The 64-antenna correlator to phase up the ALMA array

Status and Perspective

Alain Baudry

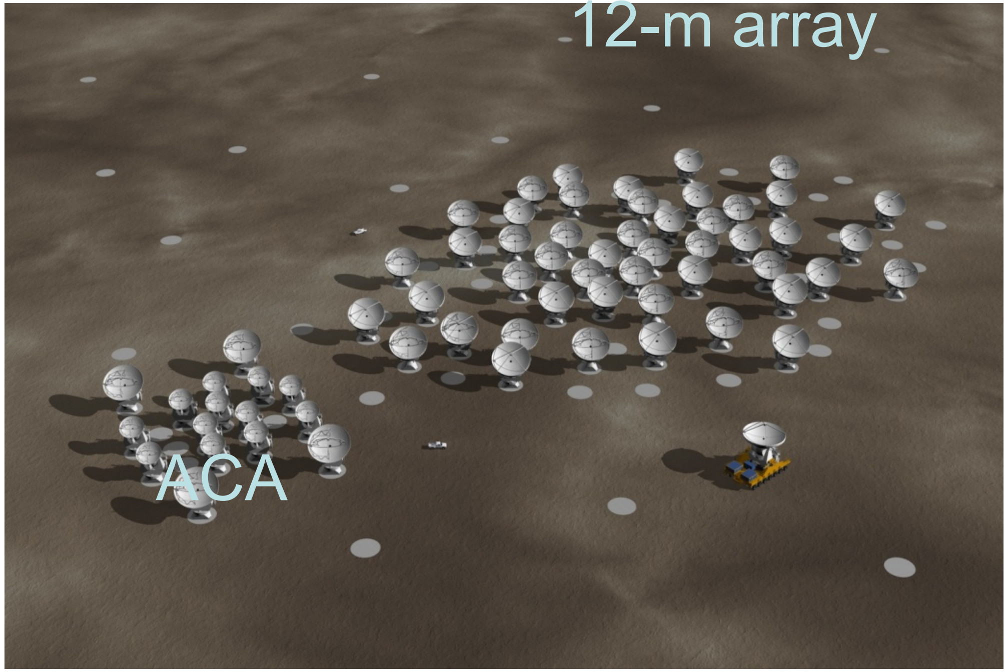
Univ. Bordeaux, OASU-Laboratoire d'Astrophysique de Bordeaux

« Workshop on mm VLBI with ALMA »

Instituto di Radioastronomia, Bologna, 22-23 January 2015

Contents

- *64-antenna correlator*
  - *A few details only*
- *Basic remarks on how to phase the array*
  - *Delay control*
- *PIC card*
  - *A new interface card for VLBI*
  - *PIC status*
- *APP status*
- *Sensitivity enhancements*
  - *Bands 3, 6, 7 examples*
- *Final remarks*
  - *Subarraying, Pulsar*

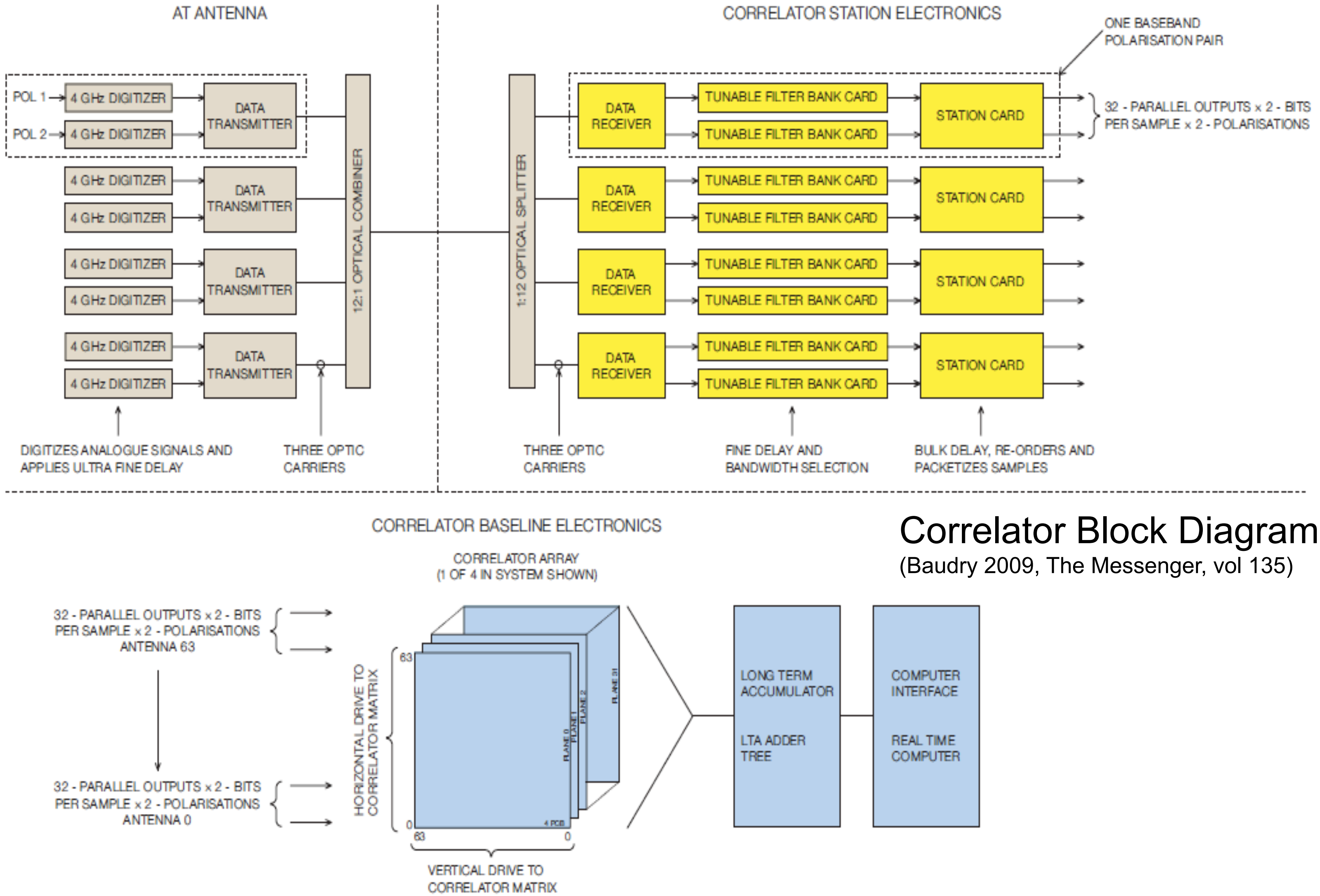


Main Specifications
64-antenna correlator

• ***Antennas***	64 (2016 pairings + 64 auto-correl.)
• ***Input / Output sample format***	3-bit ADC / 2- or 4-bit correlation
• ***Baseband per antenna***	4 x 2 GHz x 2 polars. (8 BBs)
• ***Polarization products***	1, 2 or 4
• ***Max baseline delay range***	30 km (up to 300km)
• ***Processing rate***	125 MHz
• ***Hardware correlators / baseline***	32 klags & 32 kleads
• ***Max spectral resol. & Channels***	3.8 kHz, 8192 channels

