SKA1 Low Correlator

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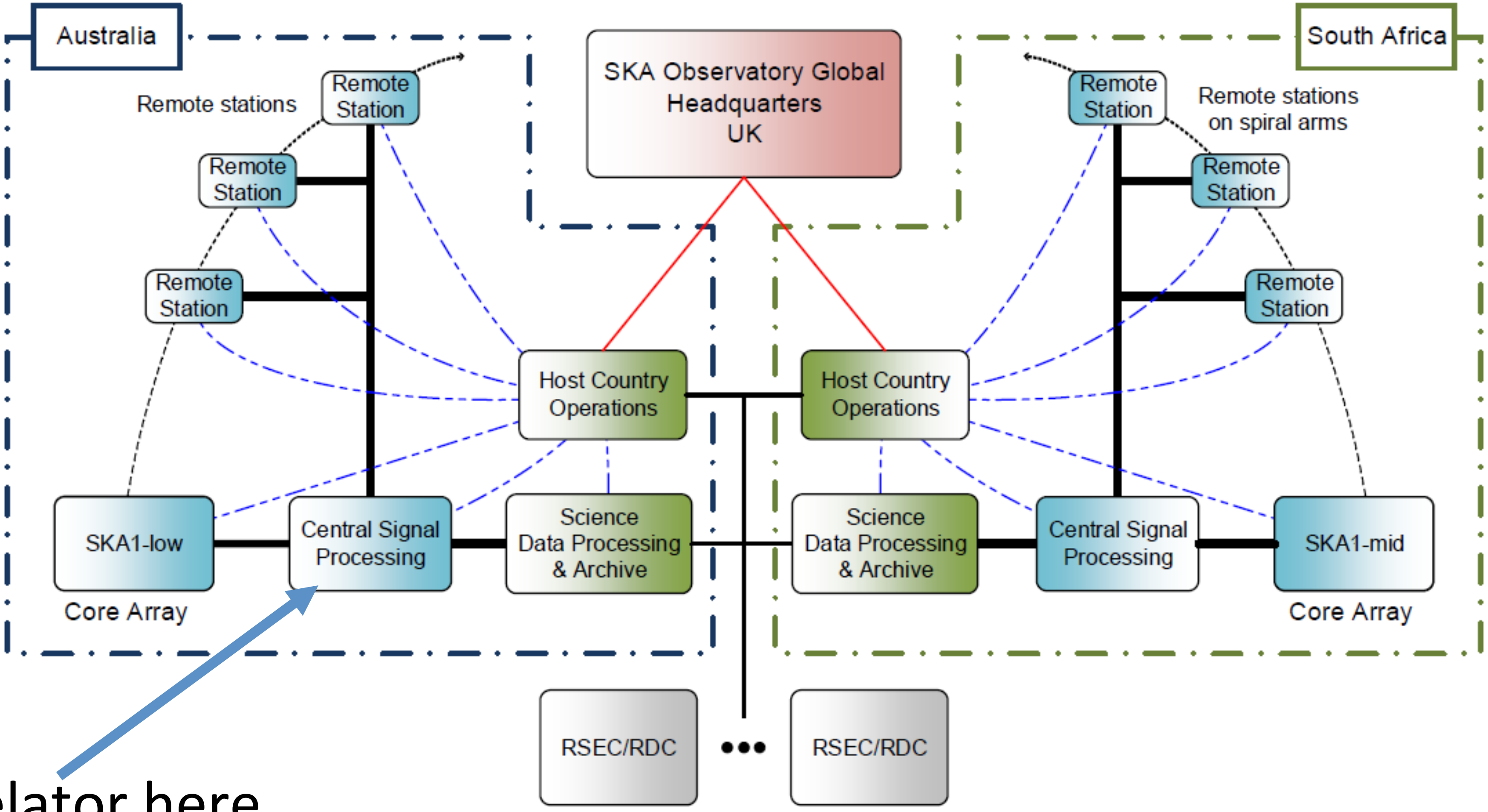
SKA1 Overview

SKA1-low stations include Station Beamformer

CSP includes *Correlator*, Tied Array beamformers, Pulsar Search Engine and Pulsar Timing Engine



Correlator here

Organisation

The Low Correlator and Beamformer (CSP_Low.CBF) consortium are part of the larger Central Signal Processing (CSP) Consortium

CSP is lead by NRC Canada with MDA managing

CSP_Low.CBF is lead by CSIRO (Australia)

With ASTRON (Netherlands) and

AUT (New Zealand) as collaborator

SKA1 Low Correlator Base Requirements

Bandwidth 300 MHz (Sky frequency 50-350 MHz)

- From low station as 384 channels of 0.781kHz each

Full Stokes

512 antenna stations

Compute load 1.25 Pflops equivalent

- About order of magnitude more than JVLA correlator
- About half of the proposed SKA1 Mid correlator

Basic operating mode is a "zoom mode" with at least 64k frequency channels – 73,728 in practice across 300MHz,

- Resolution 4.07 KHz

Plus Zoom Modes

Four Independent Zoom Bands nominally either

- 4 MHz
- 8 MHz
- 16 MHz or
- 32 MHz each
  - 256 possible combination

At least 16k channels in each zoom band – will realise 17,280 in a 3.9, 7.8, 15.6 or 31.2 MHz bands

In addition “continuum” required at frequency with in 300 MHz observing band, but not in a zoom band

Plus Subarraying

The telescope can operate as 1 to 16 INDEPENDENT subarrays

No antenna station can belong to the same subarray

Plus provision is made for a maintenance (17^{th}) subarray

Up to 512 antennas when there is a single subarray

Each subarray has independent scheduling blocks

Last implies we cannot change firmware to change modes.

