SKADS Signal Processing Workshop

November 2009

SKA Signal Processing

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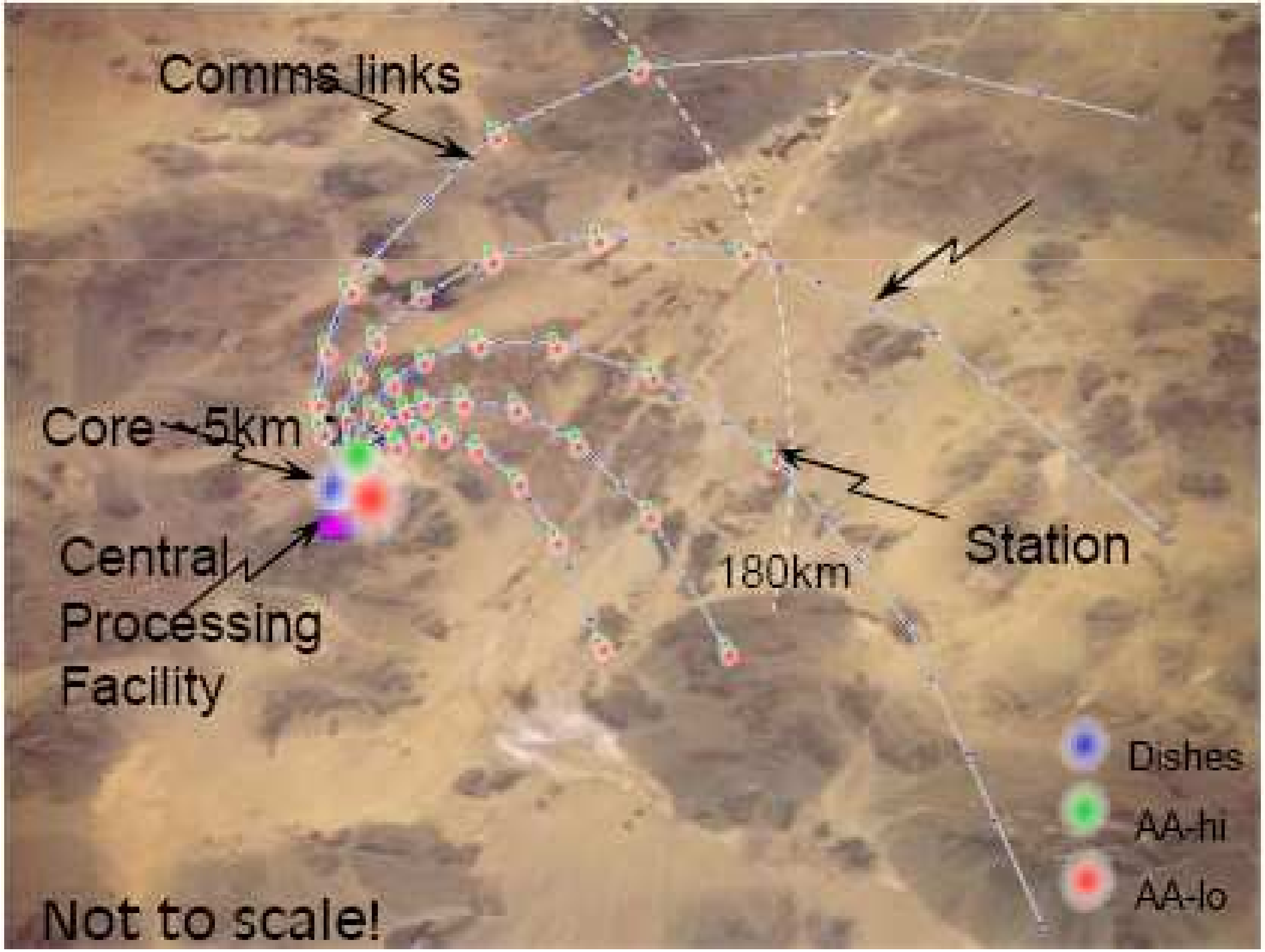
Example Configuration (Phase 2)

SPDO



Example Configuration with Dense AA + SPF

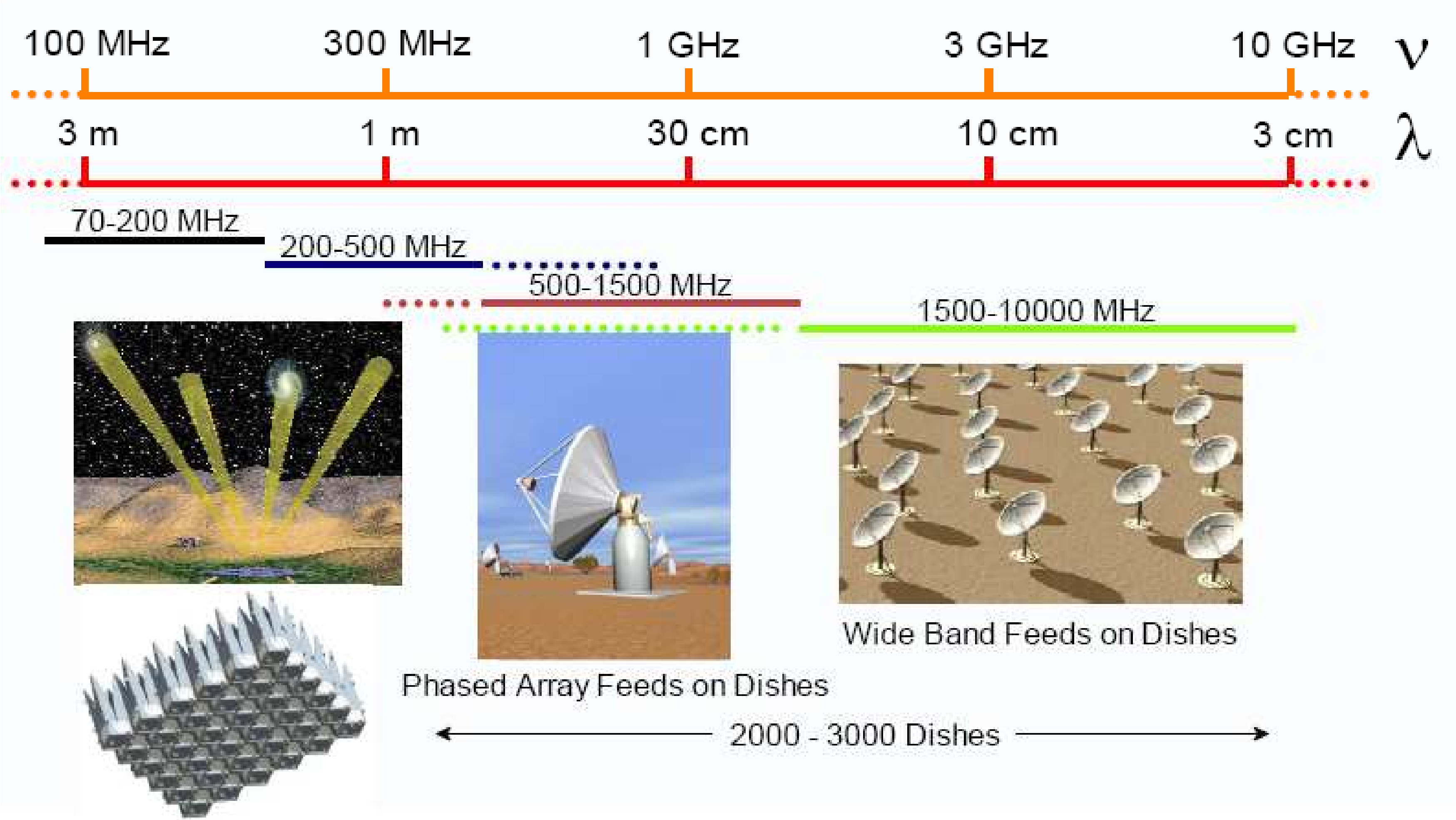
Memo 100 identifies the following options:
70-200MHz: Sparse AA-lo
200-500MHz: Sparse AA-lo

500MHz-10GHz: 3000 15m dishes
Or
500MHz- 10GHz: 2000 15m dishes with PAFs plus WBSPF
Or
500MHz-10GHz: 250 Dense AA-hi plus 2400 15m dishes/ WBSPF

Note: On going discussions 15m vs 12m dishes

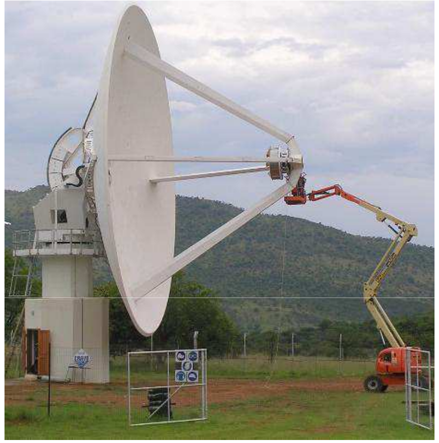
Reference Design

SPDO



Dishes+Single Pixel Feeds

American: 6m Hydroformed Dish



South Africa: 12 Composite Dish

Canadian: 10m Composite Dish

<u>Note:</u>

On going discussions 12m vs. 15m dish

Required sensitivity 10,000 m^2K^{-1}

Correlator processor and dump rate proportional to N_{ant}^2

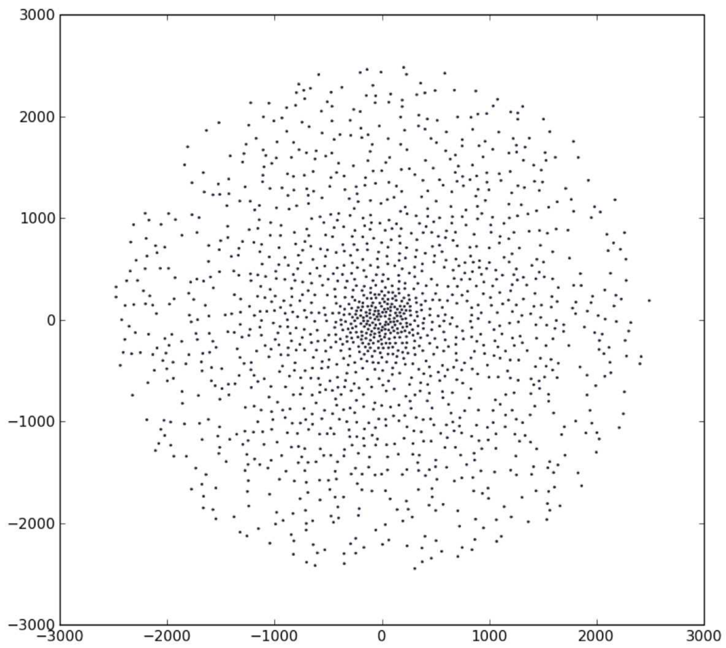
ADC likely to be at antenna (4 bit ?)