****** Min. accumulation time***	16 ms cross-correl. & 1 ms auto-correl.
****** Subarraying***	up to 6
****** Phased array outputs***	VLBI
****** Output rate 4 GByte/s per Qt.***	ALMA system supports 60 MByte/sec peak

Routine operation, ~25% peak rate or ~50GByte/hour

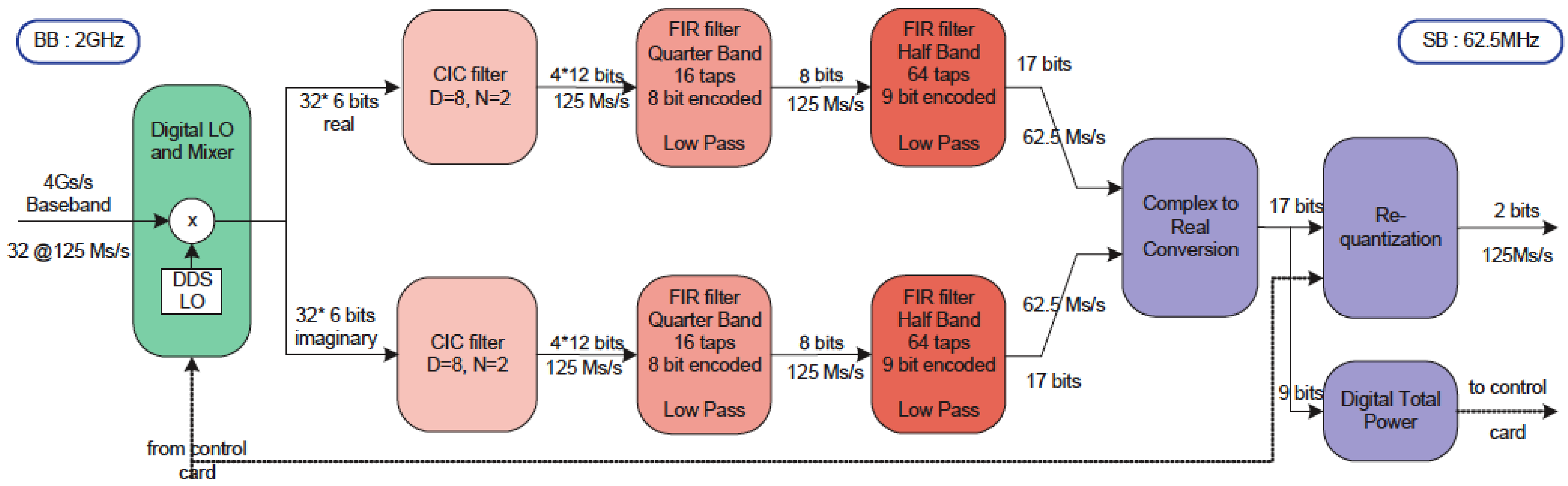


Correlator Block Diagram

(Baudry 2009, The Messenger, vol 135)

Digital Tunable Filter Bank (TFB)

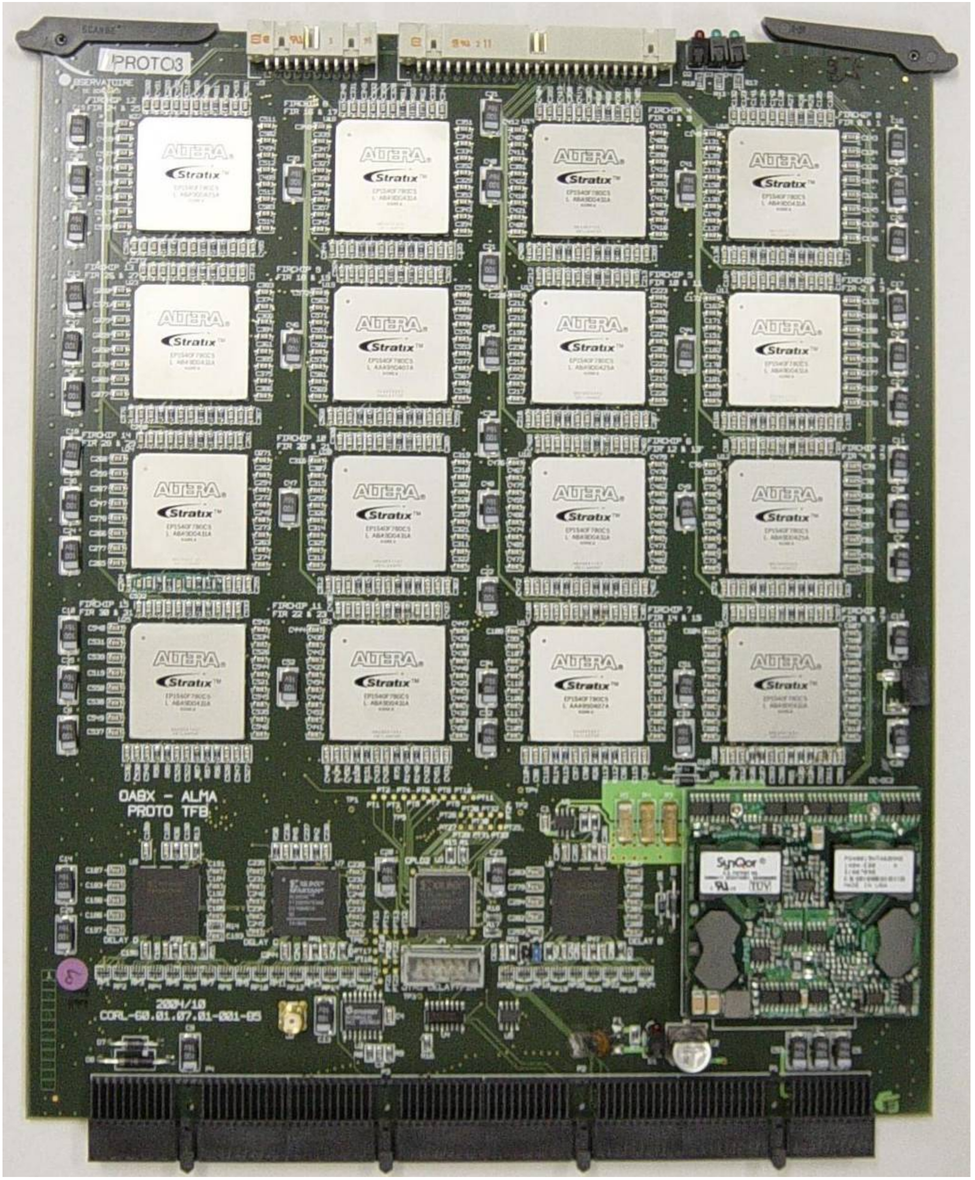
Phase and *Gain* (tot. power) adjustable with firmware available in TFB, *FDM modes*