Plus Multibeaming

Each subarray can apportion its 300MHz to 8 beams

Each beam is a contiguous section of bandwidth

Each beam pointing is independent of the other beams

Spectrum of beams can overlap

- Example 8 beams all covering 200-237.5 MHz on the sky

Large number of mode

"Normal" observing with zoom modes, subarraying, multibeaming, and independent scheduling blocks.

In the following will show how these are implemented in SKA1_Low.CBF

Additional outputs from SKA1_Low.CBF

16 voltage beams full bandwidth for pulsar timing

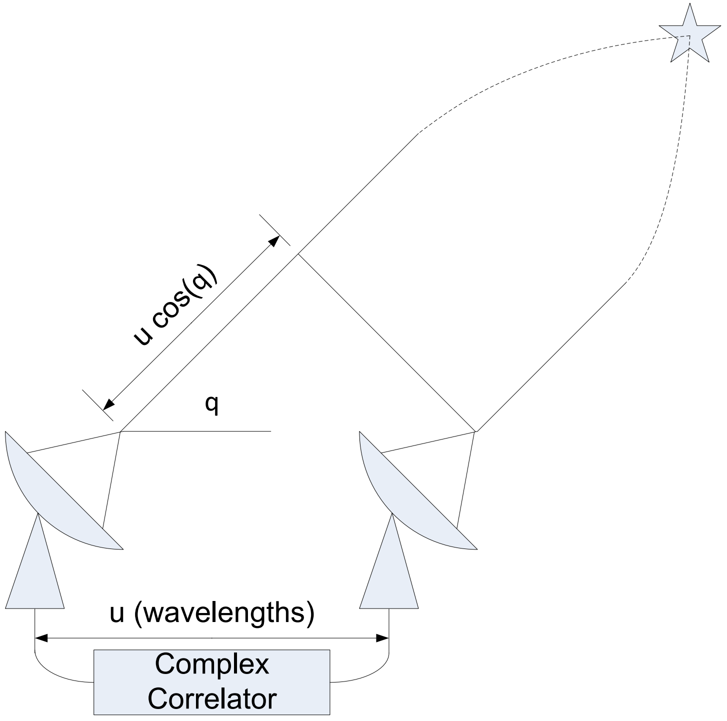
500 pulsar search beams at 128MHz bandwidth

Pulsar search can trade beams for bandwidth

- 500 beams 128 MHz,
- 250 beams 2x128 MHz, or
- 133 beams 3x128 MHz

Not covered in this talk

Implementing Delay Correction



Must bring all signal to same wavefront before correlation in effect add delay of u.cos(θ) to second antenna

Step 1 Remove bulk delay by delay sampled data (~1us accuracy for LOW).

Left with fractional delay error of up to 0.5us across ~1MHz

delay = -dθ/dω (dω.delay = 180 degrees)

Phase changes by up to 180 deg across the band

Delay Correction with Fractional Time Delay filters

FIR filter with values sampled from a continuous time filter.

Change the initial sampling point of continuous time filter changes the delay

Example equi-ripple low pass filter. Can make ripple as small as required and low pass cut-off as high as required.

Problems

- Filter length can get very large – more compute intensive than filterbank
- Residual amplitude errors, possibly delay errors
  - Changes with delay value
- Finite number of Filters leave residual phase error
  - for example~180 filter responses leaves phase error of up to 1 degree

Delay Correction with Phase Slope

In frequency domain delay is equivalent of a phase slope

“Normal” frequency resolution of correlator requires ~256 channel filterbank. Phase slope across a channel is less than 1 degree (±0.5deg), average error is zero

Apply correct phase, as a function of time, to each fine channel

Problem: rate of change of delay = Doppler Shift,

- Different Doppler shifts on different antennas (less than 10Hz)
- Fine channels select different part of the sky spectrum – correlation loss

Solution apply Doppler correction before fine filterbank

Implementing Spectral Resolution

Six spectral resolution required:

- Continuum, “normal” (4kHz) and four zoom modes

Solution 1 Five Separate filterbanks

- Implement a separate filterbank for each resolution
- No filterbank for Continuum so fine delay must be fractional delay filter

Solution 2 Combine zoom filterbanks

- Zoom filterbanks are power of 2. Build variable length filterbank
- For data from stations Normal mode is resolution not a power of 2, separate filterbank
- Have two filterbanks and fractional delay filter

