# The SKA Central Signal Processor
# Project status and Italian contribution

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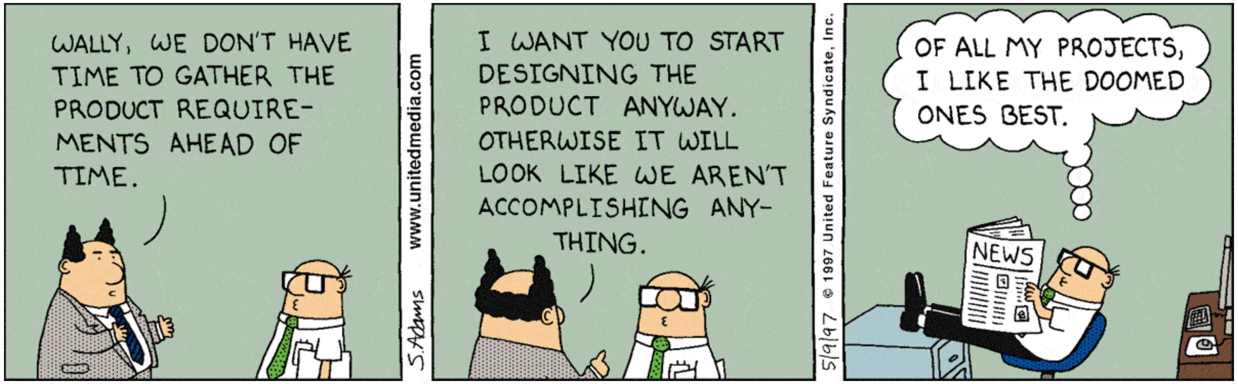
- What is the CSP
- A bit of history
- SKA LOW-MID central beamformer structure
  - Italian contribution
- Pulsar timing
- Pulsar search: structure and contribution
- Local monitor and control: contribution
- Plans for the bridging phase

# A bit of history

- 2011: SKA Organization
  - Non profit organization
- 2 Phase deployment: SKA1 (10%) & SKA2
  - Huge instrument: 1024 stations SKA-LOW, 256 antennas SKA-HIGH 64 antennas SKA-SURVEY
  - 256.000 spectral channels, 50 ms time res. → correlator **increases** data volume
  - Real time pulsar search (2000 beams) and timing (16 beams)
- 2013: Consortium starts
  - Each consortium an independent entity, self funded
- Mid 2014: Cost cap x 8-10 times, rebaselining
  - Deleted survey telescope. ASKAP is SKA1 survey instrument
  - 64k spectral channels, 0.2-0.6 s integration time
  - 512 stations for SKA-LOW, 196 dishes (incl. MeerKAT) for MID
- 2015: PDR
  - Multiple solutions presented → downselection.
  - CBF-LOW goes to CSIRO → redesigned. Italy exits CBF-LOW
- 2017: Cost reduction effort
  - “slice” architecture for CBF mid, 133 dishes
- Sep 2018: CDR



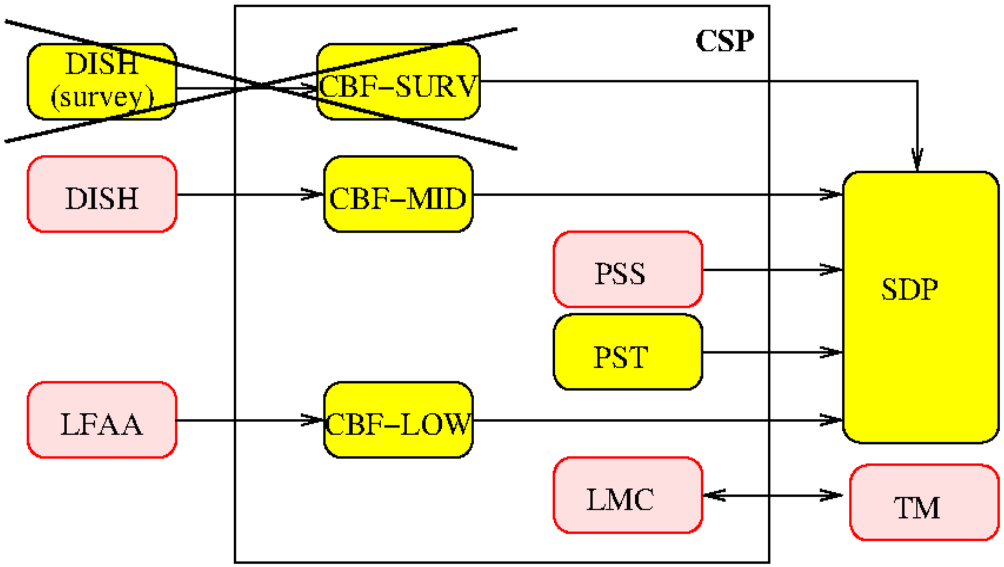
# CDR 24 September 2019



INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

SKA SQUARE KILOMETRE ARRAY CSP CENTRAL SIGNAL PROCESSOR

# SKA1-CSP STRUCTURE




**Central Signal processor elements**

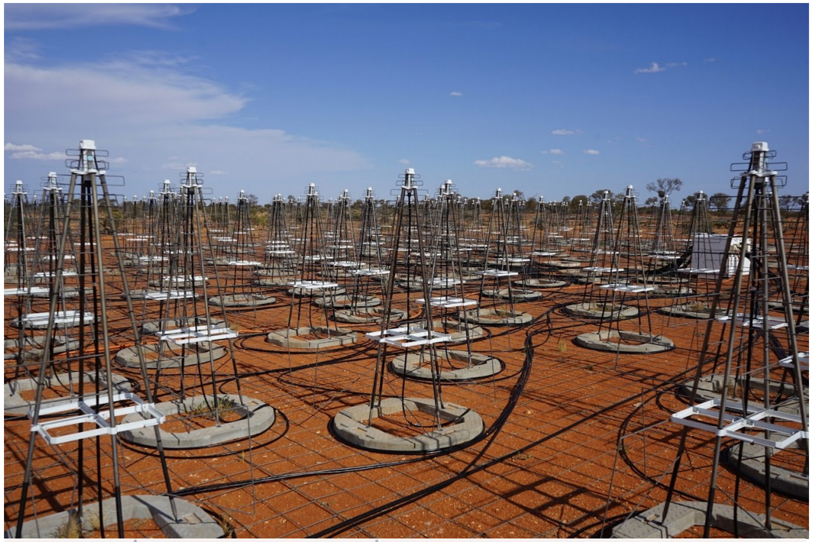
- **Central Beamformer: independent designs for Low and Mid**
- **Pulsar Search and Pulsar Timing machines**
- **Local monitor and Control**