Tunable Filter Bank card

32 x 62.5 MHz sub-bands implemented on a single card

12 layers
12300 vias/card

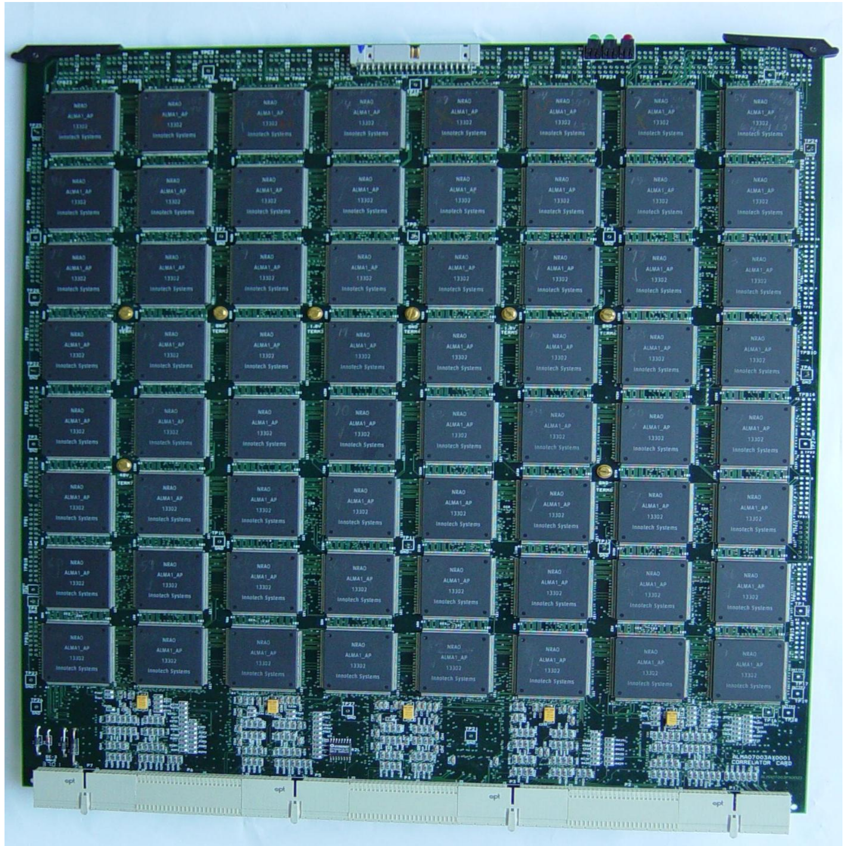


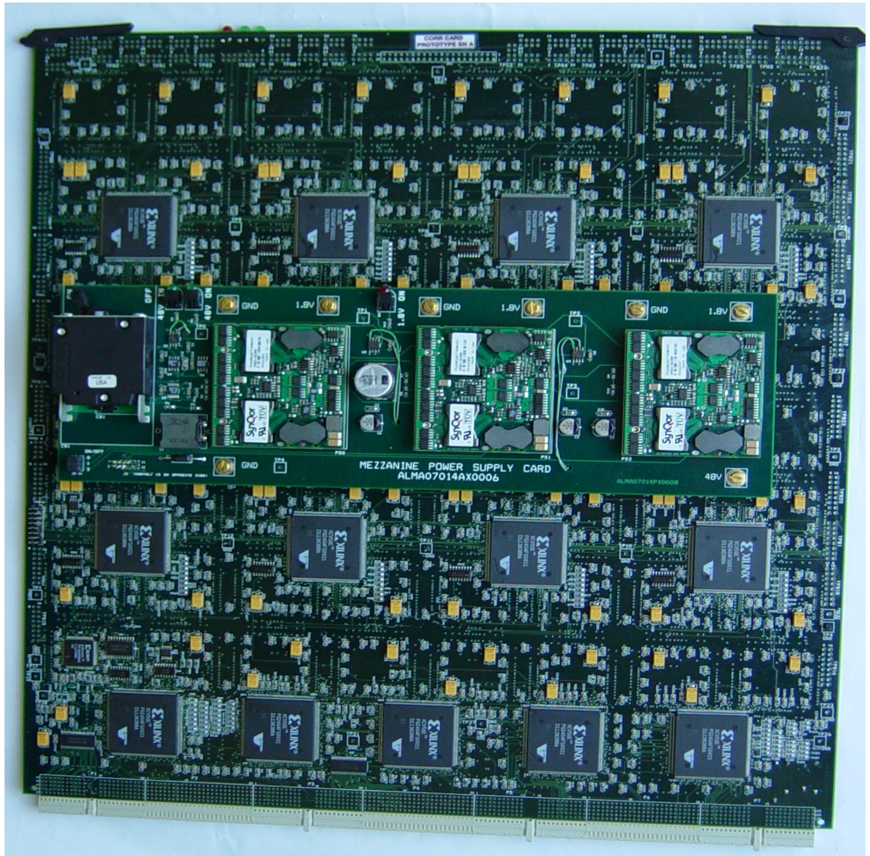
64x64 antenna matrix in 4 Correlator cards