Dish O/P_{rate} = fs.4bits

= 160 G bits/s per antenna

Where fs = sample rate likely to be split into smaller basebands

Central Core Beamforming



Potential Layout of the Core

Central 1 km diameter core ~ 600 WBSPF dishes
Depends on shadow angle tradeoffs

Narrowband case for beamforming:
Bandwidth << 300 kHz

Dish Bandwidth 500 MHz to 10 GHz
So Channelization to at least 32 k channels prior to beamforming

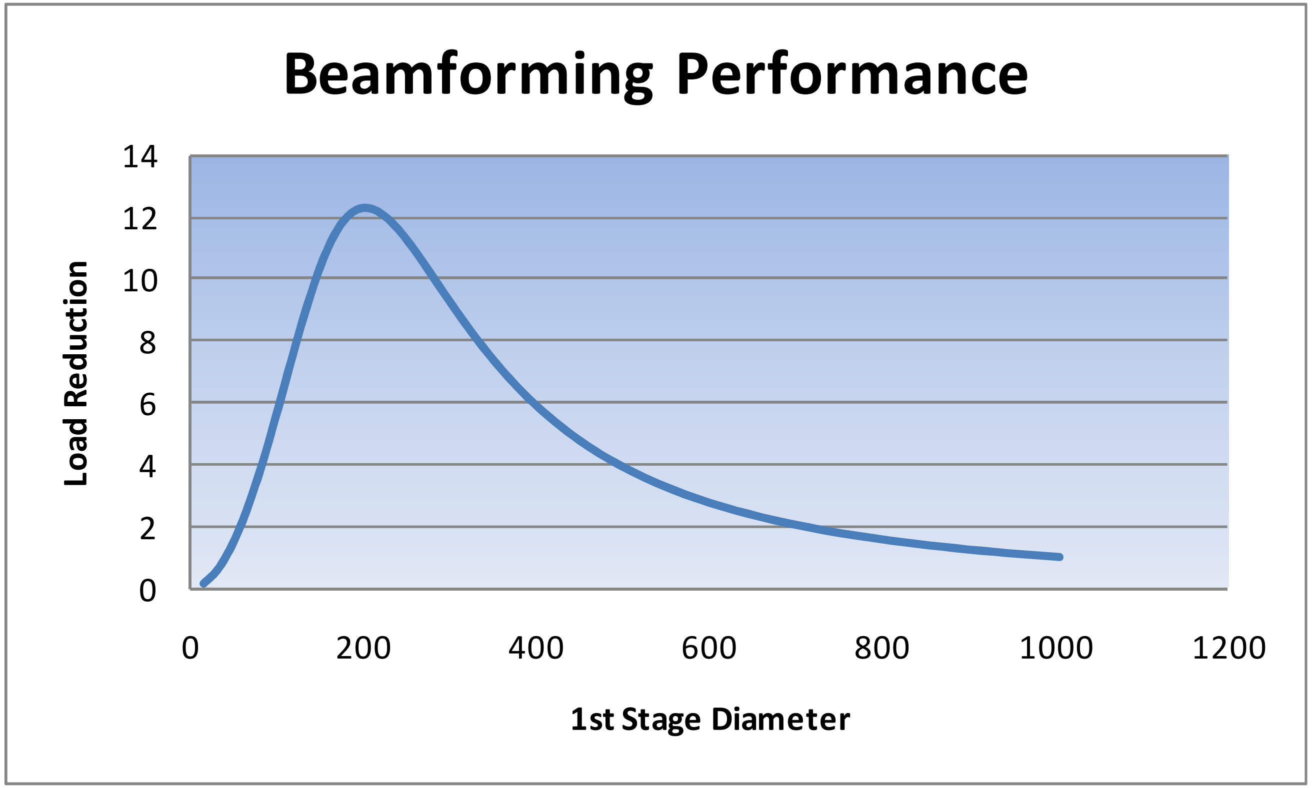
Average Core beam size (at 5.25 GHz): 8.6 x 10^{-6} sq deg
Average Dish FoV (at 5.25 GHz): 0.039 sq deg

Number of beams to cover FoV: 4482

Beamformer load one beam:
600 antennas x 10 GHz x 2pol x 2 ny x 4 MACS = **96 T MACS**
Beamformer load 4482 beams:
4482 x 96 T MACS = **430 P MACS**

2 Stage Central Core Beamformer

SPDO



Processing load can be reduced by hierarchical beam-forming

~ 24 dishes in each first stage beam-former.

~101 beams first stage

~ 24 beams 2nd stage

1st Stage Beamformer load one beam:

24 dishes x 25 areas x 181 beams x 2pol x 10 GHz x 2 ny x 4 MACS = 17 P MACS

2nd Stage Beamformer load one beam:

(25 areas x 181 beams) x 25 beams x 2 pol x 10GHz x 2 ny x 4 MACS = 18 P MACS

Total = 35 P MACS

WBSPF Dish Processing

Channelizer

- Narrowband case for beam-forming: Bandwidth << 300 kHz
- Dish Bandwidth 500 MHz to 10 GHz
- 524288 channels (2^{19}) required for < 10% frequency smearing
- Estimated 12 taps gives < 60dB aliasing
- Processing load ~ (Ntaps + 3*$\log_2$(Nchan)) x Ndish x Nel x 2pol x fs

Channelizer load

3000 dish x 2 pol x 10 GHz x 2ny x (12taps + 3$\log_2(2^{15})$) x 4MACs

= **27 P MACs**

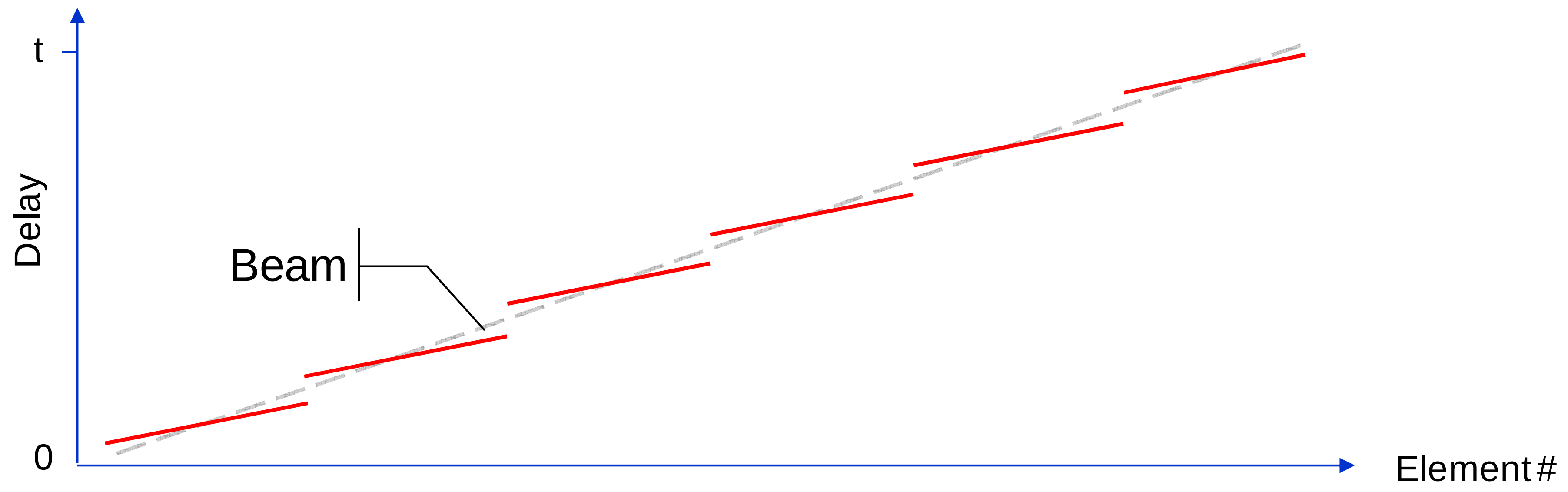
Beamformer load

From previous slide = **35 P MACs**

Correlator load

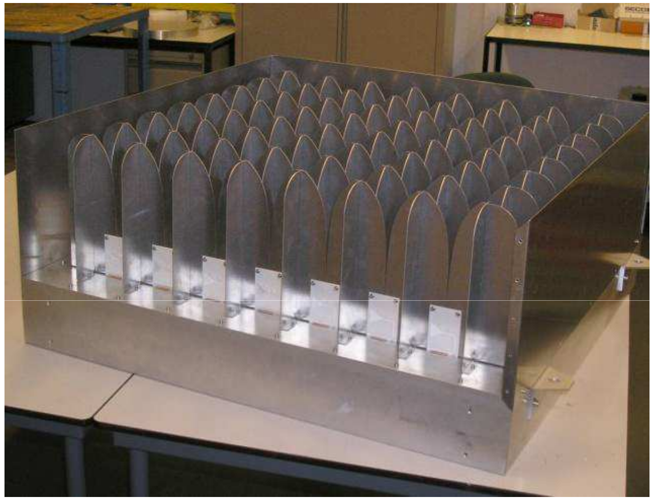
$(3000 \text{ dish})^2/2$ x 2 pol x 10 GHz x 2ny x 8MACs = **1.4 E MACs**