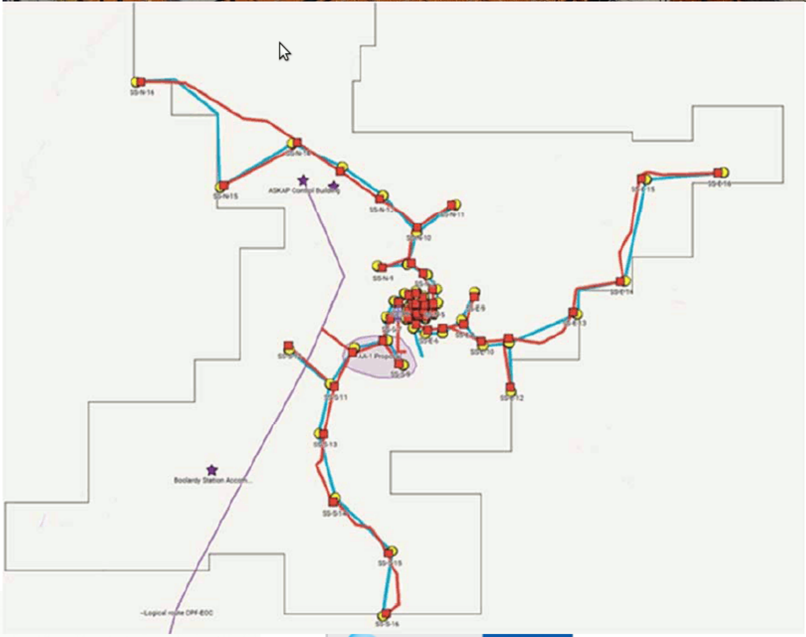
**Concurrent Imaging, pulsar search, pulsar timing**

**INAF contributed elements / sub-elements in red**

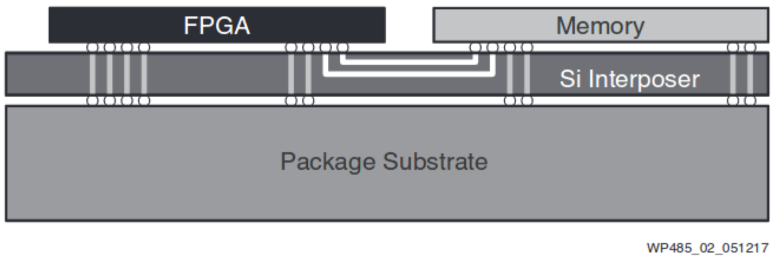
# SKA1-LOW Capabilities

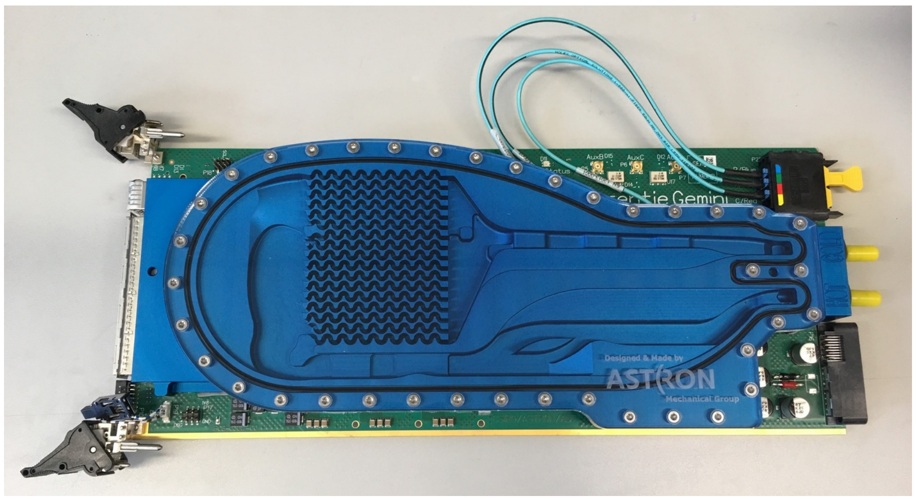
- **Frequency range 50-350 MHz**
  - Z = 4 → 27 for HI
  - Pulsar timing at 200-350 MHz
- **Velocity resolution:**
  - 4 → 30 km/s (full BW), 0.2→ 1.5 km/s (zoom mode)
- **Diameter = 38 m: FOV 1.5 – 10 deg**
  - 256 antennas per station, up to 45 deg from zenith
- **Maximum baseline 65 km: 2.8" → 19" resolution**
- **512 stations: 128K visibilities**
  - Multiple sub-stations with reduced BW
- **Sensitivity:**
  - 550 $m^2$-K between 100 and 350 MHz,
  - 60 $m^2$-K at 50 MHz
- **Multiple beams: up to 8 (less BW)**
- **Multiple sub-arrays (less stations)**





# CSP Low



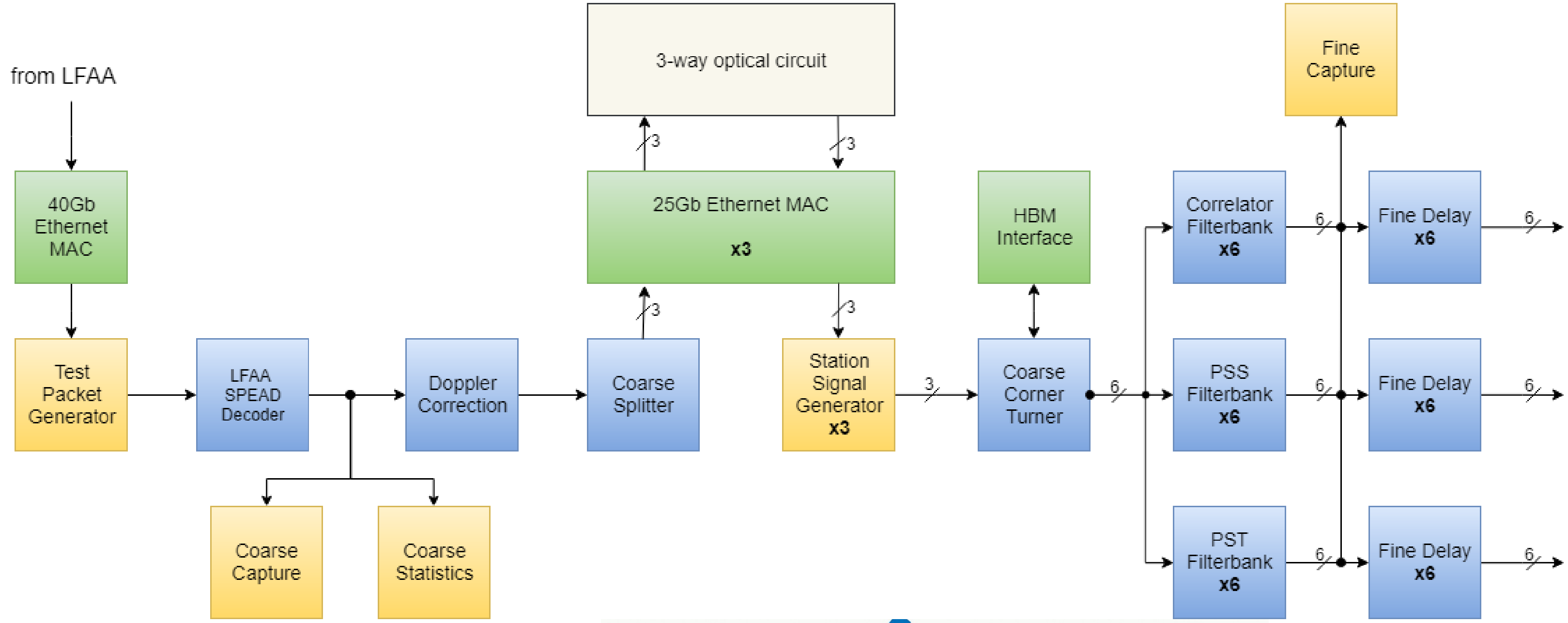





- **Architecture based on Xilinx High Memory Bandwidth FPGAs**
- **FPGA + memory chips in the same package**
- **Water cooled board in 3U subrack**

