The 64-antenna correlator to phase up the ALMA array

Status and Perspective

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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 ~50 GByte/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)

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 x 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

PIC + TFB

64-ant Correlator

AOS-OSF fiber

VLBI recorders

Local VLBI/DiFX

Correlation Center

CDP cluster

CCC

TFB
Phasing the array

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

- VLBI baseline sensitivity is enhanced
  - Baseline sensitivity improves from $\sqrt{A_i}$ to $\sqrt{N A_i}$
  - $N = 50$ i.e. 12-m array alone
    $\Rightarrow$ 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 $\Phi$ solutions
  - Apply $\Phi$ corrections to digital LO phase registers
    - Corrections depend on ALMA band, antenna location, weather…

- ‘Phasing loop’ entirely within correlator
  - Possible because $\Phi$ 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 \( \phi \) 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 $\Delta \varphi = 687^\circ$ => *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 motherboard - design based on Correl Final Adder card- & Roach 2 board
Voltage sum in Correlator Cards

Polar X / Plane 1
- Ant. 0-31
- Ant. 32-63
- Antenna mask
- Sum
- Analog sum/LVDS out
- from all other 31 Planes
- PIC 1
- 10 GbE

Polar Y / Plane 1
- Sum
- PIC 2

Correlator Cards
- from 3 other Quadrants
- 6 other inputs

FO interface
- FO to OSF
**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 & APP Status

• PIC design, hard/firmware, complete ~June2014
• Entire APP chain successfully 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 \(\Leftrightarrow\) 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 \( H_2O \) *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 \( T_b \) & sizes => stellar & maser physics

• **SiO masers**

  VY CMa   ALMA, \( H_2O \) 321 GHz
  \( T_b \) >> \( 10^6 \) K expected
Perspective

Subarraying, Pulsar observations

• VLBI supposes only one ALMA array now
  • Sub-arrays not offered to users – only to observatory 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 $A_{\text{effective}}$ 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