Solution 3 Frequency averaging

- Implement filterbank at finest frequency resolution and average in frequency to achieve other resolutions
- 4096 channel filterbank -226Hz resolution,
- Average1, 2, 4, 8 channels gives 226, 452, 904Hz, 1.8kHz - all zoom modes
- Average 18 channels give “normal” observing of 4kHz, average 3456 channels gives continuum (781kHz)

SKA_Low.CBF solution

Use frequency averaging to implement all resolutions

- A single filterbank,
- Uniform data flow into correlator (same for all resolutions)

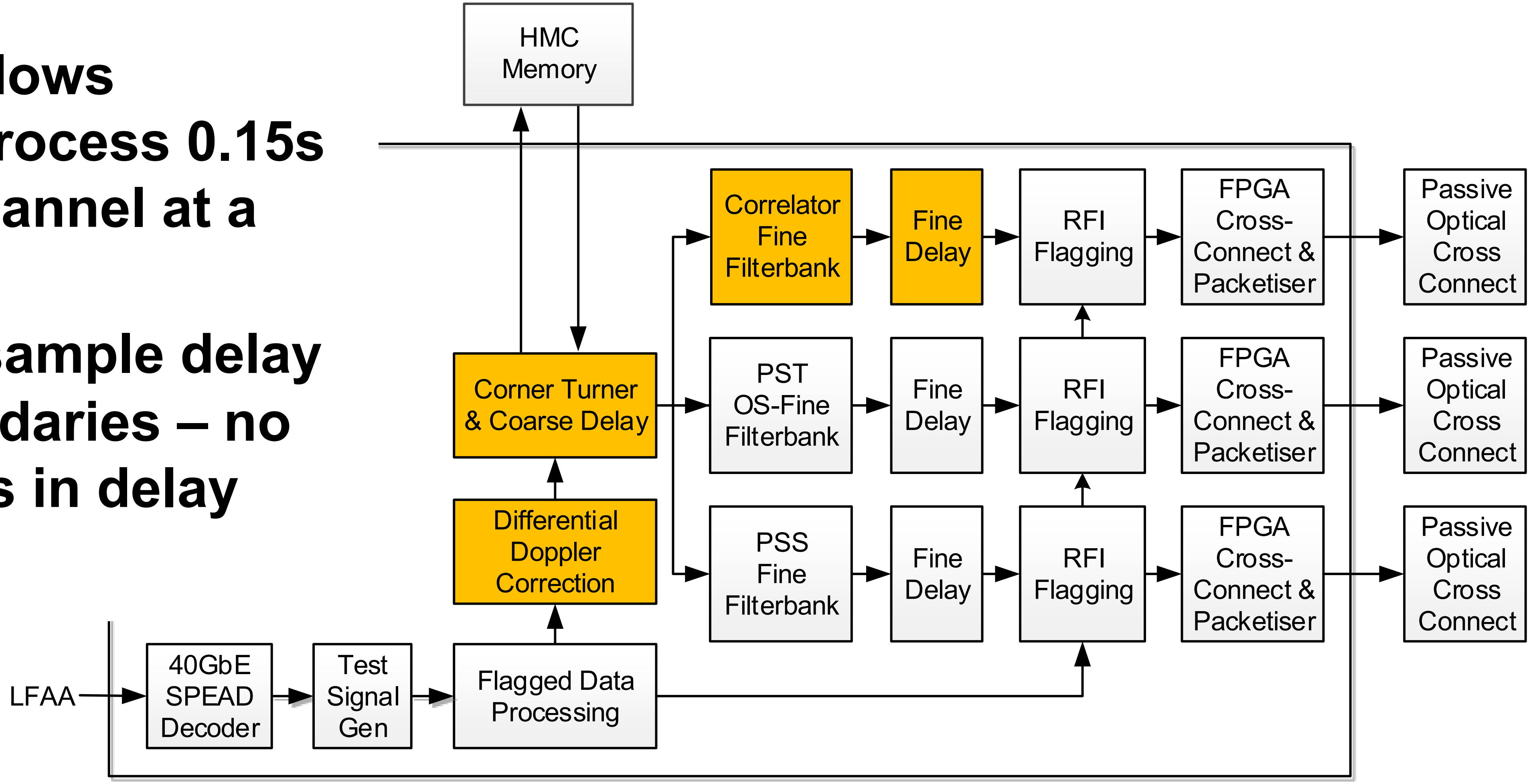
Use phase slope method for fractional delay

- 4096 channel filterbank = 0.02degree maximum phase error across channel
- Very small phase error
- No added amplitude error
- Small compute load – much less than the filterbank

