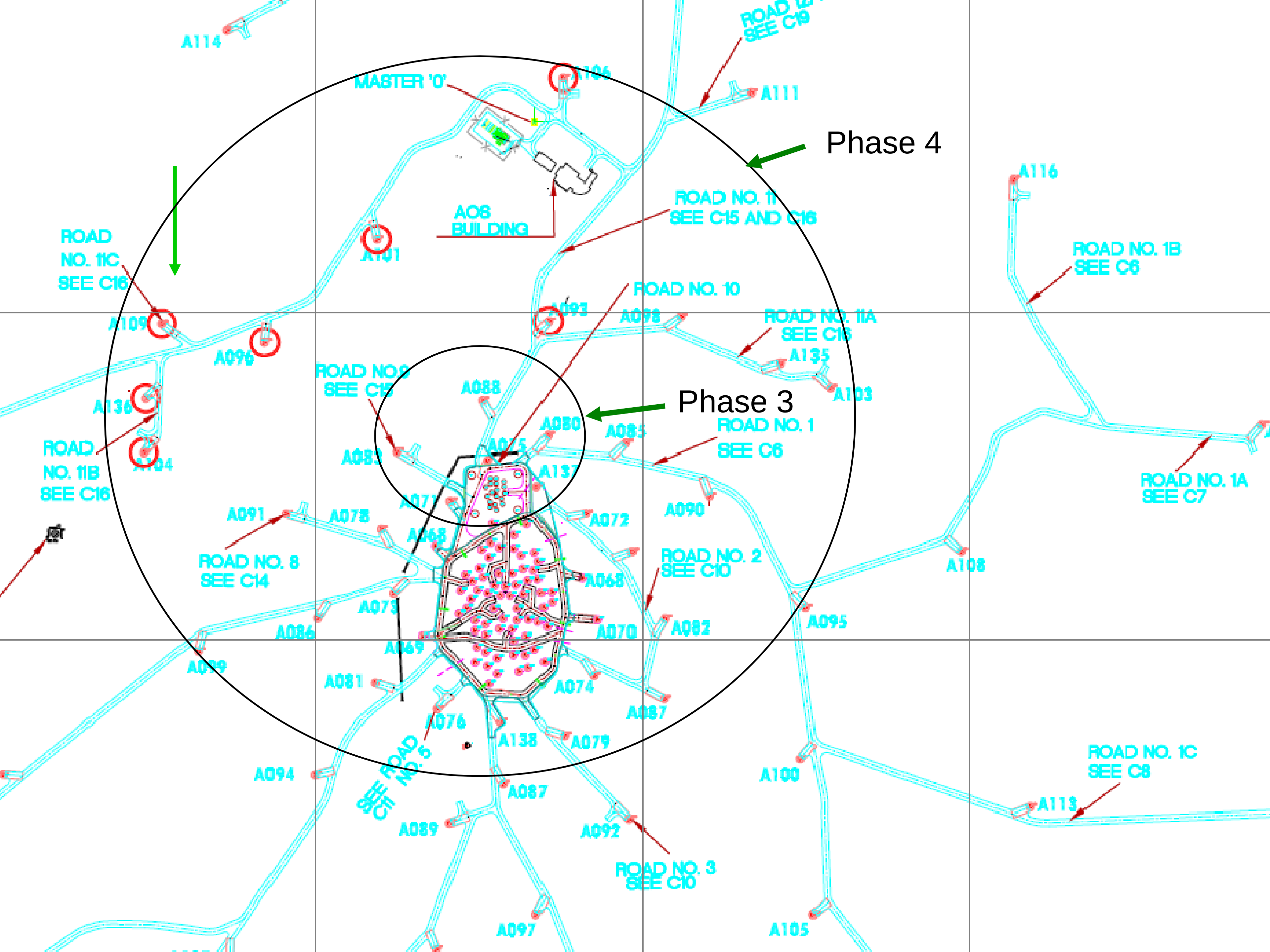
Phase 2

Pads



Baselines

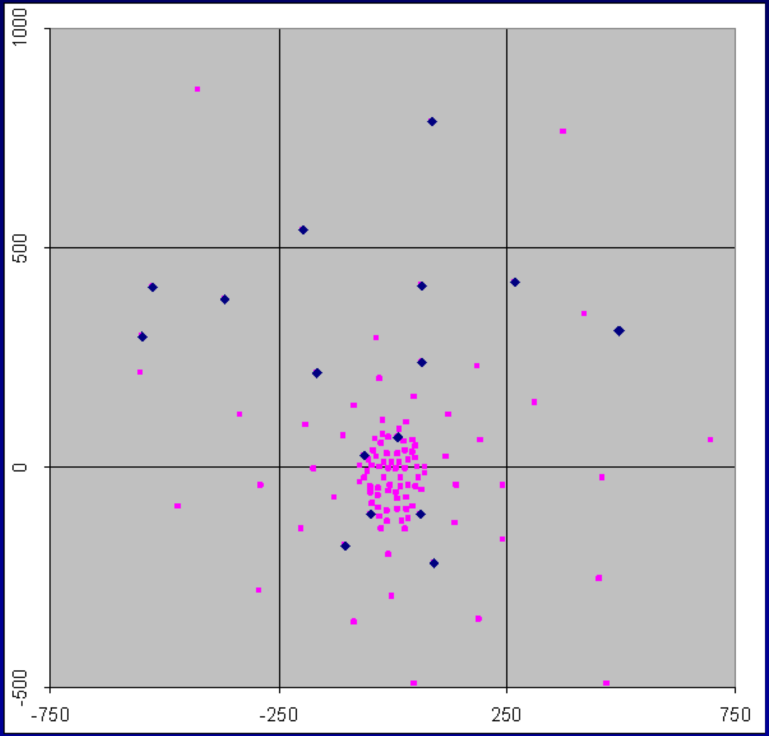




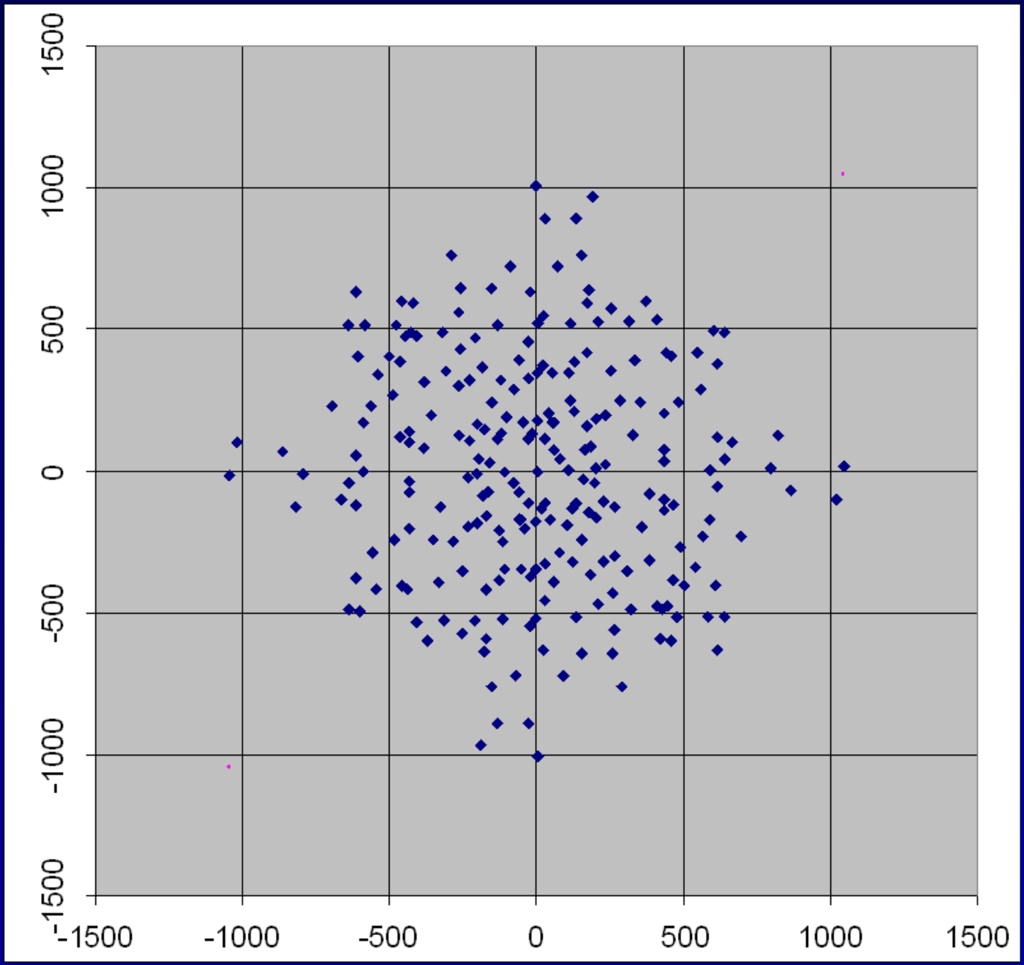
A114
SEE C19
MASTER '0'
A106
A111
Phase 4
A116
AO8
BUILDING
ROAD NO. 11
SEE C15 AND C16
ROAD
NO. 11C
SEE C16
A101
ROAD NO. 1B
SEE C6
ROAD NO. 10
A093
A098
ROAD NO. 11A
SEE C16
A135
A109
A096
ROAD NO. 9
SEE C15
A088
A103
Phase 3
A136
A080
A085
ROAD NO. 1
SEE C6
ROAD
NO. 11B
SEE C16
A104
A075
A083
A137
ROAD NO. 1A
SEE C7
A077
A091
A078
A072
A090
A065
ROAD NO. 8
SEE C14
ROAD NO. 2
SEE C10
A108
A068
A073
A086
A070
A082
A095
A099
A069
A081
A074
A087
A076
A138
A079
ROAD NO. 1C
SEE C8
A094
SEE ROAD NO. 5
C11
A100
A087
A113
A089
A092
ROAD NO. 3
SEE C10
A097
A105

Phase 4 (“large” array)

Pads

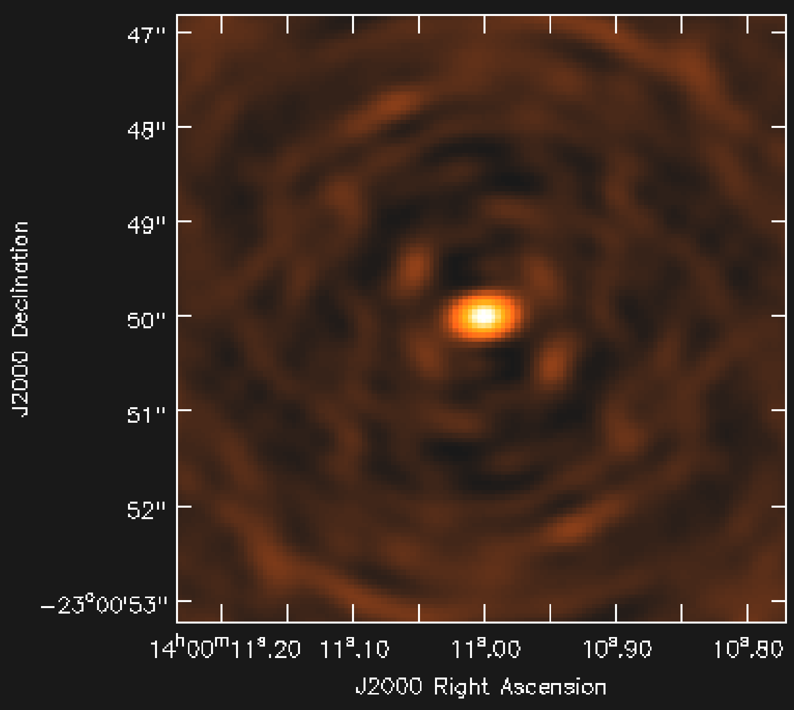


Baselines

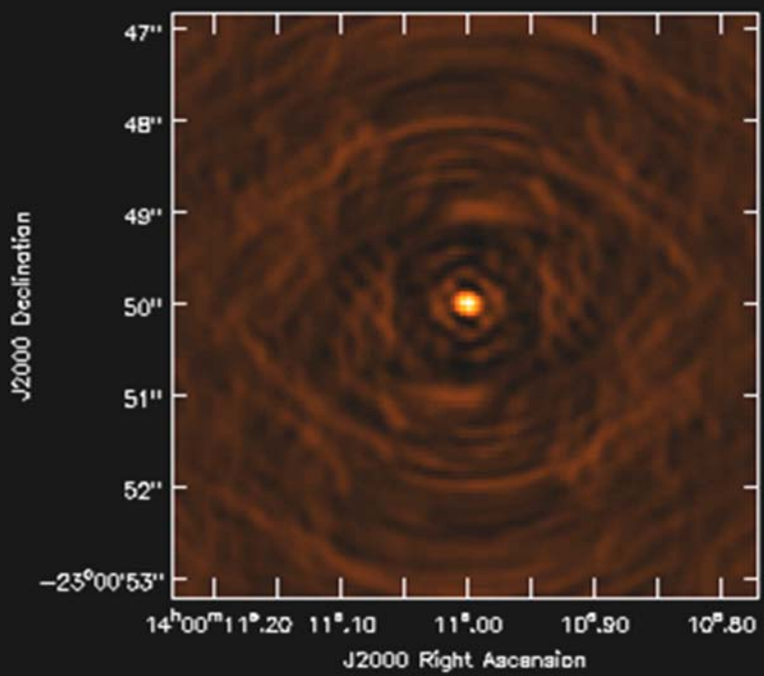


Phase 4
Early Science Beams

Medium



Large



Array Operations Site (AOS) 5000m

The ACA correlator and ¼ of 64-input one are up and running

The Operations Support Facility (OSF) 2900m

Antennas are very much state of the art
Four similar but not identical designs

- Extensive use of Carbon Fibre
- Precision panels plus holography
- Very Stiff Mounts and Accurate Drives
- “Metrology”

All-CFRP Backup Structure

AEM design

- CFRP cabin
- Stiff yoke
- Direct drives

Arrival of First European Antenna at the OSF

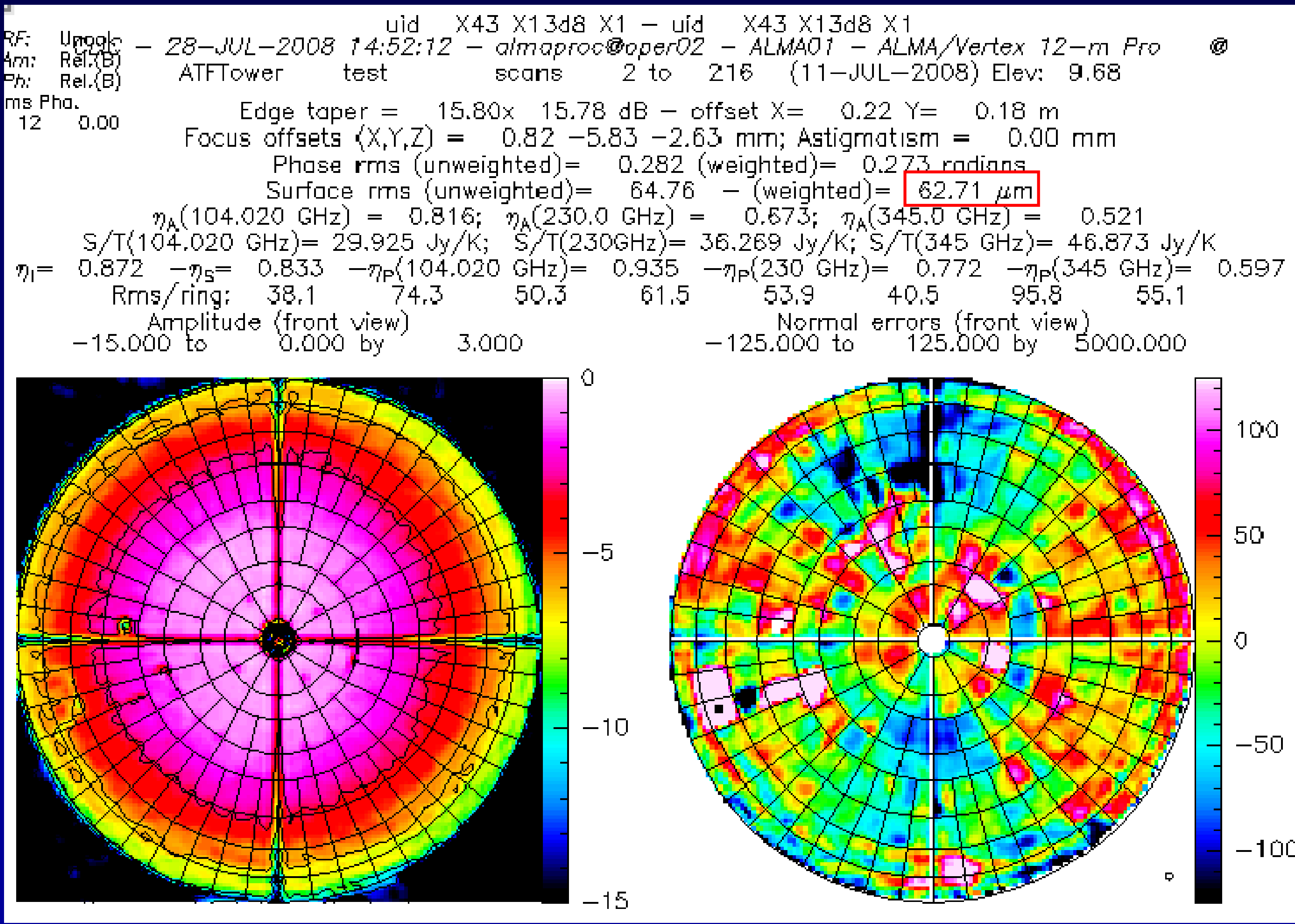
Four MELCO Antennas being tested (non-interferometrically!)

Two Vertex Antennas under test – Eight more being assembled

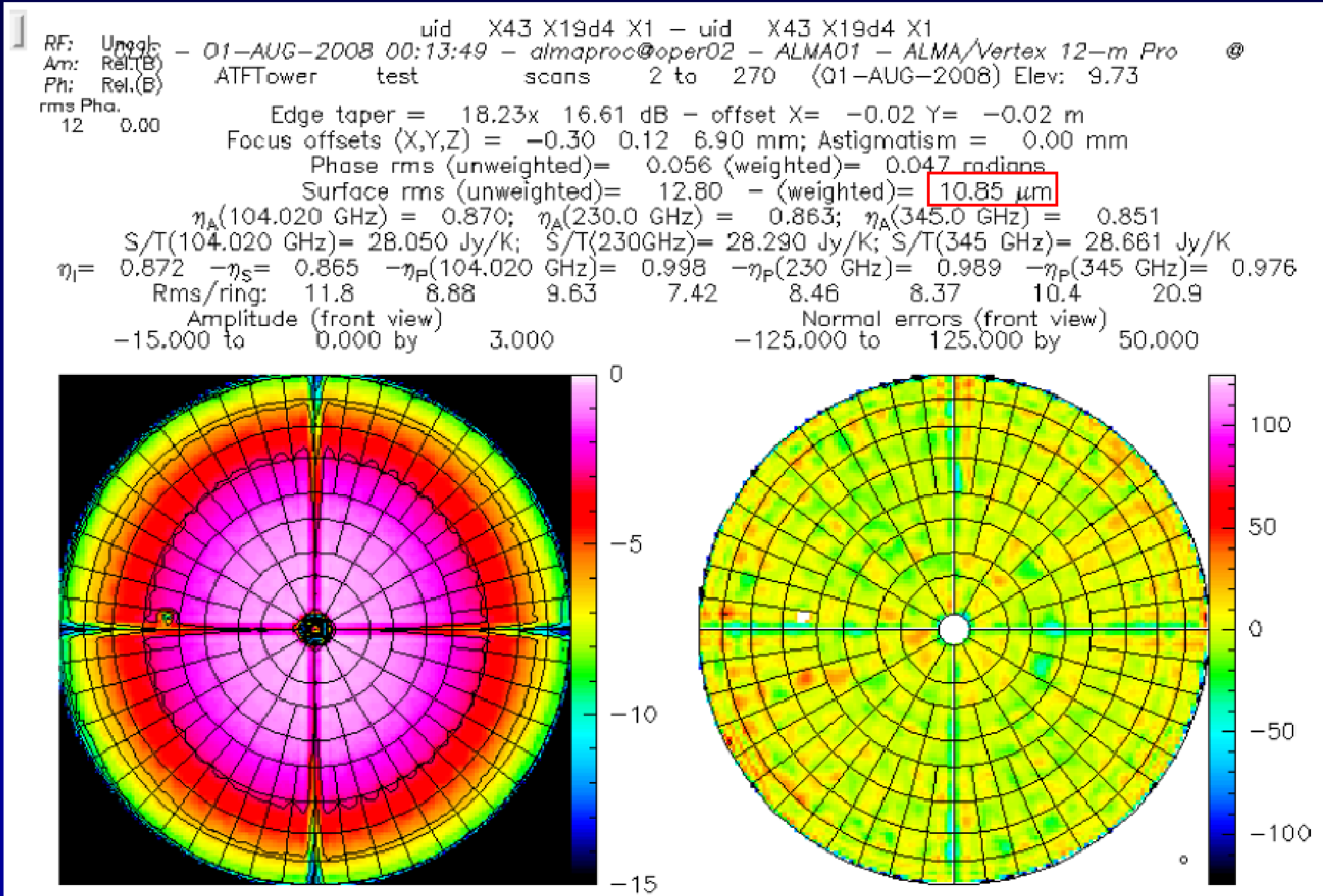
Photo – Lewis Knee

Dishes measured by holography at 104 GHz
Use source on tower at ~300m distance and correct for the curved wavefront