# FPGA processing

- Input data channelised by LFAA
- Channeliser for zoom mode resolution (226 Hz)
  - Other resolutions average channels in correlator – very flat frequency response
- Doppler correction for system (telescope) and local (station) velocity



# SKA1-MID Capabilities

- **Frequency Range: 5 bands**
- **Frequency resolution:**
  - **Full band: BW/60,000**
  - **Zoom mode:**
    - 250 Hz to 16 kHz resolution
    - 16,000 channels per window
    - 60,000 channels total
- **Pulsar phase binning for time resolved pulsar images**
  - **Up to 1024 phase bins**
  - **Traded with spectral channels**

| Band | Fmin (GHz) | Fmax (GHz) | BW (GHz) | # of slices |
|---|---|---|---|---|
| 1 | 0.35 | 1.05 | 0.7 | 4 |
| 2 | 0.95 | 1.76 | 0.81 | 5 |
| 3 | 1.65 | 3.05 | 1.4 | 7 |
| 4 | 2.80 | 5.18 | 2.38 | 12 |
| 5a | 4.70 | 8.50 | 3.9 | 20 |
| 5b | 8.30 | 15.30 | 2x2.5 | 26 |

# SKA1-MID Non imaging Capabilities

- **Pulsar search: 1500 search beams inside main beam**
  - One of the largest computing engine in the world, if built today
- **Pulsar timing: 16 beams**
- **Transient buffer for FRB**
- **RFI detection – flagging – excision**
- **VLBI tied beam array**

**Limited concurrent operation of all capabilities**

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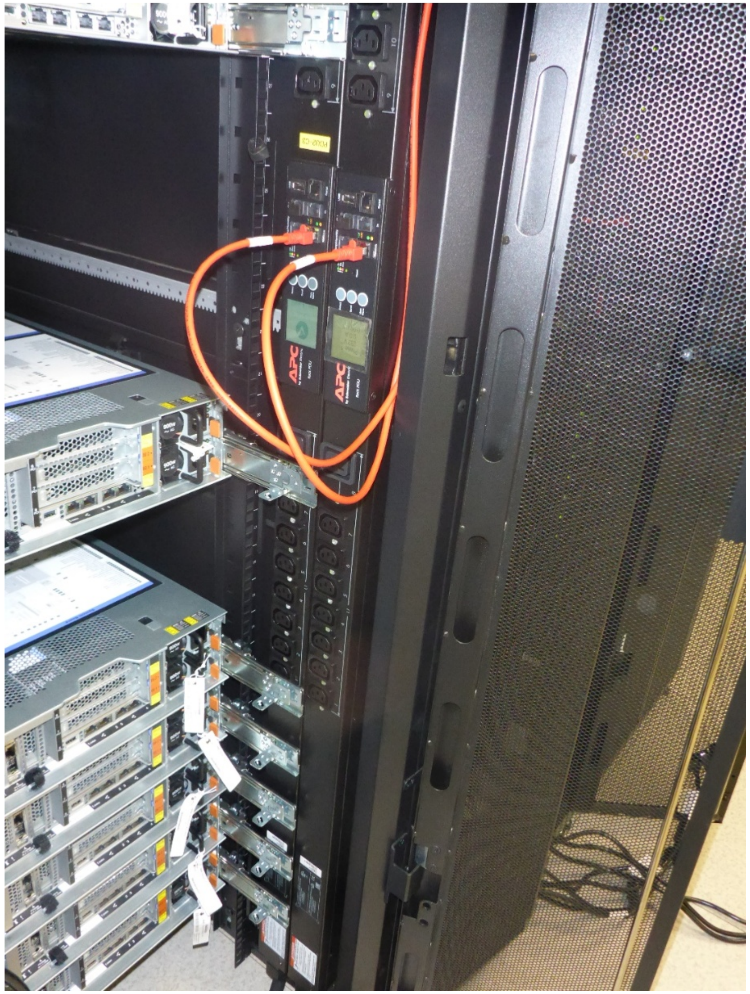
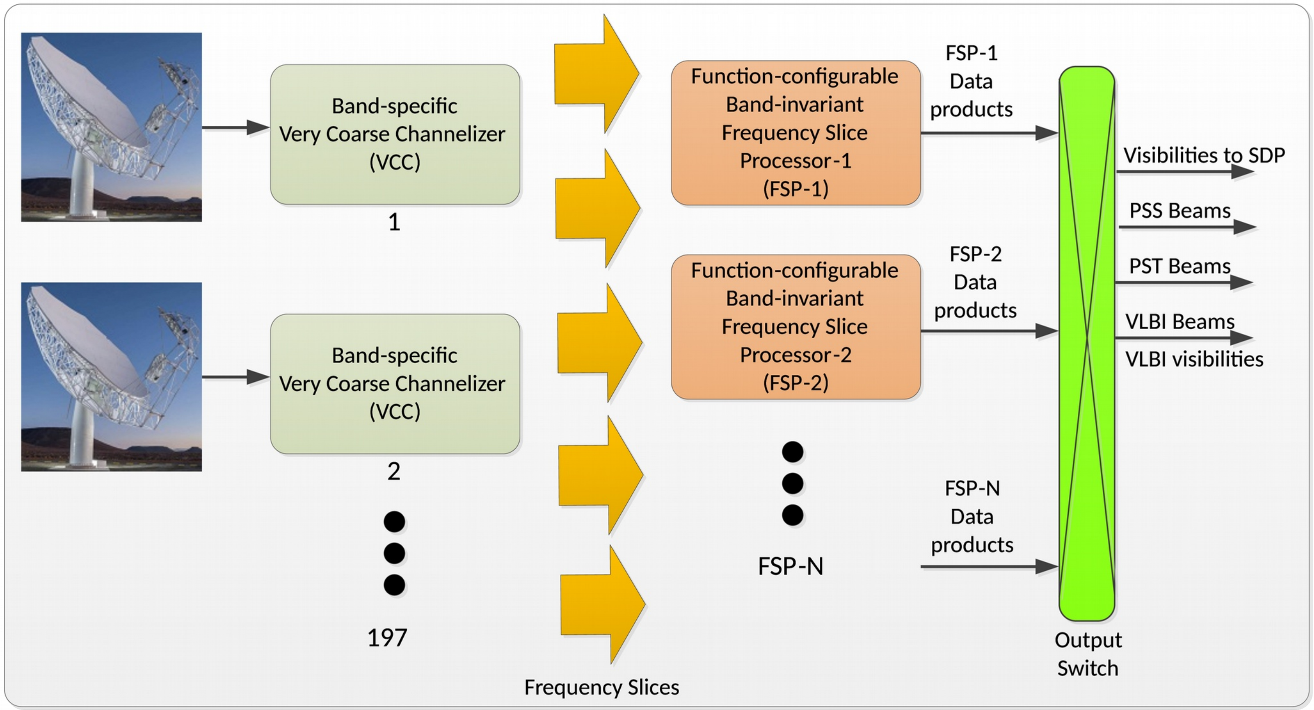
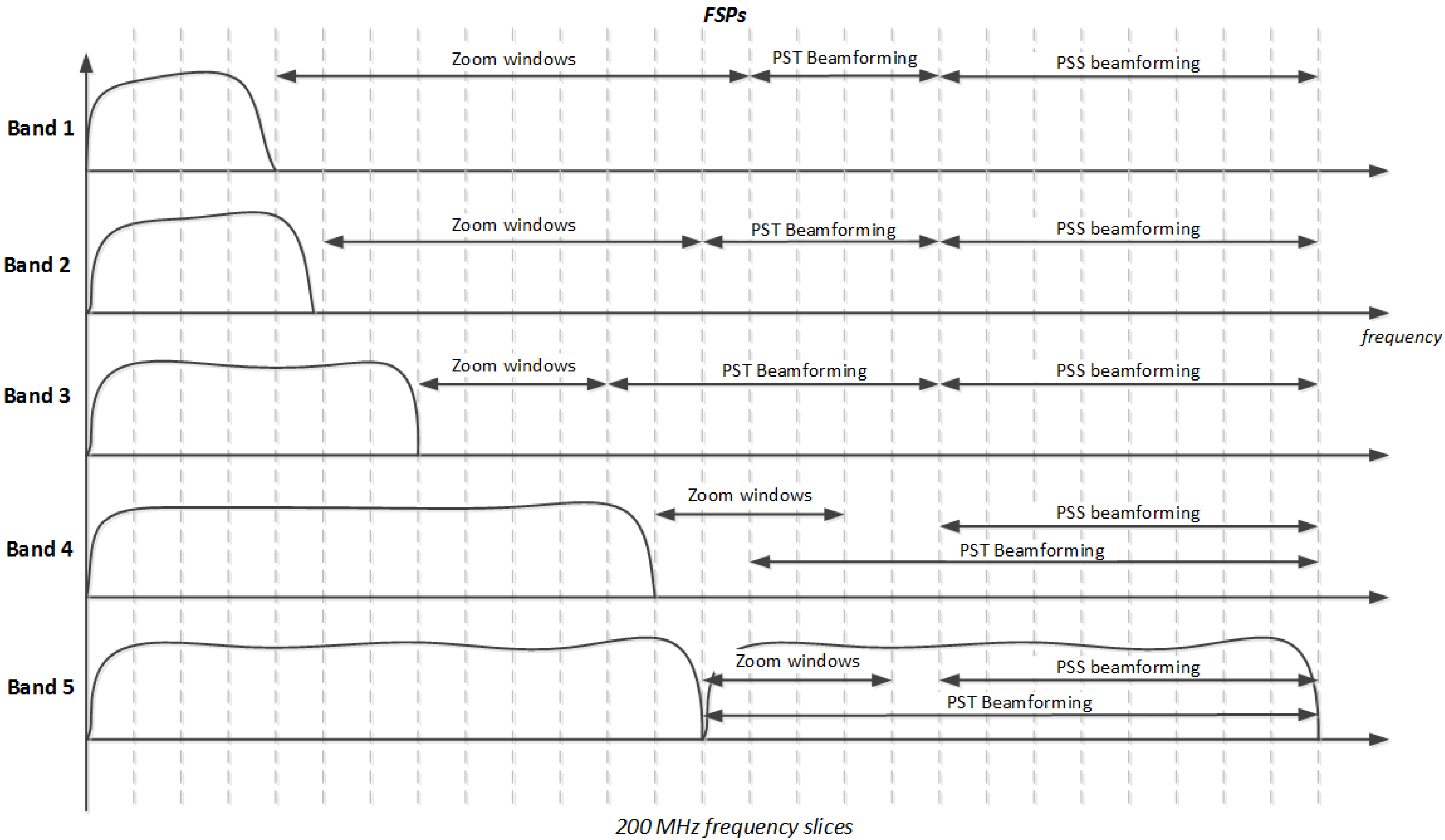