Corner Turn

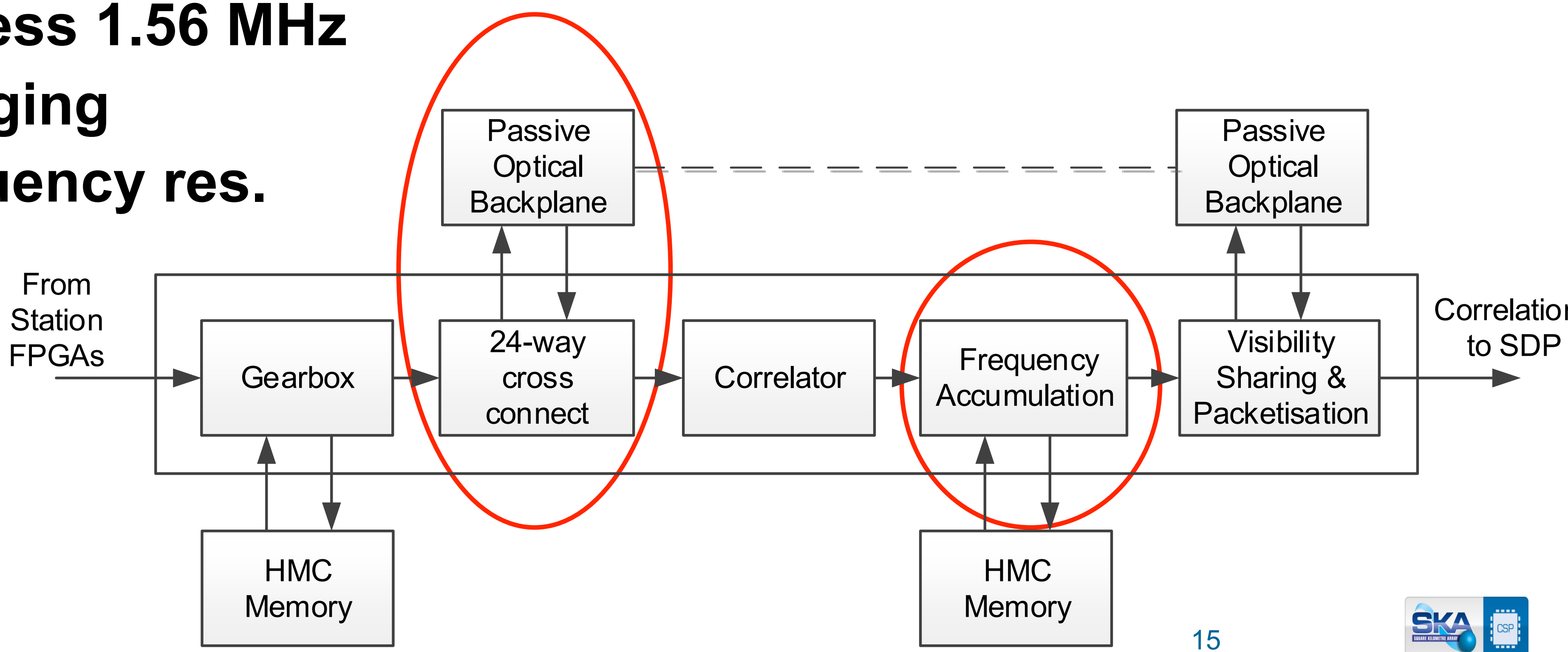
Corner turn allows filterbank to process 0.15s for a single channel at a time.

Only change sample delay on 0.15s boundaries – no discontinuities in delay correction



Correlation – six frequency resolutions

Correlator 1.25PFlops require 192 FPGAs
Data output from filterbank FPGAs on 8 x 25Gbps links
One link to group of 24 – cross connect with group of 24
Each FPGA process 1.56 MHz
Frequency averaging
for different frequency res.



Multibeaming

For correlator difference in beam is simply a different delay polynomial (description of delay as a function of time)

Each antenna station is in a single subarray.

Eight beam per subarray require 8 delay polynomials for each antenna.

For each coarse channel apply the appropriate delay polynomial.

All extra complexity with filterbanks, Correlator independent

Subarraying

If there is NO subarraying correlation between all pairs of antennas is performed.

In this design all correlation for single frequency channel occurs in a single FPGA and are stored to DRAM

A subarray selects a subset of all possible correlation

Arrange data in DRAM so that a block read are for correlation where one the antenna station inputs is common