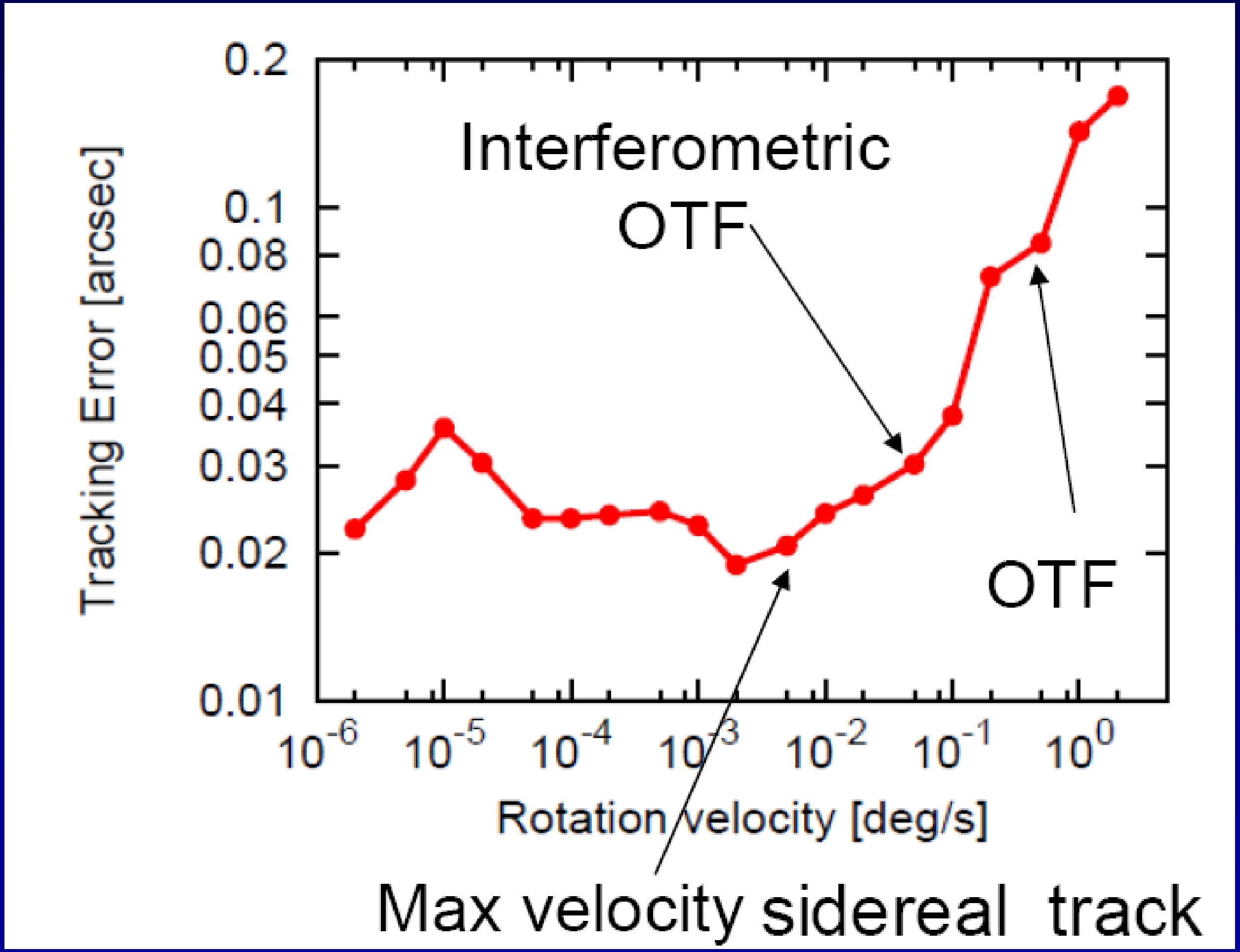
Initial Map – amplitude and phase



After adjustment

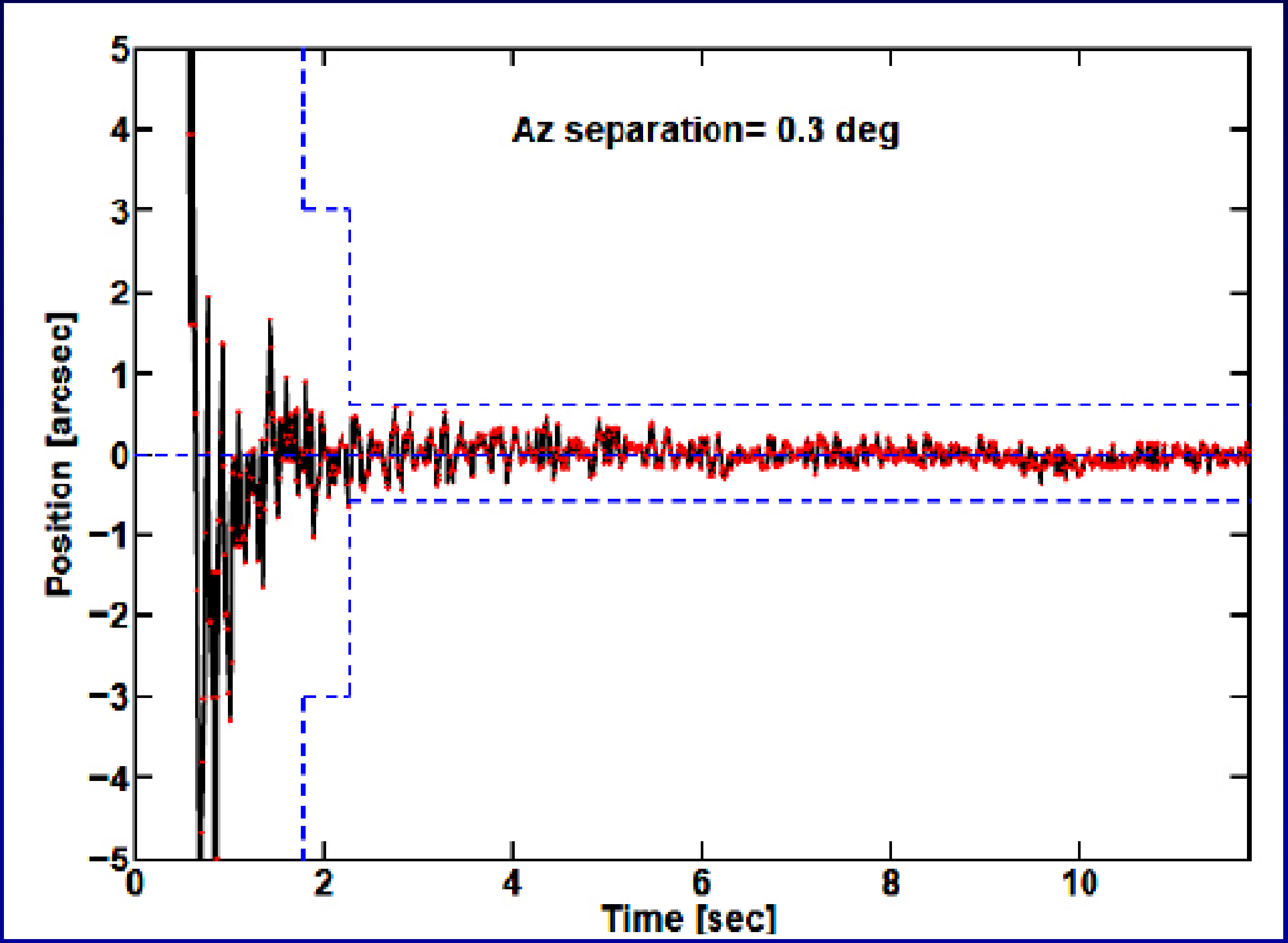


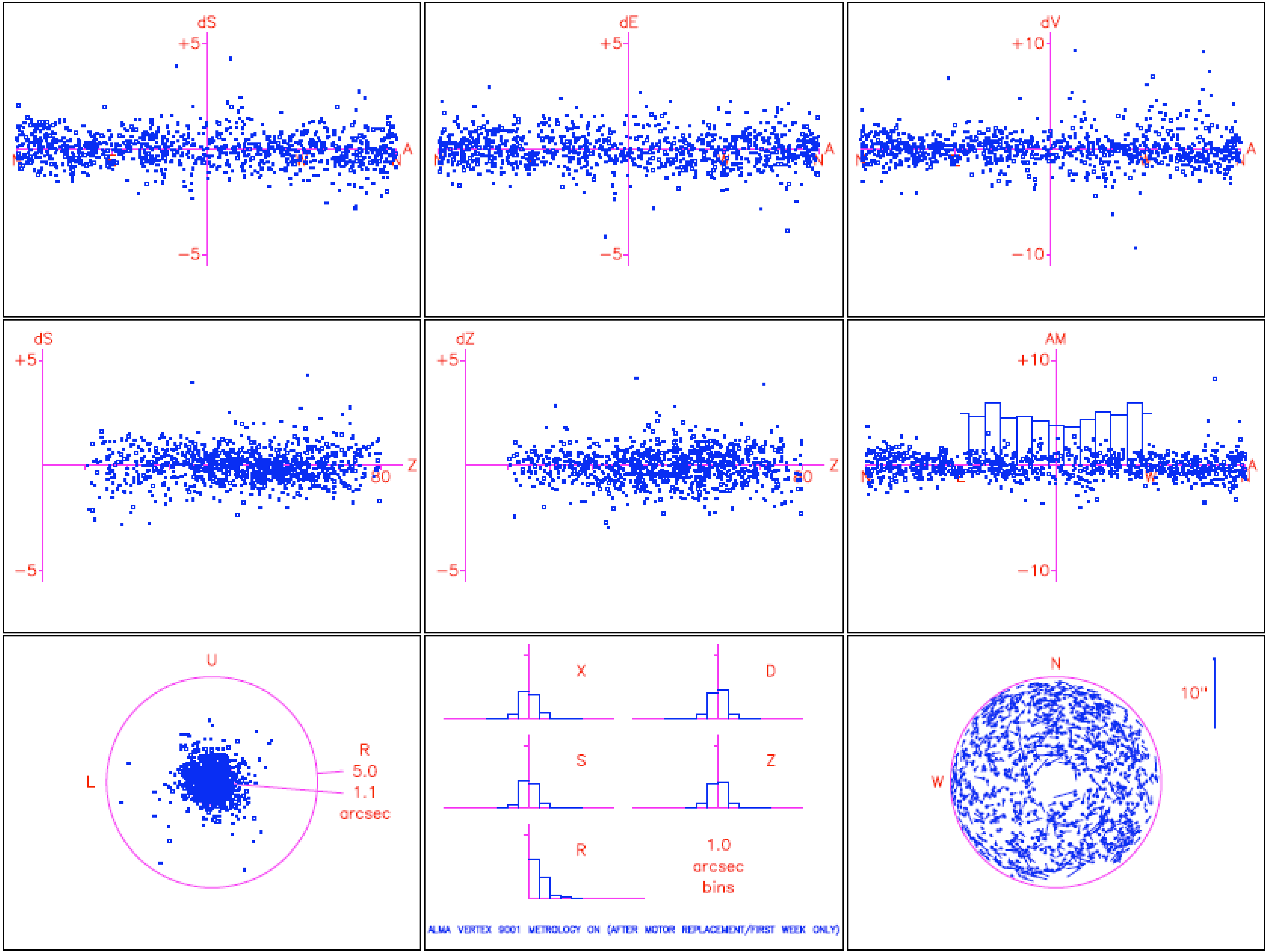
The use of direct drives gives amazingly good tracking and dynamic performance



Servo error as a function of tracking speed

Fast switching response – Radio data



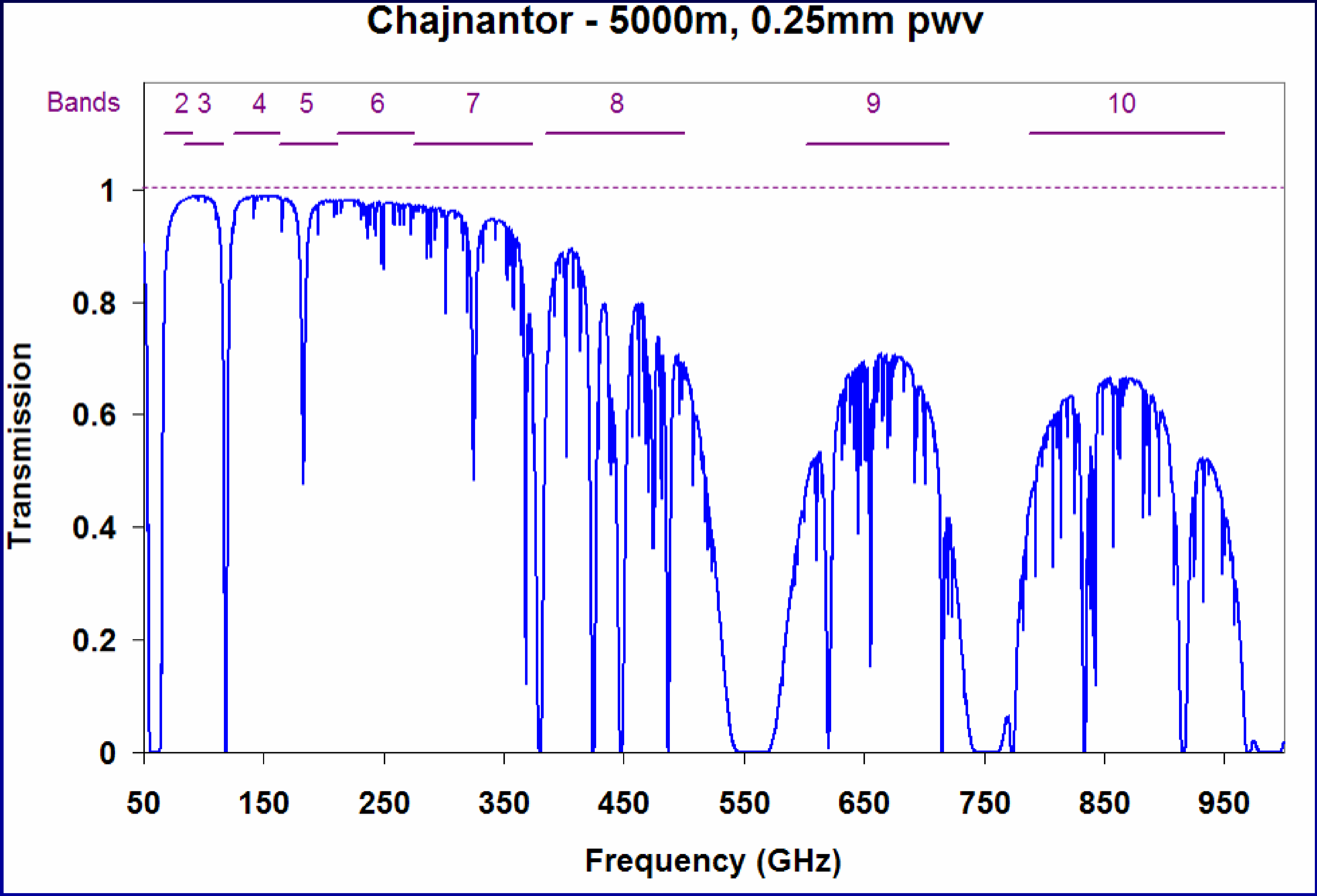


dS
+5
−5
dE
+5
−5
dV
+10
−10
N
E
W
N
A
dS
+5
−5
Z
80
dZ
+5
−5
Z
80
AM
+10
−10
U
L
R
5.0
1.1
arcsec
X
D
S
Z
R
1.0
arcsec
bins
ALMA VERTEX 9001 METROLOGY ON (AFTER MOTOR REPLACEMENT/FIRST WEEK ONLY)
N
W
10''

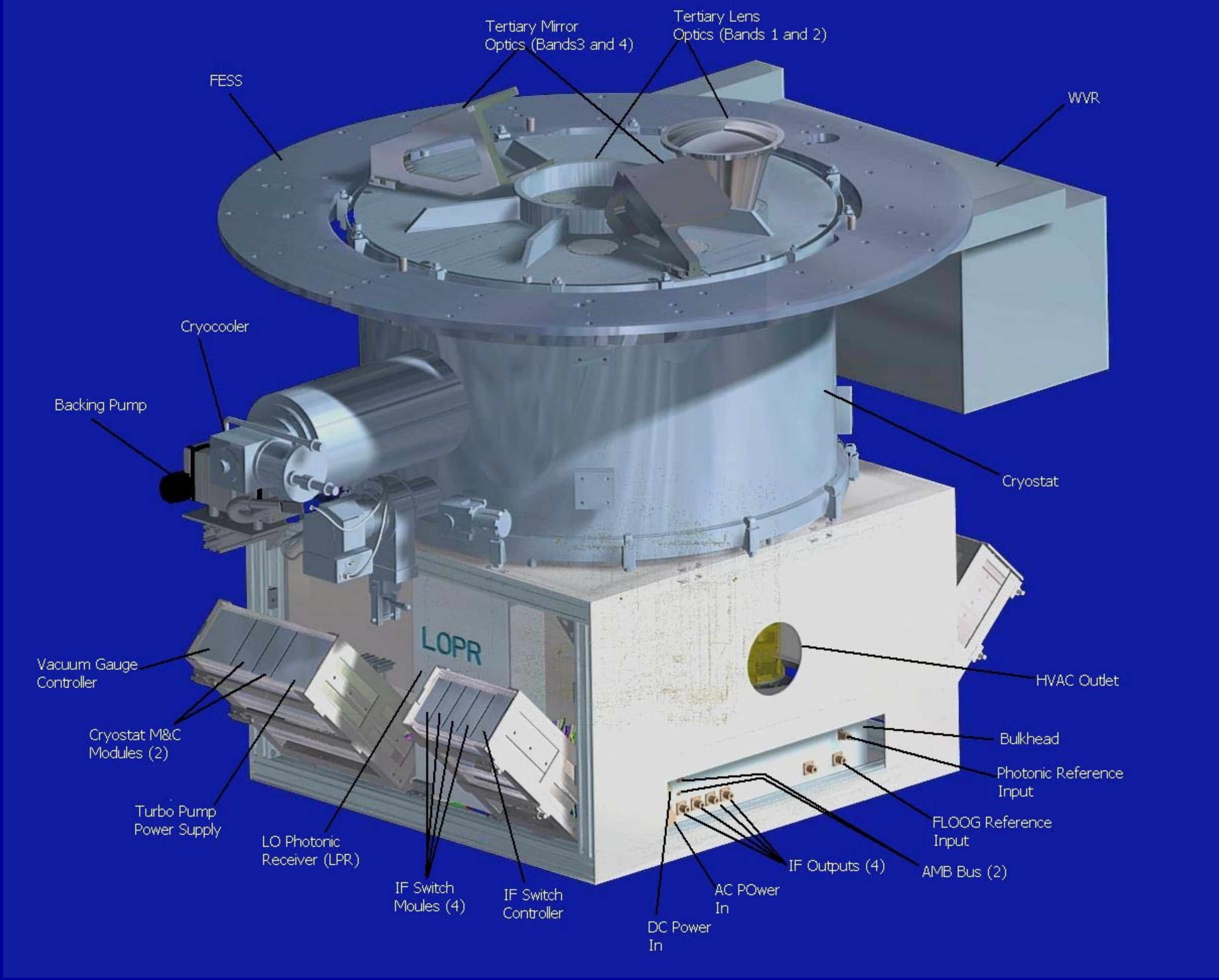
Transporters coming past the valley of moon

First Move of an ALMA Antenna
(July 8, 2008)

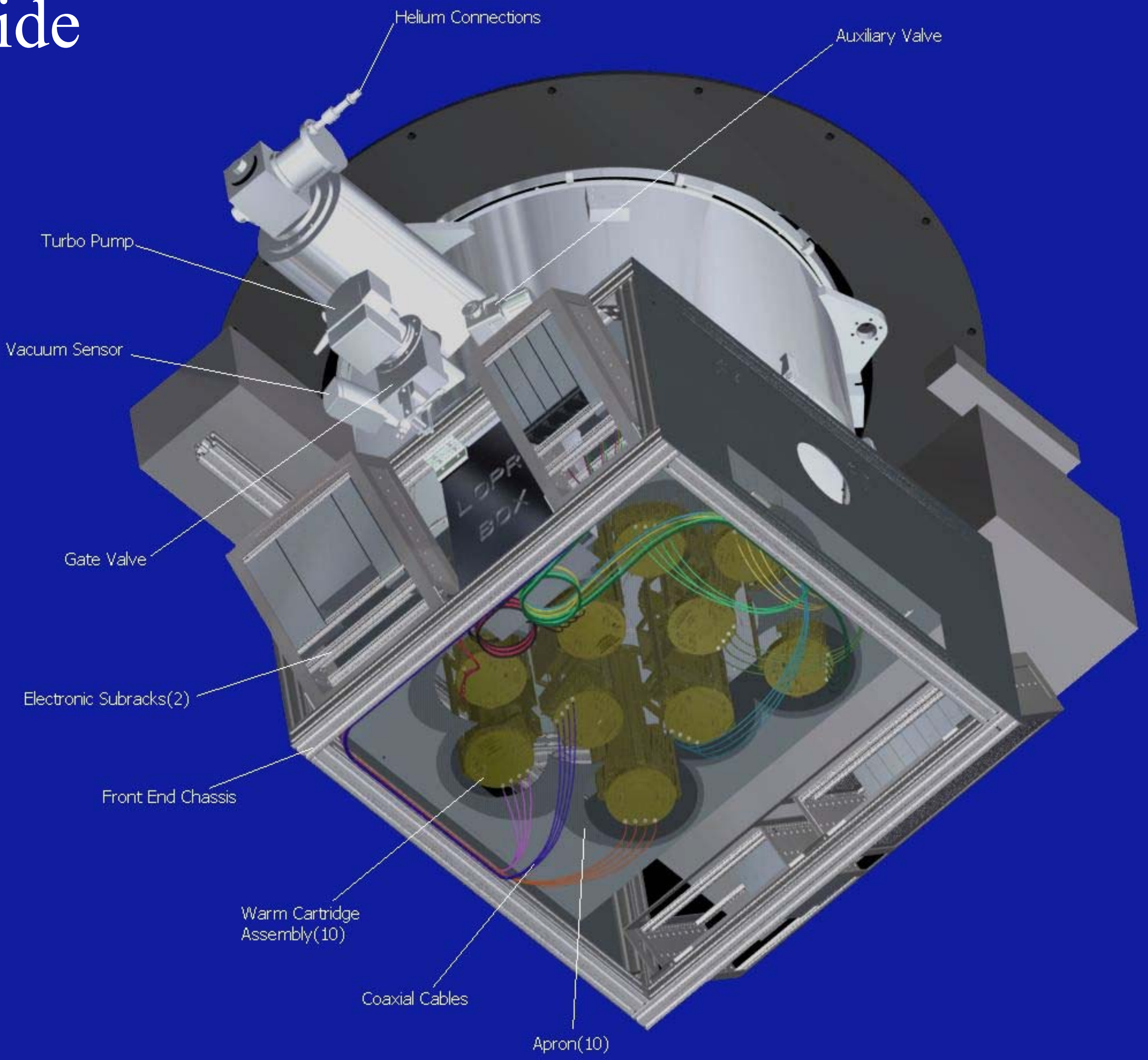
Receivers – up to 10 cartridges in one cryostat



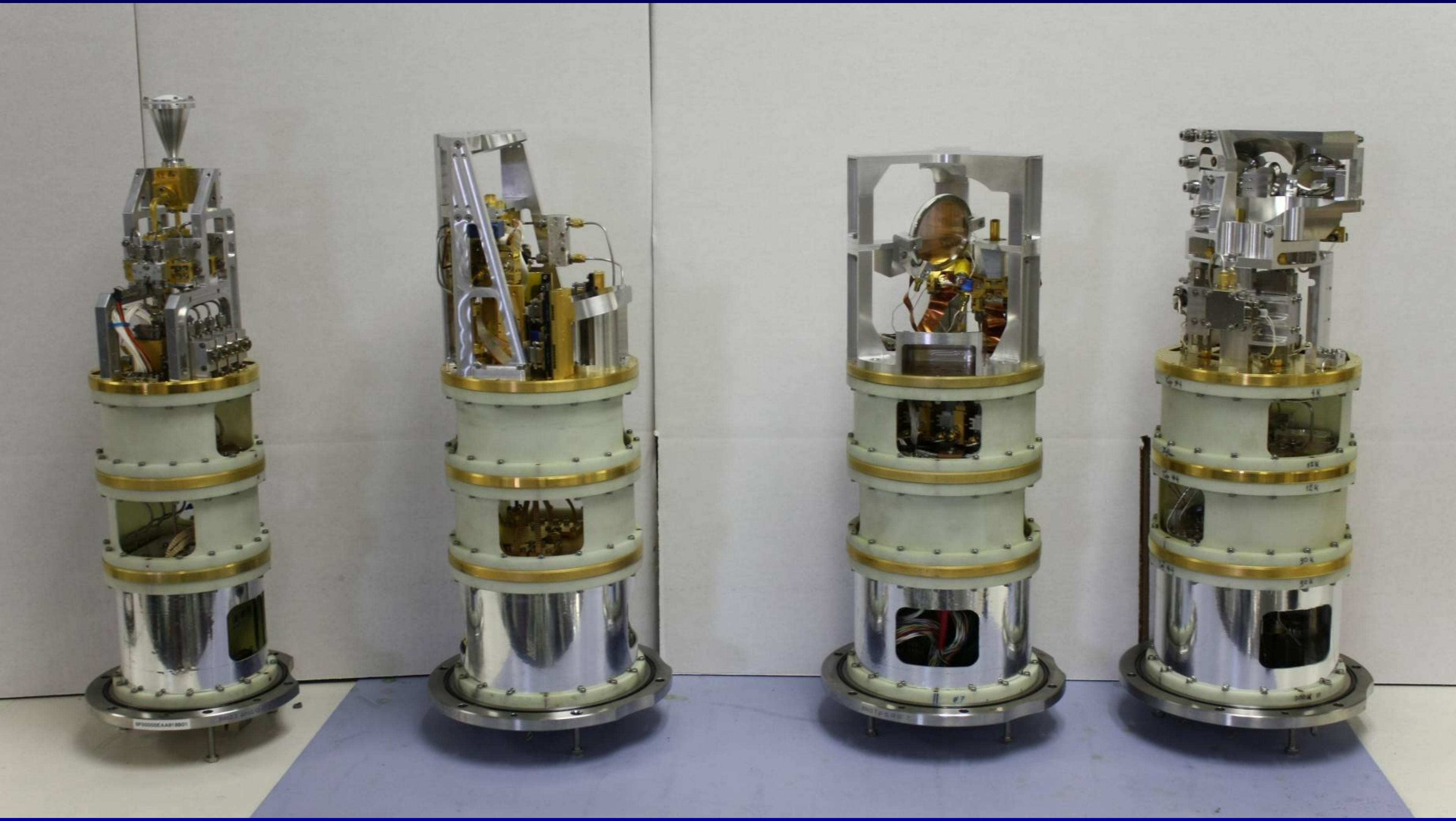
- 3-D model of the "front end"