PSS prototype at Karoo

# Slice structure for CSP-MID




- **Correlator size determined by larger bandwidth (band 5)**
- **Divide input band into variable number of identical ~200 MHz slices**
- **Process each slice for imaging, zoom mode, PSS, PST or VLBI**
- **Full concurrent capability for lower bands**
- **Full band imaging mode for band 5, but not concurrent with PSS & PST**




**"Commensality Diagram"**

# Italian contribution

- **Design of key elements**
  - Time domain delay
  - Correlator cell (complex multiplier)
- **Modelling of fixed point effects**
  - Finite step in delay/phase correction
  - Quantisation in digitiser
  - Quantisation in requantisaton stages
  - Harminic distortion due to requantisation

**Two scientific publications (accepted)**

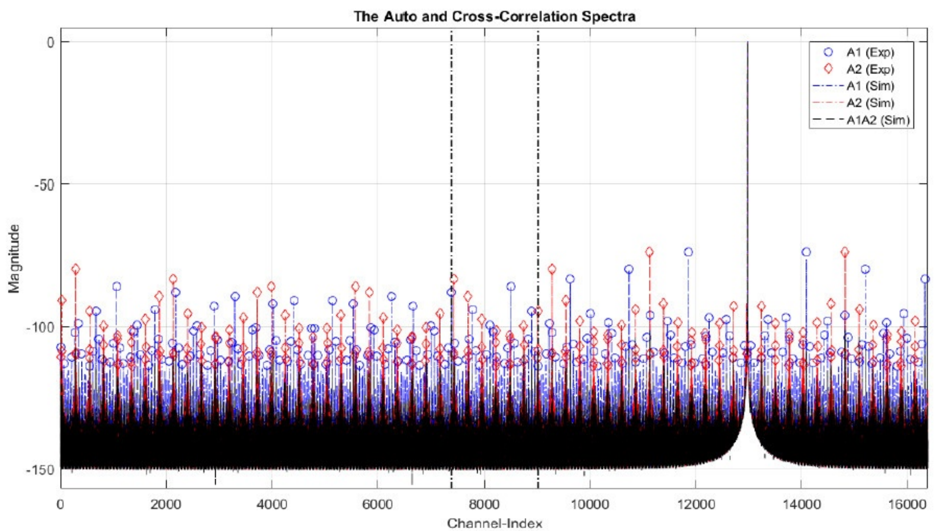
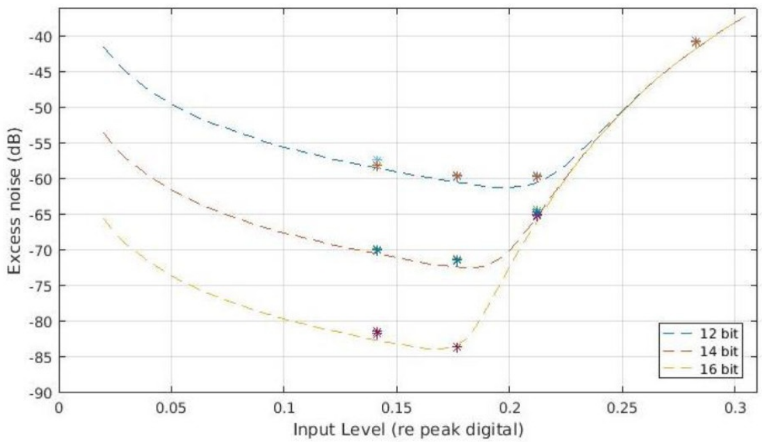
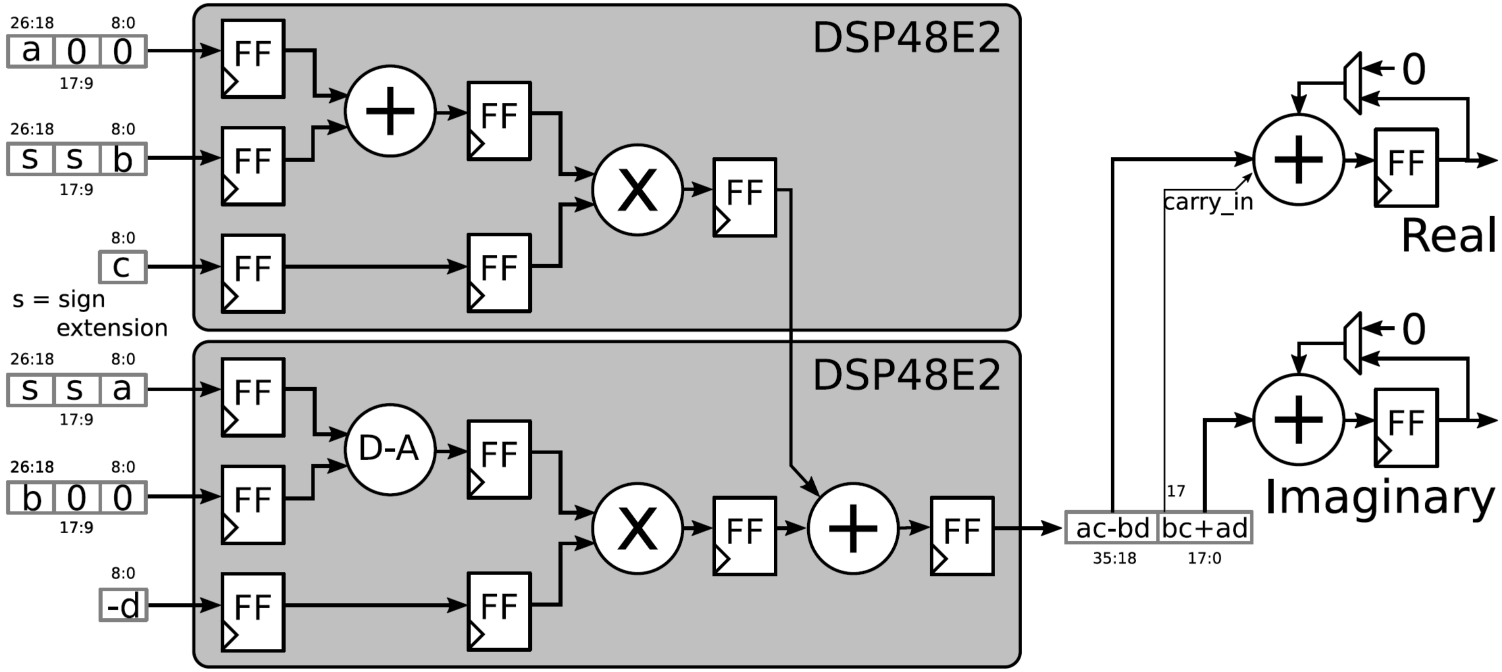



