PAF Beamformer

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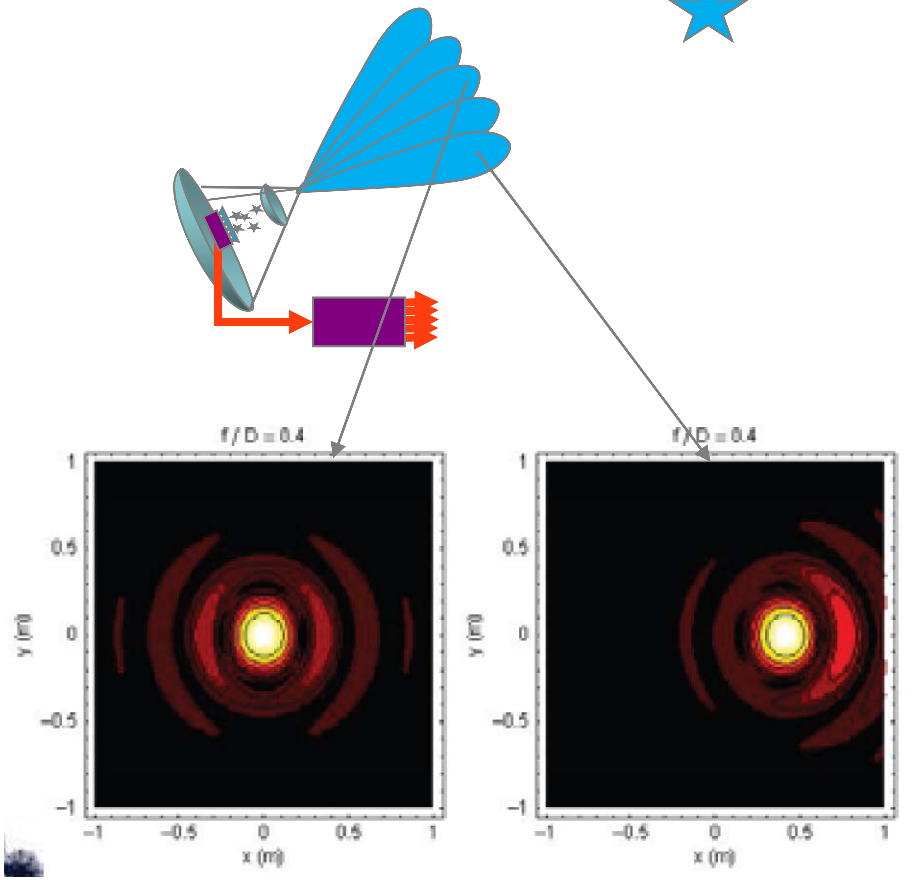
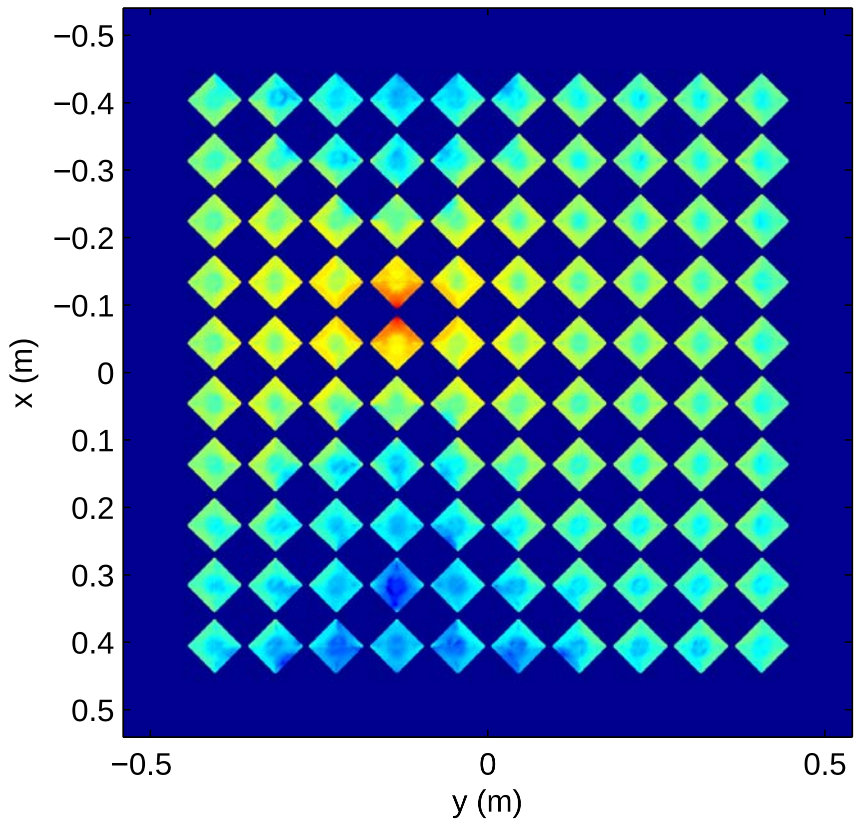
Beamforming task