Underside

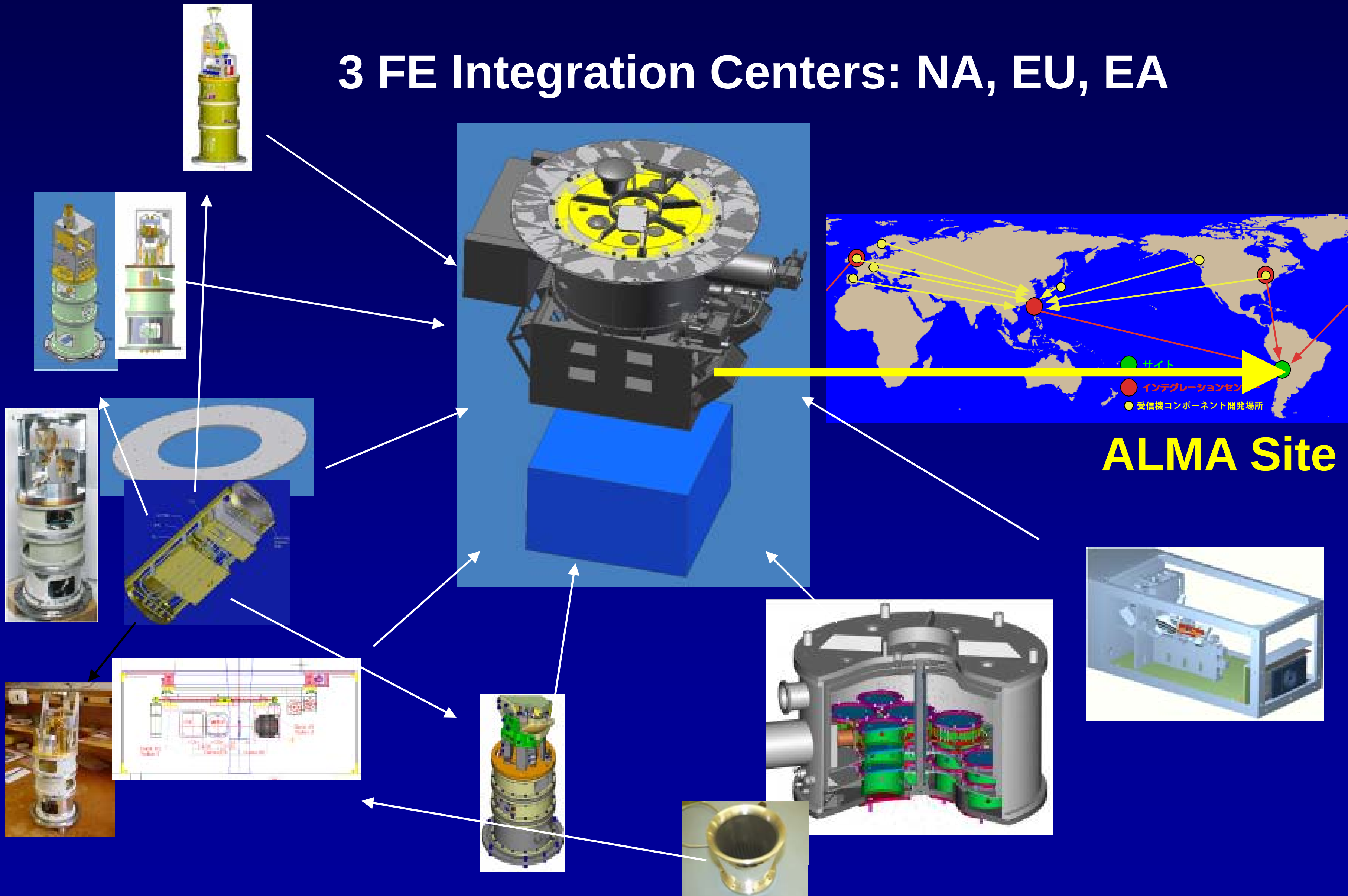

Helium Connections
Auxiliary Valve
Turbo Pump
Vacuum Sensor
LOPR BOX
Gate Valve
Electronic Subracks(2)
Front End Chassis
Warm Cartridge Assembly(10)
Coaxial Cables
Apron(10)

Bands 3 (84-116 GHz), 6 (211-275 GHz), 7 (275-373 GHz), and 9 (602-720 GHz) SIS "cartridges"



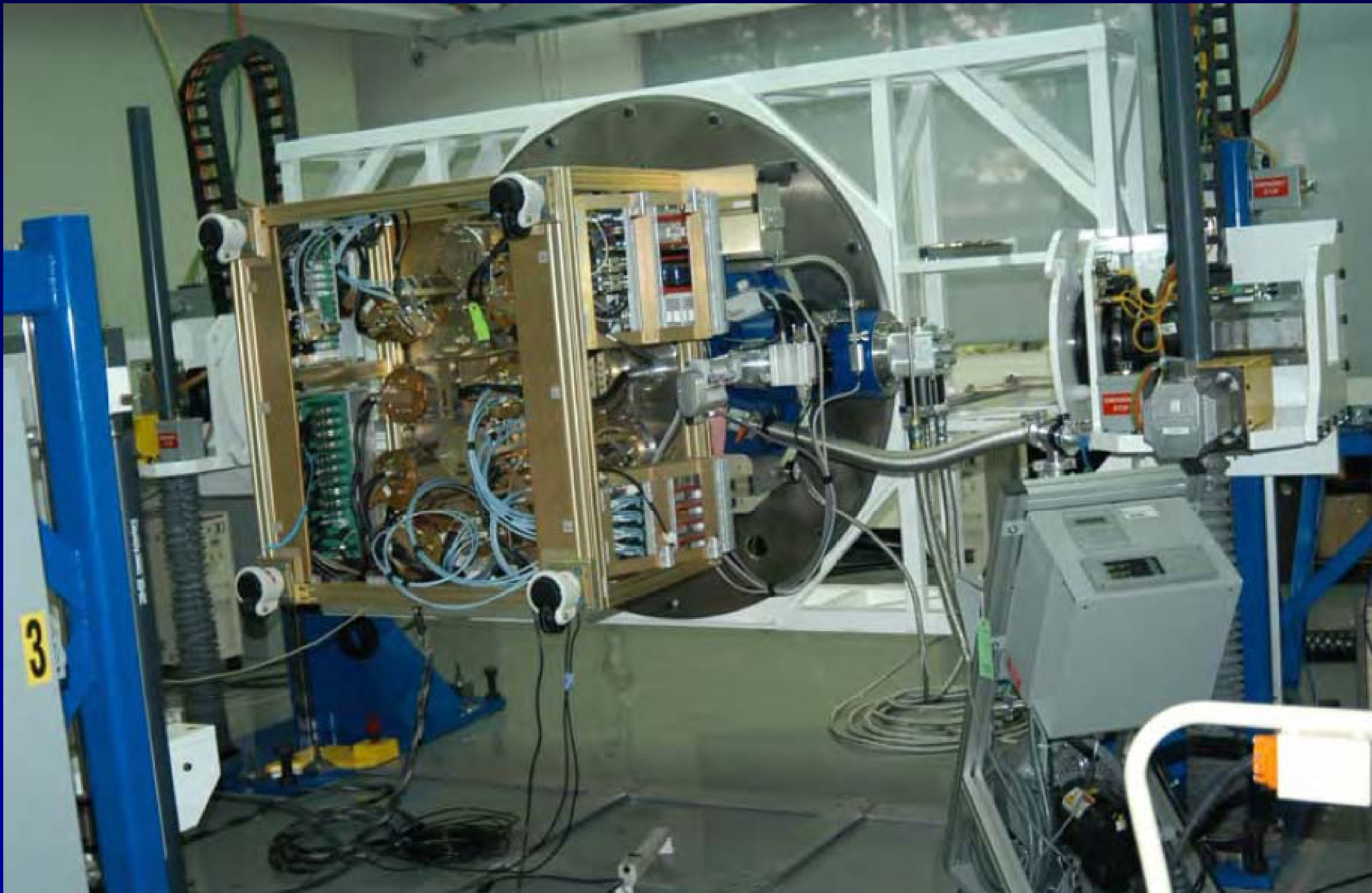
ALMA Front End System Integration

3 FE Integration Centers: NA, EU, EA

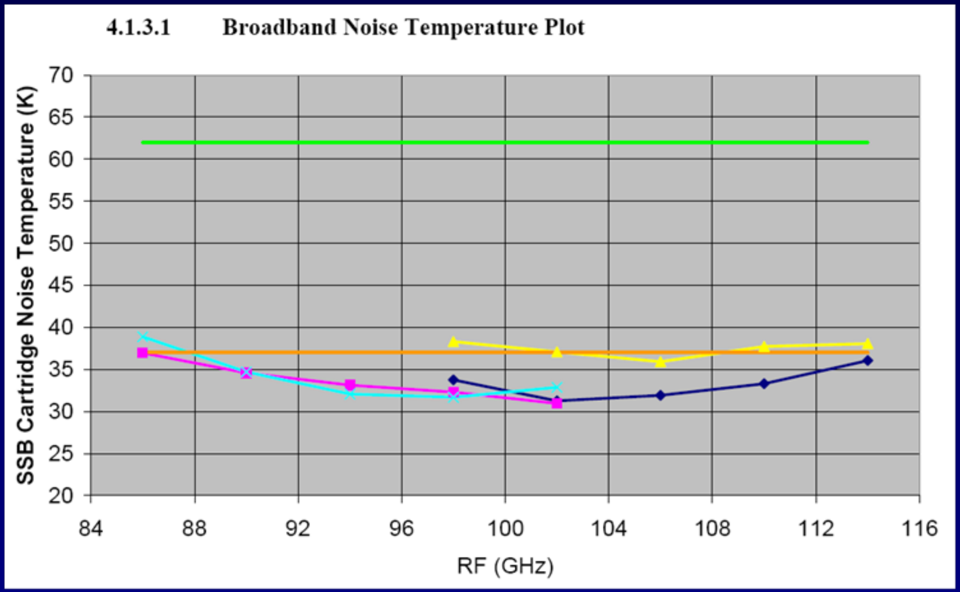


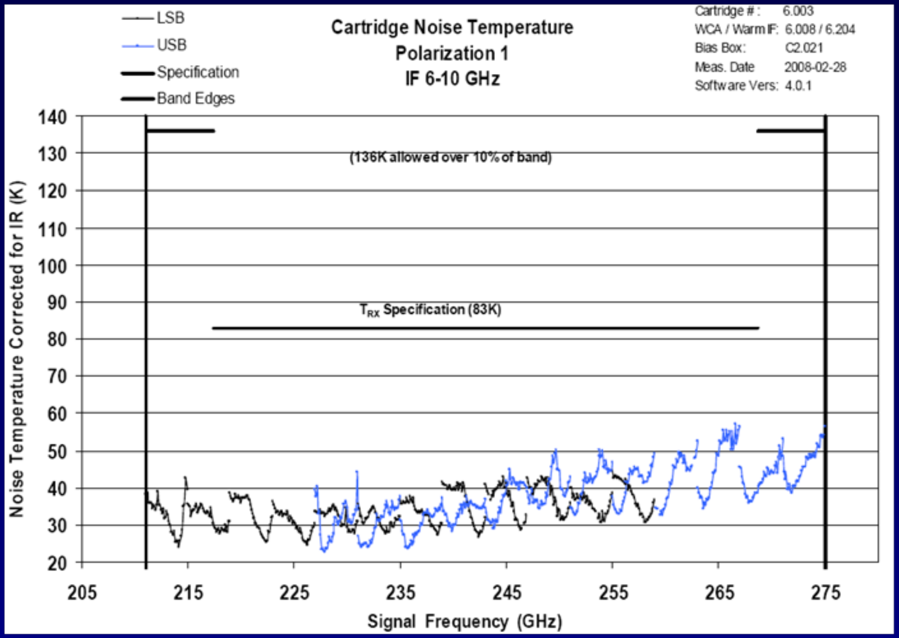
First FE/BE under test at OSF

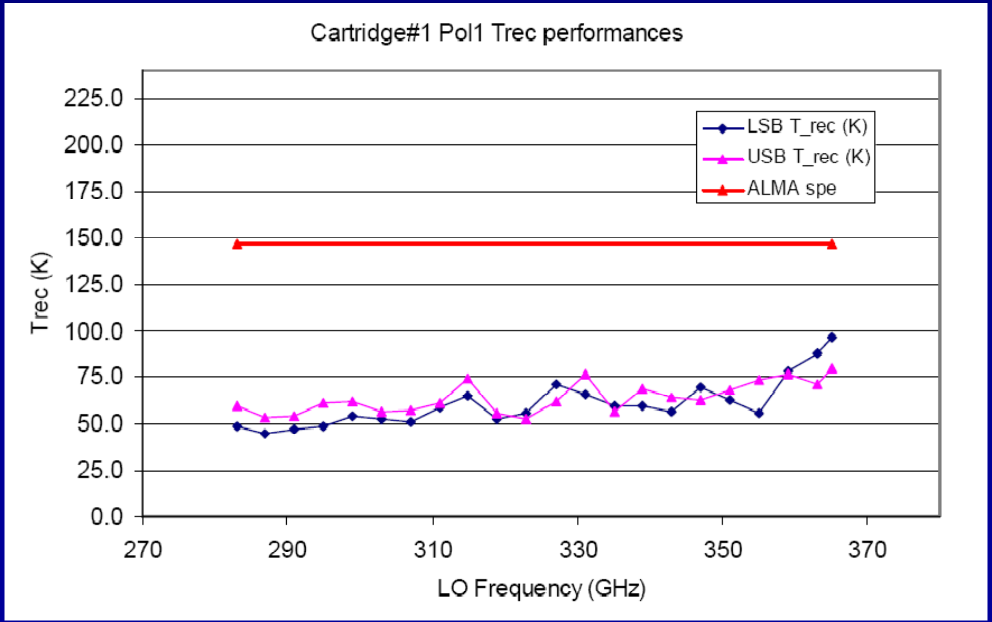
Testing and Verifying Performance is HARD!

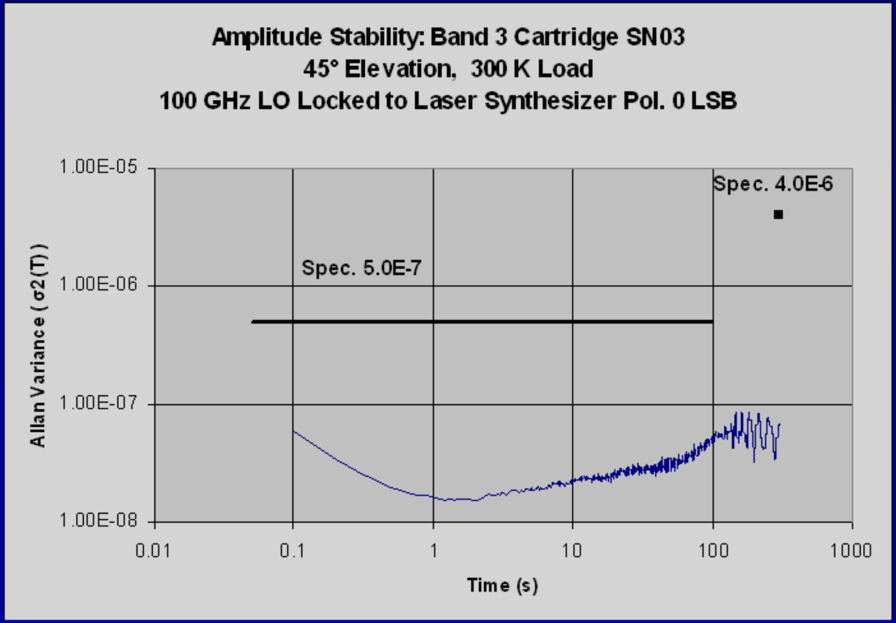


Receiver Performance Looks Excellent



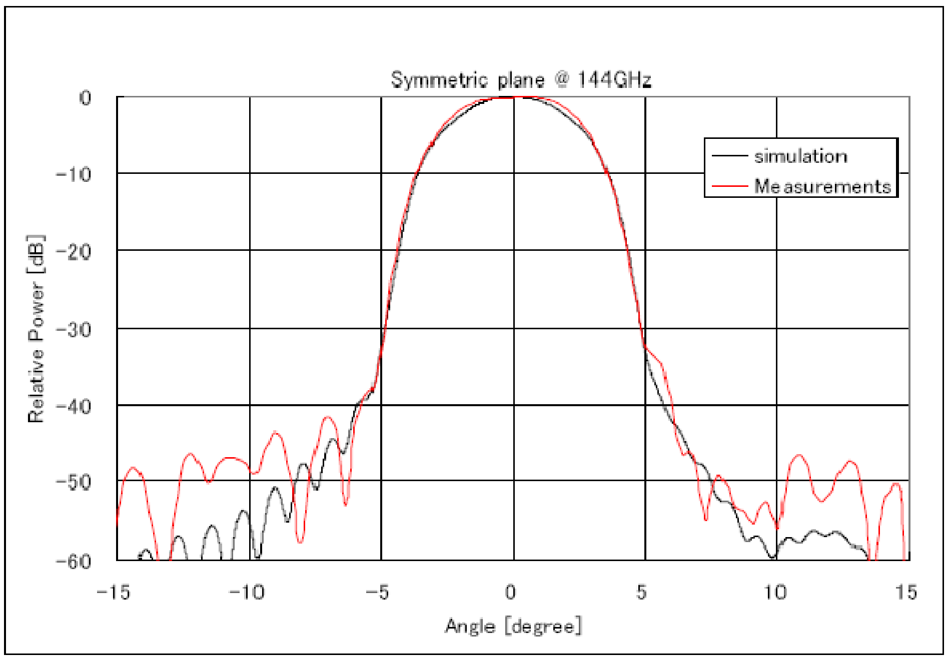


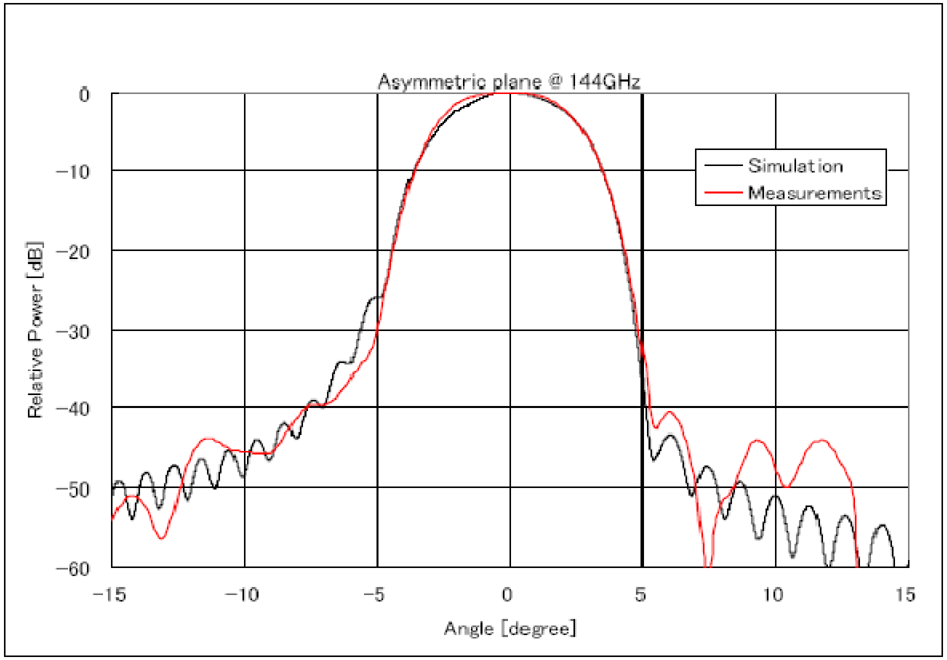




Band 4 Receiver Beam Pattern

- Cross sectional views of co-polar beam patterns in the symmetric and asymmetric plane at 144 GHz. Red lines indicate measured beam pattern of the Pol 0 port. Black lines are the physical optics calculated by M. Sugimoto.