*One correlator plane (4 cards) X-correl. 1/32 part of the input samples for all antennas; this is *TDM* with 32 planes. In *FDM* there are 32 sub-channels/BB

*64 chips, 4klags/chip with programmable blocks (1, 2, 4 products)

*Analog sum FPGAs for VLBI





64-antenna Correlator

Fully at work

32 racks in 4 Quadrants

First Quadrant installed at AOS in October 2008

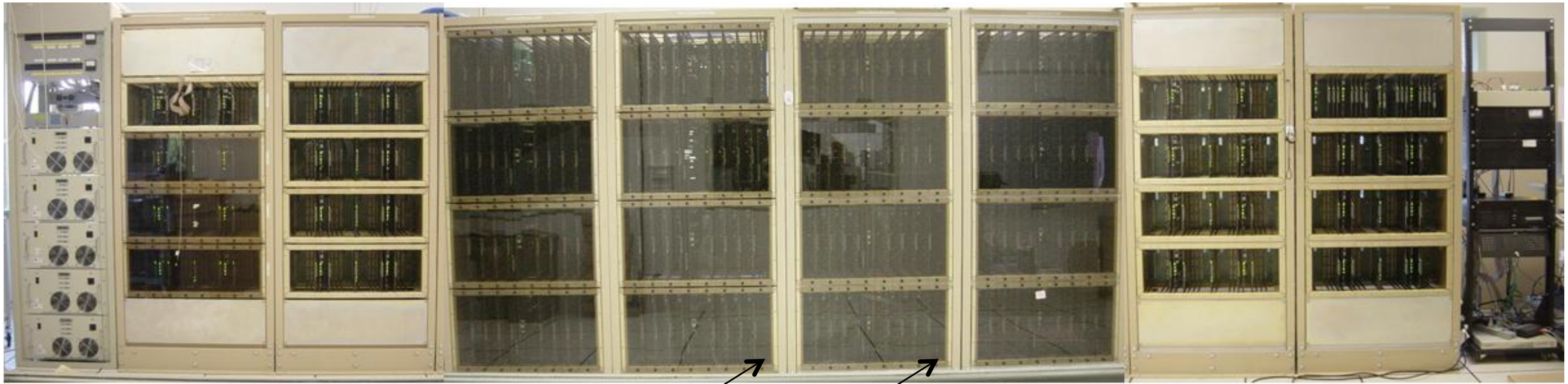
Second & third Quadrants installed in 2009 & 2010

Fourth Quadrant fully accepted in July 2012

*Migration to **4-Quadrant configuration** completed by the end of Sept 2012 in time for Early Science*

One Correlator Quadrant

(4 Station electronics & 4 Baseline electronics racks
+ power & control/computing racks)



2 PICs

Complete Correlator System, 32 racks in 4 Quadrants

- ~2600 printed circuit boards total in system
- ~20 million solder joints
- 8192 Altera Stratix II FPGAs (90 nm technology) in TFB cards
- 32768 custom correlator chips
- 64-antenna Correlator is a highly specialized computing system

1.7×10^{16} operations/sec (multiply-and-add calculations)

ALMA Correlator, Spectral modes

- Two categories of Observing Modes

  * *Frequency Division Mode (FDM)*

2 GHz BB divided into 32 sub-bands ⇔ *Digital Hybrid Architecture*

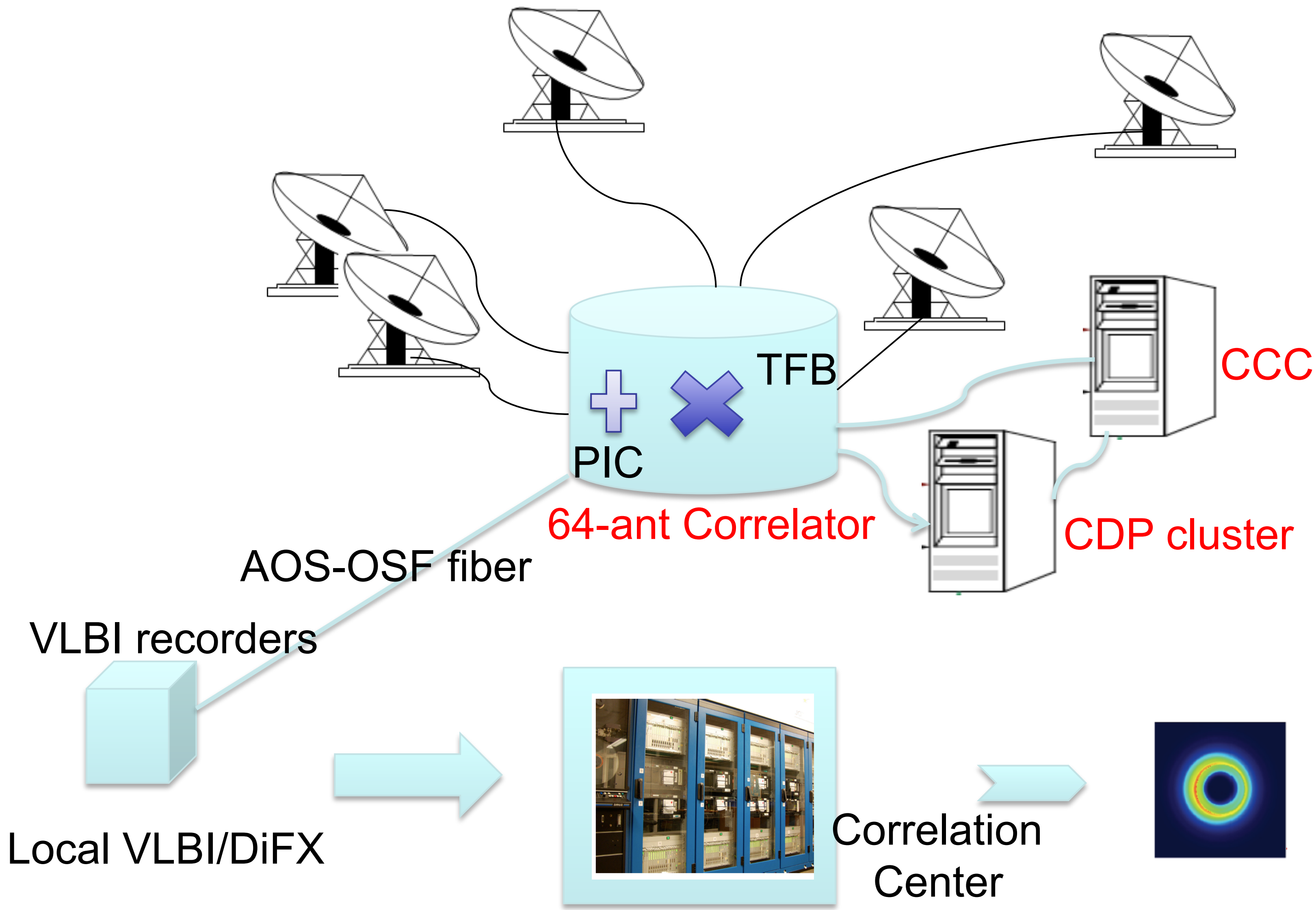
- Adequate for high resolution spectroscopy
- ***Each of 32 sub-bands in FDM mode recorded for VLBI***