- At the focus of dish illumination of phase array depends on look angle
  - See examples
- Detect signal from phased array and sum
  - Approx. conjugate match
- Do this for all look angles (beams)
- Weights different from beam to beam and are frequency dependent
  - Focal spot size proportional to wavelength



Chequer board array example

- Currents on a chequerboard array a the focus of 12m dish at 1.25GHz. Array element spacing 9cm.
- Illuminated by a point source ~1degree off boresight.
- Signal from single port does give a beam but
  - Poor aperture effeciency
  - High spill over
  - Noise and power coupling to adjacent ports
- Digital beamforming
  - improves A/T
  - Control of sidelobes
  - Control of beam shape
  - Beam steering



Time Domain Beamforming

- Beam weighted sum of all elements (some zero)
- Weighting is frequency dependent = filter *h(t)*

$$Beam(t) = \sum_{j \text{ over all ports}} h_j(t) ** v_j(t)$$

- Compute load proportional to
  - – No beams B
  - – No elements N
  - – Bandwidth BW
  - – No filter taps (>40) T
- Multiplies/s ~2.5 B.N.BW.T

Frequency Domain Beamforming

- Decimate data into frequency channels
  - Must do this for FX correlator in any case
  - Multiplies/s ~40 N.BW
- Single complex weight per frequency channel
  - Beam forming ~5 B.N.BW Multiplies/s
  - No beams B
  - No elements N
  - Bandwidth BW

Comparison

- Equality time and frequency compute load when

  2.5 B.N.BW.T = 40 N.BW+5 B.N.BW

  No taps T = 16/B + 2

- No beams B is the order of 50-100 (single pol.)
  - 25-50 Dual polarisation beams

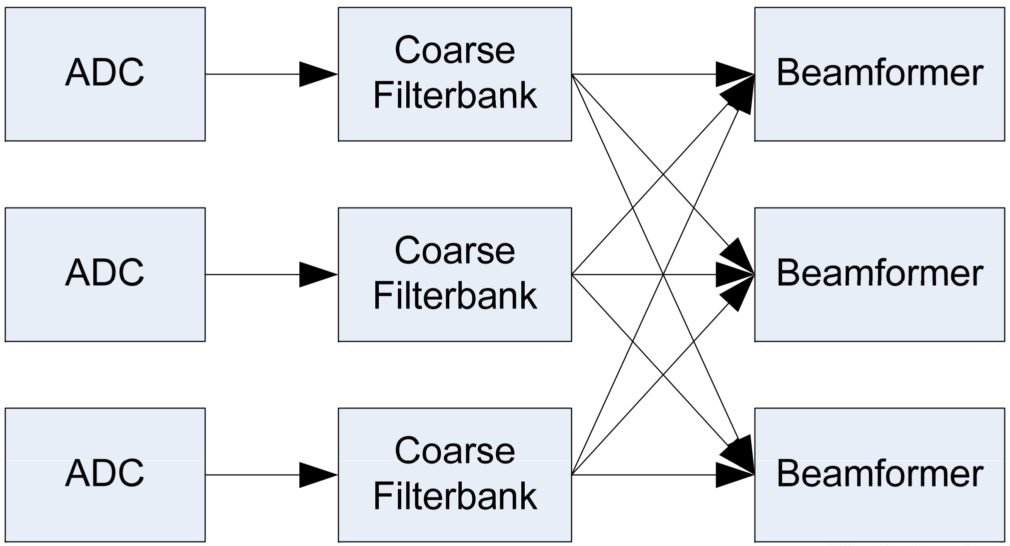
- Allowable no of taps for equal compute load is ~2, need more than 40.
- Use Frequency Domain Beamforming