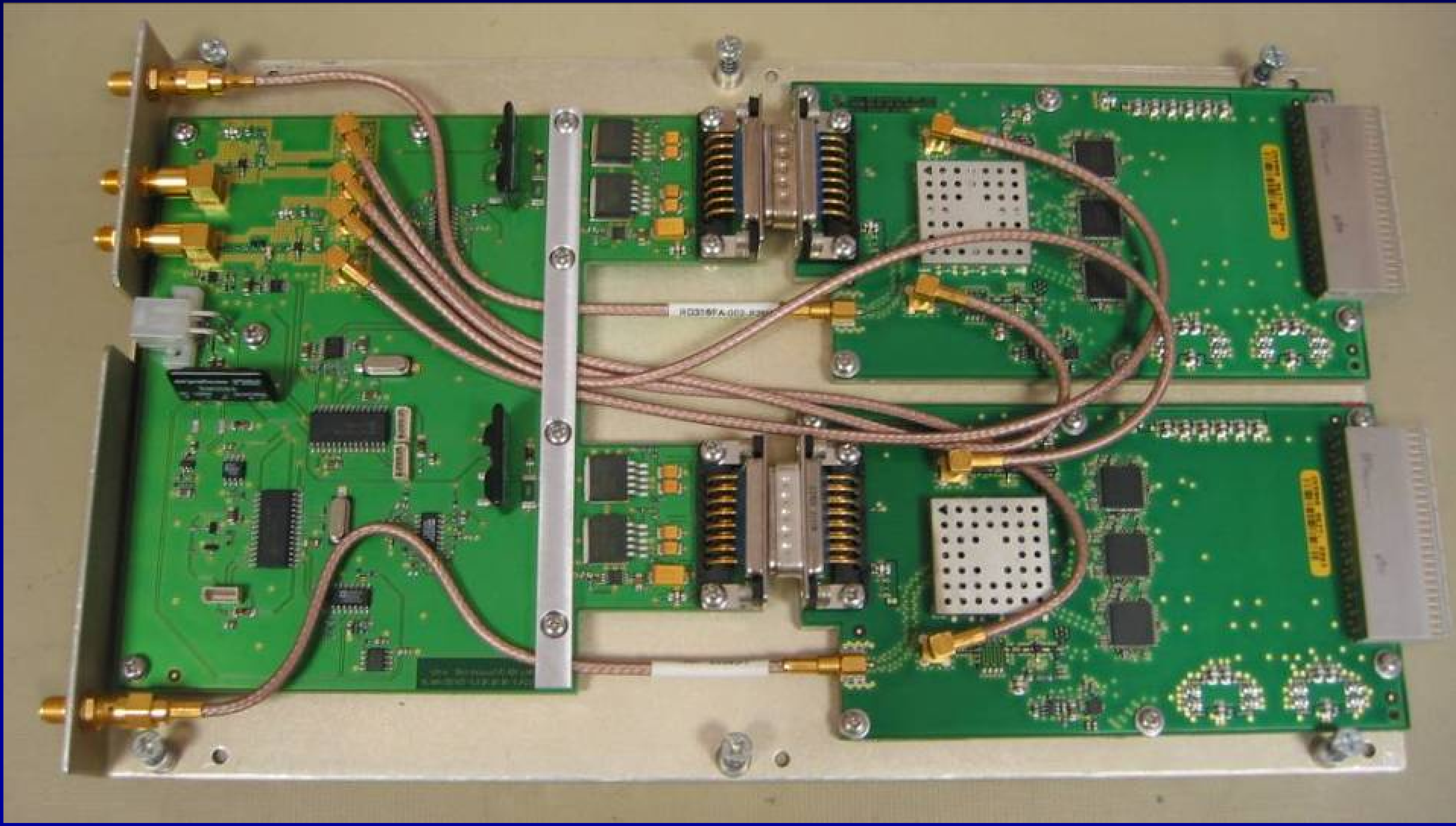


Back End racks being lifted into MELCO #2 receiver cabin

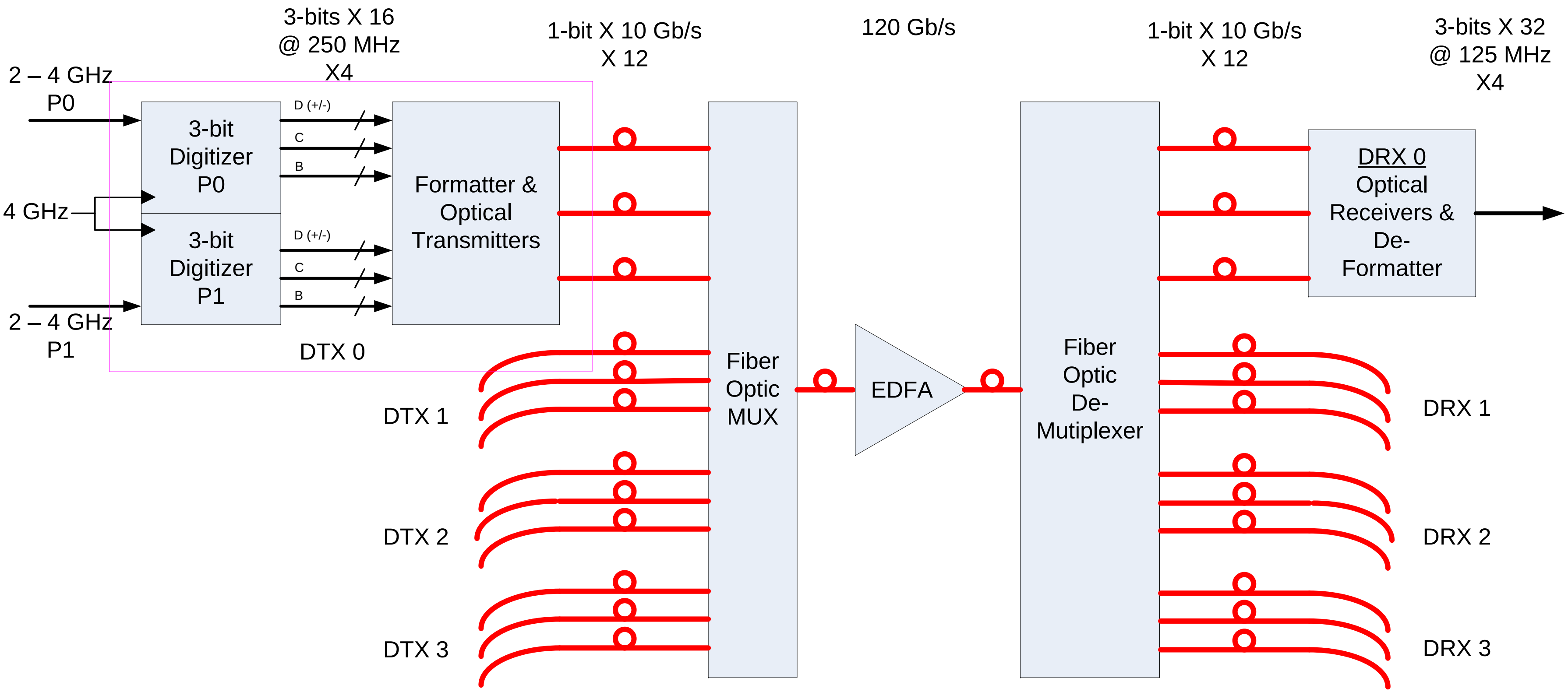
Dual-channel Digitizers on the Antennas

3 bits at 4 Gs/sec per channel

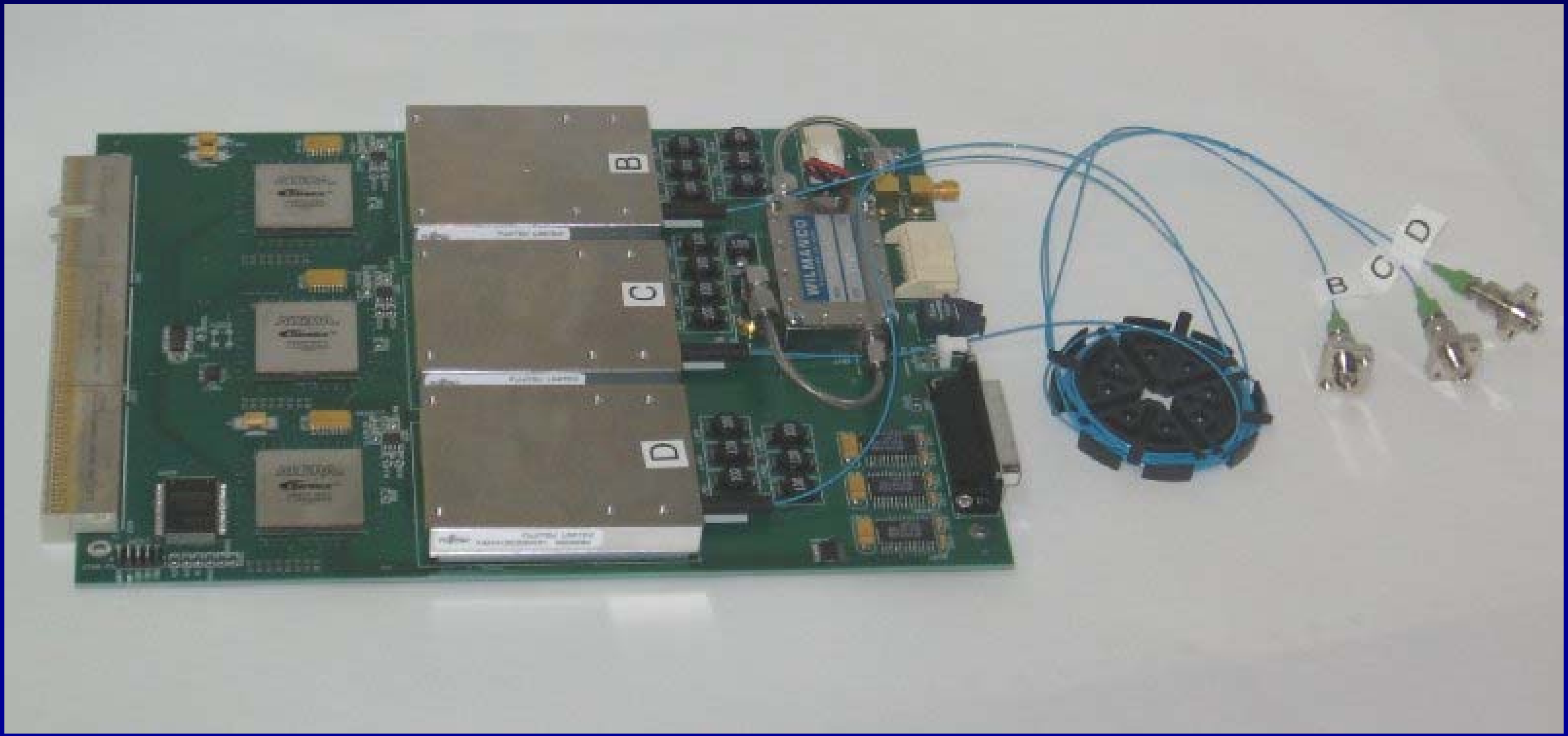
Data rate is 120 Gb/s per antenna



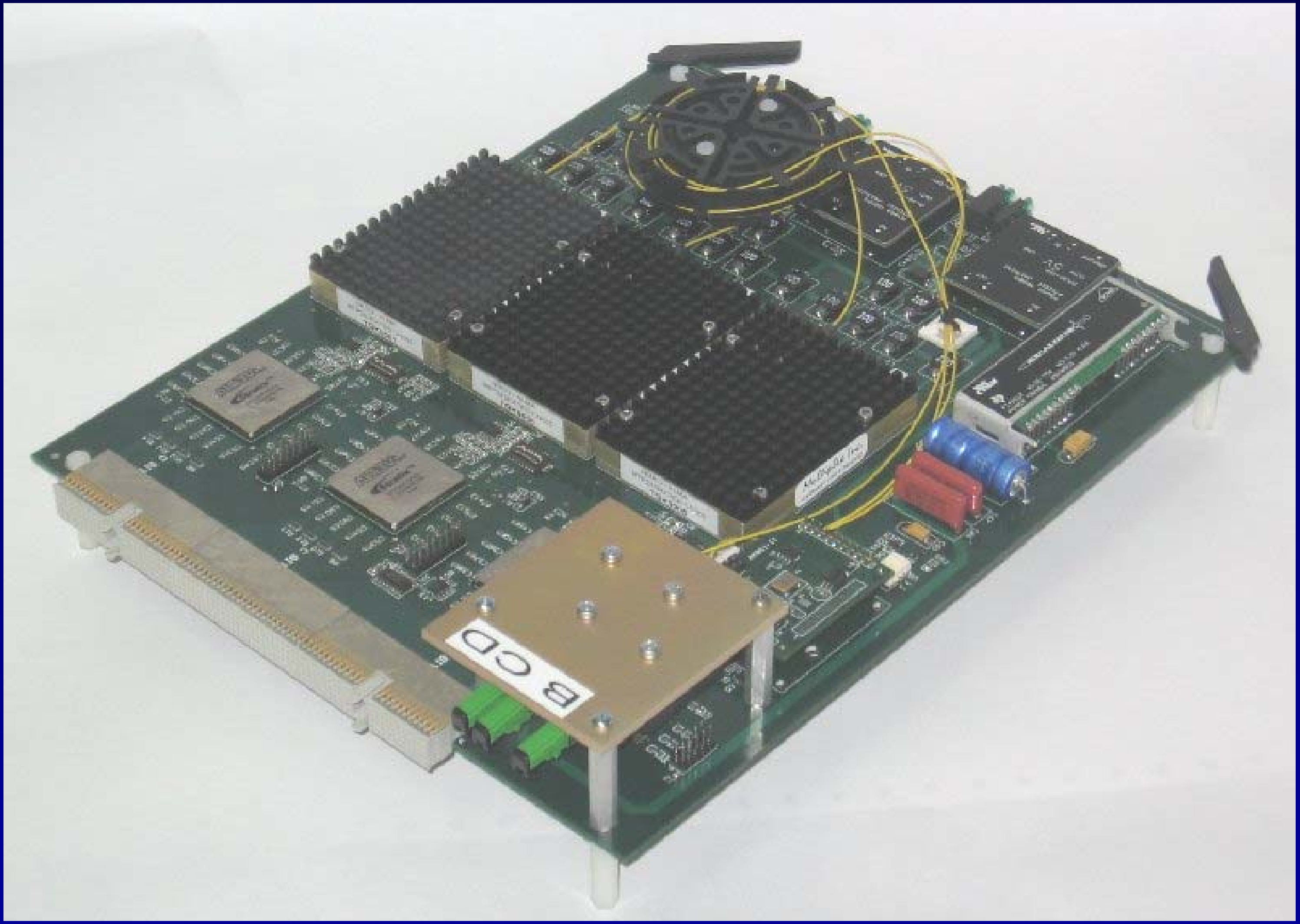
Data Transmission System



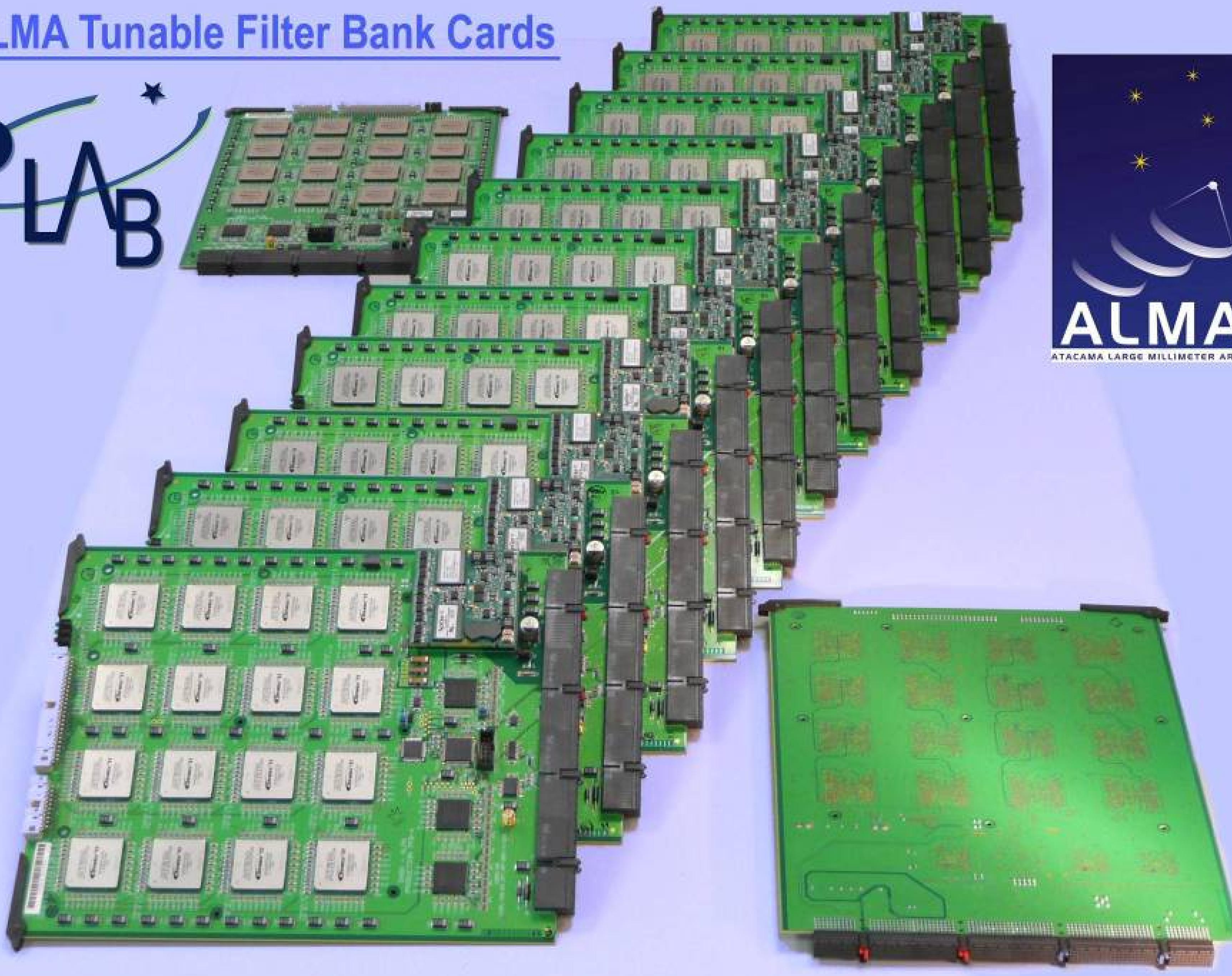
Formatter with 3 Optical Transmitting Transponders



Data Receiver Module



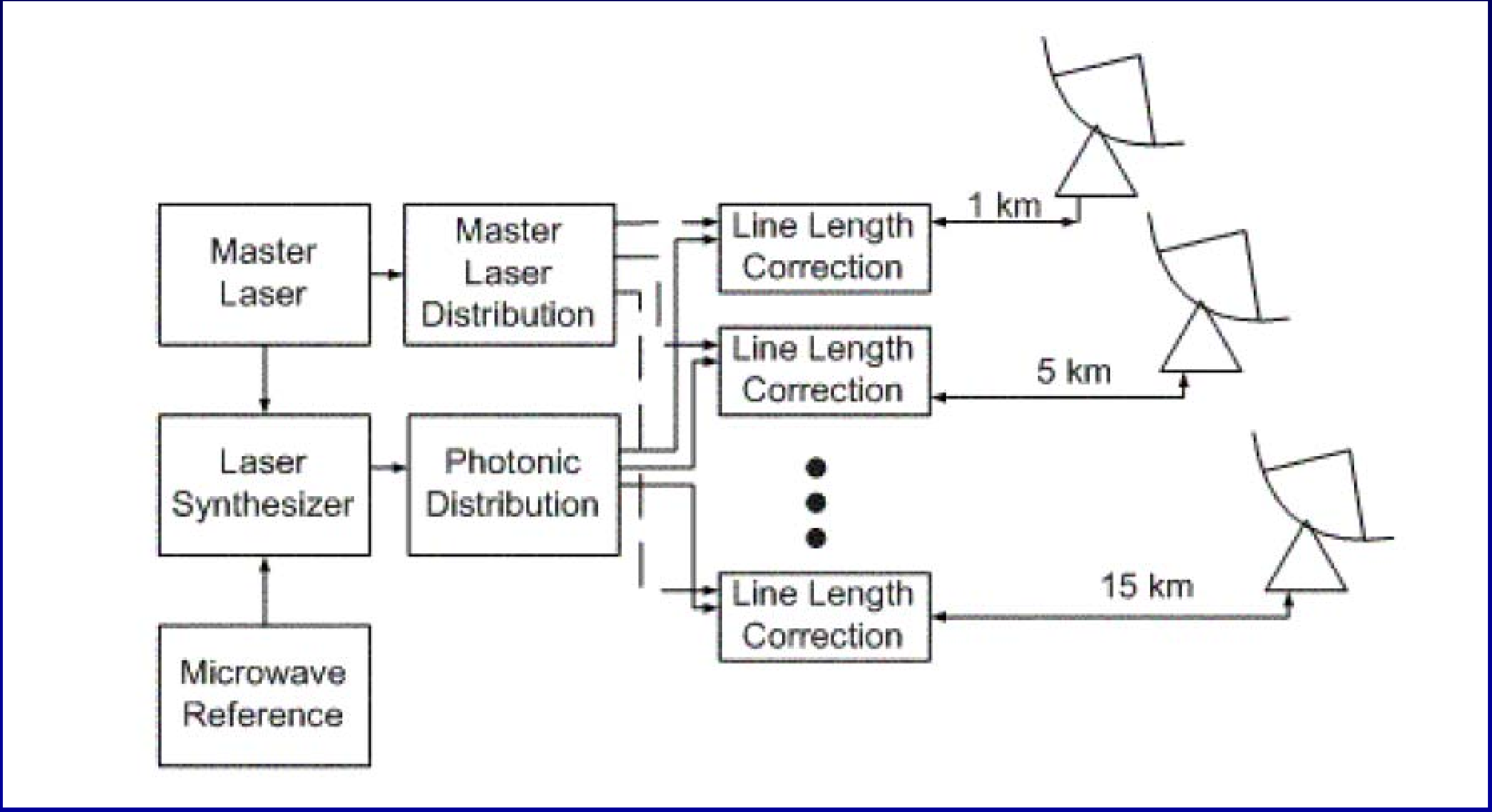
ALMA Tunable Filter Bank Cards



ALMA
ATACAMA LARGE MILLIMETER ARRAY

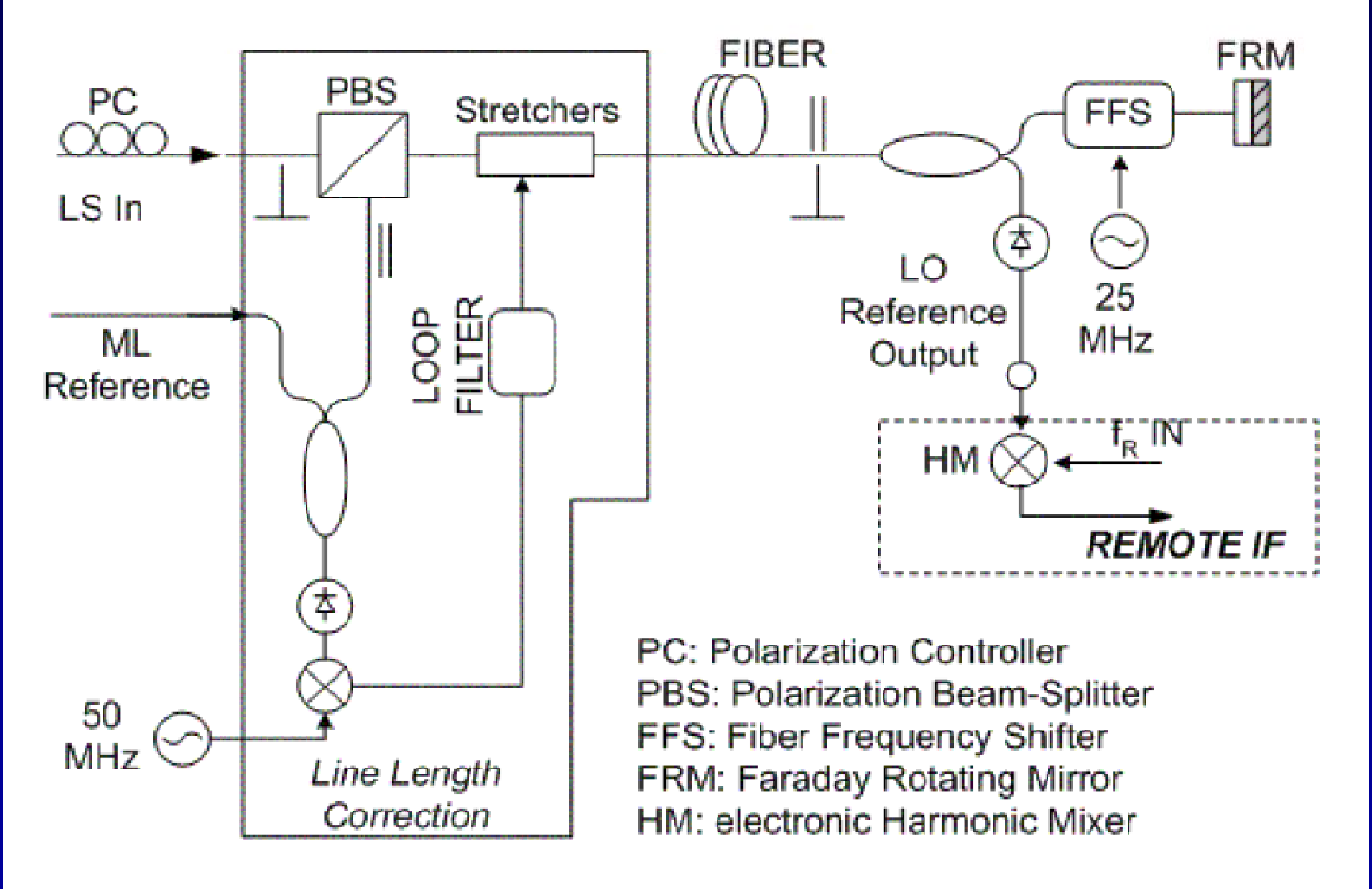
Laser Local Oscillator – Baseline

LO reference distributed optically by using two lasers – master and slave – separated by ~100 GHz