  * *Time Division Mode (TDM)* ⇔ *XF machine*

- Adequate for continuum or broad spectral emission sources

- Publications on 64-ant. & ACA correlators
  * SPIE conference, Amsterdam 2012, Proc of SPIE Vol 8452
  * ALMA Newsletter No7, 18-31 (Jan 2011)

How to phase the array?
Phased array & VLBI



Phasing the array

- ‘In phase’ addition of N voltage signals maximizes $\mathit{Sum}_{i=1\ldots N}(V_i)$
  - V_i = voltage averaged over each individual aperture A_i
  - In phase condition requires
    - Identical pathlengths/delays to each antenna A_i
    - Control Φ and delays everywhere in the system

- VLBI baseline sensitivity is enhanced
  - Baseline sensitivity improves from *sqrt* (A_i) to *sqr*t (N A_i)
  - **N = 50** i.e. 12-m array alone

    => equivalent to a **85-m dish**

Phasing the array

- Where to best meet the ‘in phase’ condition?
  - Antenna LO phases? send commands to antennas
  - Best to use adjustable phase capability of the digital LOs
- Filter cards provide 32 data streams
  - Observe with the synthesis array in FDM mode a strong, unresolved source to obtain 32 antenna Φ solutions
  - Apply Φ corrections to digital LO phase registers
    - Corrections depend on ALMA band, antenna location, weather…
- ‘Phasing loop’ entirely within correlator
  - Possible because Φ corrections are derived for narrow 62.5 MHz sub-bands

Delay control

- ALMA 250 ps delay steps adequate for VLBI
  - *Phase error* at TFB sub-band edge is *small*
  - Delay exact at sub-band center and at sub-band edge +/-125 ps or +/-31.25 MHz **φ error is 1.4° only**

- No need for ultra-fine 16 ps delays in DG Clk phase
  - 250 ps delay steps, in synchronism with bulk delay, & current source delay tracking are adequate for VLBI

Delay control and atmosphere

- *Excess pathlength* due to atmosphere
  - Max. 0.4 mm changes in water content are observed (from Tb changes observed with WVRs) => 2.5 mm *excess pathlength* or ***8.3 ps*** … *small wrt 250 ps*
  - At 230 GHz 8.3 ps give $\Delta\varphi = 687°$ => *calibrate phases*
- *Fixed delays* must be known to search for VLBI fringes
  - TFB card gives 0.75 microsec delay
  - Station electronics card gives 2 msec delay
  - Other delays due to general circuitry

Main steps in ‘phasing loop’

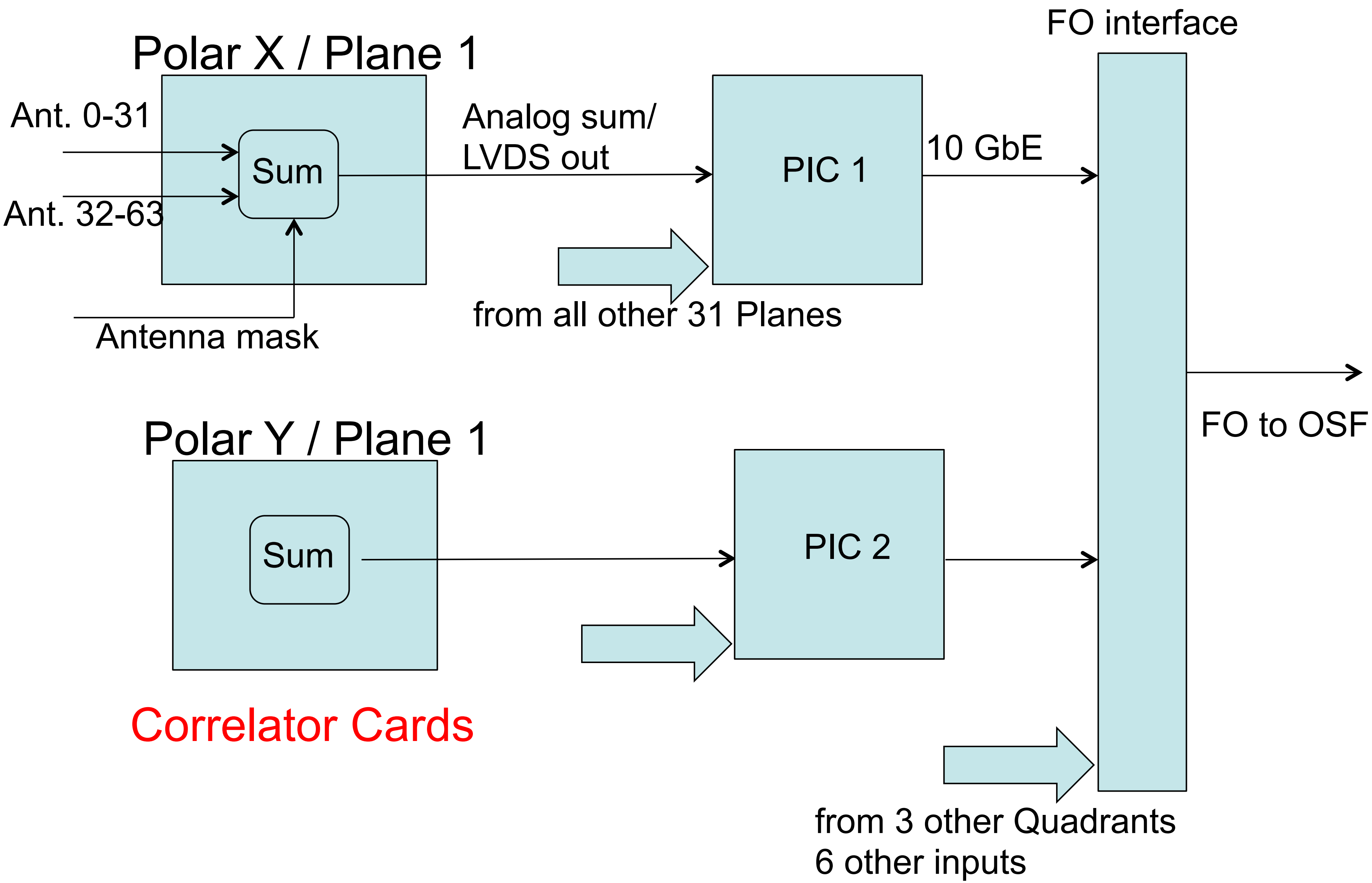
- All steps to close the overall ‘phasing loop’ understood
  - Well demonstrated during APP CDR - successfully passed in May 2013