Other Compute Requirement

- Calculation of weights require Array Covariance Matrix
  - Multiplies/s ~10BW. N^2
  - Could dominate
  - But do fraction of time samples and frequency channels at any time ~20% of beamforming
- ADC statistics, Power spectrum, Capture time sequences …

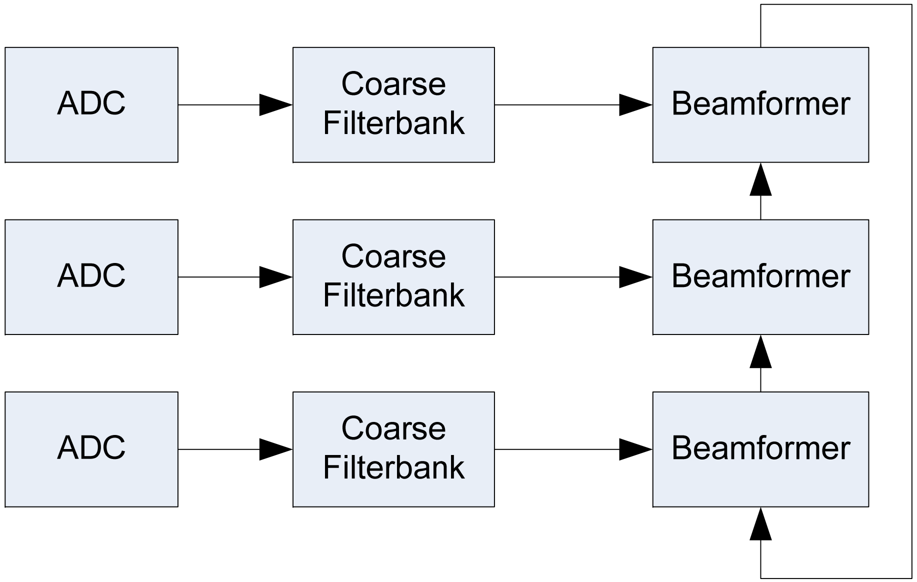
Beamformer Architecture (Cross connect)

- For SKA Phase 1 probably have multiple beamformer boards
- Pass data through filterbank and distribute part of the bandwidth to each board



Alternative Architecture (Ring)

- Connect beamformer in ring
- Same amount of input data
- But data for all beams must be transported between boards