2 Stage Beam-former Issues



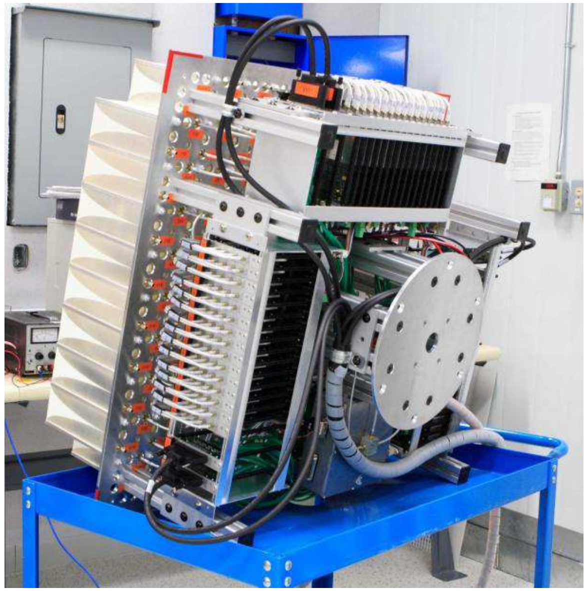
- Discontinuities at between Stage 1 boundaries
  - Need extra beams
  - Interpolate across beams
    - Extra processing load

Dishes+Phased Array Feeds



Apertif Netherlands: Vivaldi Array

ASKAP Australia: Checkerboard Array



PHAD Canada: Vivaldi Array

<u>Note:</u>
Some Channelization and Beamforming likely to be at antenna.
Maximum Field of View limited by Array size and focal length of dish.
Achievable field of view limited by network bandwidth.

Simplistic View of PAF Processing

SPDO

PAF maximum Field of View :

$$\omega_{FOV} = \pi \left(\frac{d_{PAF}}{D_{dish}} \times \frac{180}{\pi}\right)^2$$

Note that the PAF FoV in independent of λ.
Element spacing 10cm ($\lambda/2$ at 1.5 GHz)
For a 9 x 11 array $d_{paf} \approx 1$ metre
And D_{dish} = 15 metres
$\omega_{FoV} \approx$ 46 square degrees

PAF Beam Size :

$$\omega_{Beam} = \frac{\pi}{4} \left(\frac{\lambda}{D_{dish}} \times \frac{180}{\pi}\right)^2$$

For frequency range 500 to 1500 MHz
Average beam size at 1000 MHz
$\omega_{Beam} \approx$ 1.03 square degrees

The average number of beams across frequency range of 500 to 1500 MHz to fill Memo 100 FoV of 20 square degrees = 20 beams

$N_{beam\ av} \approx 20$

PAF Processing

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Channelizer

- Narrowband case for beam-forming: Bandwidth << 300 MHz
- PAF Bandwidth 500 MHz to 1500 MHz
- 32768 channels (2^{15}) required for < 10% frequency smearing
- Estimated 12 taps gives < 60dB aliasing
- Processing load ~ (Ntaps + 3*$\log_2$(Nchan)) x Ndish x Nel x 2pol x fs
- Nel = 96 x 2pol

Channelizer load

2000 dish x 96el x 2 pol x 1 GHz x 2ny x (12taps + 3$\log_2(2^{15})$) x 4MACs

= **175 P MACs**

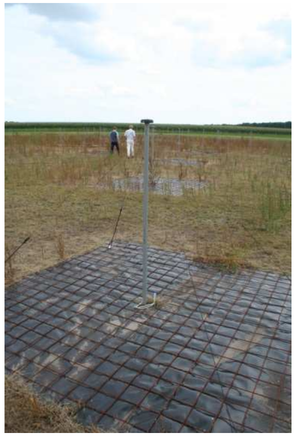
Beamformer load

2000 dish x 96el x 2 pol x 20 bms x 1 GHz x 2ny x 4MACs = **60 P MACs**

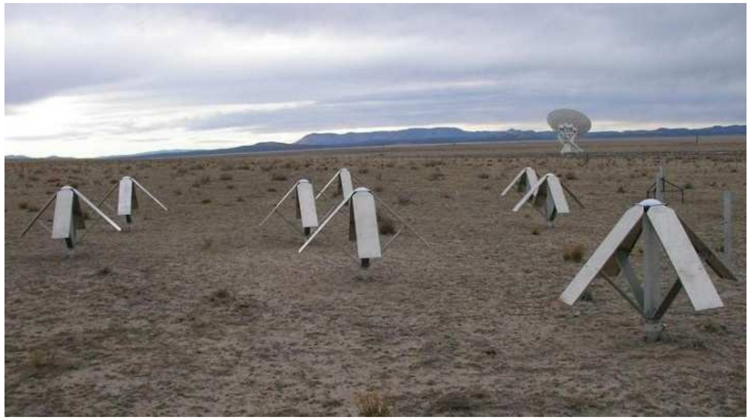
Correlator load

$(2000\ \text{dish})^2/2$ x 20 beams x 2 pol x 1 GHz x 2ny x 8MACs = **1.3 E MACs**

Sparse Aperture Arrays



LOFAR: Netherlands et al



LWA: USA

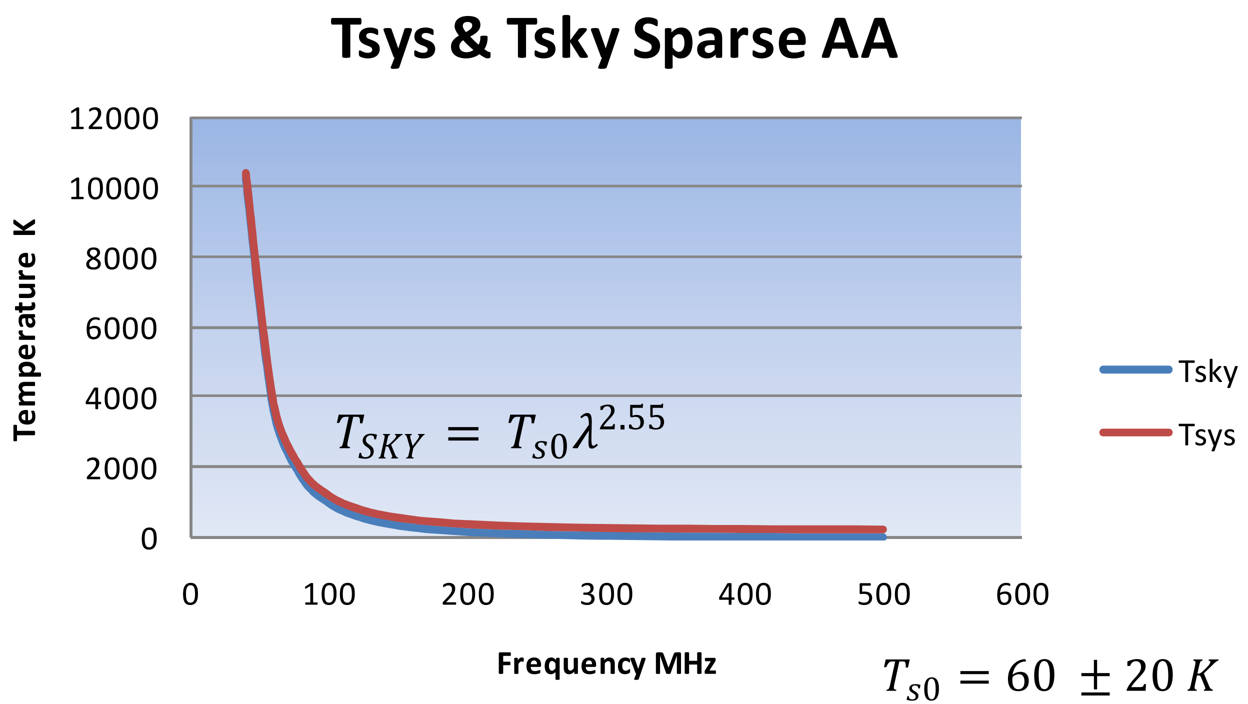
MWA: USA & Australia

<u>Note:</u>
Possibly two types of sparse AA required:
70MHz – 200 MHz
200MHz – 500 MHz

250 stations
4000 to 10000 $m^2\ K^{-1}$

$FoV = \pi\left(\frac{FWHM}{2}\right)^2$

Sparse AA



$T_{s0} = 60 \pm 20\ K$

Station Beam

$$FWHM = \alpha_1 \frac{\lambda}{D} \qquad \alpha_1 = 1.3$$

Field of View (FoV)

$$FoV = \pi\left(\frac{FWHM}{2}\right)^2$$

No. Pointings (full sky)

$$N_{pointings} = \frac{64800}{FoV}$$

Sensitivity

$$A_{eff\ dipole} = \min\left\{\frac{\lambda^2}{3}, \frac{\pi d^2}{4}\right\} \qquad N_{dipoles} = \frac{Sensitivity \times T_{sys}}{A_{eff\ dipole}}$$

d = dipole separation: random logarithmic at low frequency

For:
Sensitivity =4,000 $m^2\ K^{-1}$
250 Stations
Station diameter = 230m
Tsys = 10500 K at 40MHz

$N_{dipoles}$ = 37k per station

Sparse AA Processing

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Channelizer

- Narrowband case for beam-forming: Bandwidth << 1.7 MHz
- Sparse AA Bandwidth 40 MHz to 500 MHz
- 270 channels Nb case & (2^{17}) required for < 10% frequency smearing
- Estimated 12 taps gives < 60dB aliasing
- Processing load ~ (Ntaps + 3*$\log_2$(Nchan)) Nstations x Nel x 2pol x fs x 4MACs
- Nel = 22,000 x 2pol

Channelizer load (per station)

37,000el x 2 pol x 450 MHz x 2ny x (12taps + 3$\log_2$(2^{17})) x 4MACs = **17 P MACs**