**Figure 5-21 Expected and simulated auto- and cross- correlations of channelized ReSampler outputs with no delay dithering.**




**Added quantization noise for 12, 14, and 16-bit intermediate quantizations as a function of the input signal level.**

# Matrix Correlator Cell




**Basis of correlator**

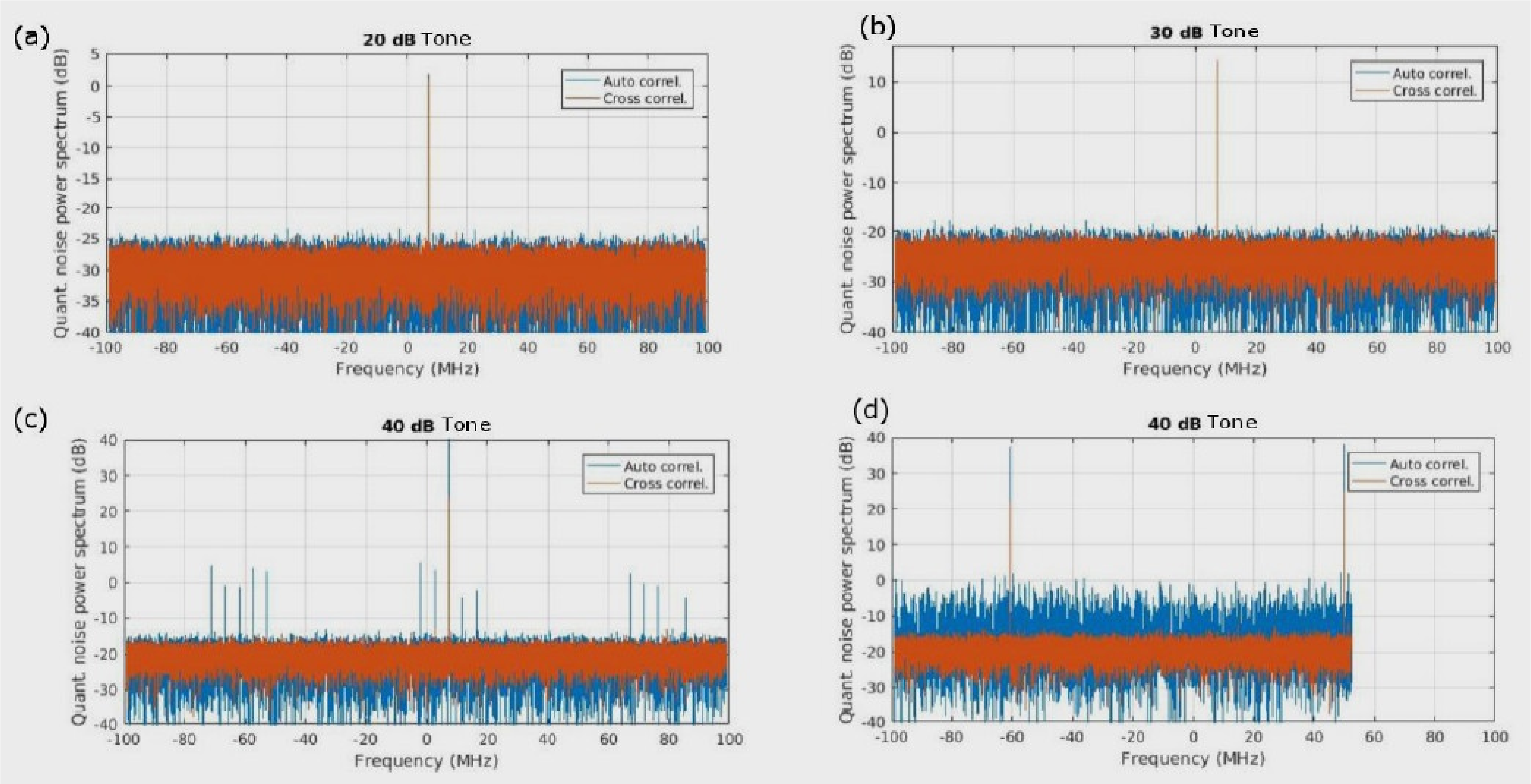
**Both for Altera (MID) and Xilinx (LOW) architectures**

**Published in *Conference on Reconfigurable Computing and FPGAs (ReConFig 2018)***

IMPLEMENTATION RESULTS FOR XILINX ULTRASCALE+

| Style | Width | LUTs | FFs | DSPs | Fmax |
|---|---|---|---|---|---|
| optimised | 9-bit | 86 | 54 | 2 | 640 MHz |
| inferred | 9-bit | 99 | 163 | 2 | 450 MHz |