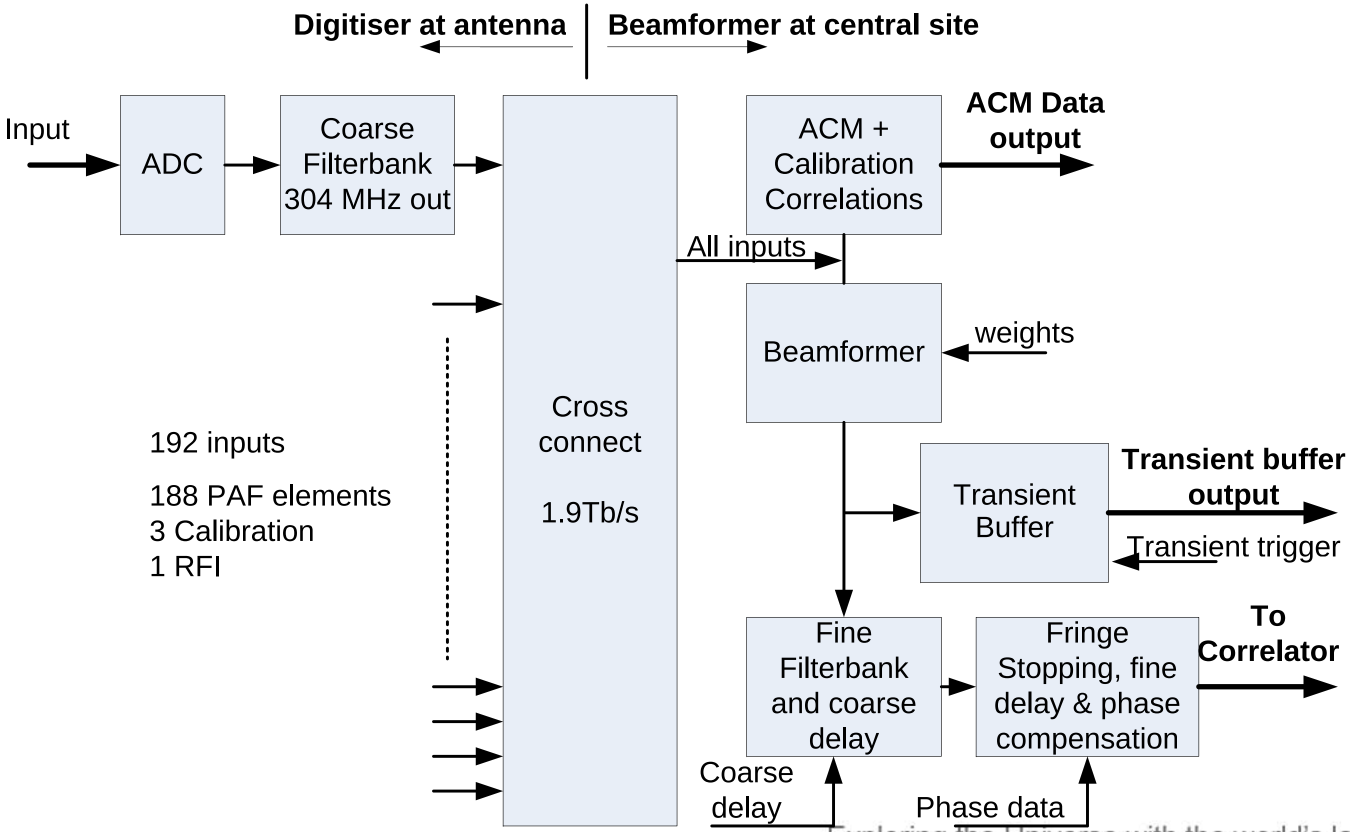


- Use

  Cross Connect

Example – ASKAP Processing

- Note fine filterbank, coarse delay, transient buffer, fringe stopping considered part of correlator here



Data Transport form PAF

- Two options: Coaxial cable or Fibre
- Coaxial cables expensive, bulky and lossy
  - Used in ASKAP and APERTIF
  - Transport signal to ground level
- Fibre is relatively cheap, low loss and easy to install
  - Until recently transmitters too expensive in weight or $$. But this is changing.

Fibre data transport (Digital)

- Target solution
  - 100-200 analogue inputs means multiple boards
  - ASKAP PAF digitiser shown ~140kg
  - Currently digitising system is too large and heavy to install in PAF
  - Will get small and lighter with time
  - Ideally ADC in PAF

- Small low power ADC with simple connection to optical transmitter needed
  - Expected for Phase 2
  - High degree of uncertainty for Phase1

Fibre data transport (RF over Fibre)

- RF over Fibre has normally used external modulator
  - Very good performance
  - But cost is high
- Directly modulate DFB laser have brought cost down to reasonable values
  - Limitation high second order modulation,
    - At most one octave bandwidth
    - Bandwidth similar to that of the proposed octave band feeds
  - Small size and low power allows installation in PAF
- Assume this is the solution used for SKA Phase 1