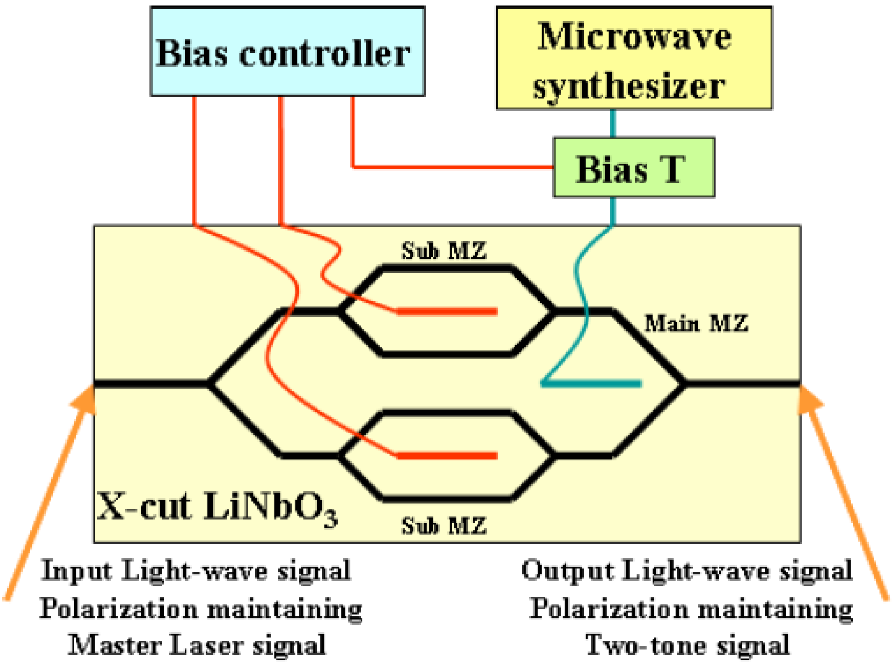


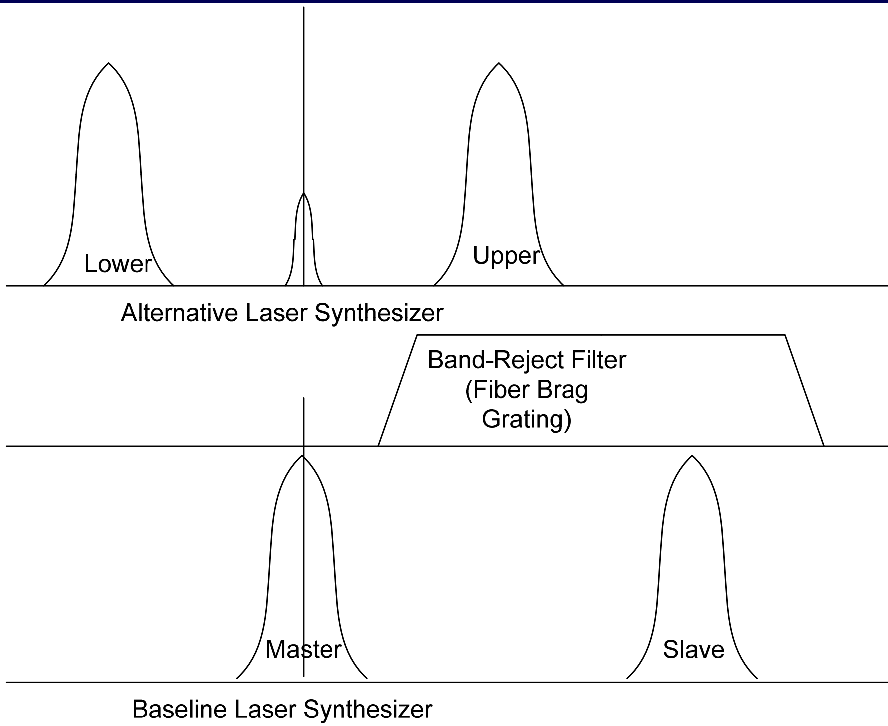
Correcting Fibre Length Changes – Baseline

Close the loop on the optical Master Laser fringes



Alternative Scheme for generating the two optical frequencies – one laser with fast modulation.

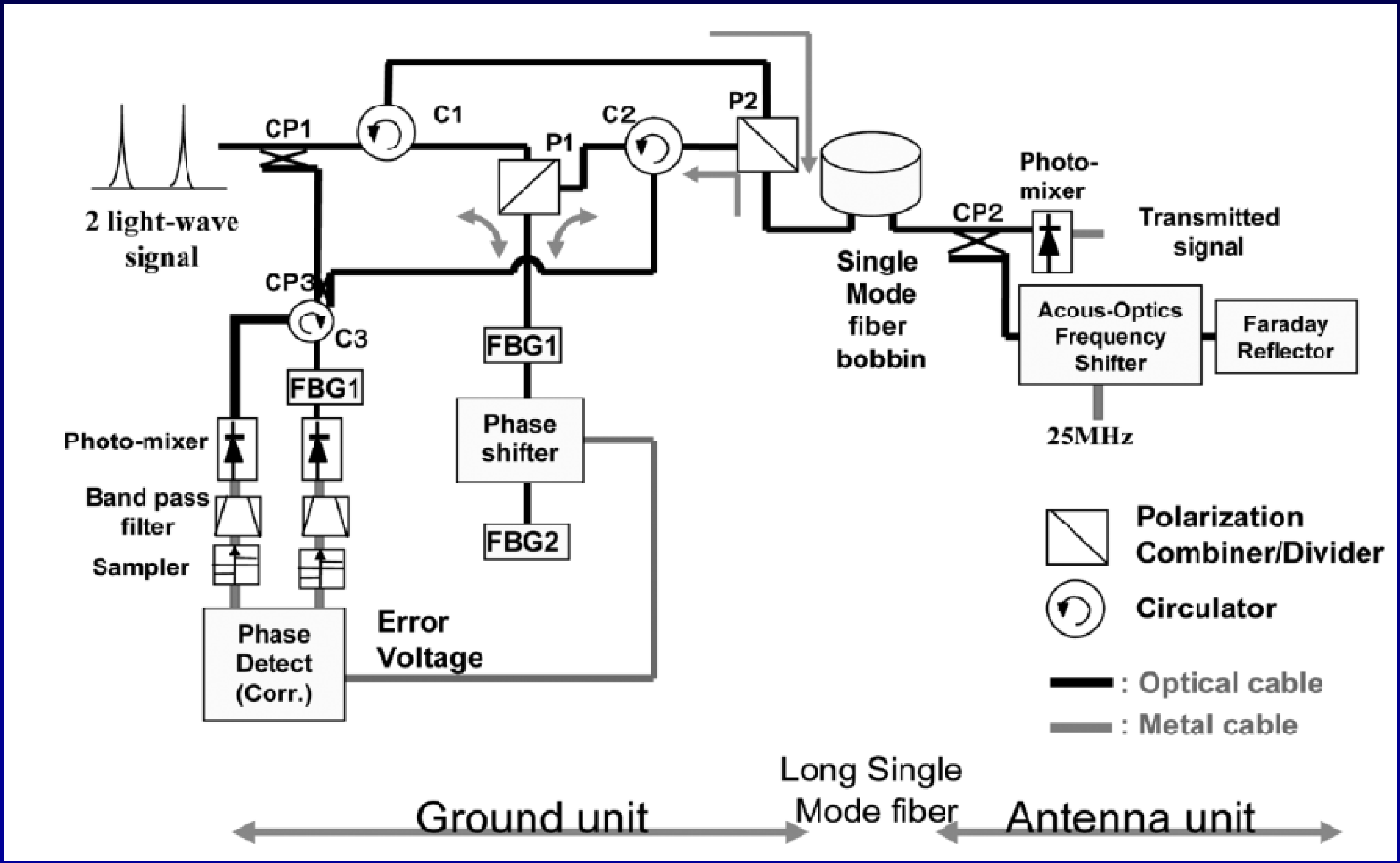




This should provide somewhat lower phase noise than the “baseline” design and rather more flexibility in terms of rapid frequency changes and the like. The plan is for our East Asia partners to build a synthesizer based on this approach as a test.

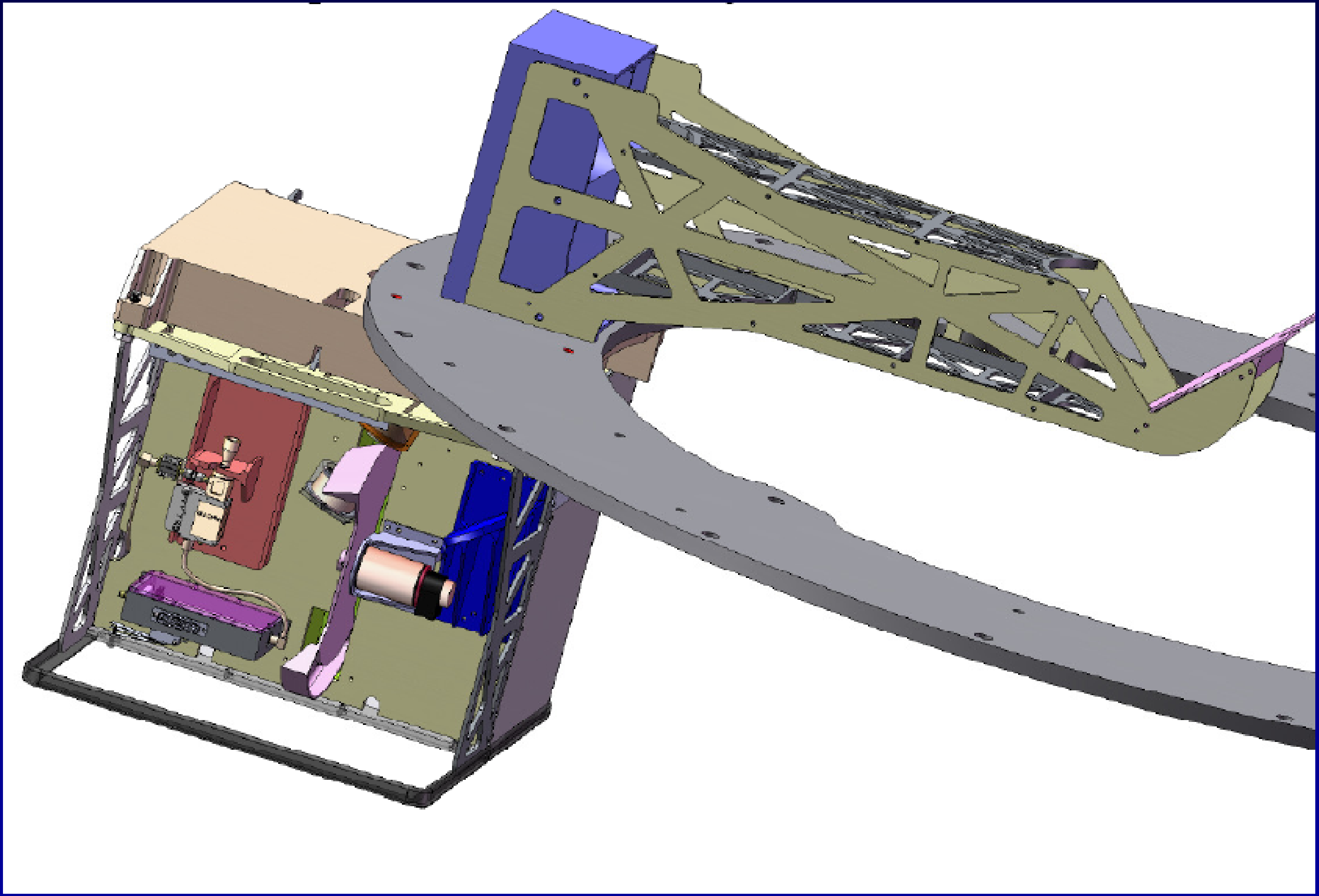
Alternative Line Length Correction Scheme

Locks on modulation instead of on the optical wave

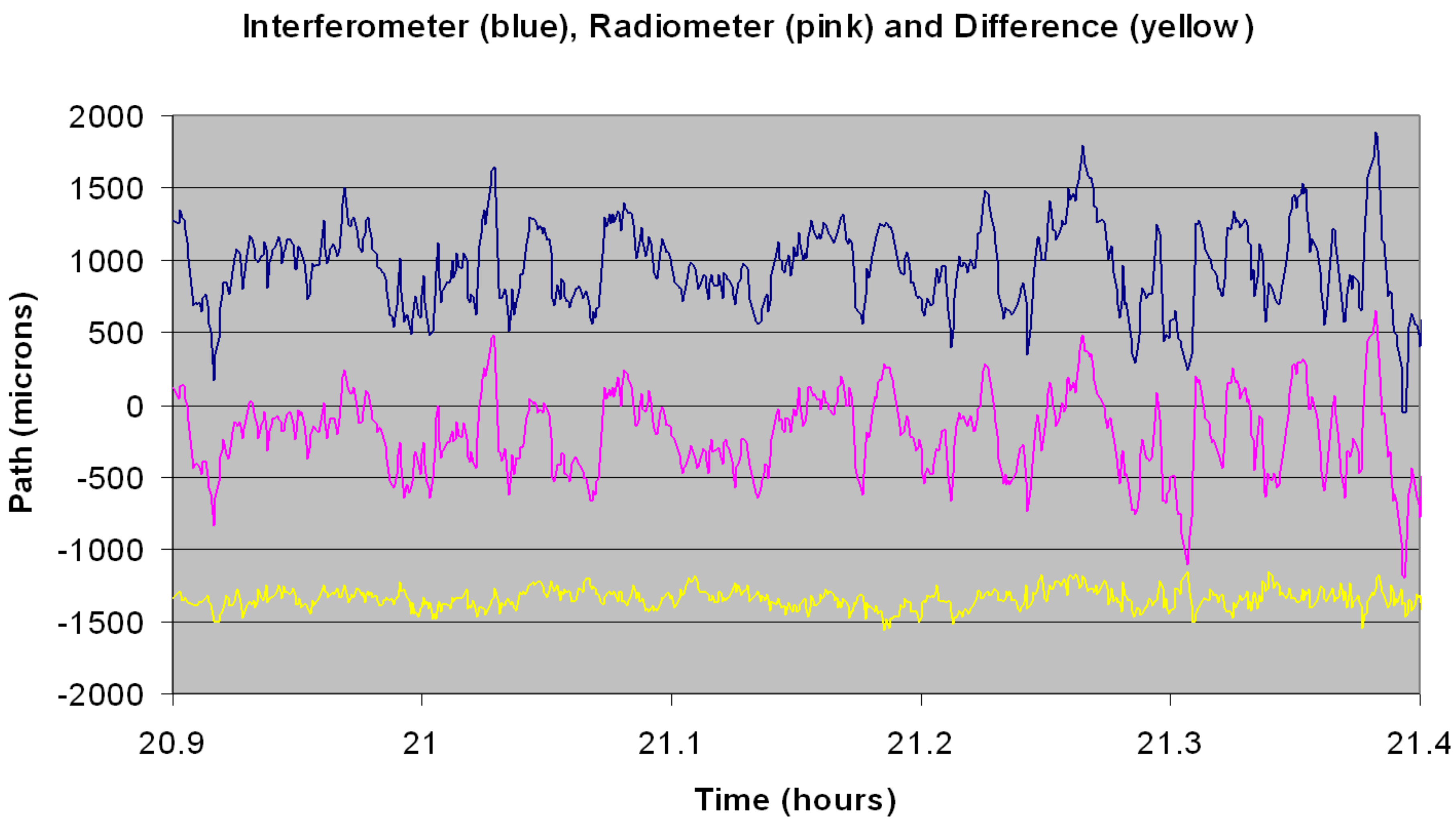


Trying to find way of building a test version of this without delaying the production of the baseline system

183 GHz WVR for phase correction



Test of phase correction at the SMA

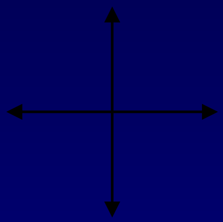


Polarization

- Each receiver cartridge has two channels that should respond to one linear polarization only.
- Requirement was set at 99.5% polarization purity
- Some pre-production cartridges were only achieving ~97 or 98%.
- Even 99.5% leaves a demanding job to be done in terms of calibration. Values below ~99% will cause problems for basic total power imaging.

Measuring Stoke's Visibilities

- **IF** we had perfect linear feeds these come from:
- $I = X_1.X_2^* + Y_1.Y_2^*$ Total power
- $Q = X_1.X_2^* - Y_1.Y_2^*$ Linear 0 / 90deg
- $U = X_1.Y_2^* + Y_1.X_2^*$ Linear 45 / 135deg
- $V = jX_1.Y_2^* - jY_1.X_2^*$ Circular



- For a weakly polarized source X.X* and Y.Y* are LARGE So measuring Q is mainly a stability issue – have to maintain <1 part in 1000 going from source to calibrator.
- But X.Y*, etc., are small, so for U and V stability is (a bit) less critical, the problem is purity and calibration:

- The Leakage Problem:

  - Front End actually gives us $X' = X + \delta Y$, $Y' = Y + \varepsilon X$ where $|\delta| \sim |\varepsilon| \sim 0.1$ for 20dB polarization leakage.

  - Find $Q' = Q - \delta_1 \delta_2 Y_1.Y_2^* + \varepsilon_1 \varepsilon_2 X_1.X_2^*$
    i.e. errors of order 1% of total flux

  - But $U' = U + (\delta_1 + \delta_2^*) Y_1.Y_2^* + (\varepsilon_1^* + \varepsilon_2) X_1.X_2^* + \ldots$
    i.e. errors of order 10% of total flux

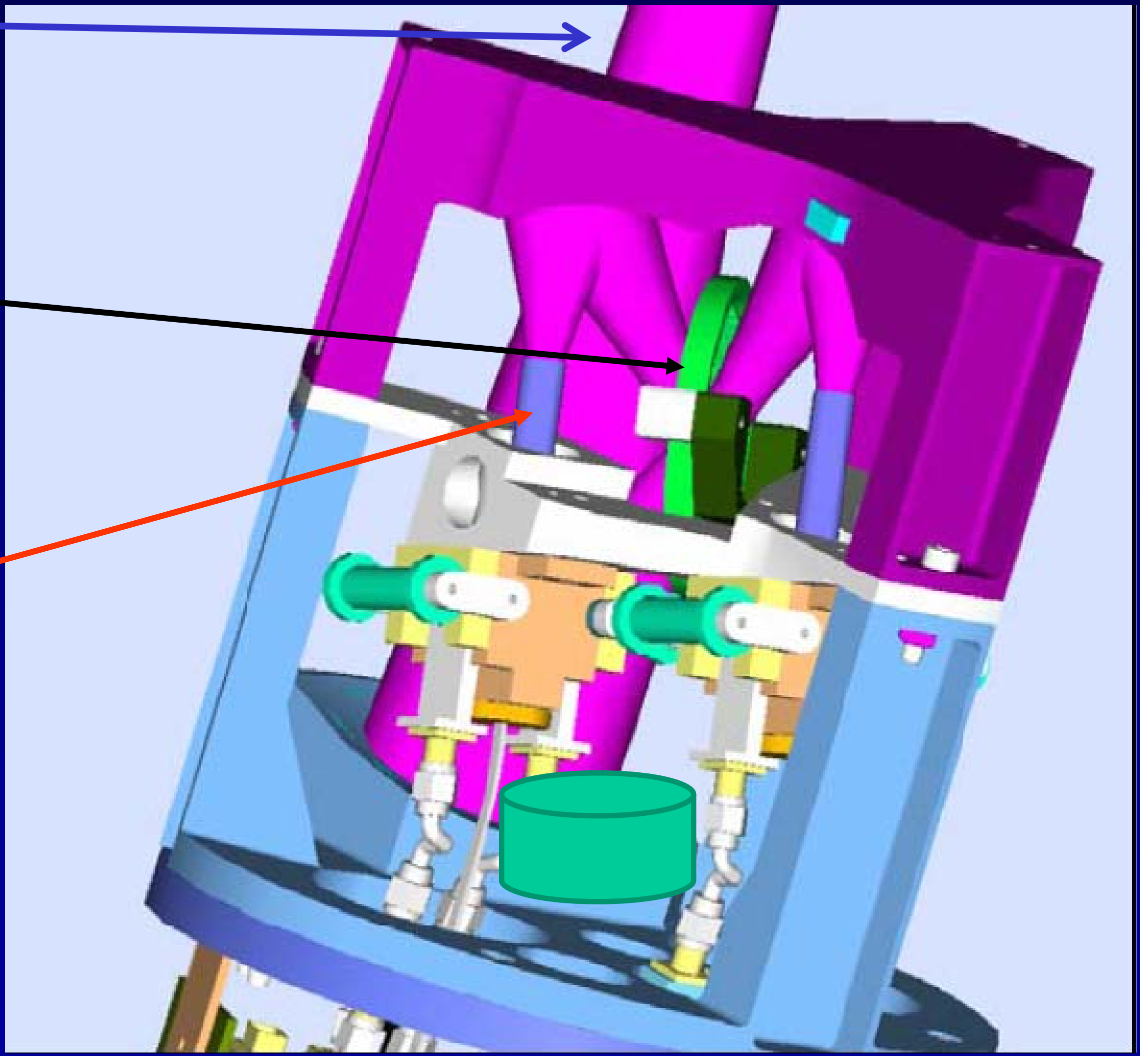
So we then need to calibrate these to ~1 part in 100 to make measurements at the 0.1% level.