# Modelling example




**Quantisation noise for strong RFI – 8 bit ADC – SKA Mid band 1**

**RFI from 100 to $10^4$ times the broaddband sky signal**

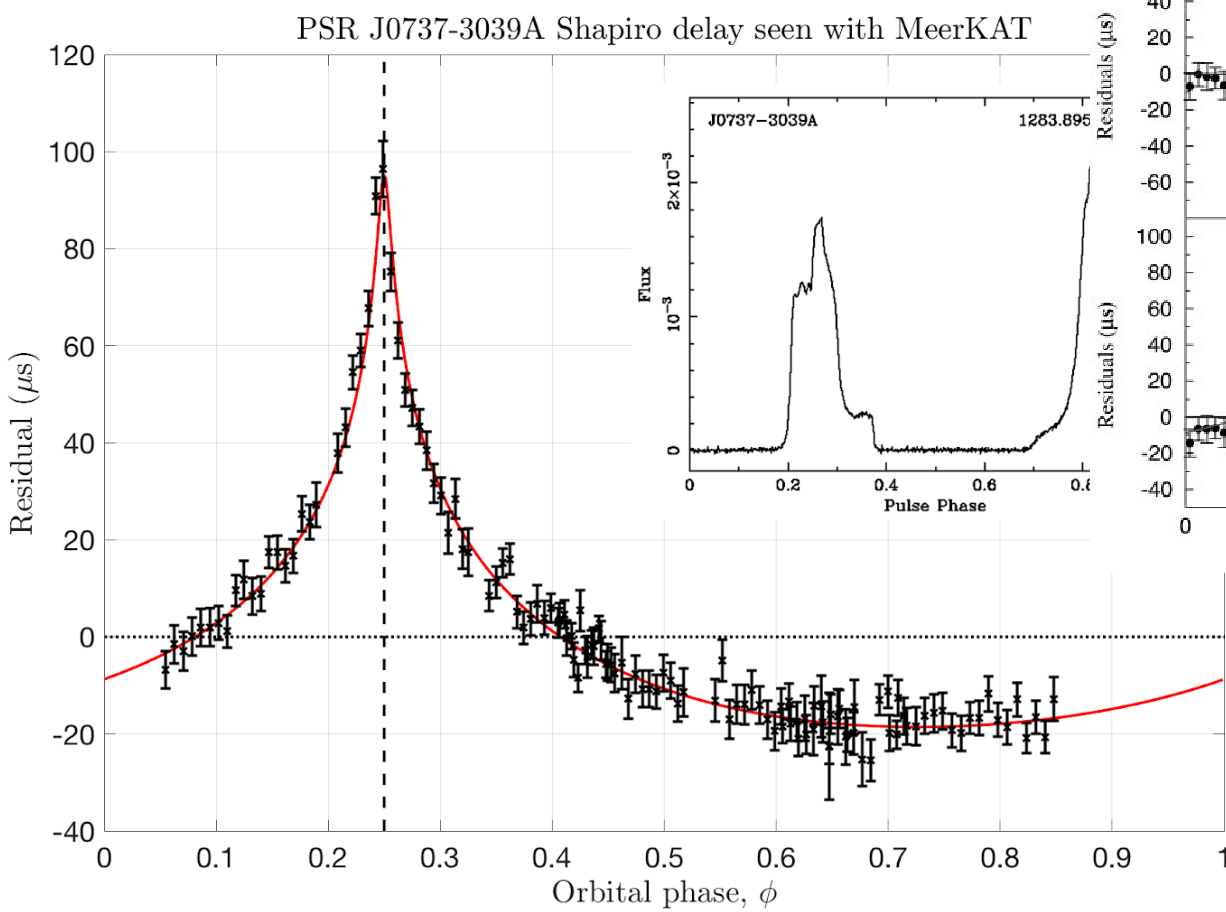
# Pulsar timing (PST)

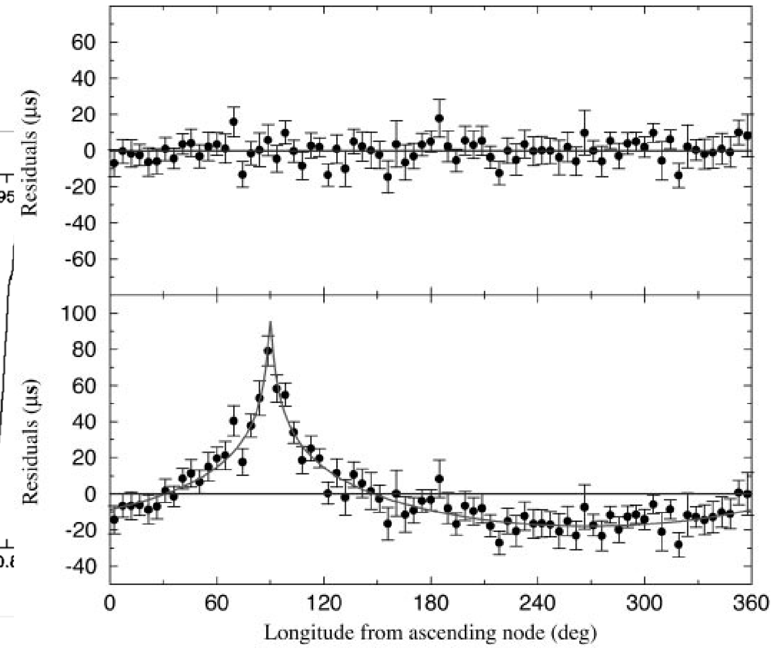
- Prototype at MeerKAT.
  - 4 x Nvidia TitanX GPUs
  - Pulsar Timing & Dynamic Spectrum Modes
  - 2 x 856 MHz tied-array beams
- Almost no Italian involvement
  - Some contribution to simulations