- Summarize main steps to phase ALMA
  - Determine phase corrections for each antenna and send them to **TFB cards**
  - Pass corrected signals to Correl cards which output **antenna sums**
  - Process data in a new interface card, **Phasing Interface Card – PIC**, connected to Fiber Link and VLBI Terminal

Data sum sent to PIC

- Summing logic in Correlator cards
  - Add up to N = 64 2-bit values (a tree of adder chips) represented with 8 bits
  - Final 2-bit sum, scaled by *sqrt* N, done for all 32 frequency channels
- 32 channels of 2-bit data routed to new interface card – PIC card
  - PIC card: assembly of mother board -design based on Correl Final Adder card- & Roach 2 board

Voltage sum in Correlator Cards



PIC Main function & Test Fixture

PIC main function with large FPGA

Format data into VDIF packets for 10Gb ethernet link to VLBI terminal

* Two PIC cards per Quadrant developed by NRAO
  - Unused space exists in correl racks
  - Correlator power capacity sufficient to add PICs
* PIC firmware modules
  - Designed with Xilinx tools & VHDL (not Casper)
* PIC Test Fixture
  - Perform tests in the lab prior to ALMA site

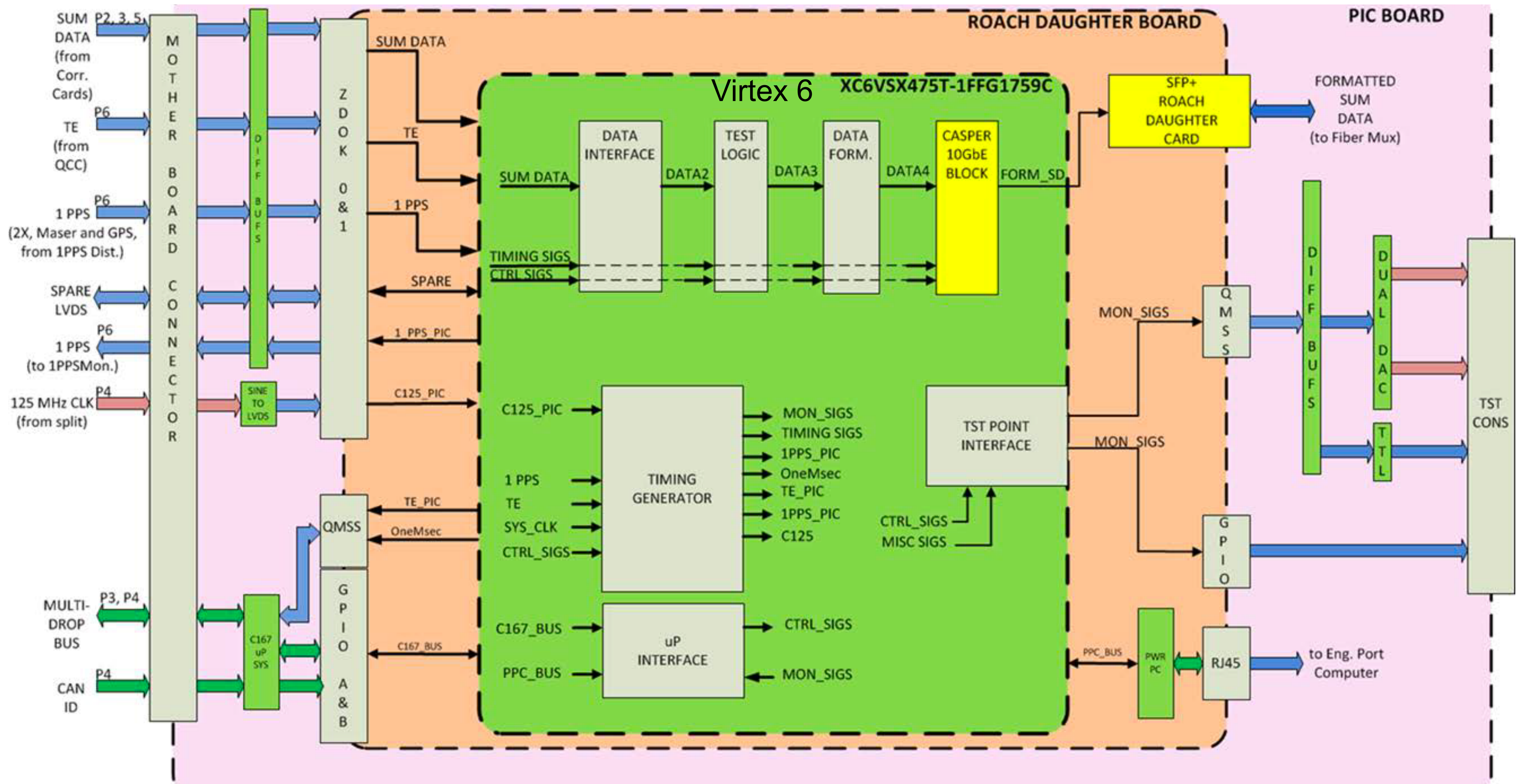
Phasing Interface Card

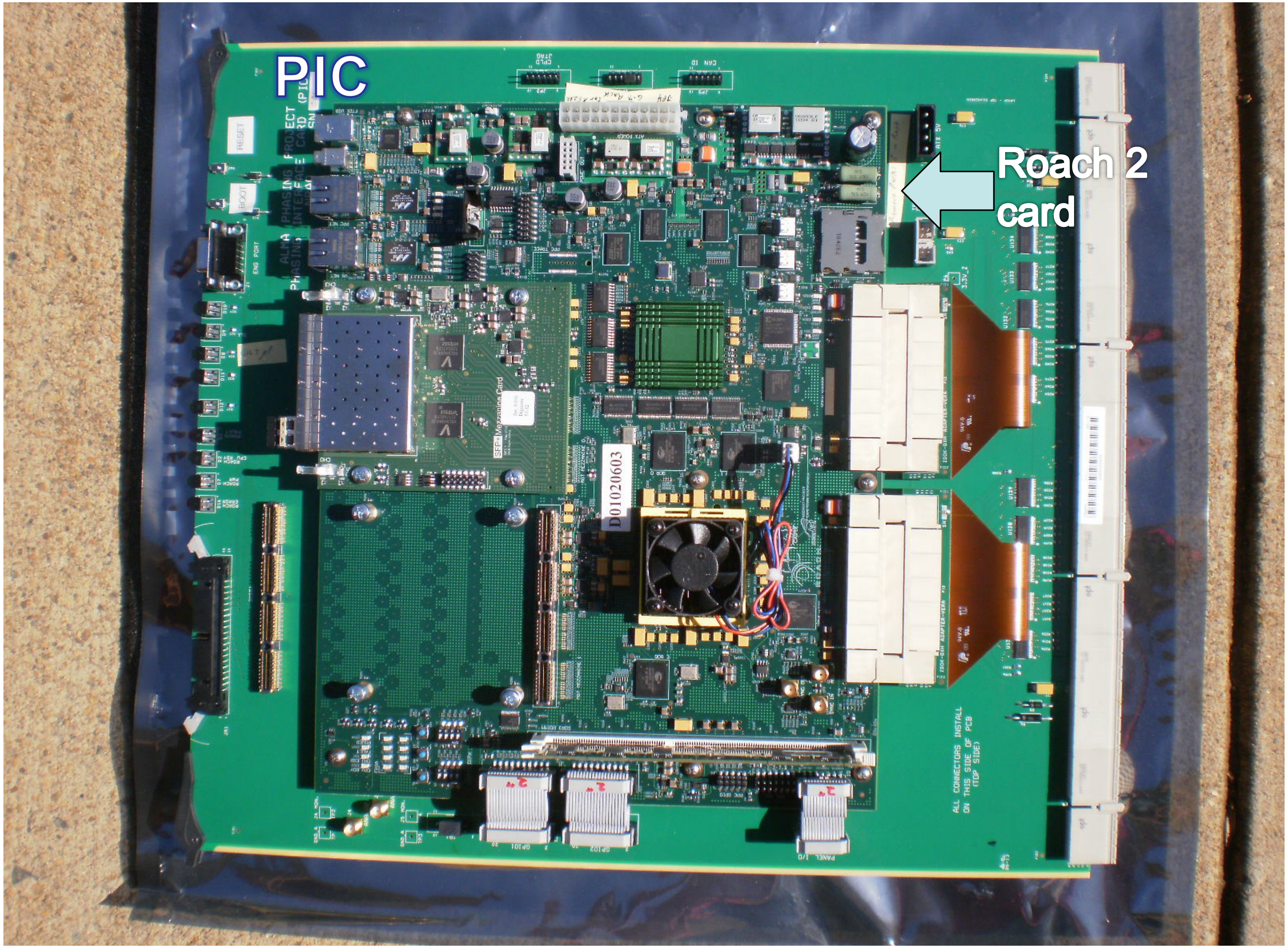
from Correl card backplane *32x2bits LVDS Sum Data (125MHz)*