2 stage Beamformer load (per station)

√(37000el) x 2 pol x 450 MHz x 2ny x 1785bms* x 4MACs **= 2 P MACs**

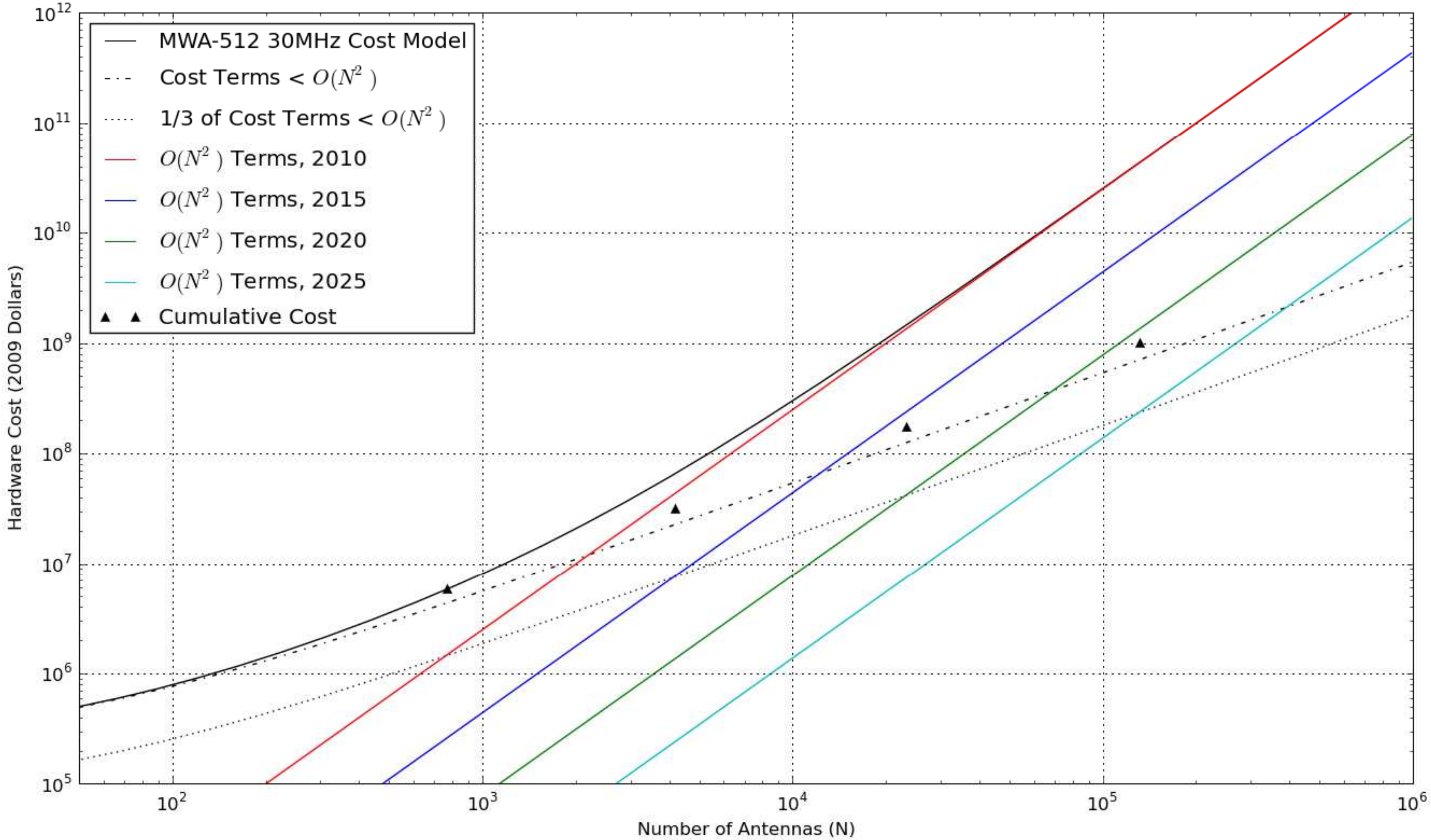
Correlator load

(250 stat)^2/2 x 1785 beams* x 2 pol x 450 MHz x 2ny x 8MACs **= 1 E MACs**

*Assumed max FoV 250 deg^2

MWA Correlator Cost Model

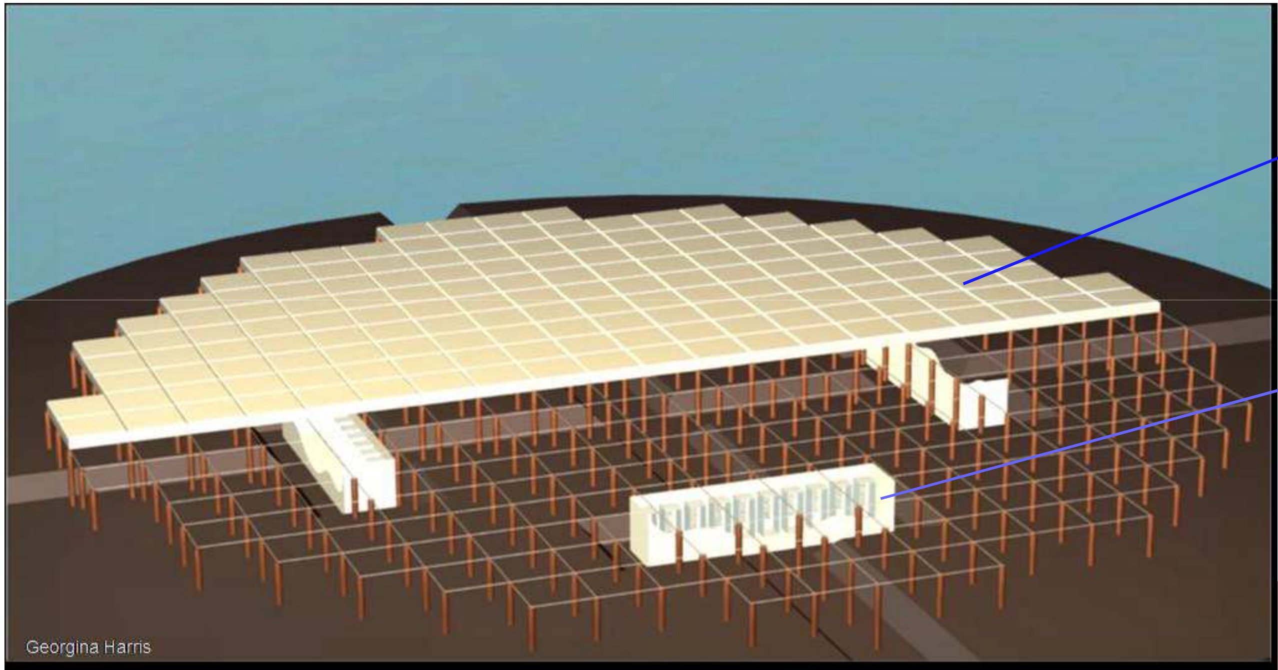
Rides Moore's Law: Potentially cheaper solution



What are the hidden costs?
Regression testing for example.

Dense Aperture Array Station

SPDO



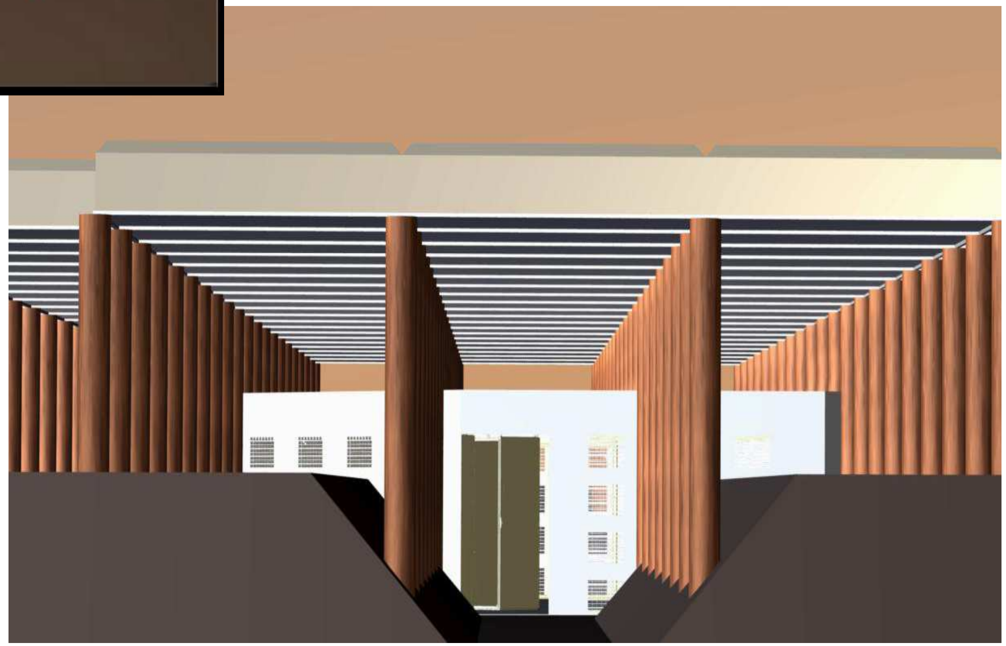
Tile ~ 16 x 16 elements

Processing Bunker

Dense AA Detail

Assumed:

~256 tiles x 256 elements per tile
Element spacing 19cm
2 polarisations per element
56 m diameter
250 stations
Tsys now 120K
Target 35K Memo 100



Processing Bunker

Simplistic View of Dense Aperture Array Processing

SPDO

Channelizer

- Narrowband case for beam-forming: Channel Bandwidth << 5.4 MHz
- Dense AA Bandwidth 300 MHz to 1000 MHz
- >>129 channels Nb case & (2^{17}) required for < 10% frequency smearing
- Estimated 12 taps gives < 60dB aliasing
- Processing load ~ (Ntaps + 3*$\log_2$(Nchan)) x Nel x 2pol x fs
- Nel = 256 tiles * 256elements per tile = 65536