Bandwidth and location

- RF over Fibre uses single mode fibre.
  - Transport for more than 10km (central site?)
- PAF say 1.5 – 0.6GHz need two octave bands
  - One is 1.2-0.6GHz
  - Some transition zone needed
  - assume correlator and beamformer 0.5GHz bandwidth
- Octave band direct sample in second Nyquist zone of ADC
- Second band would be 1.5 to 1.0GHz

Beamformer requirements

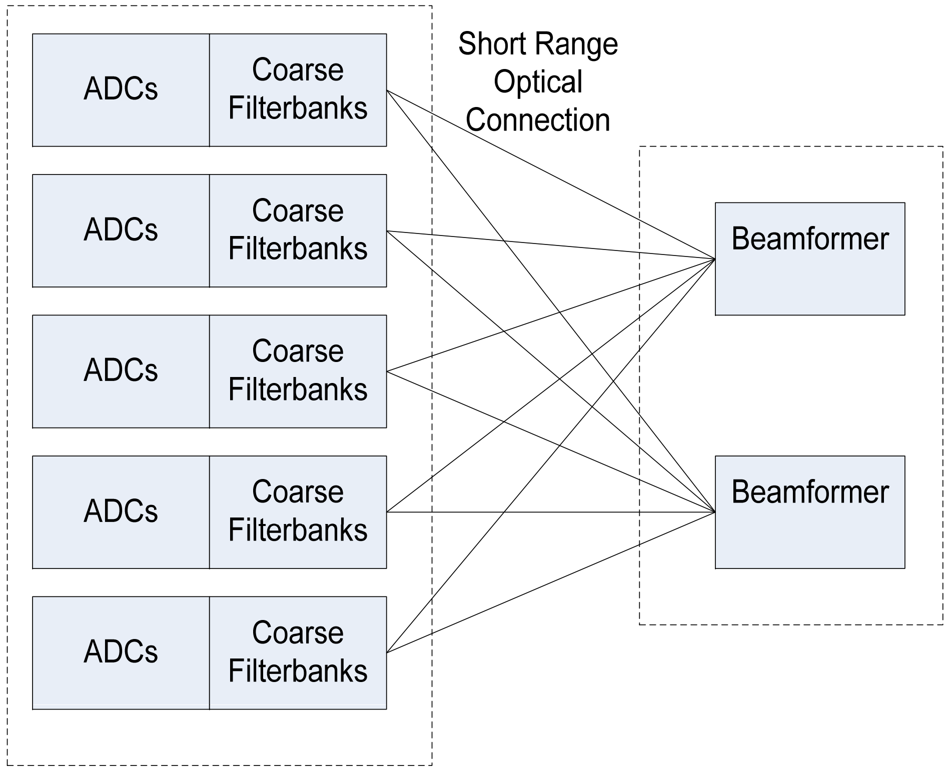
- 500MHz bandwidth, 36 dual pol beams, 100 element per single pol beam
- Compute load
  - 500MHz x 72 single pol beams x100 complex MACs/beam x 4 multiplies/Complex MAC
  - 14.4T mult/sec plus over head ~20Tmult/s
- FPGA in 2016-17 has 8000 multipliers at 0.45GHz
  - 3.6T mults/s per FPGA - 6 FPGAs needed
  - Two boards to implement beamformer
- Smaller lower performance PAF – fewer FPGAs

ADC/Filterbank

- ADC system has 100-200 optical RF inputs.
- Assume quad ADC = 25 to 50 ADCs
  - Say, 5 Quad ADC per board
  - 5 to 10 ADC boards
- Optical link to beamformer needed
  - Use FPGA to packetise data and drive optical TX
  - Two links needed – one per beamformer board
- Use same FPGA for filterbank and each link carries data for half the bandwidth
- Filterbank for 1.6GHz sample rate ~32Gmultiplies/s
  - For 200 elements – 6.4Tmuliplies/s = 10 small FPGAs

Beamformer System

- ADC/coarse filterbank board takes in ~20 optical RF and filters to 1MHz bands
  - 5-10 boards
- Half BW to each BF
- 20 inputs x 250MHz x 16bits/Hz = 80Gb/s
  - Single 12 fibre SNAP12 optical TX has 12x8.5Gb/s = 100Gb/s
- Each BF receives 5-10 12 fibre ribbons