Band 7 – seen as most critical

Windows
& filters

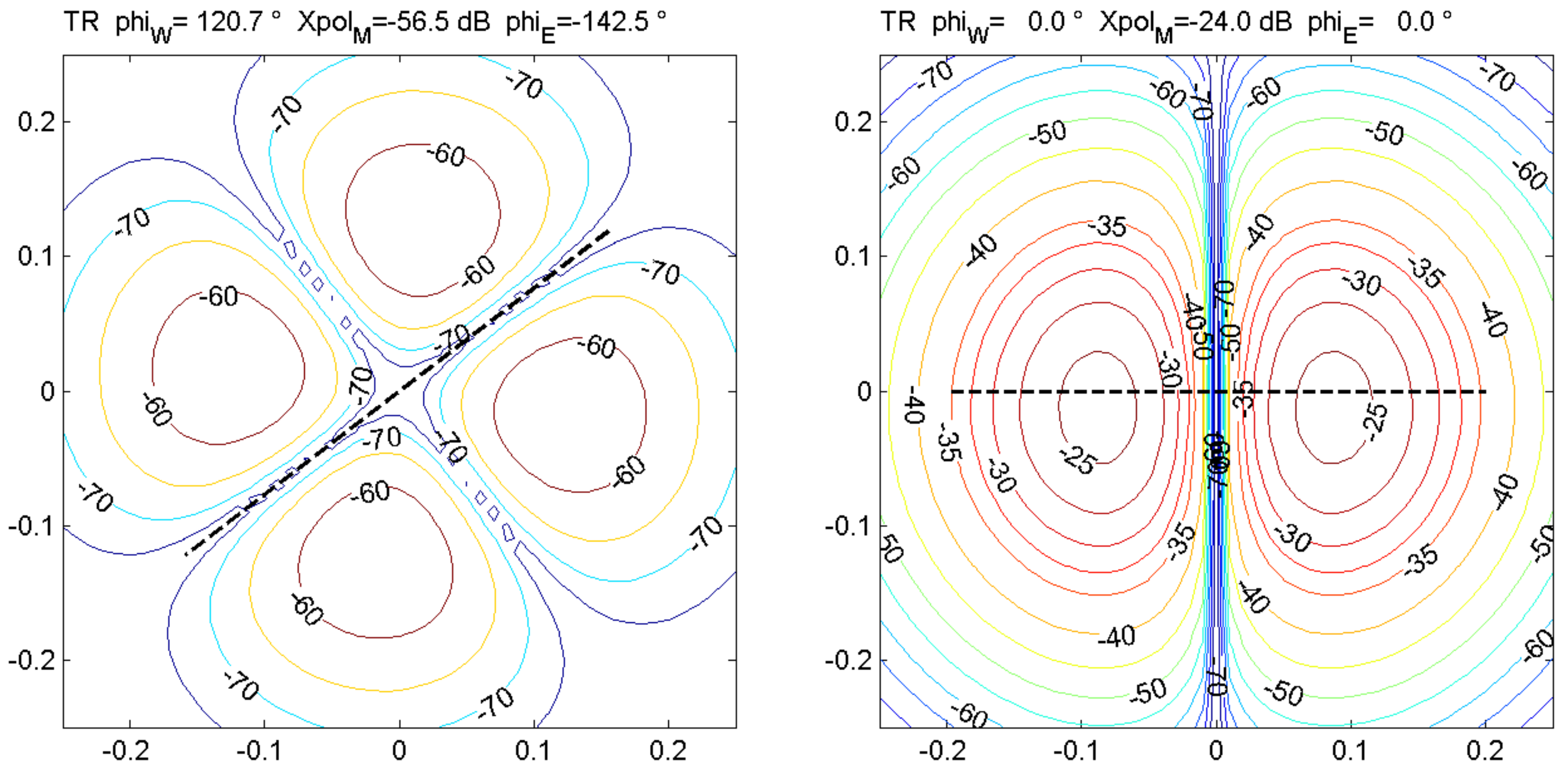
Grid

Feeds



Band 7 – solution

- Filter problem due to moulding – new process
- Effect of grid – is being fixed by rotating it

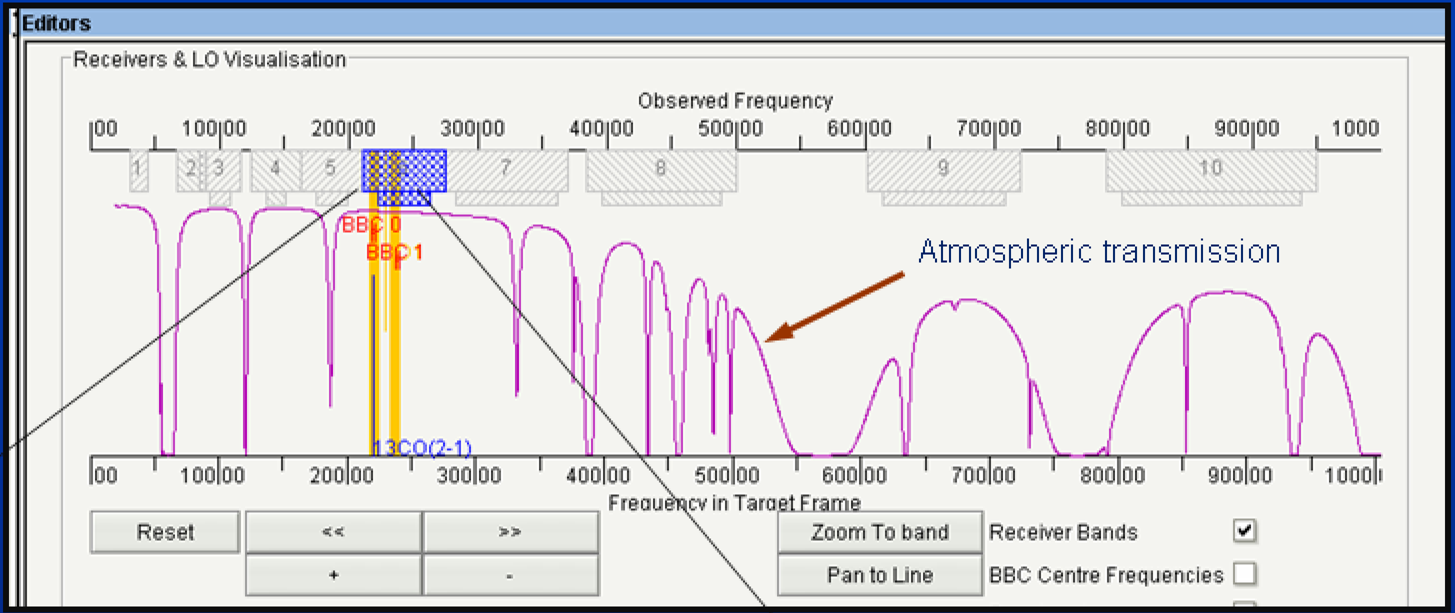


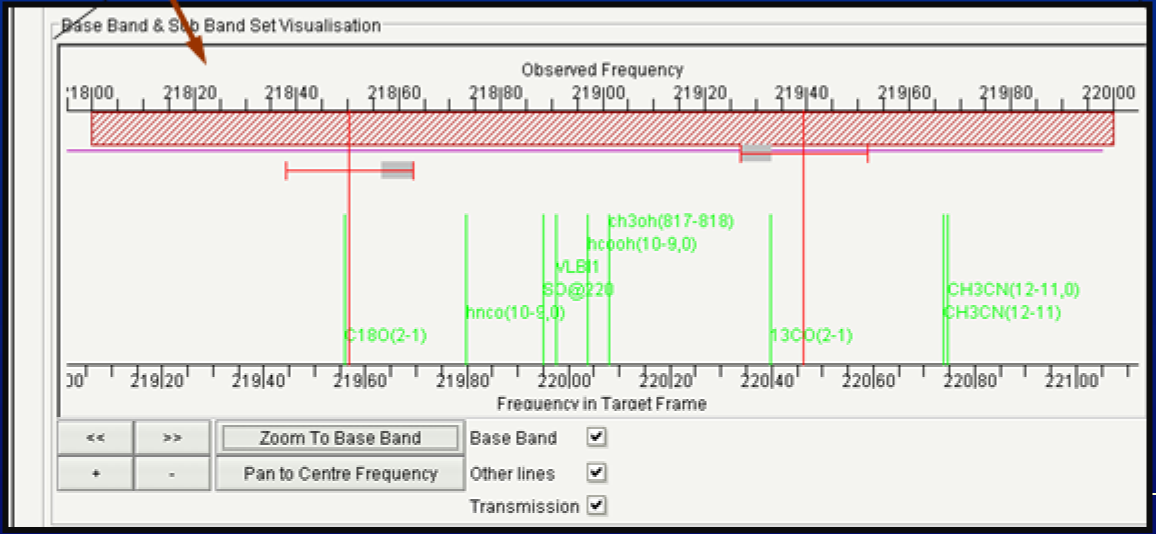
Software

- Hugely important aspect of ALMA
- Multiple levels from individual micros controlling devices, through the overall real-time control and data taking, on to data reduction and calibration and up to the broad issues of user support – proposal writing tools and the like.
- A very complete data reduction system, CASA, is now available for down-loading

Observing Tool

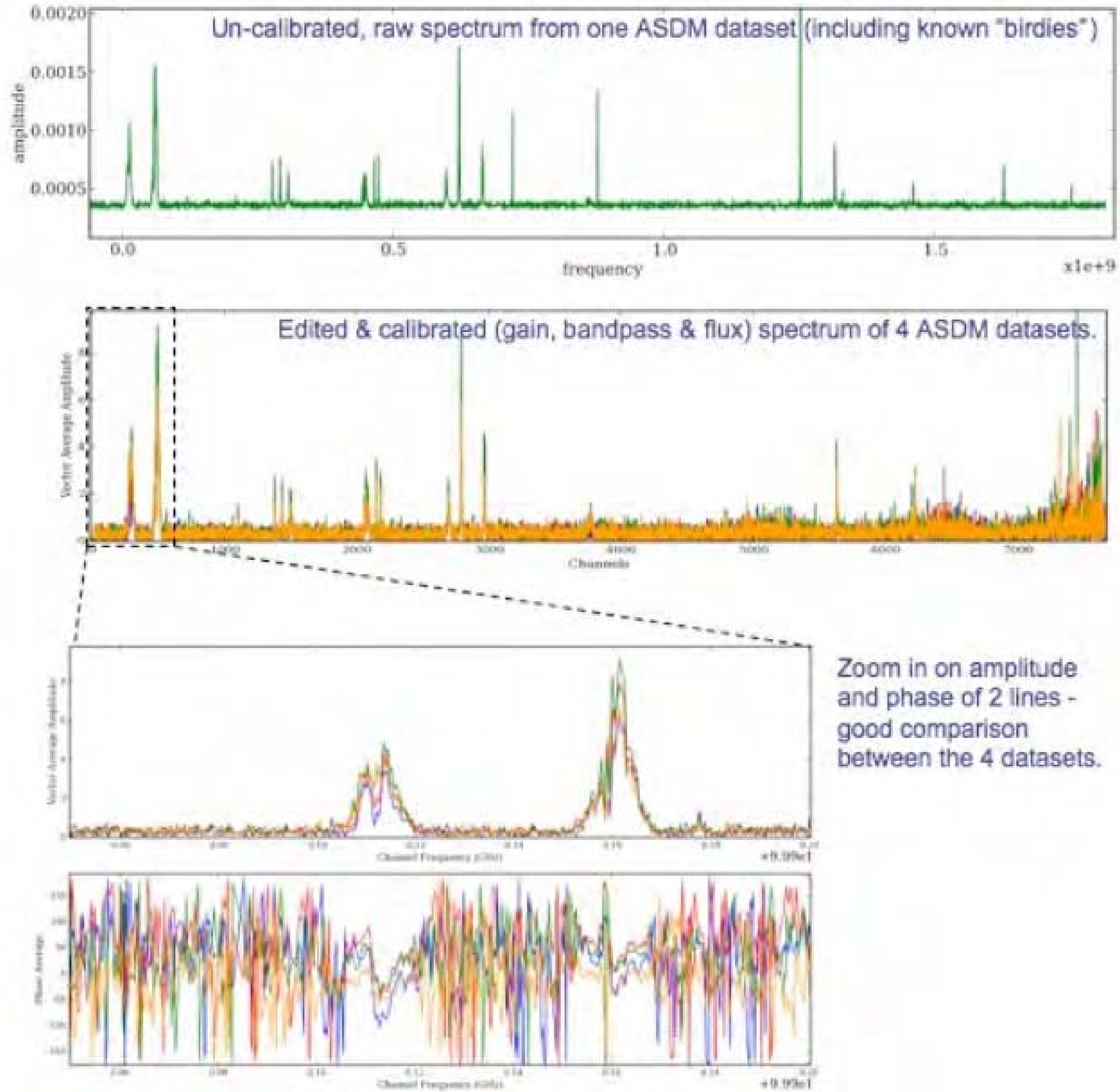
Band 6 close up showing lines in spectral database and windows on selected lines.





Target source visual representation of correlator setup to observe multiple lines at 1mm Band 6 ($C^{18}O$ 2-1 & ^{13}CO 2-1)

Interferometry data from the ALMA test facility

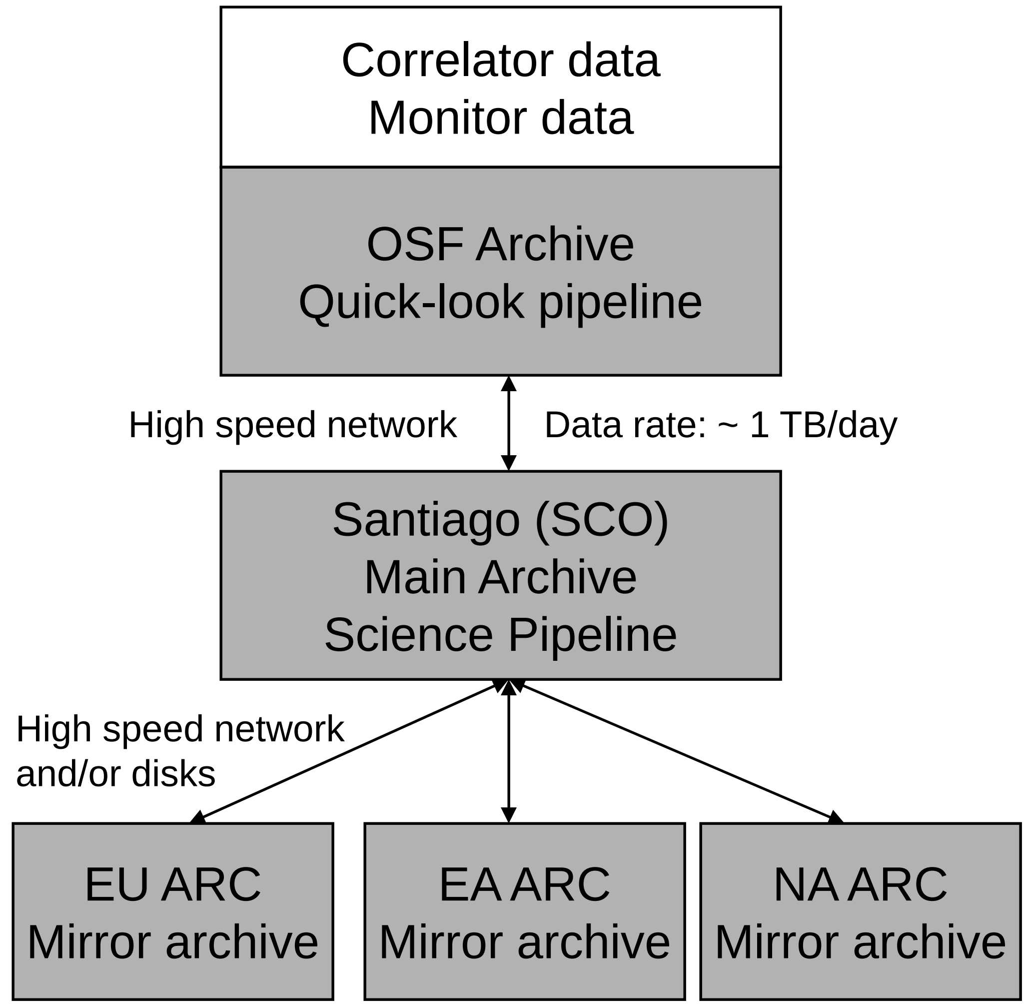


Archive has a central role

Archive content:

- All raw and calibration data
- All monitor data
- All data products produced by the standard pipeline (images etc.)
- Observing logs
- Proposals
- SBs
- Publications and other information

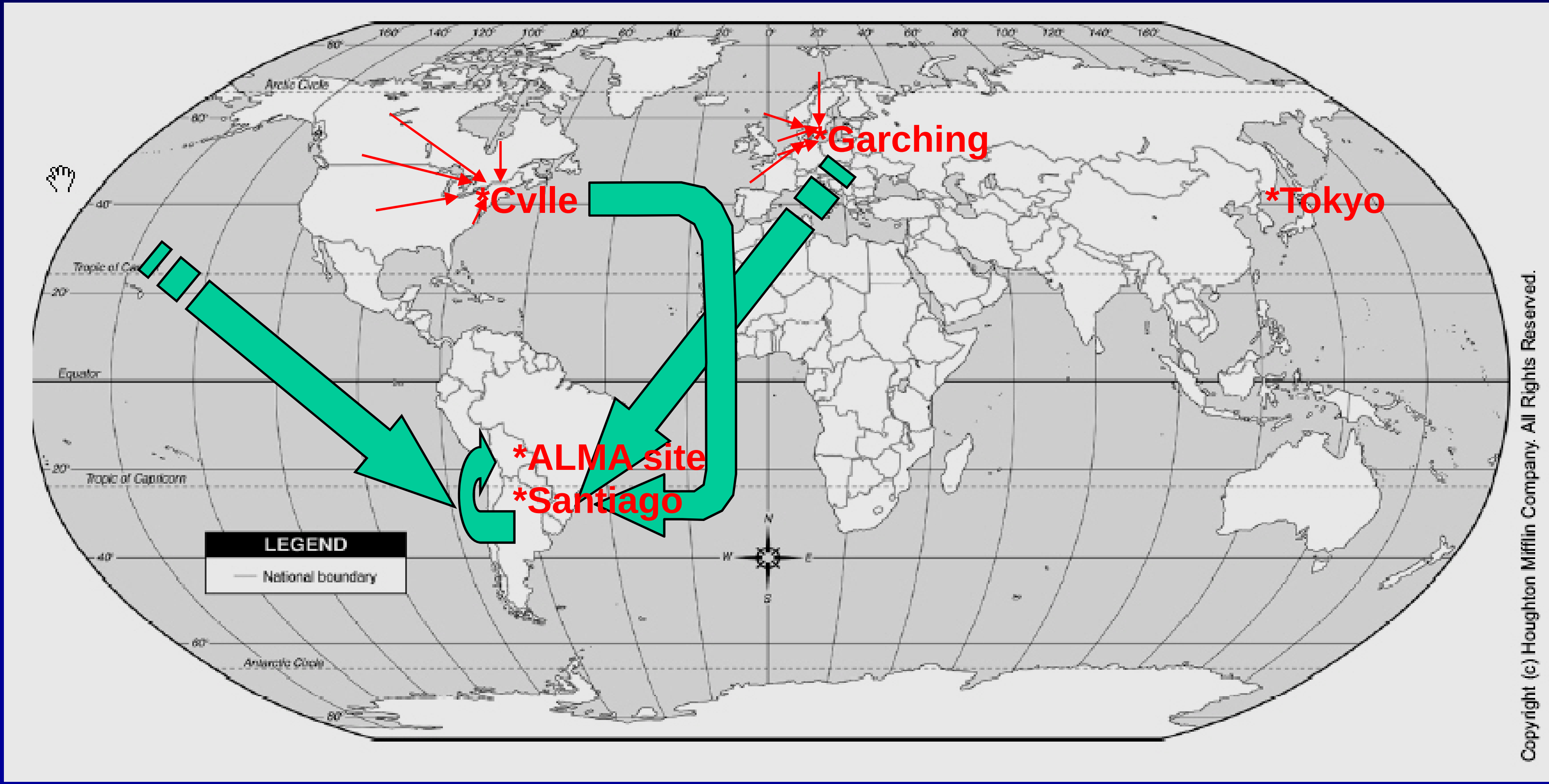
Virtual Observatory compliant



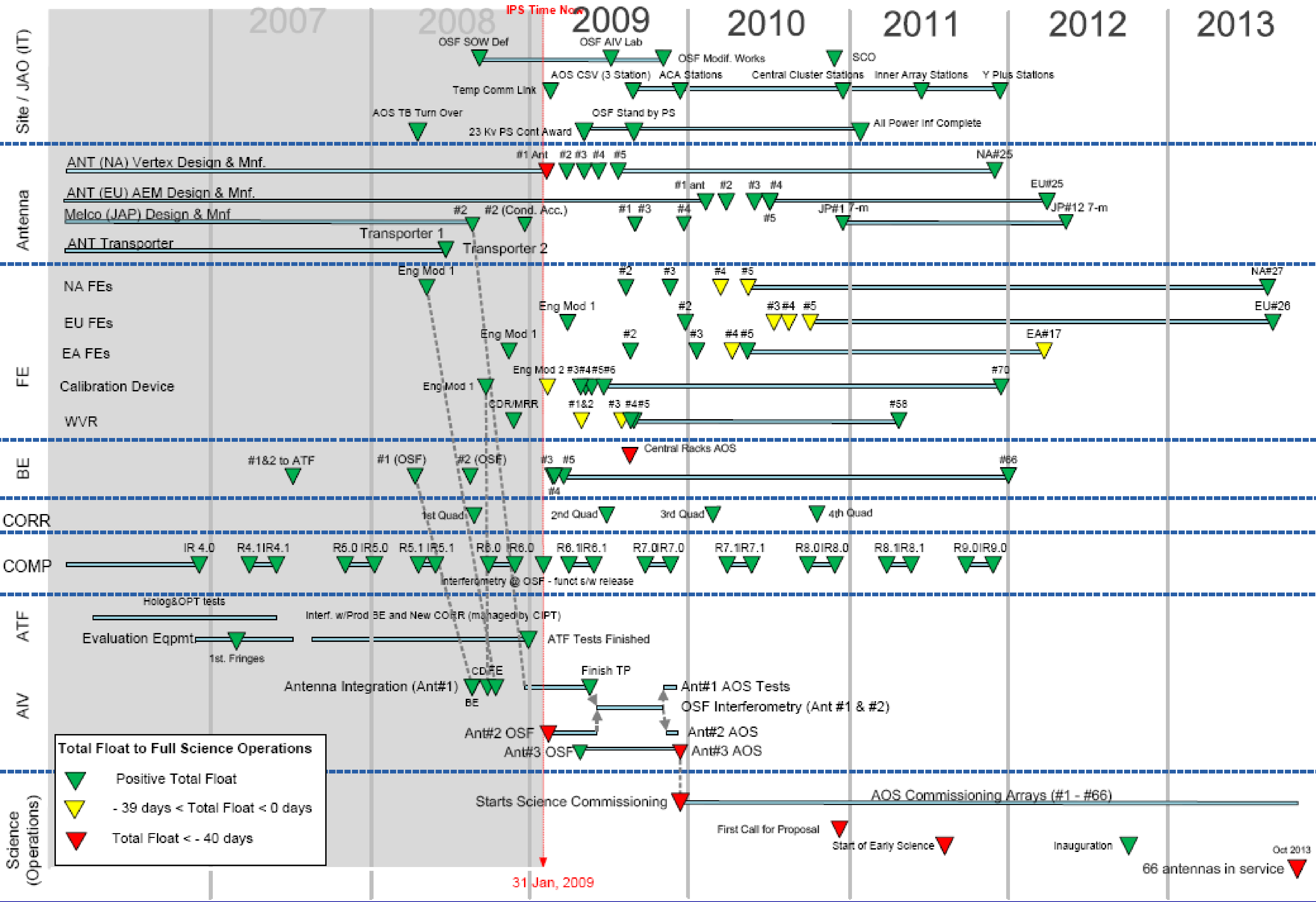
ALMA Regional Centers

The ARC's will provide support to the user community.