Channelizer load (per station)

65536el x 2 pol x 700 MHz x 2ny x (12taps + 3$\log_2(2^{17})$) x 4MACs

= **48 P MACs**

Beamformer load (per station)

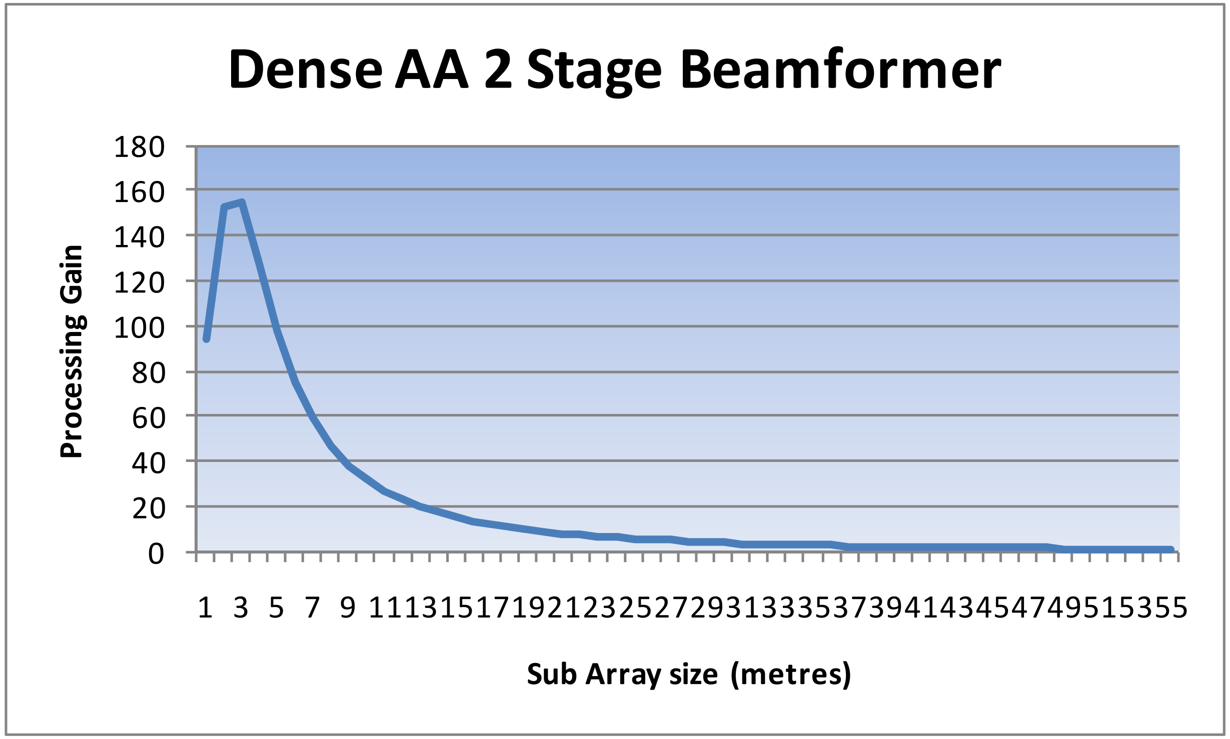
65536el x 2 pol x 1502bms x 700 MHz x 2ny x 4MACs = **1 E MACs**

Correlator load

$(250\ \text{stat})^2/2$ x 2932 beams x 2 pol x 700 MHz x 2ny x 8MACs = **2 E MACs**

2 Stage Dense AA Beamformer

SPDO



Processing load can be reduced by hierarchical beam-forming

~ 256 elements in each first stage beam-former.

~8 beams first stage

~ 196 beams 2nd stage

1st Stage Beamformer load one beam:

256 elements x 256 areas x 8 beams x 2pol x 700 MHz x 2 ny x 4 MACS = 6 P MACs

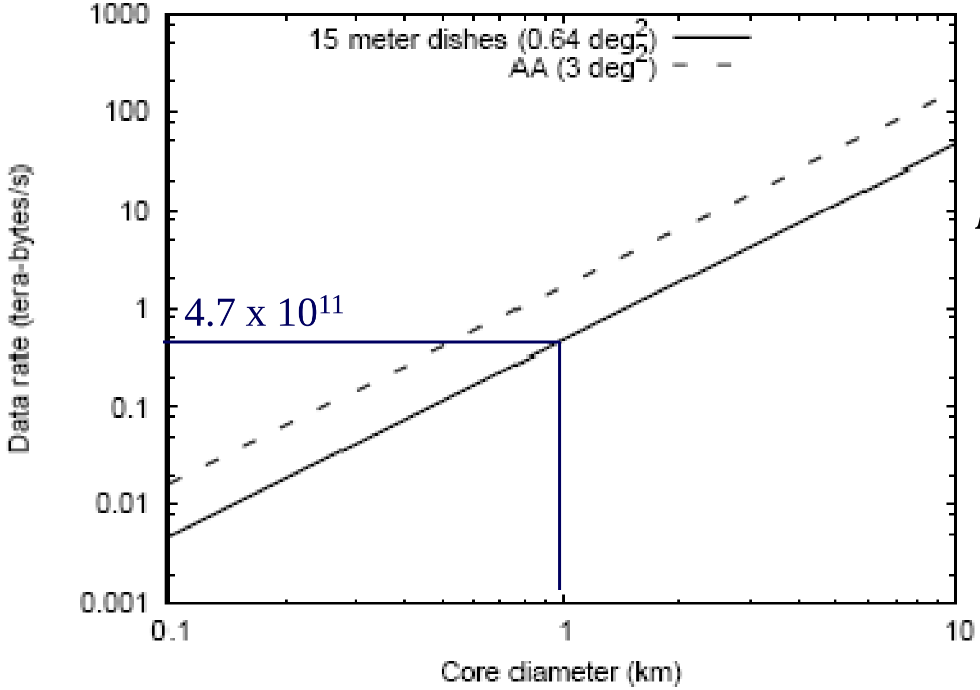
2nd Stage Beamformer load one beam:

(256 areas x 8 beams) x 196 beams x 2 pol x 700 MHz x 2 ny x 4 MACS = 5 P MACs

Total = 11 P MACs

Non-Visibility Processing

From 'Pulsar Searches and Timing with the SKA'



$$D_{dish} = \frac{1}{t_{samp}} \frac{B}{\Delta\nu} N_{pol} \frac{N_{bits}}{8} \; Bytes\ per\ sec$$

$$D_{AA} = \frac{1}{t_{samp}} \frac{B}{\Delta\nu} N_{pol} \frac{N_{bits}}{8} 3 \left(\frac{\pi}{180c}\right)^2 D_{core}^2 \nu_{max}^2$$

tsamp	sampling time
B	bandwidth
Δν	frequency channel width
Npol	number of polarisations

$$\Delta\nu(GHz) = \frac{t_{samp}\,(\mu s)\nu_{min}^3\ (GHz)}{8.3\ \times\ 10^3 DM_{max}}$$

Note:
Assume AA Station FoV of 3 degrees²
AA likely to have FoV ~ 250 degrees²

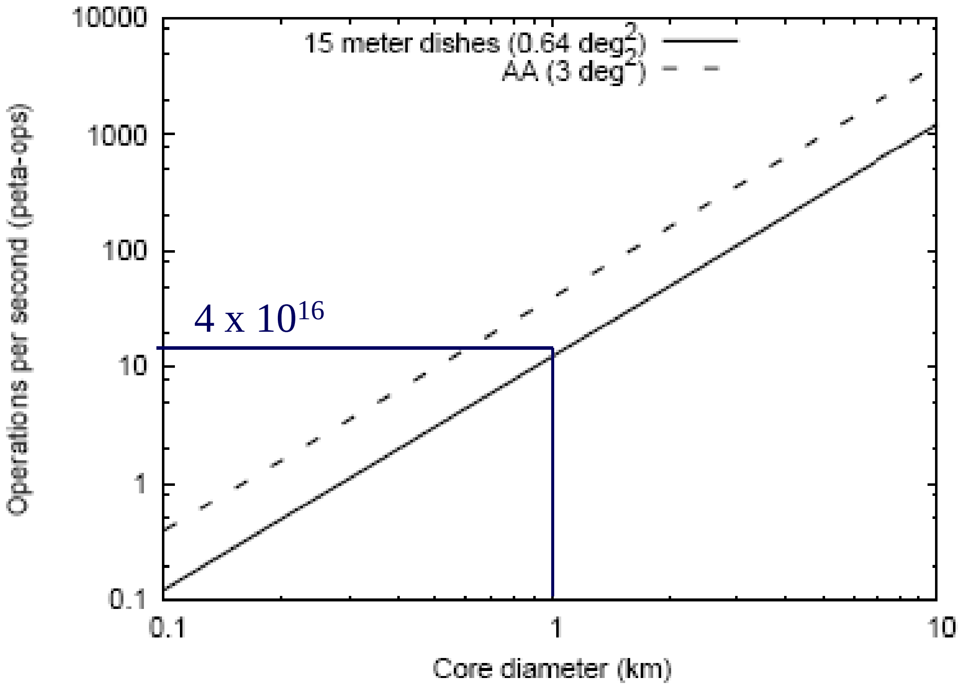
Assumes:

DM_{max}	1000 cm^{-3}pc dish
DM_{max}	500 cm^{-3}pc dish
Tsamp	100 µs
Npol	1 (sum of 2 polorisations)

Frequency range 500 to 800 GHz AA
Frequency range 1 to 1.5 GHz dish

Acceleration Processing Load

From ‘Pulsar Searches and Timing with the SKA’



Question:

What is included in an OP ?

Is it simply a MAC or FLOP

Or are slower storage access required?