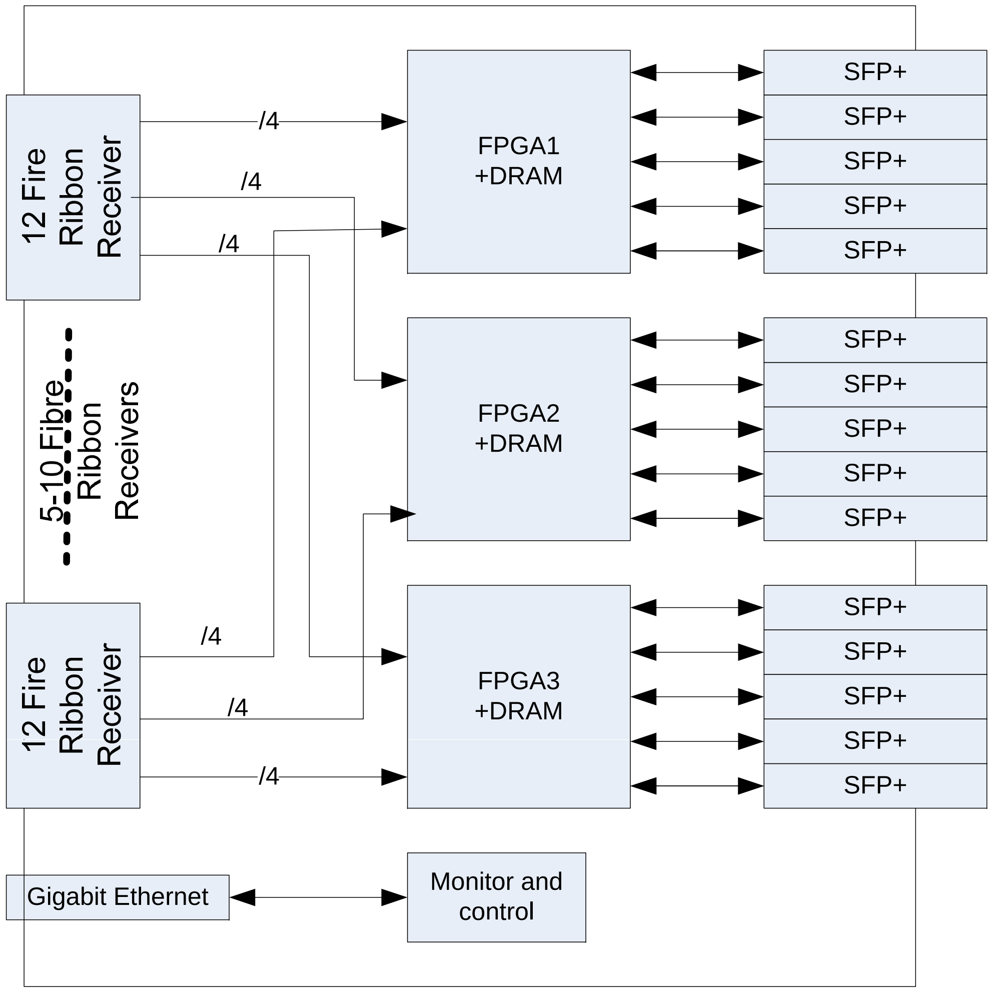


Data output

- After beamforming pass data through filterbank to get final frequency resolution
- Quantise to 4+4bit resolution for correlator
- 72 single pol beams x 500MHz x 8bits/Hz = 288Gb/s or 30x10G optical links for output data
  - 15 per board

Possible beamformer board

- Two boards required for Phase 1
- 40x8.5G in and 5x10G out with current technology
- FPGAs with required I/O available this year



Cost estimate
Phase 1 (includes RF over Fibre)

- Assume 8000 multiplier FPGA ~$1k, ADC $40/input, RF over Fibre $100/link
- Cost for 200 element PAF beamformer ~54k€
- 120 element PAF ~35k€ ($=0.75€)