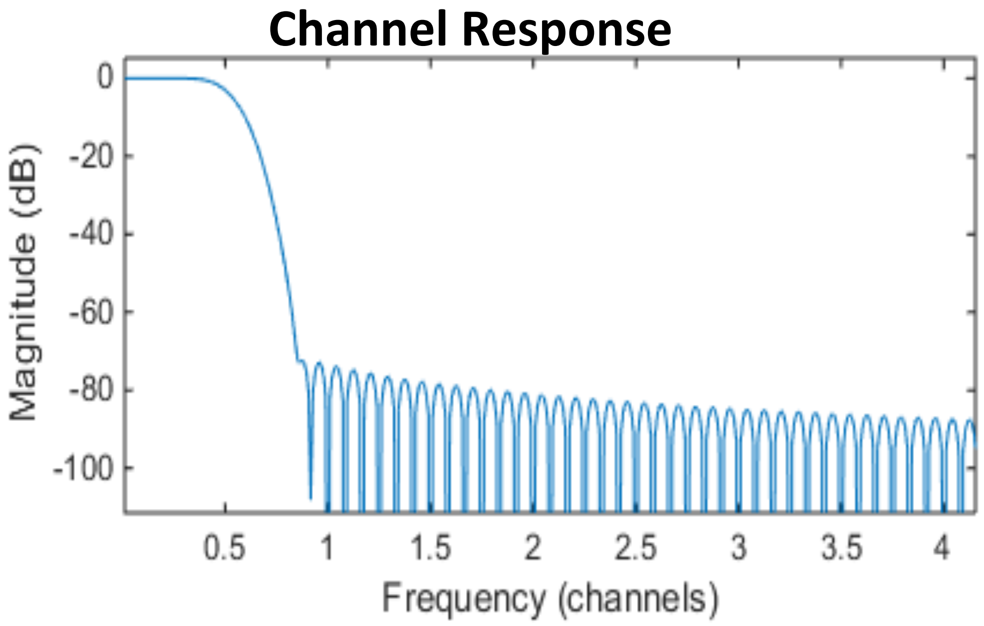
SUBARRAYING becomes

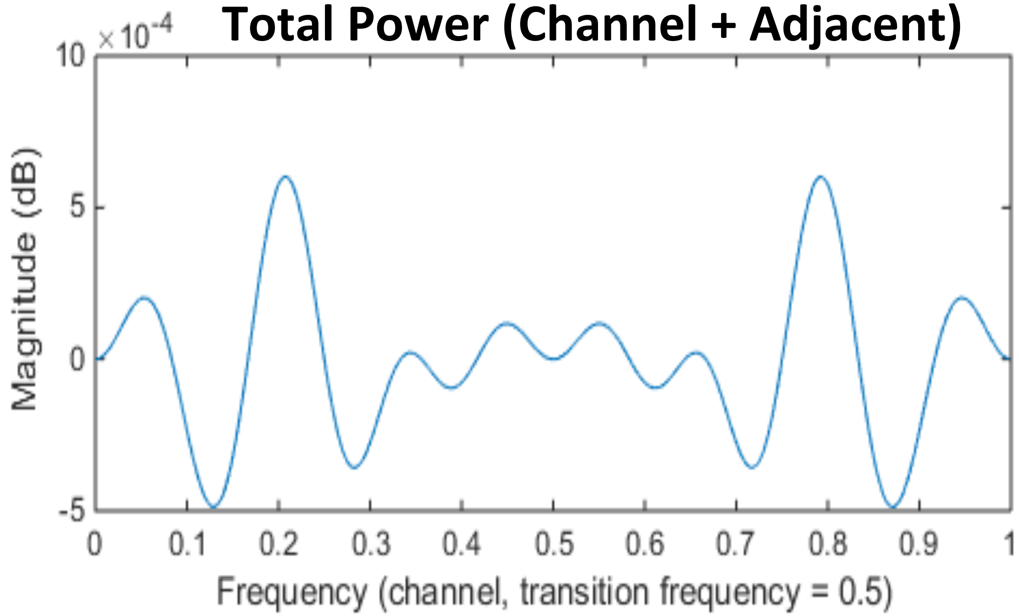
- **For each antenna station in a subarray read blocks for that antenna station**
- **Select the subset of correlation for the subarray and transmit for data processing**

Correlator Fine Filter Response

Requirement

- Montonic to -60dB across adjacent channel
- -3dB at channel edge
- Total power (in channel plus adjacent channel) variation 0.01dB
  - Achieve 0.0006dB, 12-tap FIR section





Data Rates and Optical Links

Input data rate 11.4 Gbps per antenna station

512 antenna station 5.8 Tbs on 171 40GE links

(684 optical fibres input, same for output to meet Ethernet standards)

Output data rate from Filterbanks the same but on 344 25Gbps links (344 fibres) for correlator