Needs to be benchmarked

Acceleration processing load N_{oa}

$$N_{oa} = N_{DM} \times N_{acc} \times 5N_{samp} \, log_2(N_{samp})$$

$$N_{DM} = \frac{4150 DM_{max} \left(\nu_{min}^{-2}(GHz) - \nu_{max}^{-2}(GHz)\right)}{t_{samp}(\mu s)}$$

N_{dm} is the numer of trial DM values

N_{acc} is number of trial accelerations

Scales as $Nsamp^2$

Assumes:

100 trial accelerations

Sample time 100us

Observation time 1800s

DM_{max} 1000 cm^{-3} dish

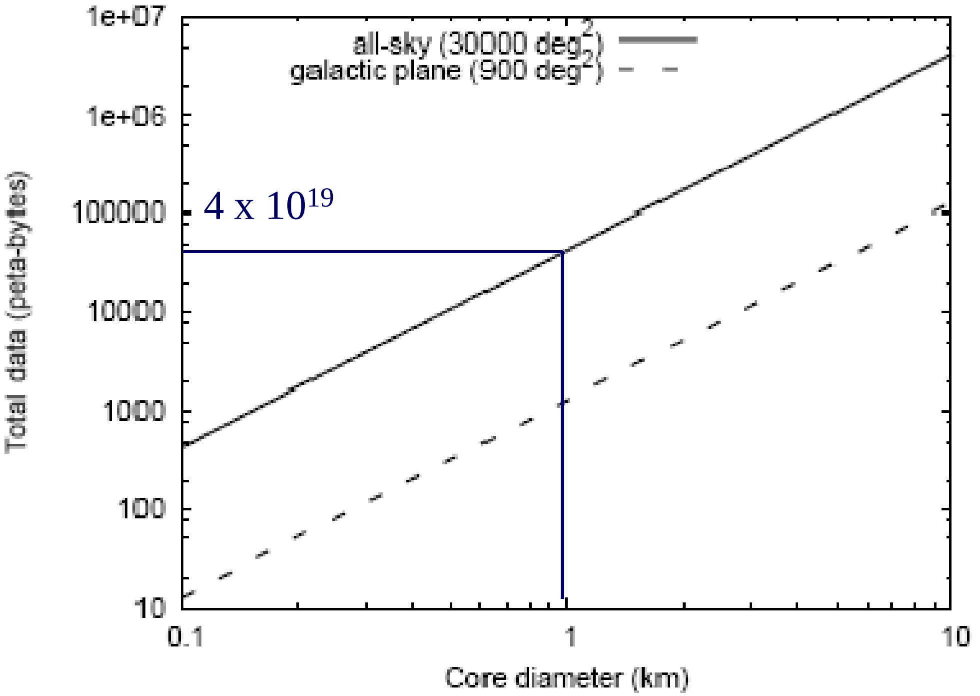
DM_{max} 500 cm^{-3} dish

Frequency range 500 to 800 GHz AA

Frequency range 1 to 1.5 GHz dish

Non-Visibility Data Storage

From 'Pulsar Searches and Timing with the SKA'



Assumes:

Sample time 100us
Observation time 1800s
DM_{max} 1000 cm^{-3} dish
Frequency range 1 to 1.5 GHz dish
$N_{pol} = 1$
2 bit digitisation

If Exa-Byte storage is available then survey would need to be in 40 parts to store data.

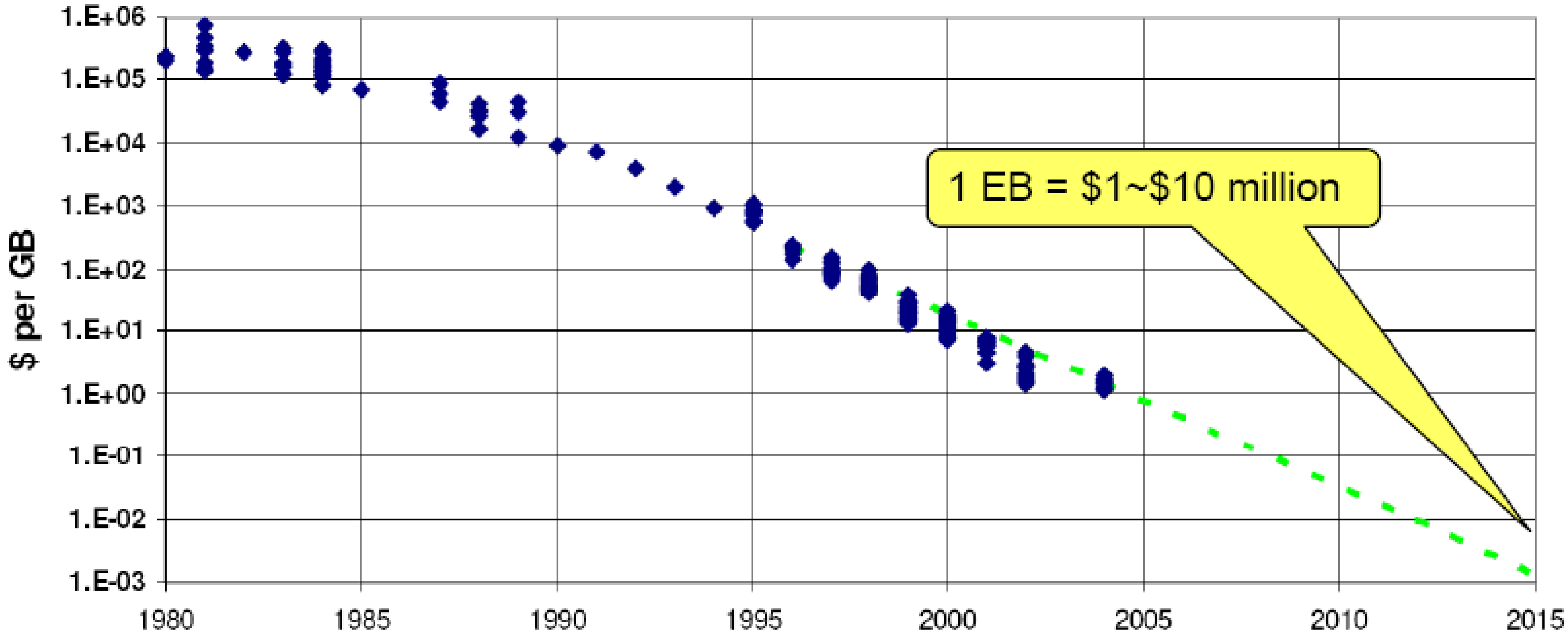
Data storage requirements for an all-sky survey (35,000 deg^2) and Galactic Plane (900 deg^2)

Most flexible solution:

Allows multiple analysis of data offline

Disk Storage Cost Forcast

SPDO

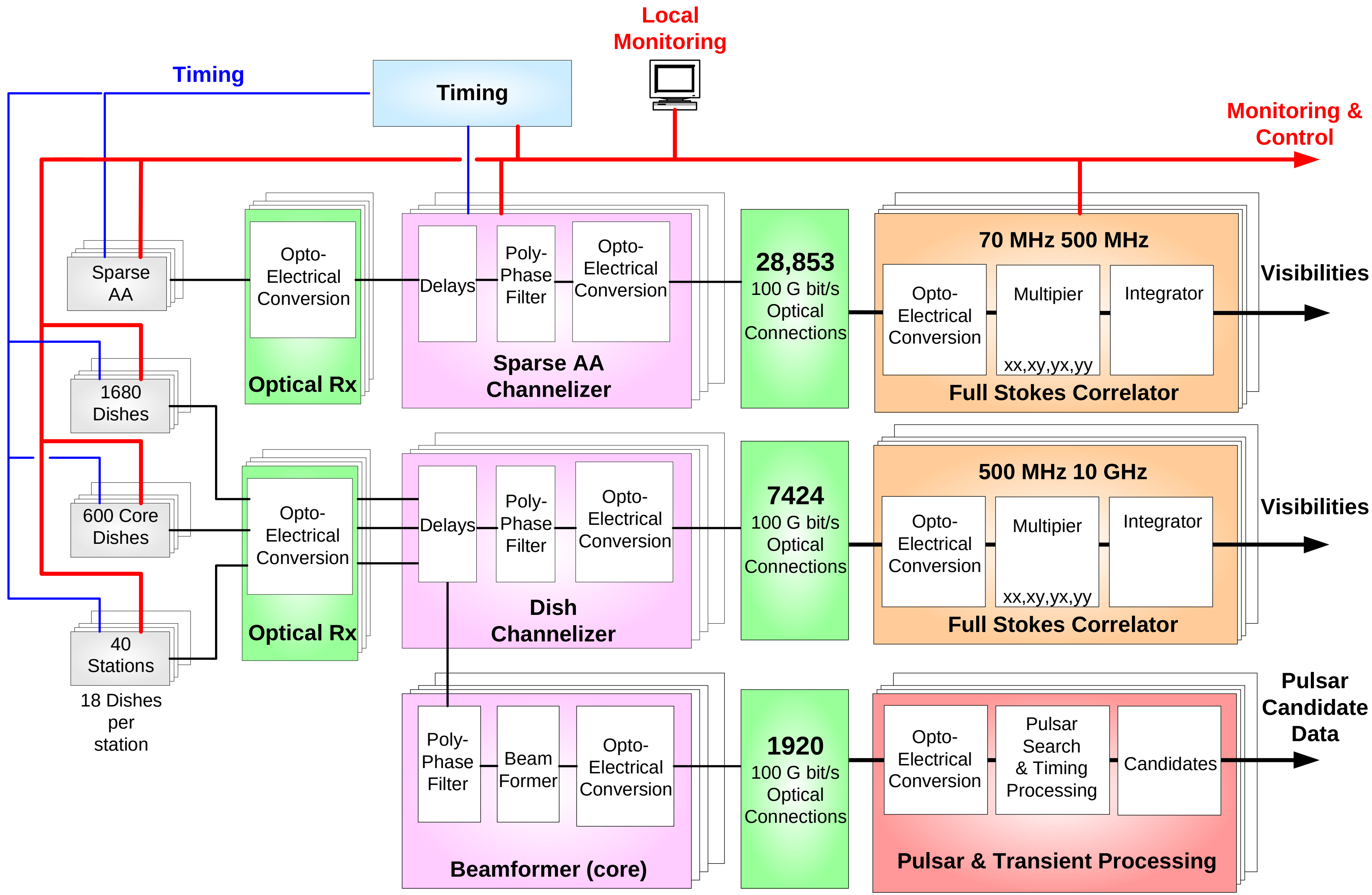


Nominally 50% anual cost improvement

P. Kogge et alia "ExaScale Computing Study: Technology Challenges in Achieving Exascale Systems"; TR-2008-13, DARPA ExaScale Computing Study, 2008 Sep 28, page 125
Note: neither RAID, controllers, nor interconnect cables are included in these estimates