Beamformer component	Cost
Beamformer boards and FPGAs	$18,000
ADC-Beamformer optical links	$4,000
Coarse filterbank FPGA	$2,500
ADC	$8,000
ADC / Coarse filterbank boards	$10,000
Transport of Analogue data to ADC	$20,000
Card cages, racks, power supplies	$10,000

Estimate for 200 element PAF (10x10 dual pol)

NRE

- Processing board simple
  - Three FPGAs
- ADC some complication from 20 RF over Fibre receivers and five ADC.
  - Must take care with analogue parts
  - Total hardware development ~1 man year
- Firmware – borrow most from existing PAF development, filterbanks, beamform, command/control, ACM …
  - Main extras are ADC interfaces and data transport to PAF.
  - Estimate 3 man years
- NRE less than 1M€ compared to 8-13M€ for hardware

Coaxial Cable Revisited

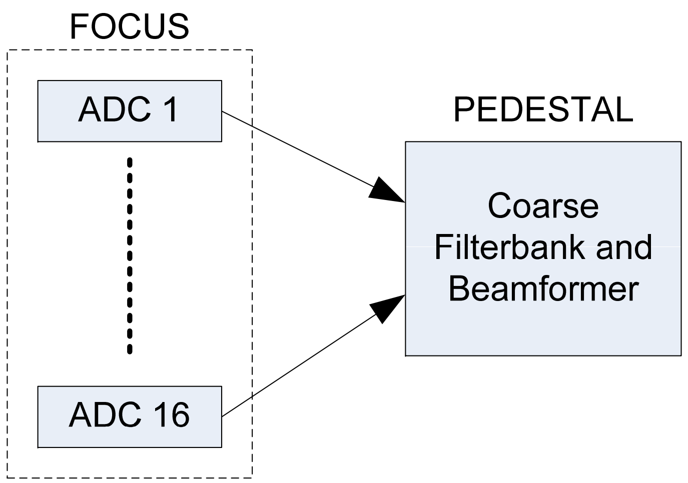
- Beamformer comprises ~10 boards.
  - Fits in a single chassis
  - But limited by need to attach 100-200 coaxial cables.
- Is small enough to mount on the dish, say under dish surface or on offset dish feed arm
  - Low cable loss, No coaxial cable through cable wraps
- Would allow wider bandwidth system but probably no cost savings.
  - Maintenance more difficult
  - RFI shielding
  - Remote cooling
  - Need weather proof RF connectors and enclosure.

SKA Phase 2 PAF Beamformer

- Assume small, low power ADC and laser driver developed. But must solve RFI problem for ADC in PAF
- Can now direct sample full RF 1.5-0.6 GHz
- ADC 8-bits at 3.2 GS/s = 25.6GS/s
- Integrate 28Gb/s serialisers that directly drive laser TX.
- Target power 100-300mW per channel
- Integrated on board with LNA or aggregate many per board

Beamformer – Phase 2

- Assume FPGA performance quadruples
- 4 FPGAs for beamforming and coarse (1MHz) filterbank – 1000 channels/1GHz BW
  - Single board beamformer
- ADC data aggregated onto 12 Fibre ribbon
  - Up to 12 required.



Costs Phase 2 Beamformer

- Assume Quad ADC, without NRE, $32, FPGAs sill $1000, optical 12 channel TX $200.
- Total cost 15k€ for 200 elements

Beamformer component	Cost
ADC	$1,600
ADC-Beamformer digital optical	$2.400
ADC board and RFI enclosure x16	$3,200
Processing board including FPGA	$8,000
100 GE outputs x 8	$1,600
“Pizza” box and power supplies	$2,000

Conclusion

- Single board beamformer/filterbank by Phase 2
- Digital electronics cost continue to decrease
- COTS ADC and RF over Fibre data transport major cost for Phase 1
  - Estimate beamformer cost 2015-17
  - 200 element PAF ~54k€
  - 120 element PAF ~35k€
- For lowest cost Phase 2 need to develop integrated ADC the directly drives optical TX at ~25Gb/s
  - Cost for beamformer could be as low as ~15k€