This is where proposals will be sent, data will arrive and expert help on analysis will be provided.



ALMA General Overview – Forecast Dates as of 31 Jan 2009



Level 1 Science Requirements

1. The ability to detect spectral line emission from CO or C II in a normal galaxy like the Milky Way at a redshift of z=3, in less than 24 hours of observation.

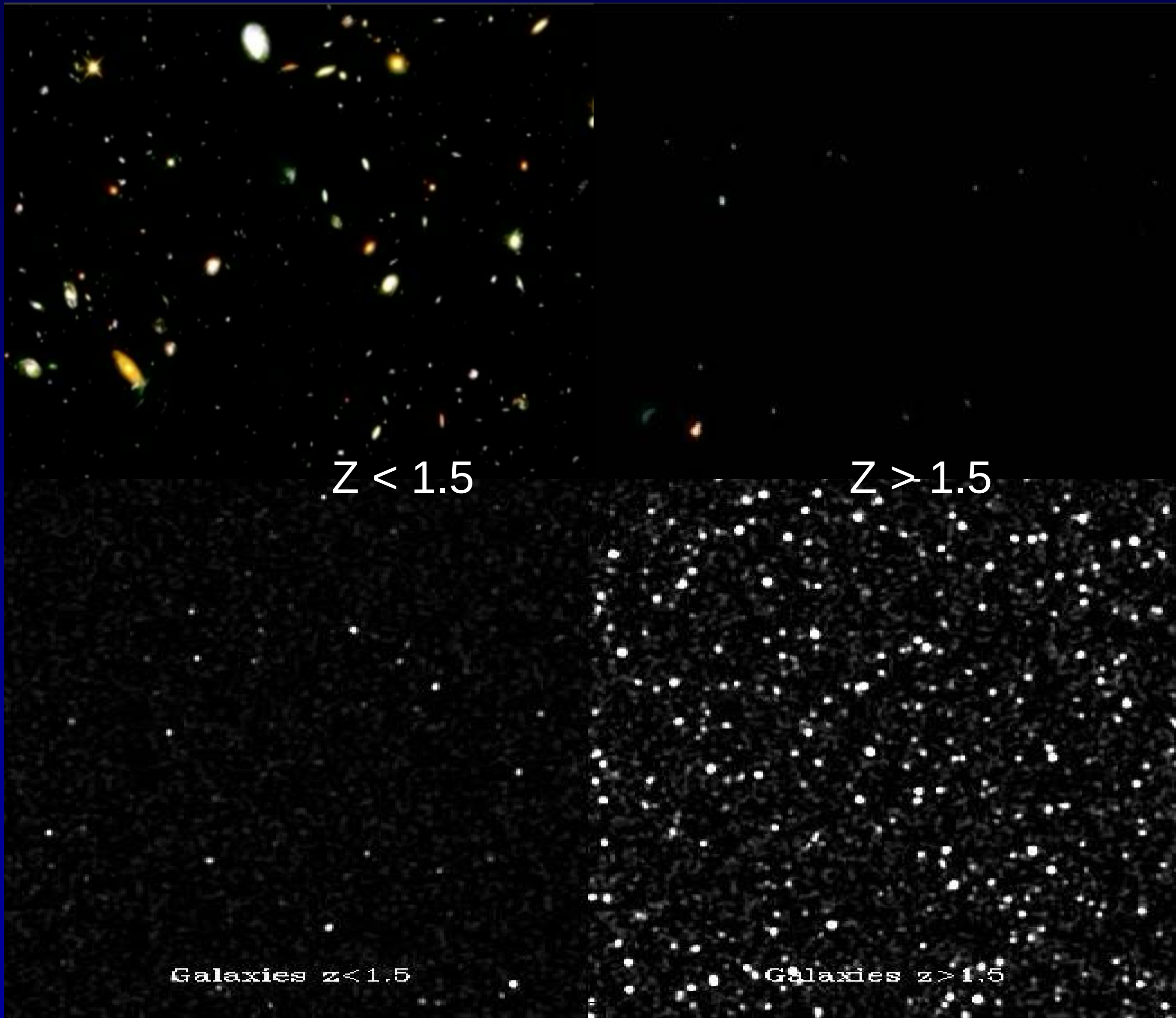
2. The ability to image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars at a distance of 150 pc (roughly the distance of the star forming clouds in Ophiuchus or Corona Australis), enabling one to study their physical, chemical and magnetic field structures and to detect the tidal gaps created by planets undergoing formation in the disks.

3. The ability to provide precise images at an angular resolution of 0.”1. Here the term precise image means representing within the noise level the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

Goal for sensitivity at 1.3 mm wavelength (continuum) is 10 microJy in 1hour

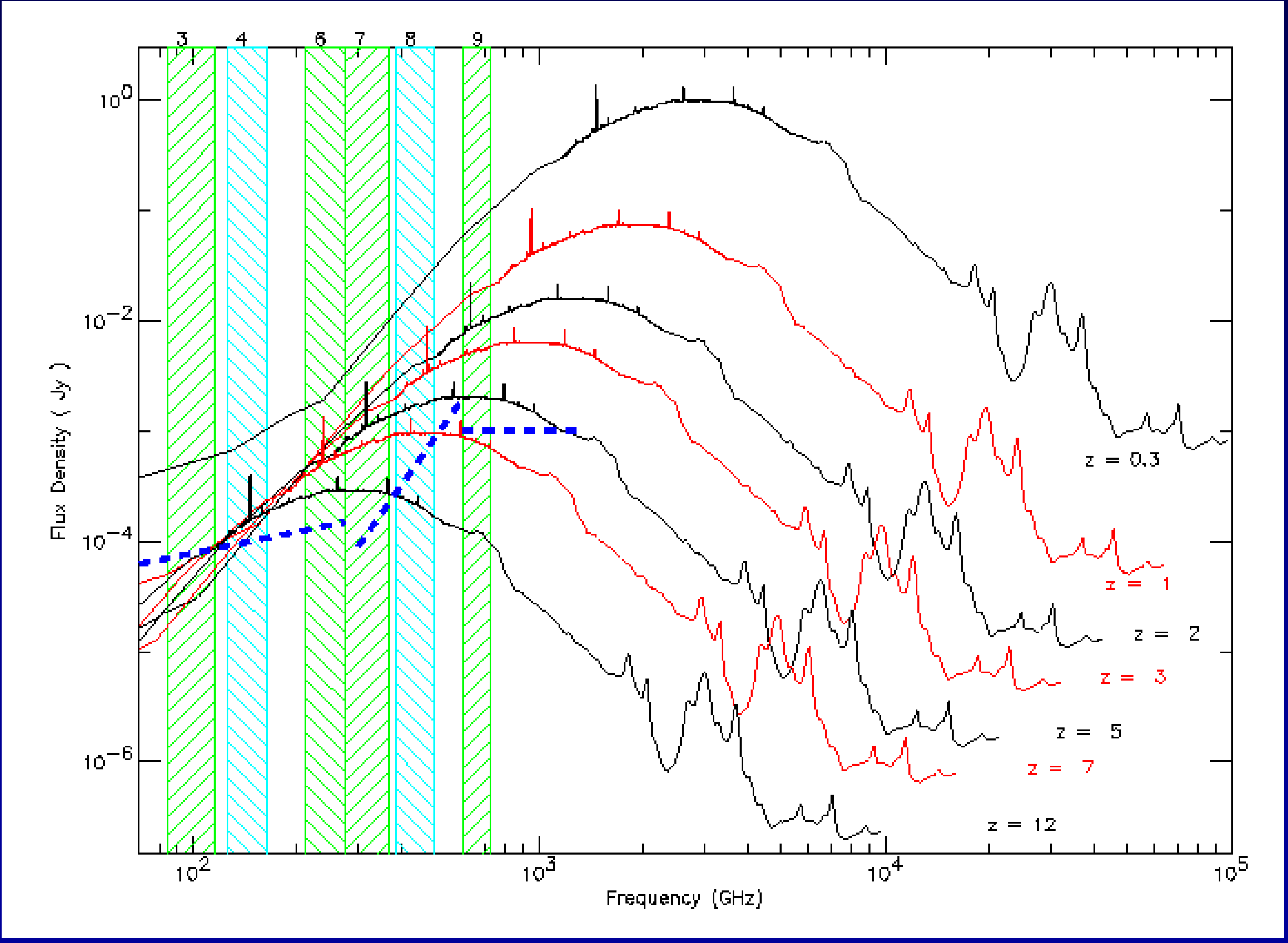
Hubble:

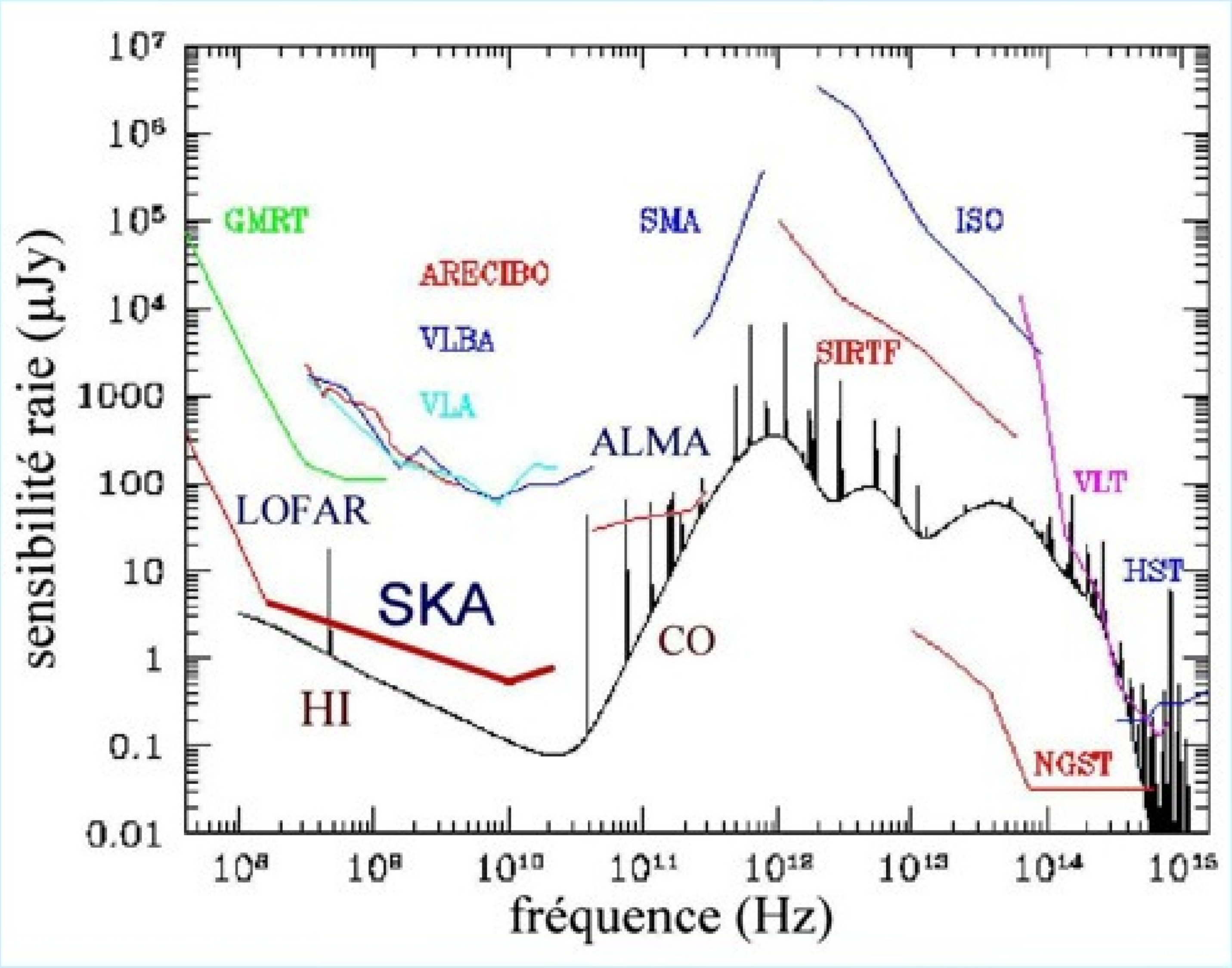
ALMA:



Red-shifted far-IR peak

M82 shifted to z = 1,2…12





Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

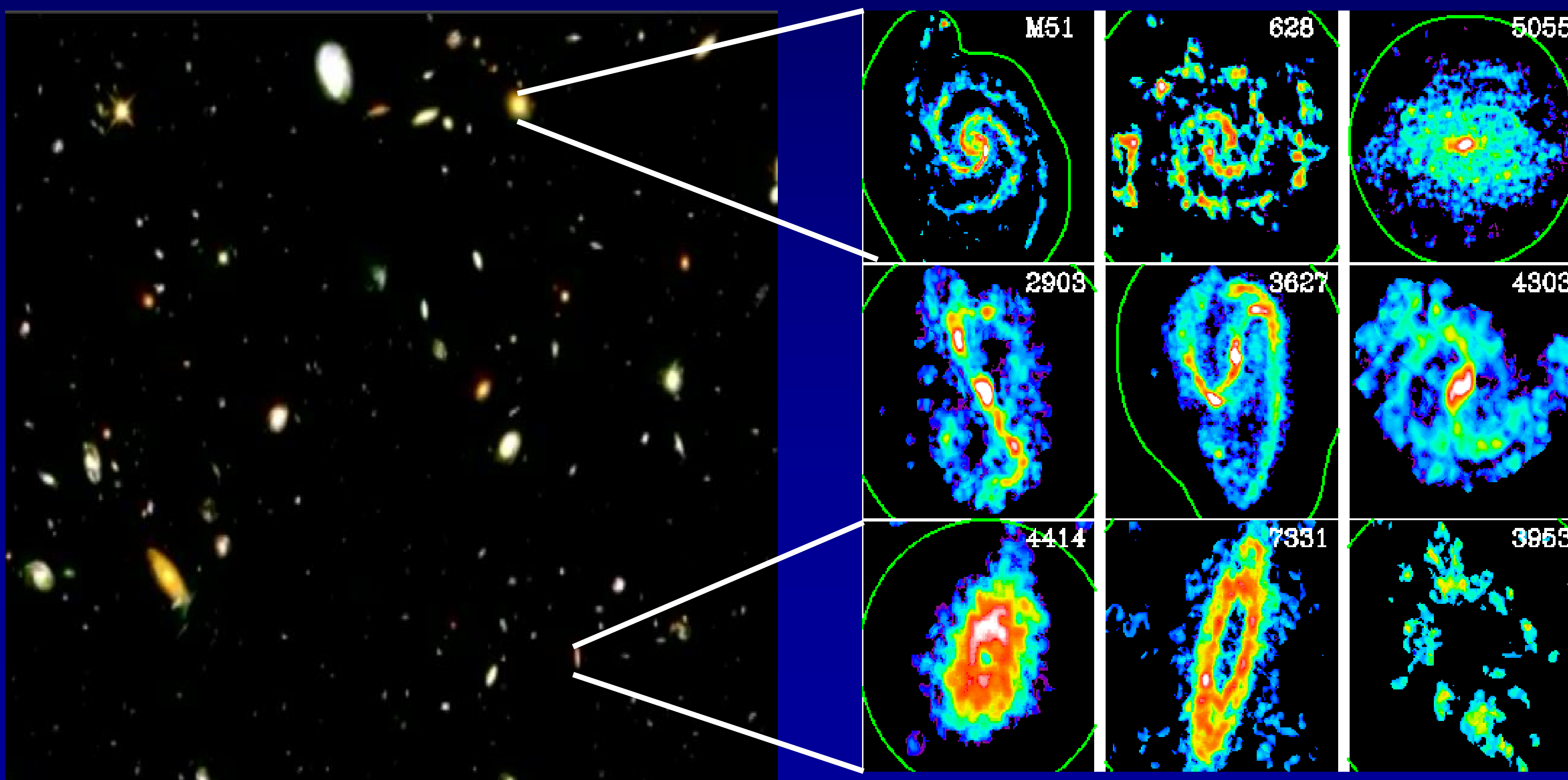
5σ in 1hour

Scientific Goals

Map the most distant parts of the Universe – this means looking back in time about 12 Gyrs

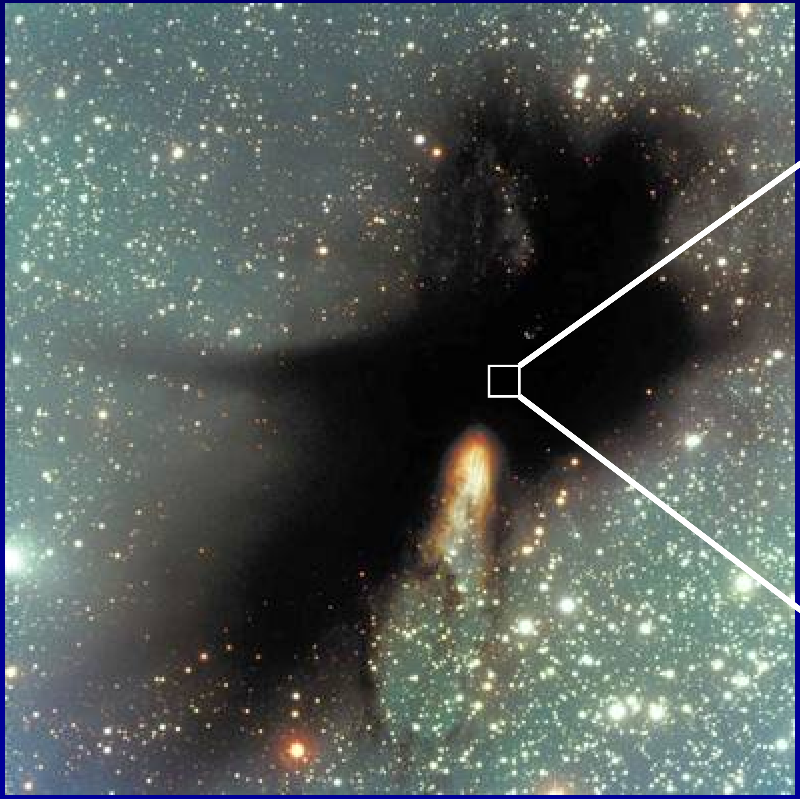
Left: Hubble image of distant galaxies

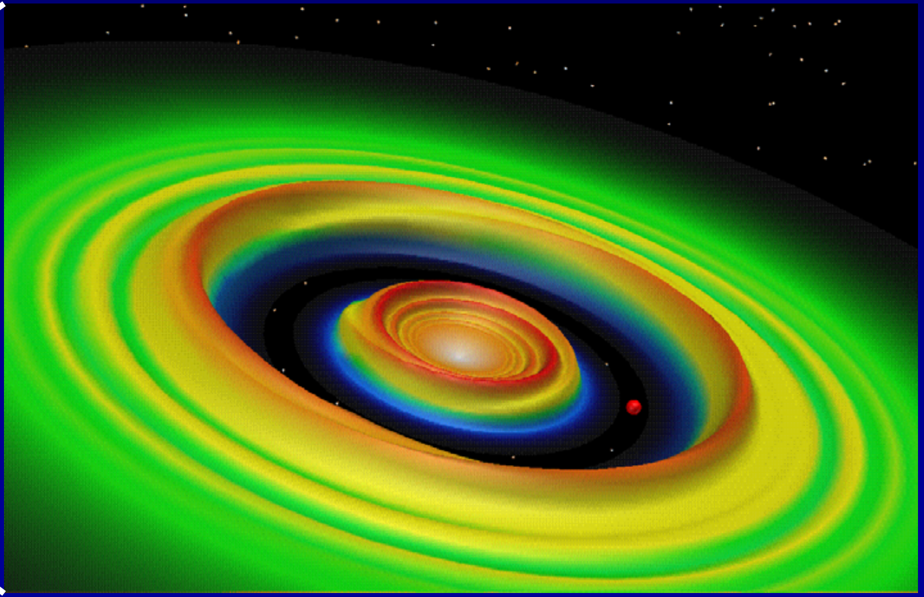
Right: Mm-wave images of nearby galaxies

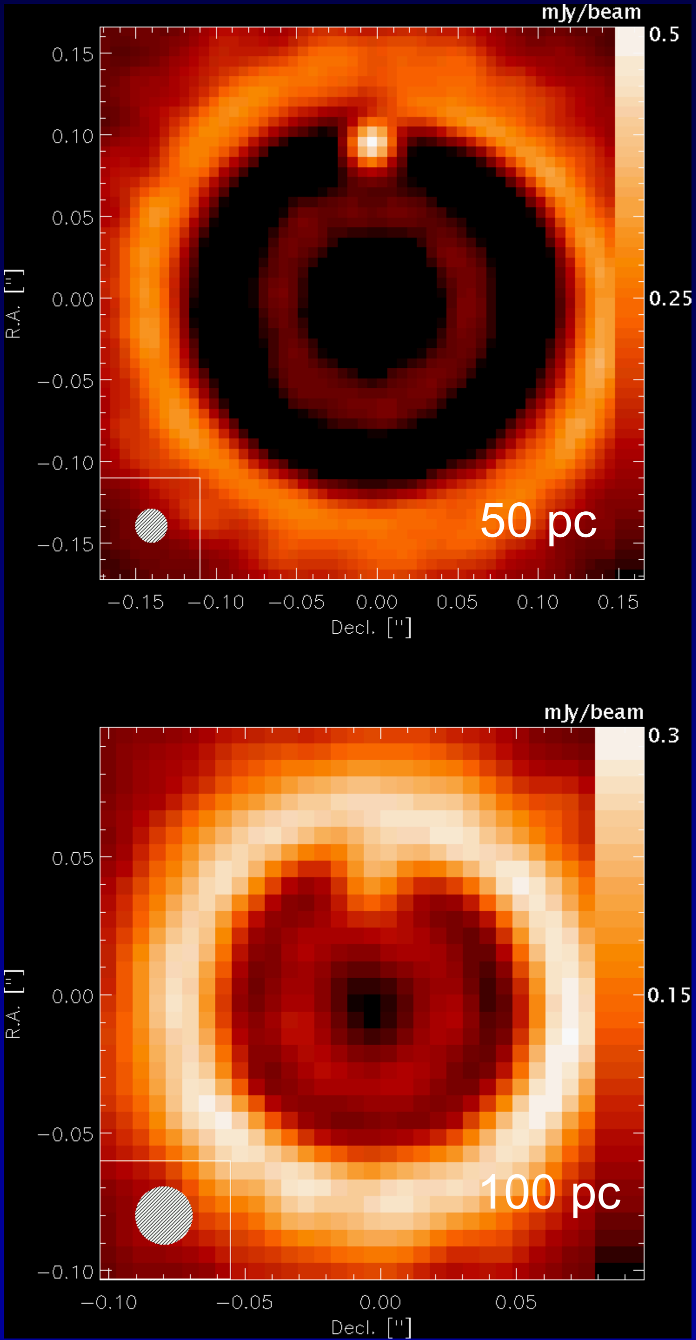


Scientific Goals (2)

Make <u>images</u> of new stars being formed, with planets emerging from the disks around them.