to *10Gbe Optical transmitter*

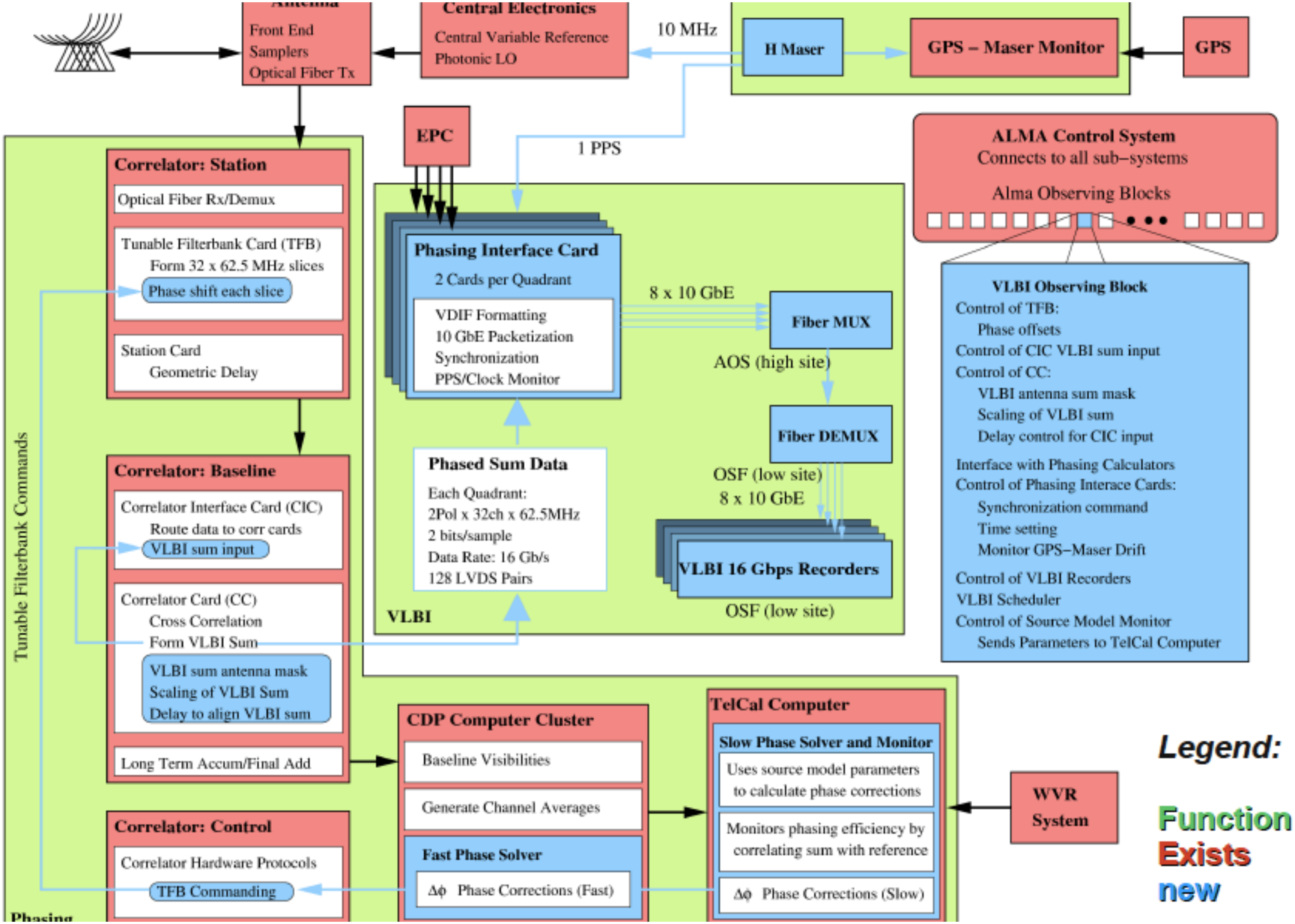
Sum Data

to:10Gbe optical transmitter




PIC
Roach 2
card

ALMA Phasing



PIC & APP Status

- **PIC design, hard/firmware, complete ~June2014**
- **Entire APP chain successfuly tested in Oct. 2014**
    - All components of phasing system were integrated
        - Signal sum, fast/slow loop corrections … to Mk6 recording
    - « Zero baseline correlation test »: data from one antenna sent to different correlator quadrants => good coherence
- **Excellent performance of H Maser** demonstrated in July 2014 during ALMA high freq. campaign
    - New 5 MHz standard for ALMA ! important step toward VLBI
- **APP commissioning on-going**
    - APP at AOS, APEX, 1 OSF antenna, (SPT)

Sensitivity in ALMA Band 3

Phased ALMA enhances sensitivity of mm arrays

- *7 sigma threshold* at 86 GHz in 20 s (typical coherence time) for 2Gbps (500 MHz, 2-bit)
  - *Best baseline sensitivity* in *GMVA*: 14 and 20 mJy for ***GBT*** – ***Bure*** *(6x15m)* and ***GBT*** – ***Effelsberg***
  - IRAM – IRAM: 30 mJy
- **ALMA** – **PdB** 9 mJy
  - Improved to 4.5 mJy ⇔ 8 Gbps (2GHz BW)
  - With NOEMA 3.8 mJy

VLBI *array* sensitivity even better !

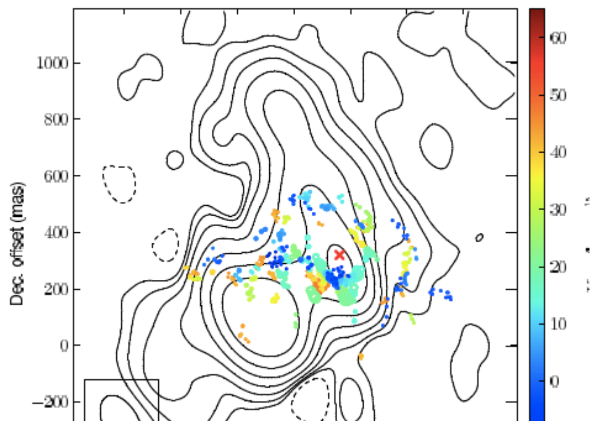
Excellent sensitivity in Bands 6 & 7

Continuum & Line

- **230 GHz** in 10 s, 1 GHz BW: 7 sigma *baseline sensitivity* ~**20** or **24 mJy** for ALMA – PdB or eSMA
- **345 GHz** *baseline sensitivity* ~**50-55 mJy**
  - ~5 stations only but this number will grow
- Many interesting *H_20 stellar masers at 321 GHz*
  - ALMA – eSMA sensitivity with 0.4 km/s resol. in 1 hour is ~**0.11 Jy** (5 sigma) => many 1 Jy features expected
  - VLBI will give Tb & sizes => stellar & maser physics
- *SiO masers*

VY CMa   ALMA, H_2O 321 GHz

Tb >> 10^6 K expected



Perspective

Subarraying, Pulsar observations

- VLBI supposes only one ALMA array now
  - Sub-arrays not offered to users –only to obsevatory staff