# Measurement of Shapiro Delay

7 months Lovell

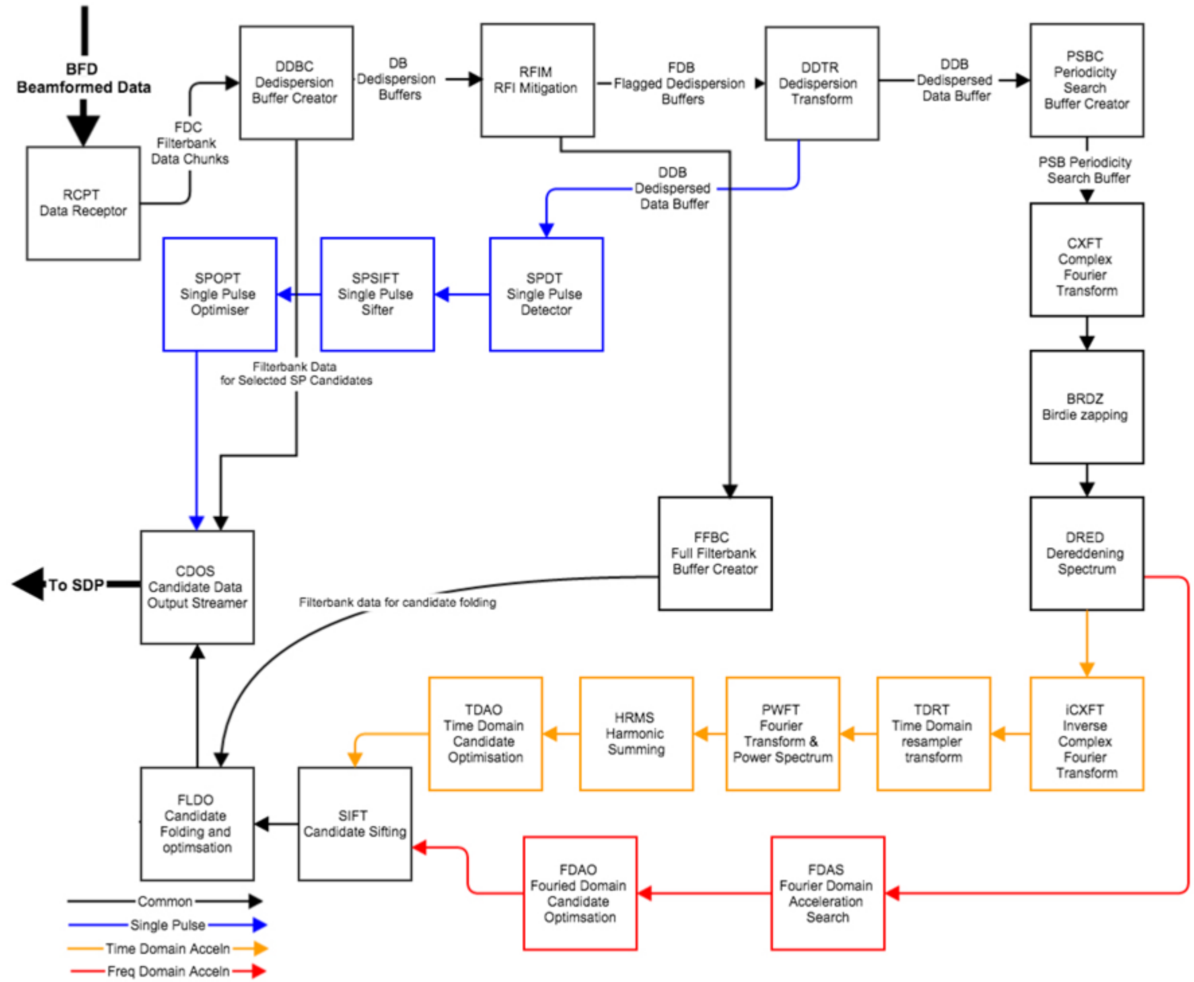
2.3 hours MeerKAT



# Pulsar search (PSS)

- Input data volume: 1 PB per pointing → real time search
- Small interferometer beam → large number of beams (1500 mid + 500 low)
- Unknown period and DM
- Relativistic binaries → unknown acceleration
  **Dominant computational request**
- Detection of FRB (for detection capture)
- Power constraints
- Physical space constraints



# On site hardware prototype

## ProtoNIP: a PSS prototype in the Karoo

- 18x 2U, dual socket, dual accelerator servers
- 2x Intel Xeon 14 cores
- Arria 10 PCIe FPGA board
- NVIDIA P100 GPU card
- 512 GB TruDDR4 RAM
- Rack allocation for tests of power, cooling, system stability, running Cheetah/Panda prototype software.
- Hardware all in place and operational.

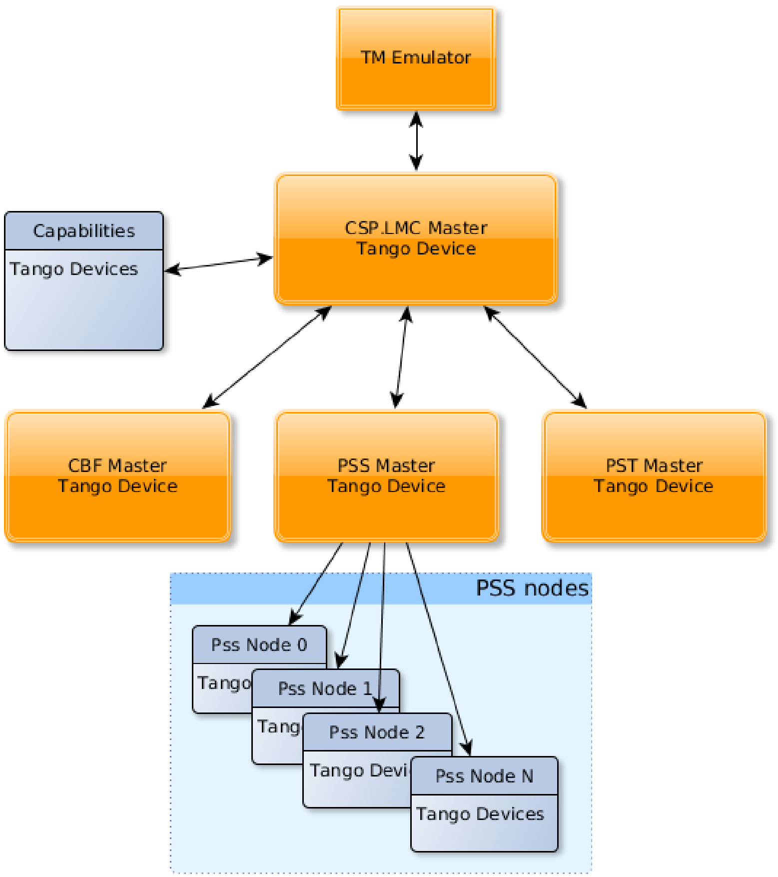
# PSS – Code Development

Red: Inaf contribution

| | | |
|---|---|---|
| GPU (DDTR/FDAS) | -- | 23,000 lines of code (Cuda/C++) |
| GPU (FLDO) | -- | 15,000 lines of code (Cuda/OpenCL) |
| LMC | -- | 10,000 lines of code (C++) |
| PANDA | -- | 22,000 lines of code (C++) |
| CHEETAH | -- | 31,000 lines of code (C++) |
| FPGA (DDTR/SPDT) | -- | 1,500 lines of code (OpenCL) |
| FPGA (CXFT/FDAS) | -- | 1,500 lines of code (OpenCL) |
| FPGA (FDAS/FLDO) | -- | 40,000 lines of code (VHDL) |
| CPU (TestVectors) | -- | 10,000 lines of code (python) |
| Signal Model | -- | 12,000 lines of code (Matlab/C++) |