Planet formation in nearby disks

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

Orbital radius: 5 AU

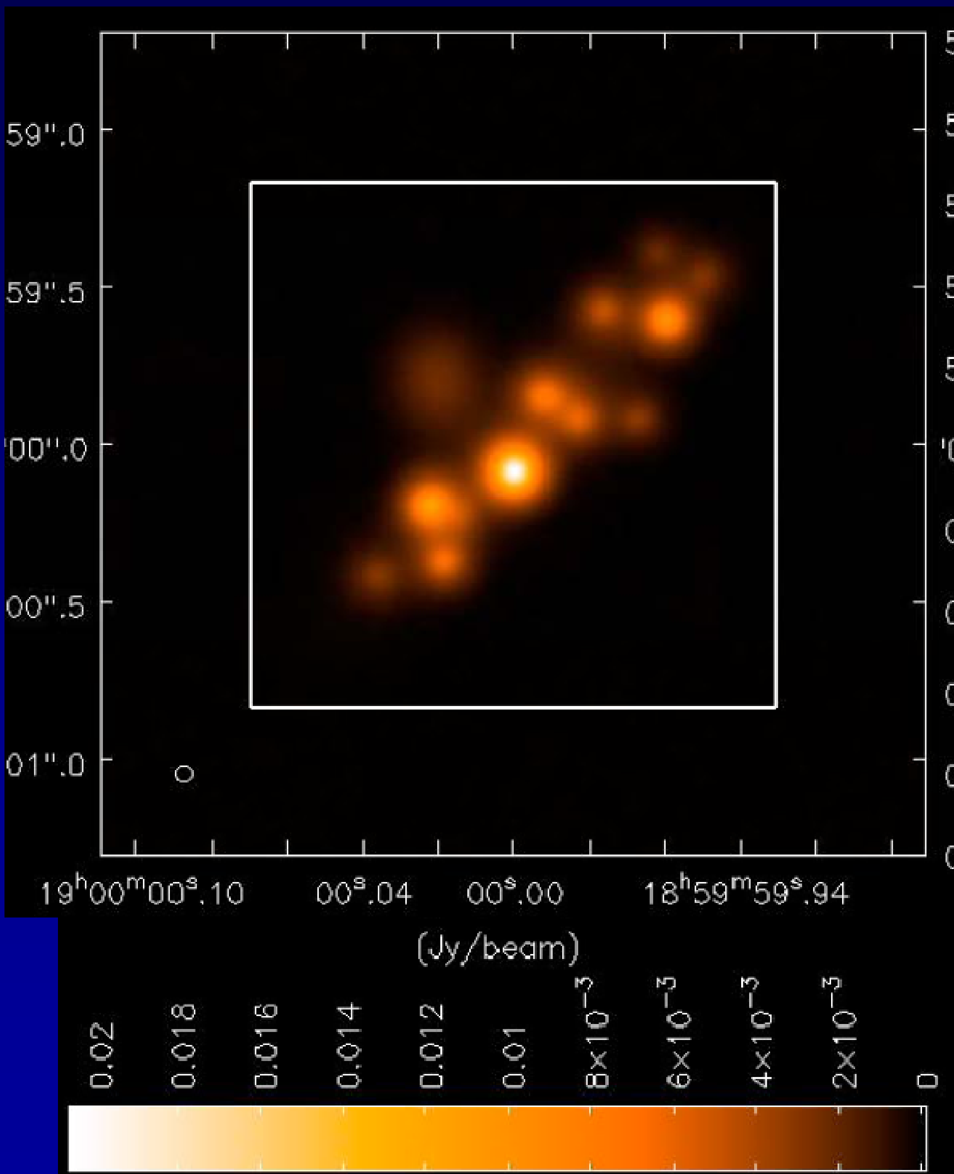
Disk mass as in the circumstellar disk around the Butterfly Star in Taurus

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

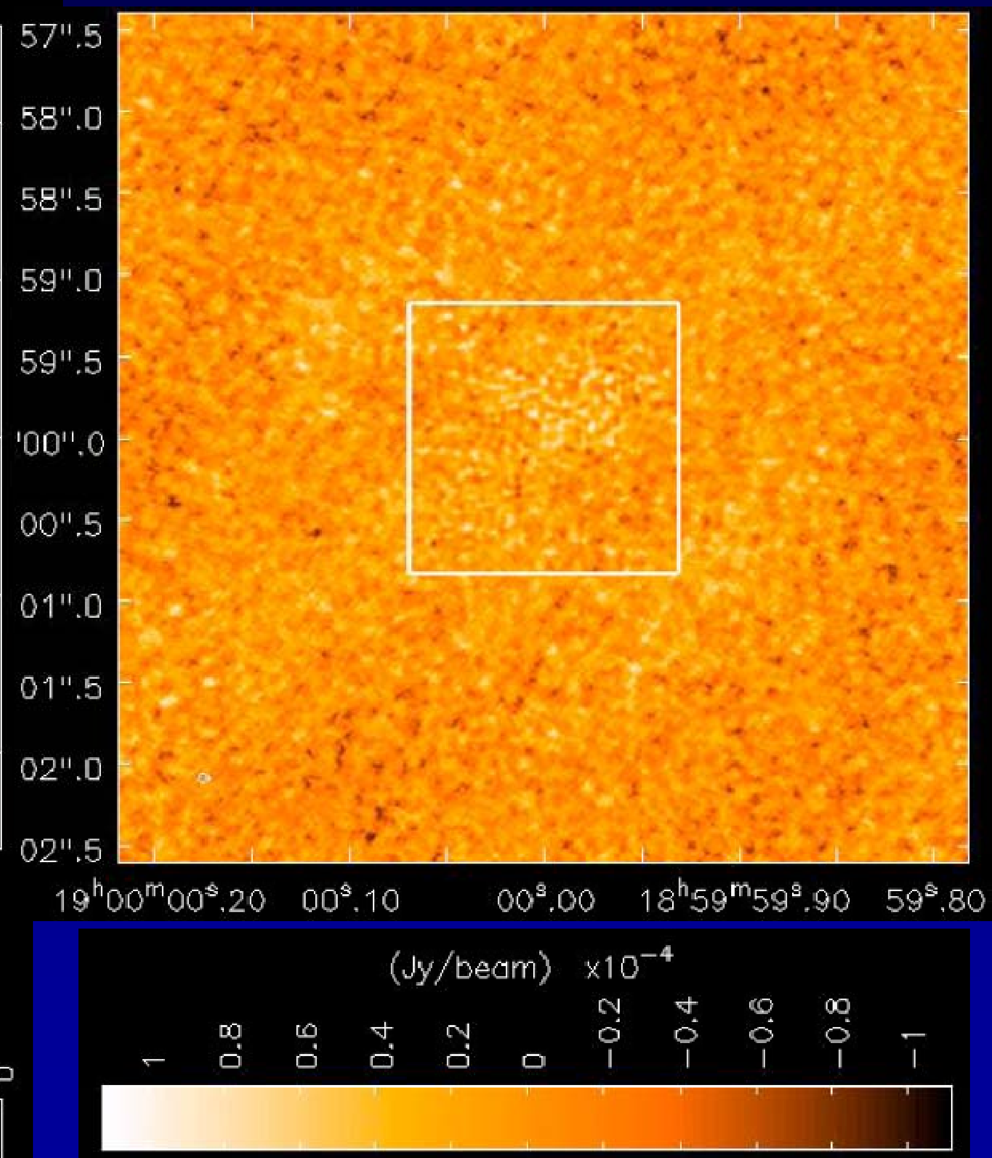
Goal for angular resolution is 0.005 arcsec at 950 GHz and 0.015 arcsec at 300 GHz

Imaging Quality

- Simulated map

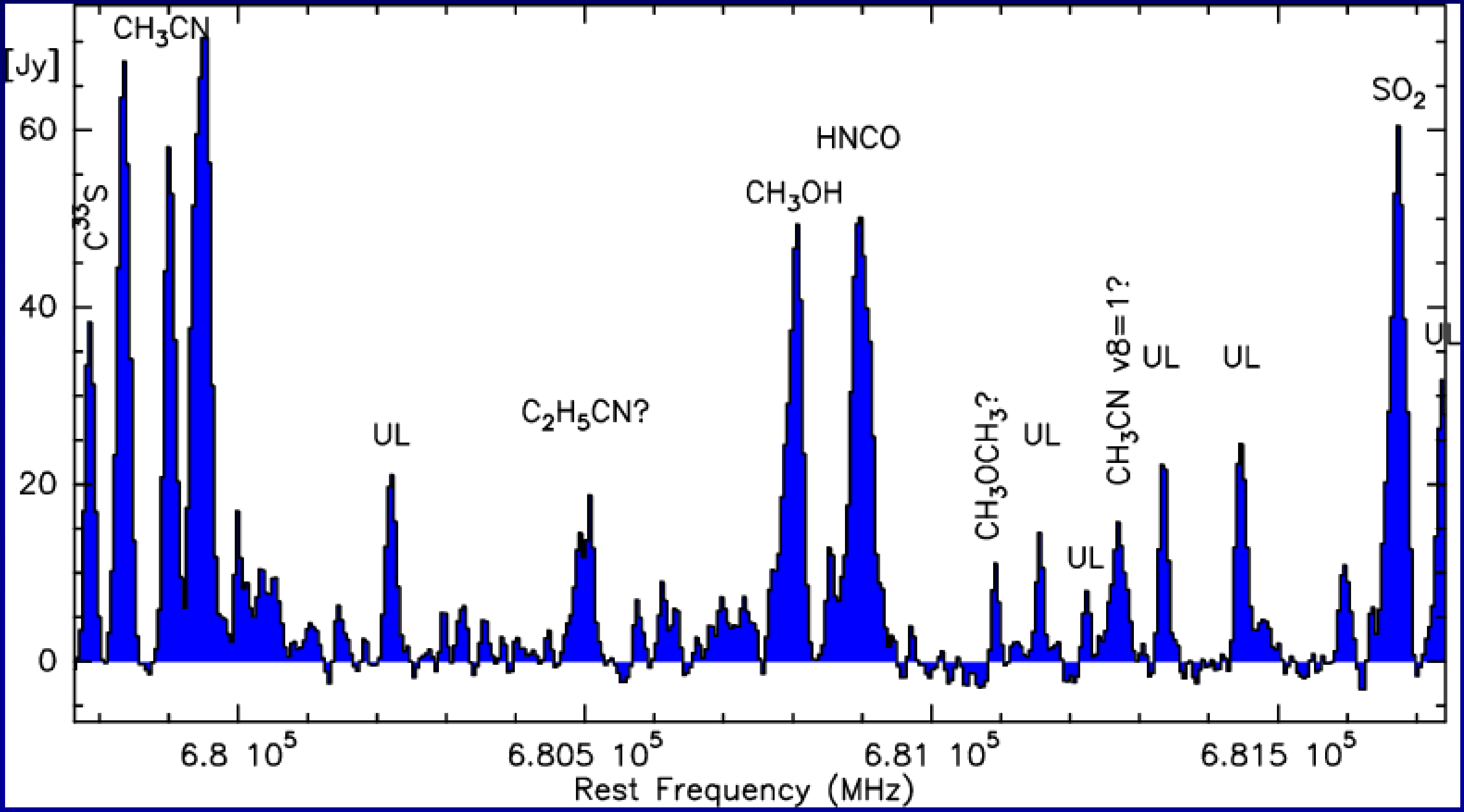


Error map



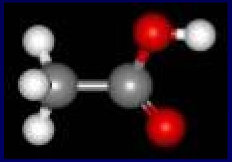
Scientific Goals

Spectroscopy: up to 8 GHz of instantaneous bandwidth. Resolution down to kHz on selected regions

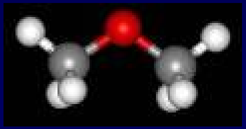


Some complex organic molecules

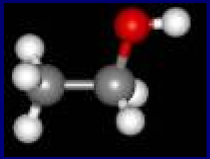
Detected



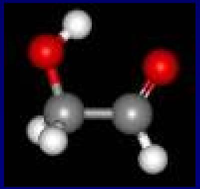
Acetic acid



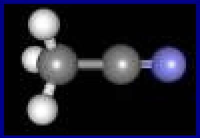
Di-methyl ether



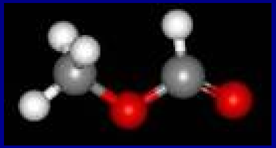
Ethanol



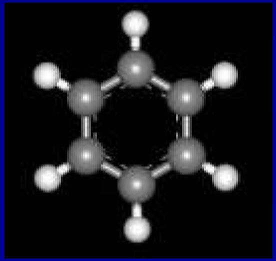
Sugar



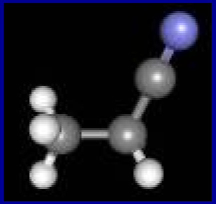
Methyl cyanide



Methyl formate

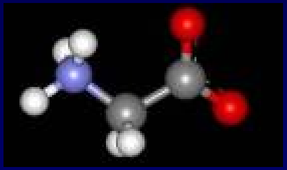


Benzene

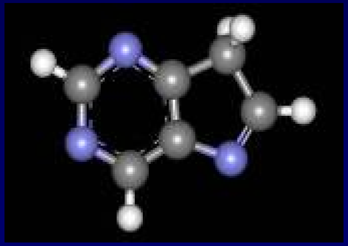


Ethyl cyanide

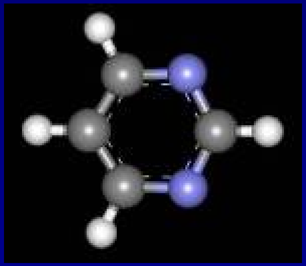
Not (yet) detected



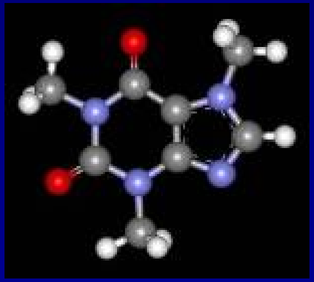
Glycine



Purine



Pyrimidine



Caffeine

We do not how far this chemical complexity extends.

Based on Ehrenfreund 2003

Scientific Goals

With 100 times more sensitivity and angular resolution than existing telescopes ALMA will extend our understanding of the nature of almost every type of astronomical object – from our own sun and planets to the most distant quasars.

In addition to these key properties we have high specifications on accuracy (i.e. calibration), time resolution and polarization, which is critical for determination of magnetic fields.

We are also aiming to achieve great flexibility in observing – e.g. spectral line setup, scheduling

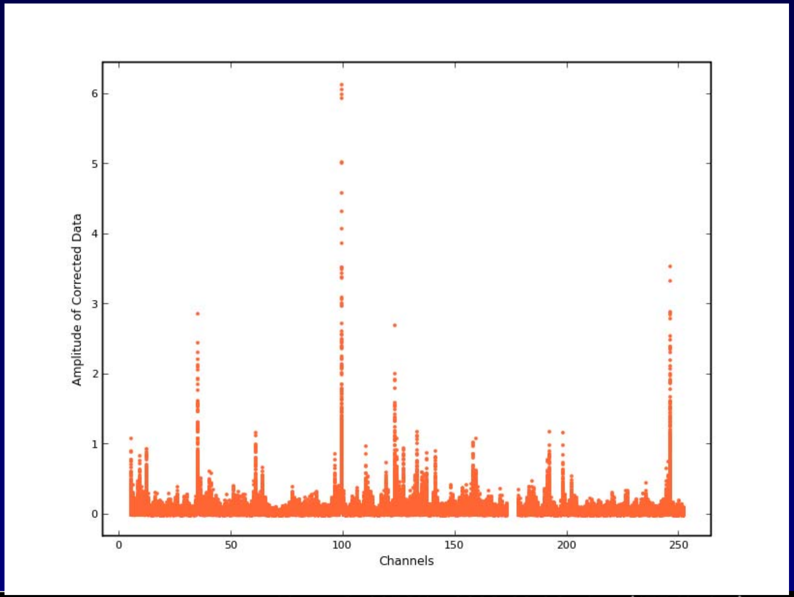
Additional Requirements

- Total power ("zero spacing") and short spacings provided by the ACA (ALMA Compact Array) – four 12m antennas plus twelve 7m antennas
- Ability to observe the Sun. Time resolution 16ms
- Track comets and other relatively nearby objects
- Polarization measurements – goal is 0.1% accuracy in Stokes parameters
- To be added ?: ability to phase-up antennas so that ALMA can be one element in a VLBI array

Milestones Achieved at ATF

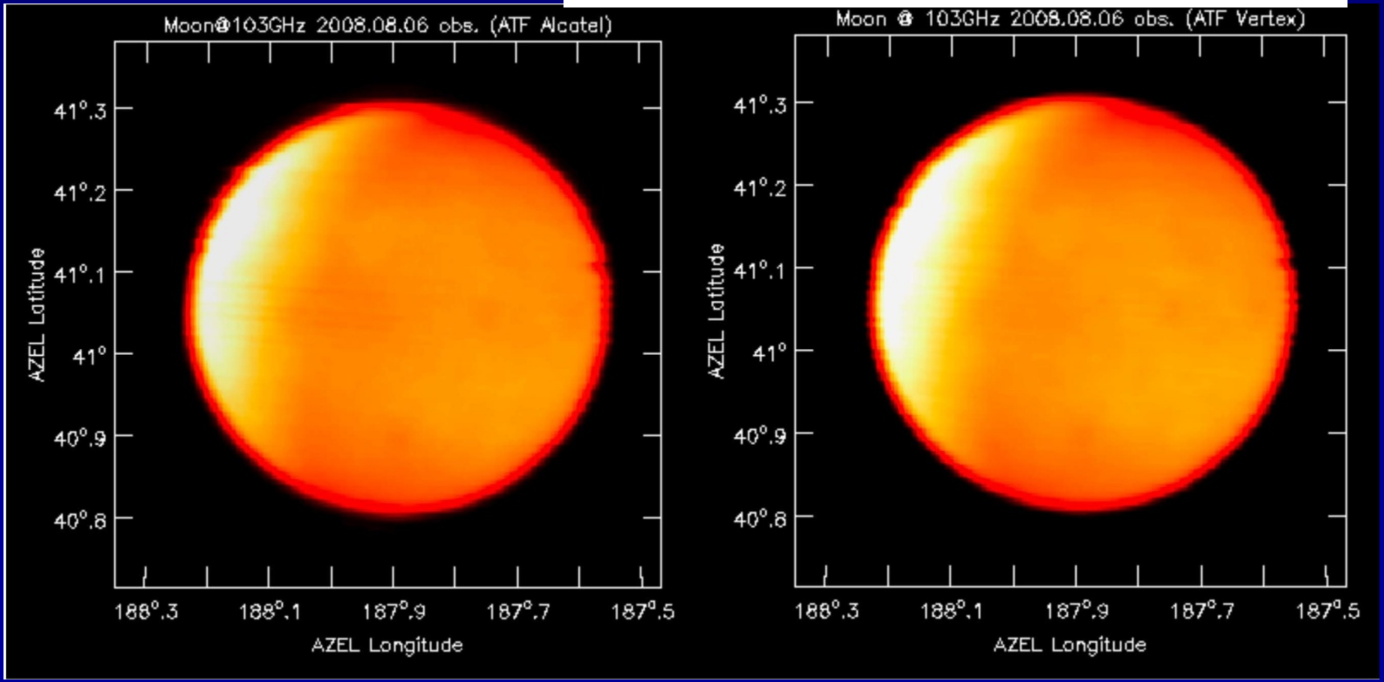
Software testing:

Sgr B2 Spectrum
97.9 GHz

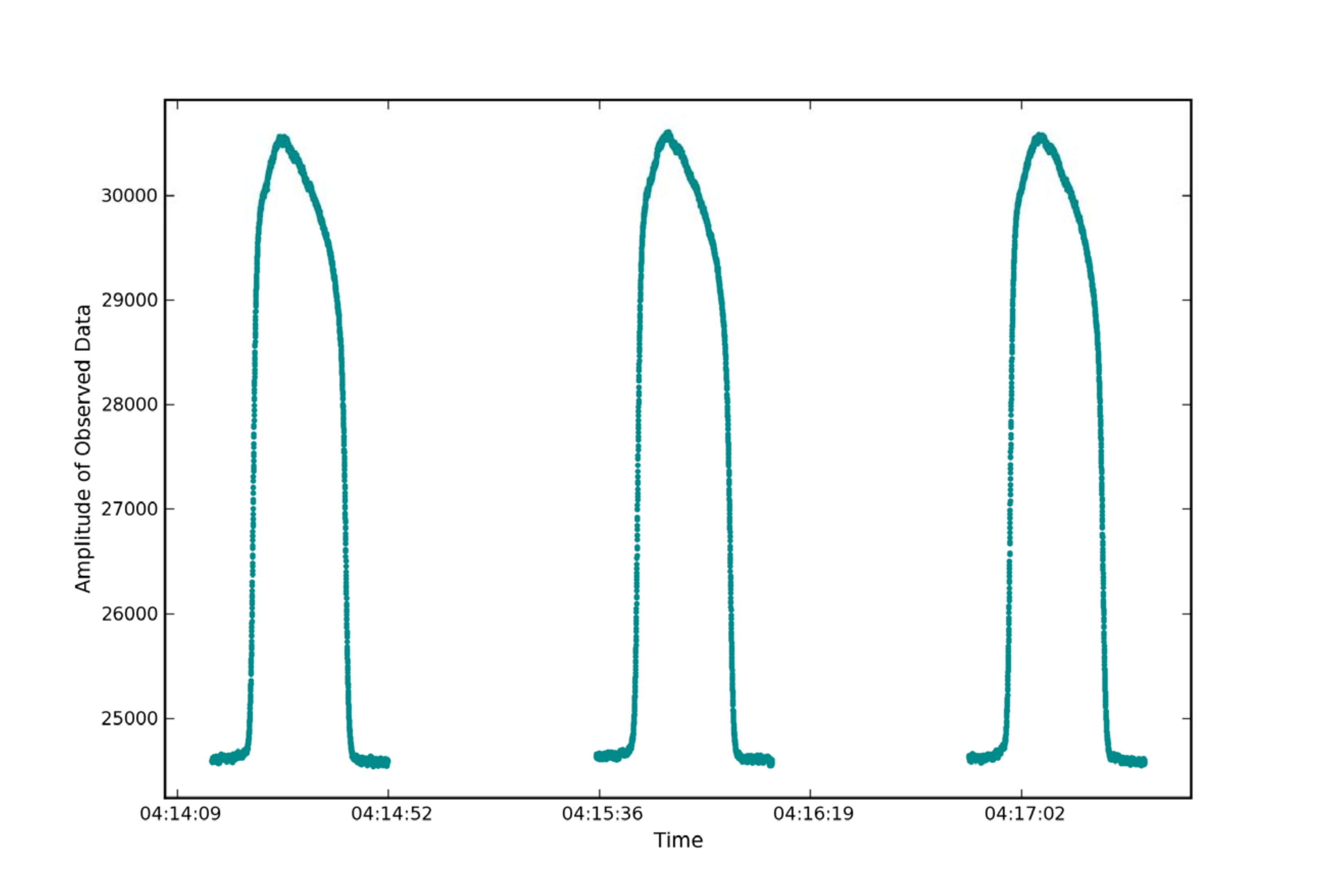


Raster on Moon with Total Power detectors simultaneously on 2 antennas

Taken at ATF, not using production receivers, but verifying software for control, tuning, correlator and data reduction



Scans of Moon 11th March 09 at OSF



Advertisement

- ALMA is recruiting!
- We have vacancies for:
- Commissioning Scientists – includes 3 year posts and shorter secondments – "visitors program", etc.
- Systems Astronomers
- Operations Astronomers
- Head of the Archive Operations Group

….

See me, Alison Peck or Lars Nyman and/or look at the ESO or NRAO web pages www.alma.cl

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