  - Subarraying would be useful for ‘cluster/cluster’ VLBI or VLBI baselines with B in the range 10 to ~200 - 300 km
    - Imaging stars with ‘nearby’ dishes, eg *LLAMA*
- Sub-arraying and VLBI possible in the future
  - Requires significant effort due to several limitations
  - Potential conflicts in task priorities
    - *PIC card commands* (after and prior to subscan starts) and other sub-array set-ups; *Phase corrections* applied within a subscan and priority on CAN bus; *Fixed UT start time constraint* in VLBI and other requests to correlator from other sub-arrays
  - Data rate limitations with multiple arrays

Pulsars

- A few pulsars in 35-100 GHz domain
  - ALMA brings unprecedented $A_{effective}$ in the phased array mode
  - Search for pulsars near Sgr A* / observe X-ray binaries
- Several possibilities
  - Phased array + pulsar processor (eg FFT spectrometer & high time resolution) for pulse profile and timing
  - Use APP 'system' for
    - » Blindly recording all data and search for new pulsars ... *primary beam is that of* A_i not a single dish with N A_i
    - » Specific VLBI observations … going later to Correlation Center or doing local VLBI with DiFX correlator

Pulsars

- No specific new hardware needed at AOS

  except for pulse and timing obsons => processor

  - Blanking gate circuitry exists for current correlation data dump, can be used to restrict the correlation to pulsar P
    - » Blanking resolution can be a small fraction of 1msec
- Software development needed
  - Pulsar model phase and rate to be derived in CCC with updates in the LTA microprocessor (1msec sufficient?)
  - Blanking 'generator'
  - Investigate whether FDM is best

Correlator Integrated Product Team

Those who built the 64-antenna correlator

NRAO

- J. Webber
- R. Escoffier
- R. Lacasse
- J. Greenberg
- R. Treacy
- A. Saez

Europe/ESO

- A. Baudry
- P. Cais
- G. Comoretto
- B. Quertier
- W. d'Anna

Computing: R. Amestica, J. Perez

Blue: APP team members or involved in APP