Same number of fibres for PSS and PST

1720 fibres outputs from antenna based process

Use 43 FPGAs for antenna based 40 SERDES each for I/O

- Underutilises compute but other SERDES needed for HMC Memory

Add 192 FPGA for Correlation function

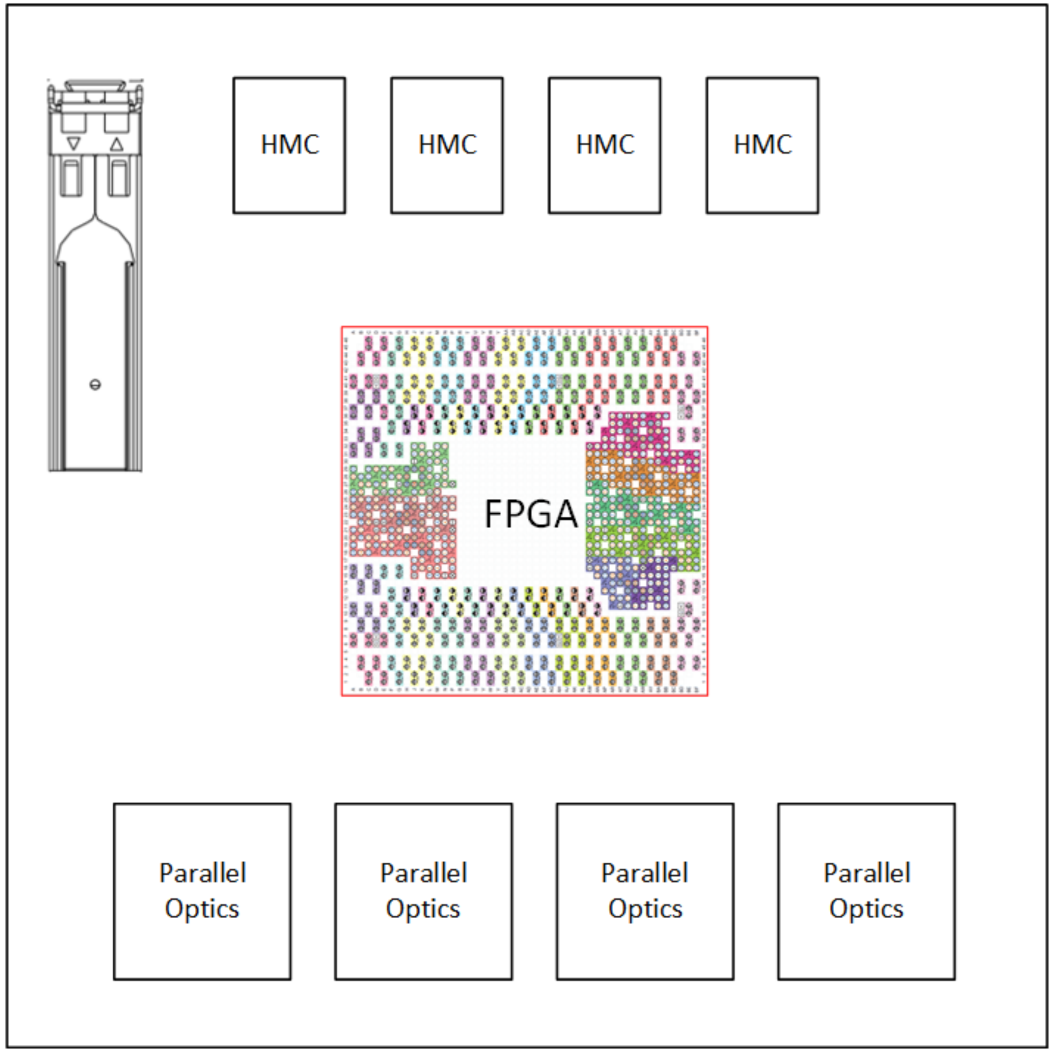
Processing board

Optical Transceiver and FPGA SERDES number now allow

FULL OPTICAL DATA CONNECTIONS

Proposed processing board is a simple single board unit with

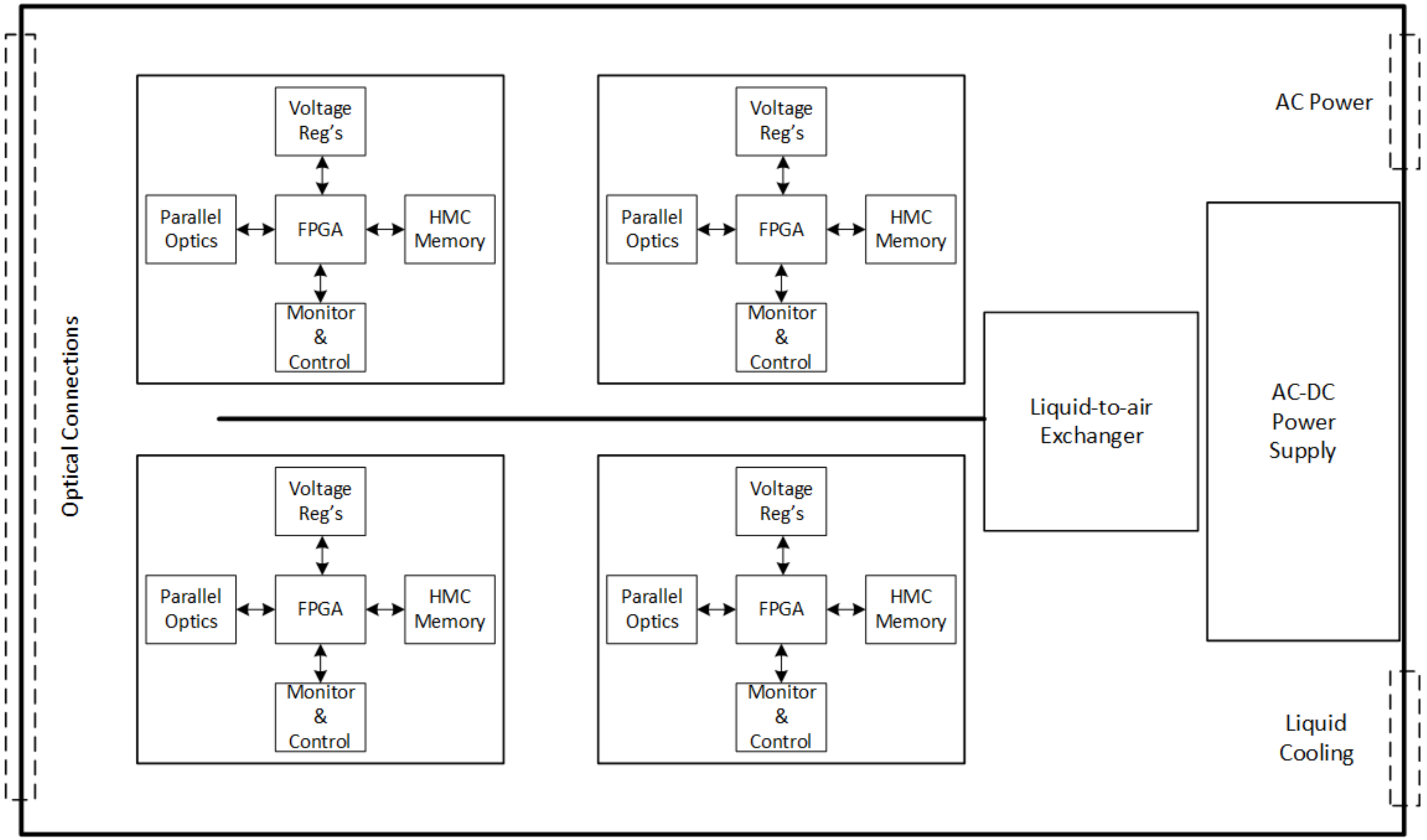
- **A single FPGA**
- **Parallel Optical transceivers for I/O**
  (48 fibres total)
- **Four HMC for data storage**
- **SFP+ 10GE for Monitor&Control**