NZ Alliance

# PSS Local Monitor & Control

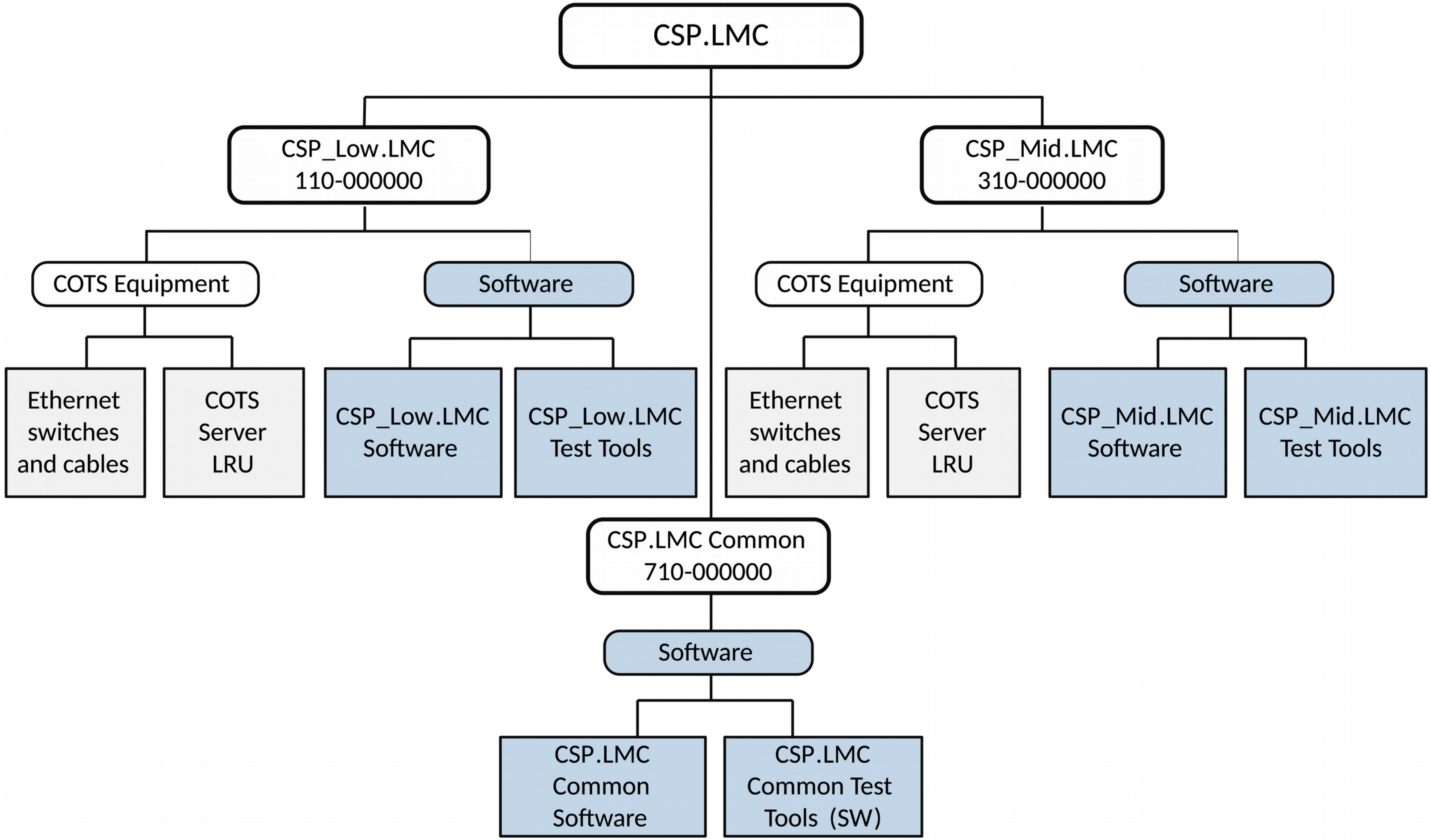



## 90% Italian contribution

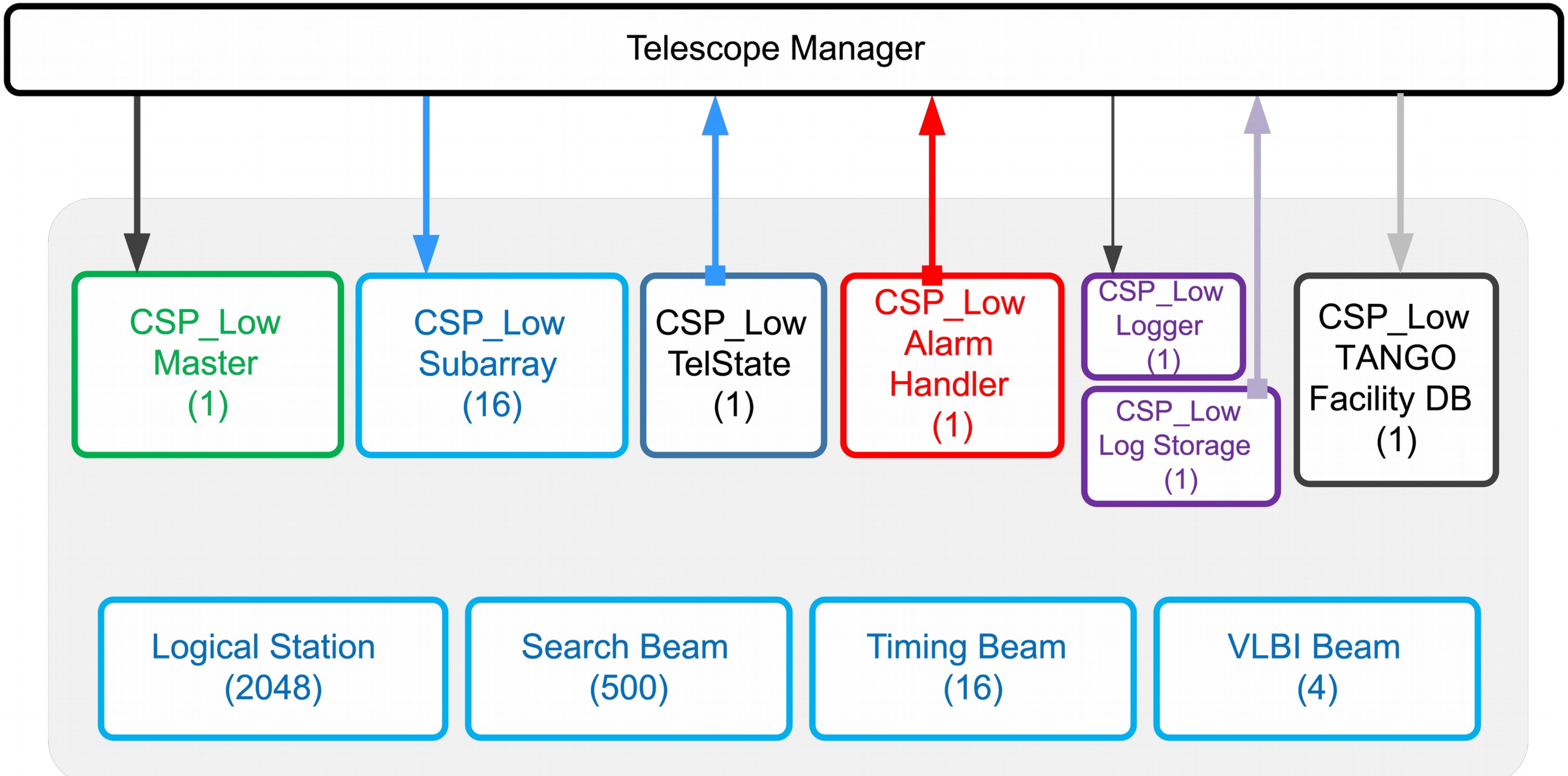
## PSS LMC evolutionary prototype:

- Main Tango Control Devices in place.
- Init/program/start scan working. interface with (small) real nodes.
- Interface with simulated pipelines.
- Compatible with the (evolving) SKA standards.

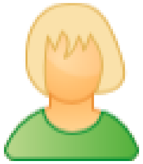
# CSP Local Monitor and Control



# CSP_Low - TM View (TANGO API)



# CSP LMC prototyping

| | | |
|---|---|---|
|  | Carlo Baffa | Prototype design and development |
|  | Elisabetta Giani | Prototype design and development |
|  | Marina Vela Nunez | GUI design and implementation |
|  | Sonja Vrcic | CSP.LMC Lead |

# INAF contribution
# Summary & Bridging phase

- **CBF**
  - Correlator cell structure
  - Modelling quantization effects
- **PSS**
  - Folding-Optimization
  - Local Monitor & Control
- **LMC**
  - Prototype: test of the basic structure
- **Signal chain modelling**
  - Linearity
  - RFI immunity
- **PSS prototype**
  - Incremeт of the Technological Readness Level: tests at MeerKAT
- **LMC Prototype**
  - Improve current prototype to a production level framework