Signal Processing Overview Option 1

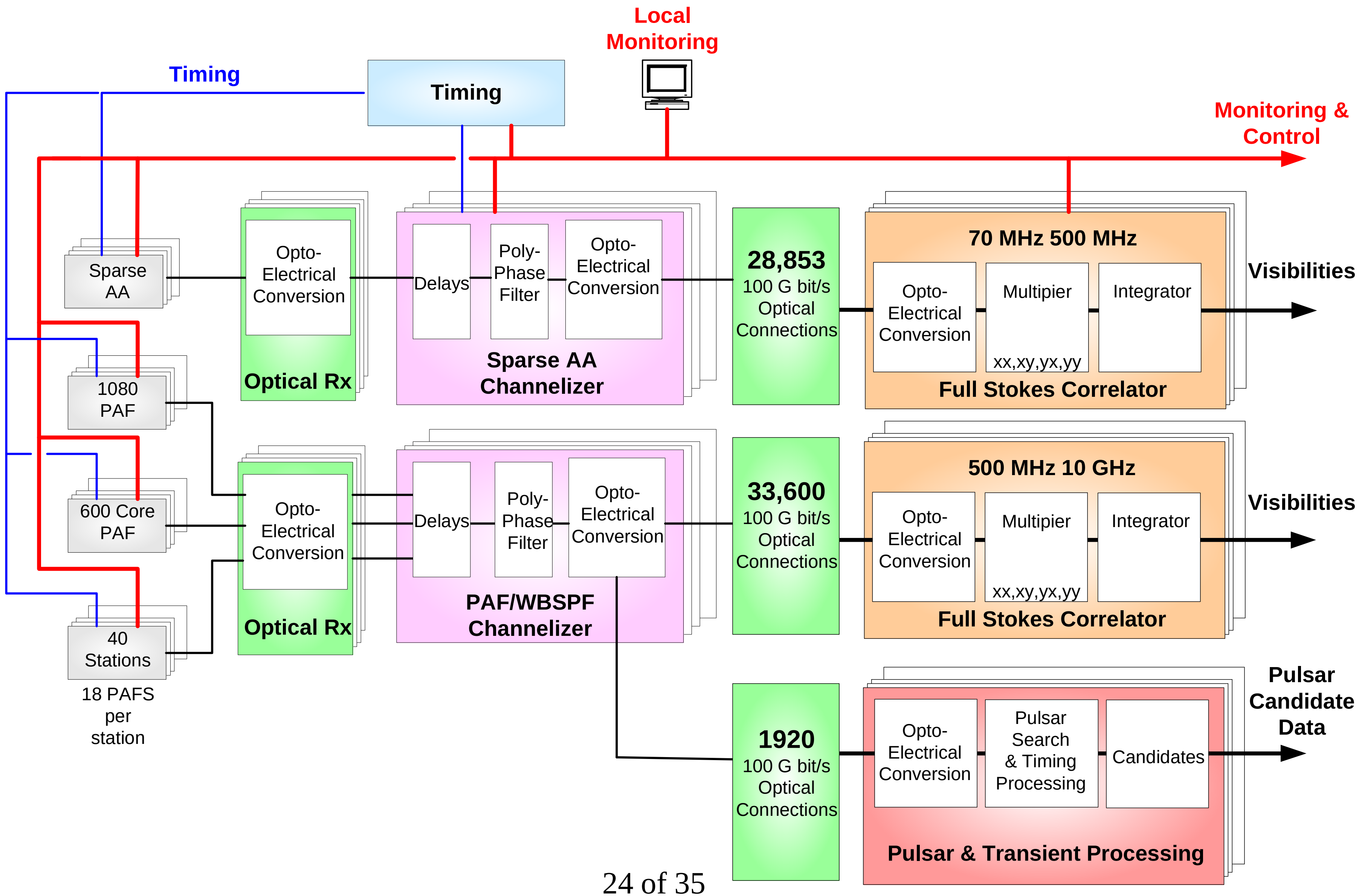
SPDO



* Sparse AAs + 3000 15-m dishes with SPFs

Signal Processing Overview Option 2

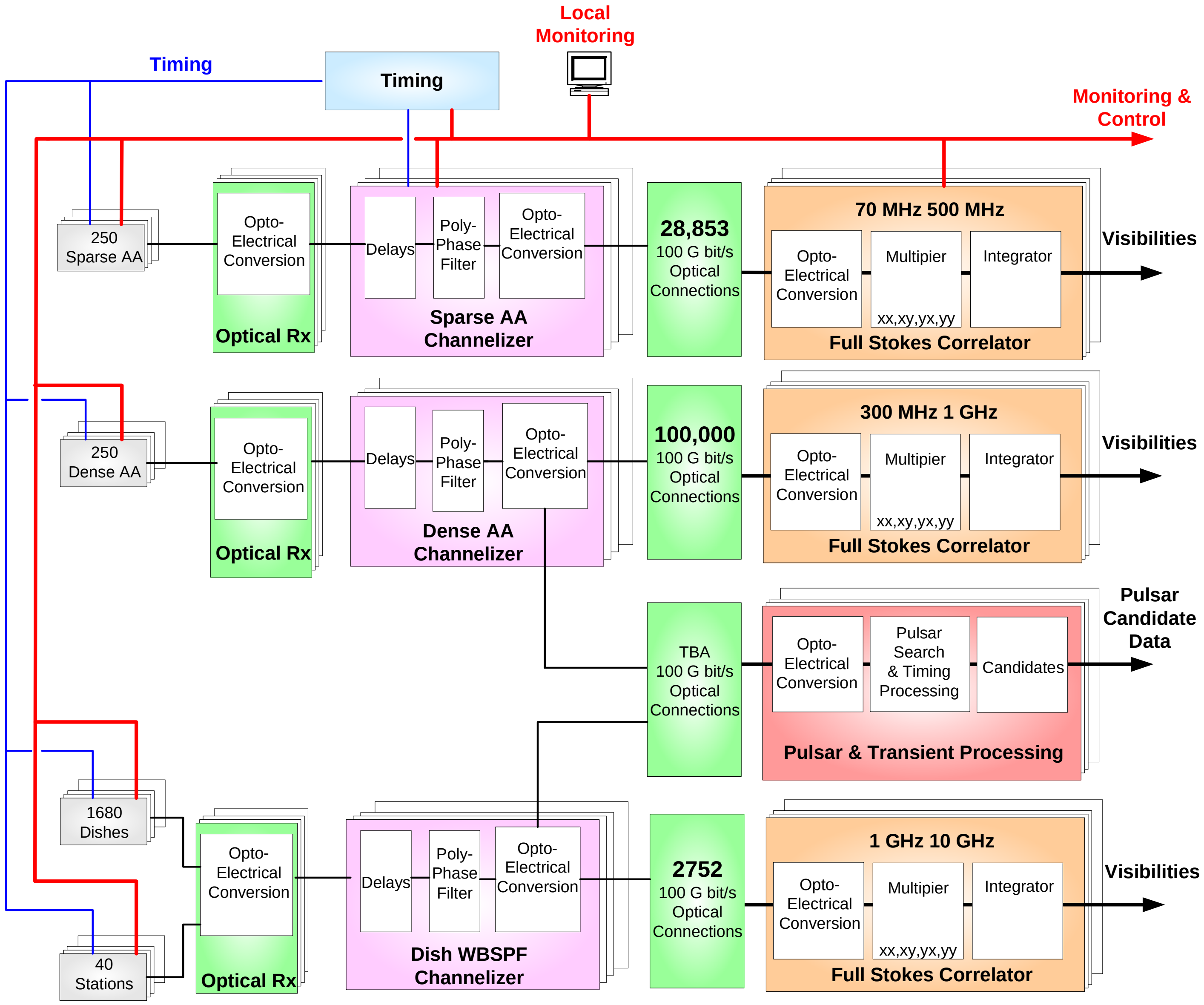
SPDO



* Sparse AAs + 2400 15-m dishes with PAFS & WBSPF

Signal Processing Overview Option 3

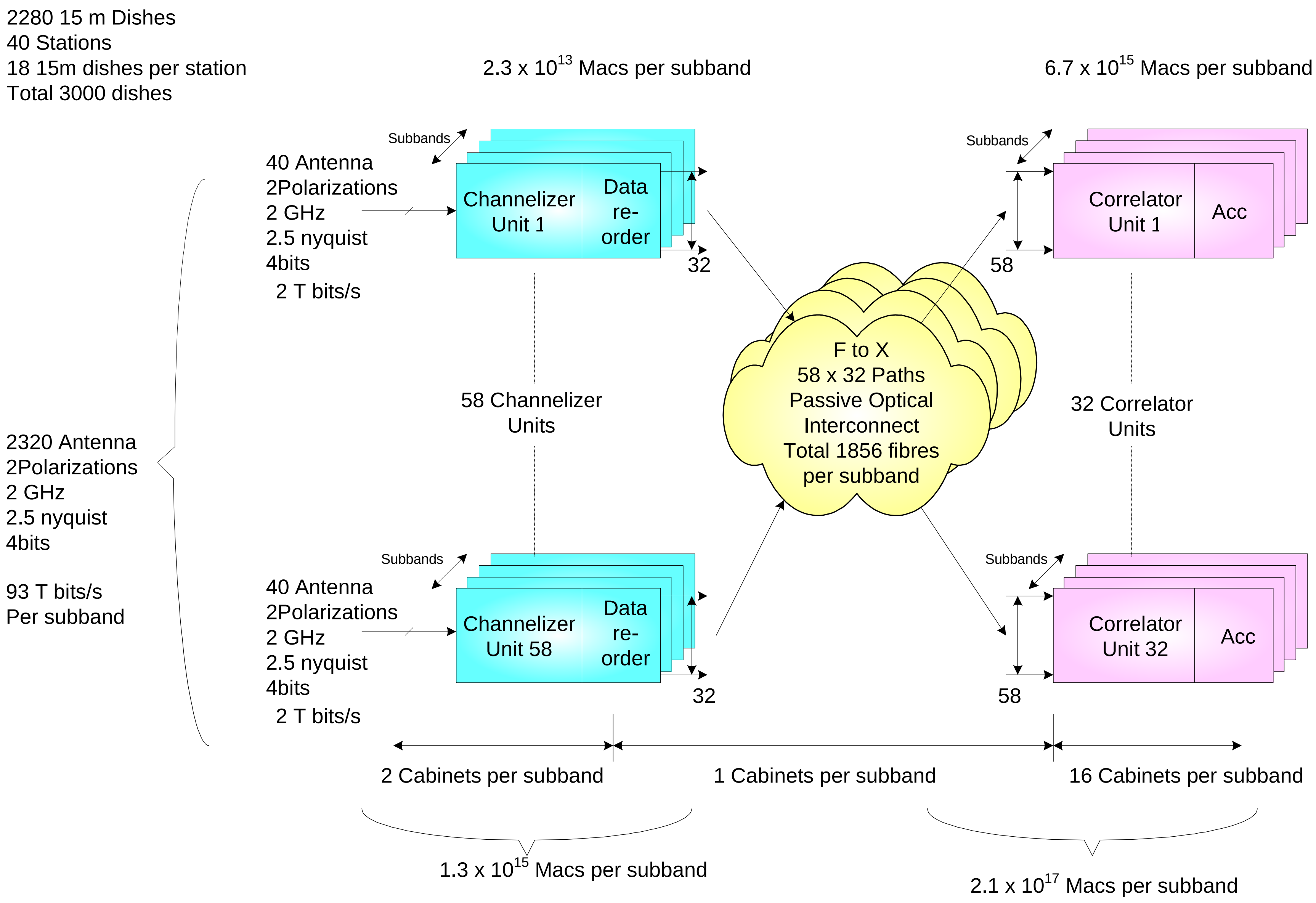
SPDO



* Sparse AAs + 250 Dense AA + 2000 15-m dishes with SPFs

Strawman FX Architecture
15 m Dish in 2 GHz sub-bands

SPDO



Loosely based on the FX architecture proposed in the SKA Memo 25 (D'Addario and Timoc)

Cabling

SPDO

Cabling will be a significantly more complex than the EVLA Correlator (above)

Picture courtesy of G.Hovey

Technology Options

- FPGA
  - Virtex 6 (available 2010):