Perentie Rack Unit

Packaging

- Four processing boards
- Liquid cooling
- COTS Power
- Optical to Front Panel
- In a standard 1U rack unit

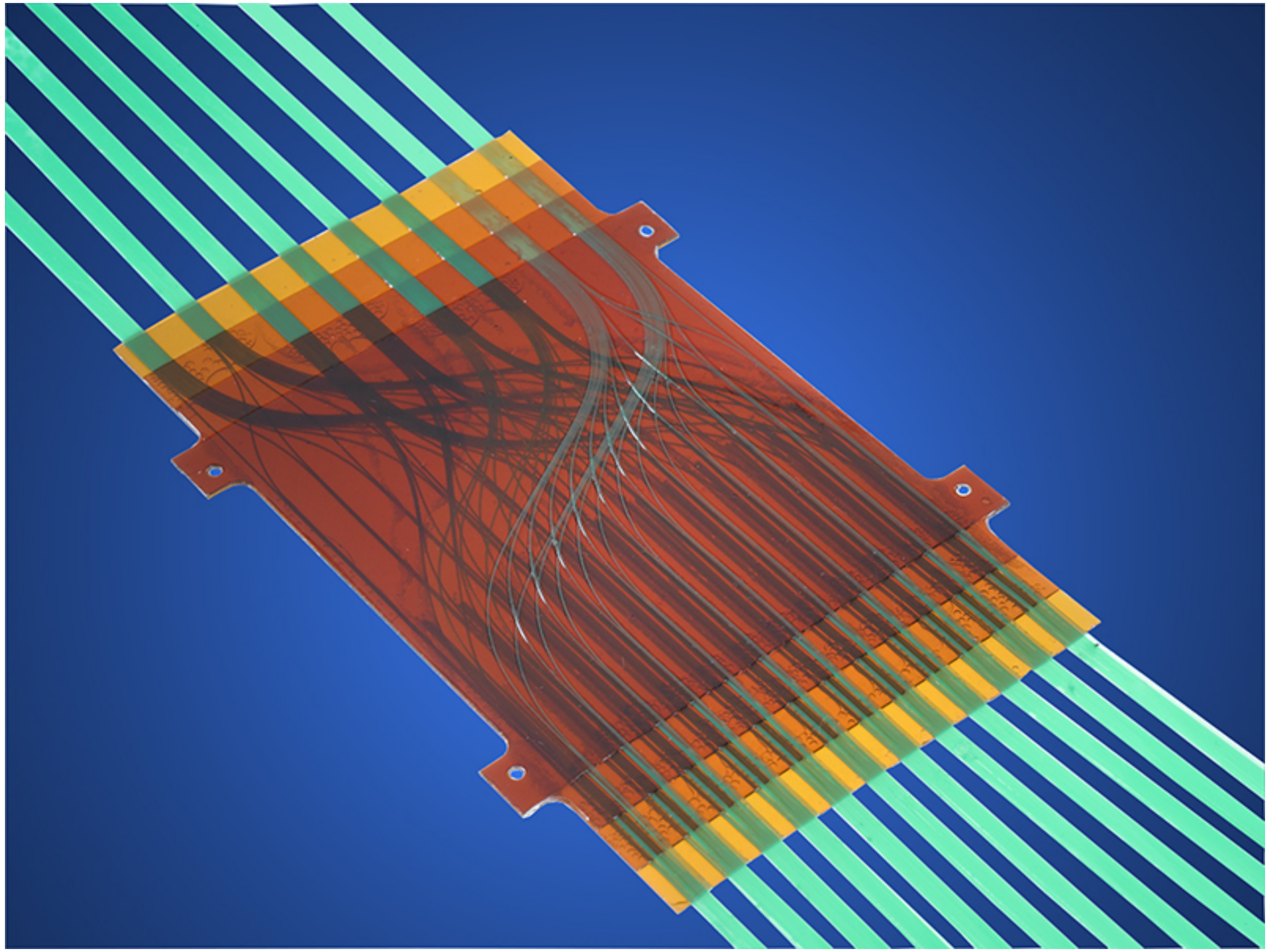


Interconnecting Perentie Rack Units

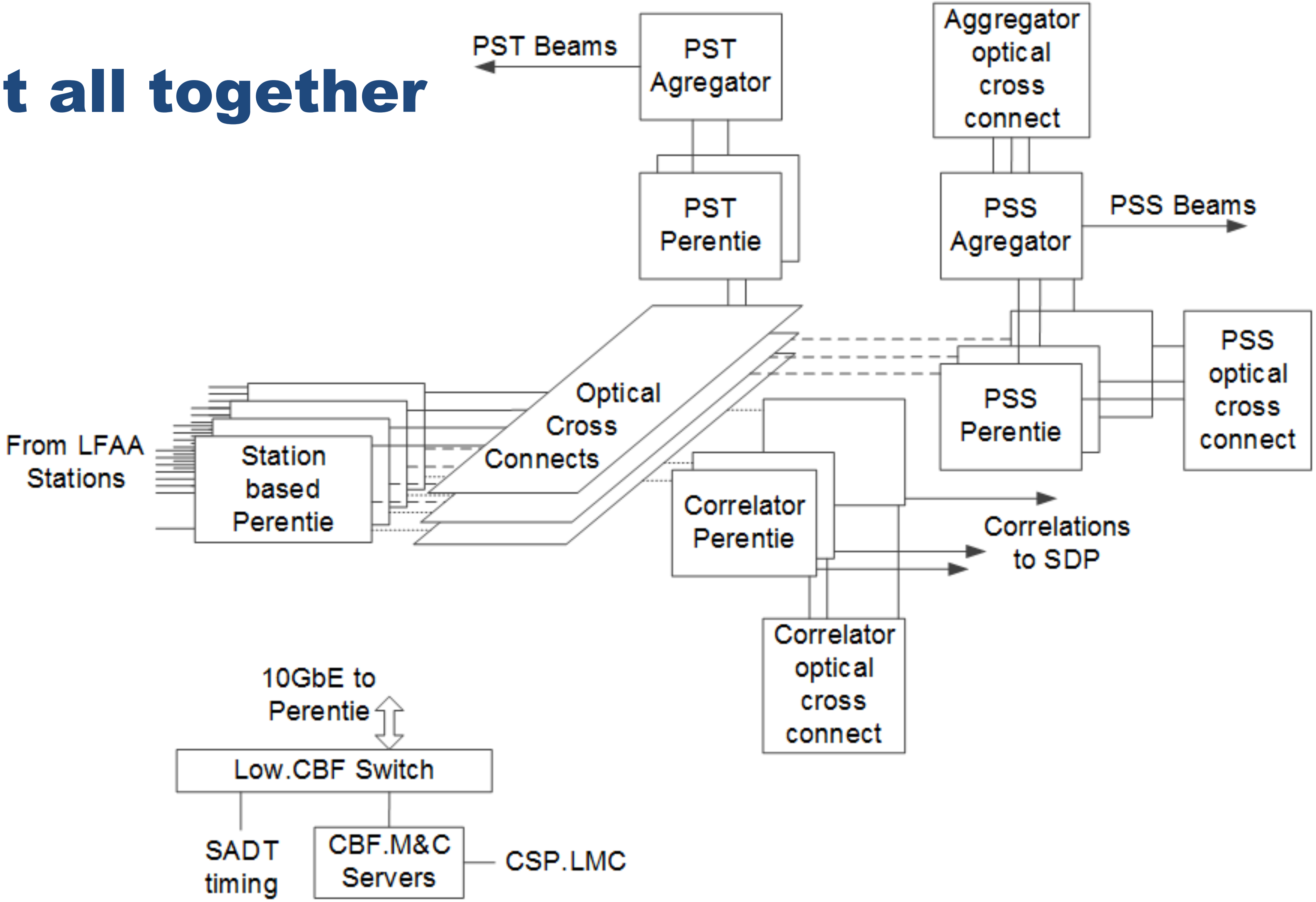
If Front Panel had single fibres simply route each fibre to destination

But to keep density down have multi-fibre ribbons (up to 16)

COTS Passive Optical Backplanes connect a single fibre from one ribbon to another. User writes specifications and has it built. Similar to acquiring circuit boards.



Putting it all together



Questions?

Thankyou for your participation!

Interferometry 101

Star brightness B
at position *l* = cos(θ)

Correlate output of two telescopes separated by u wavelengths

$$output \propto Be^{j2\pi ul}$$

Summing over all *l* we find the output as a function of u is the Inverse Fourier Transform of the sky brightness B

$$output(u) \propto \int B(l)e^{j2\pi ul}dl$$