2016 x DSP slices clocked at 600 MHz -> 1200 G MACS

~ 25 G MACs per Watt

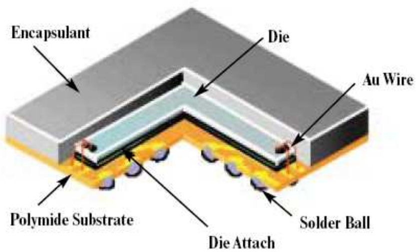
10^{18} MACS requires ~ 10^{6} FPGAS

=> 48 W per device and ~ 48 M Watts for 10^{18} MACS

Operating cost 1$ per Watt per year => $48M per annum

Plus cost of cooling and delivering power

- ASIC
  - 22nm (available 2010):



2.5 nW/MHz/Gate

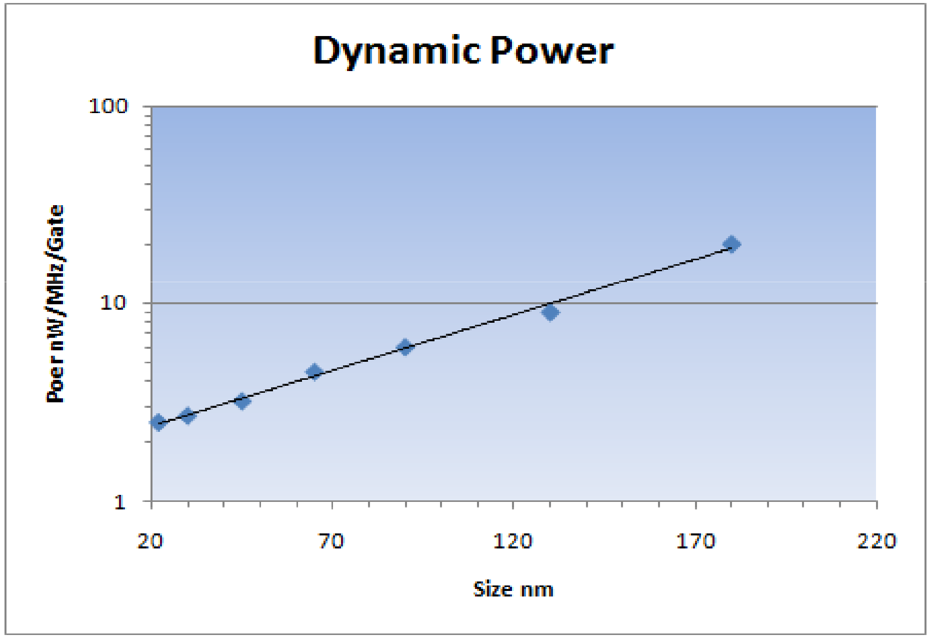
> 40 T MACS (4 bit) per device => 25,000 devices

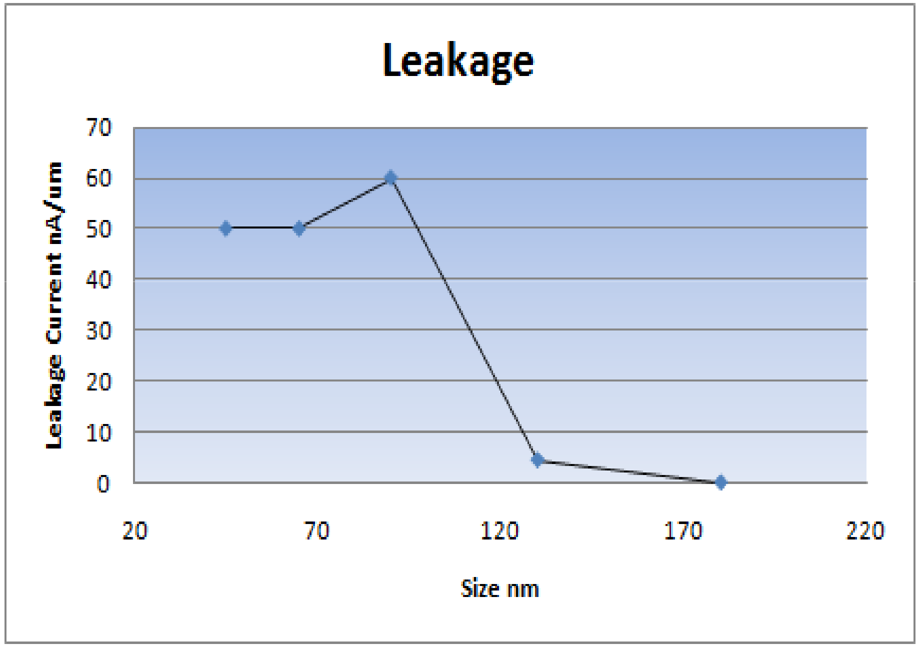
Assuming < 50 % gates switching at any one time: 600kW

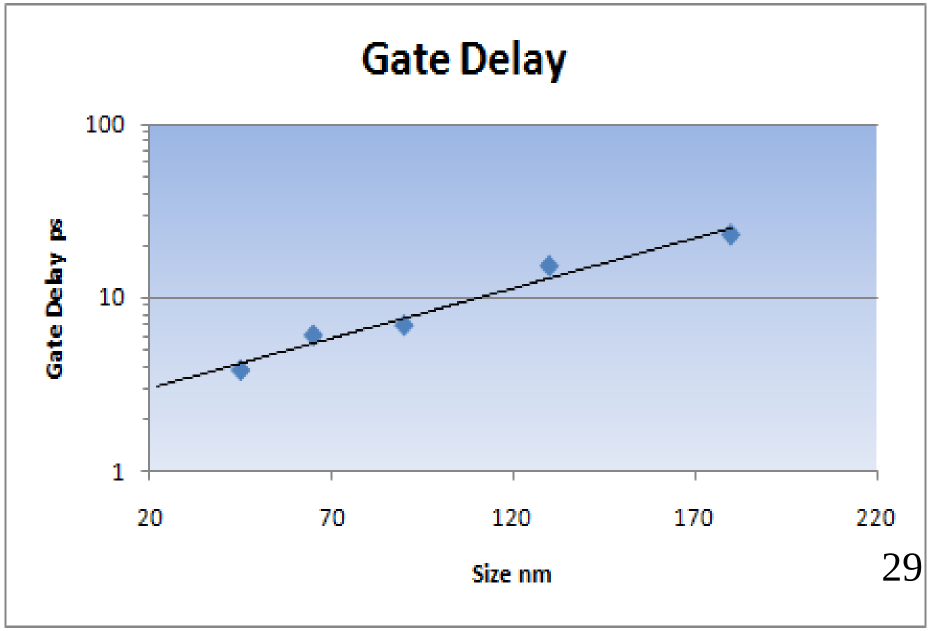
Operating cost $600k per annum

ASIC Characteristics

SPDO







Full Custom ASIC vs Standard cell ASIC

- 3 to 8 times faster
- 15 times the density
- 3 to 10 times more power efficient

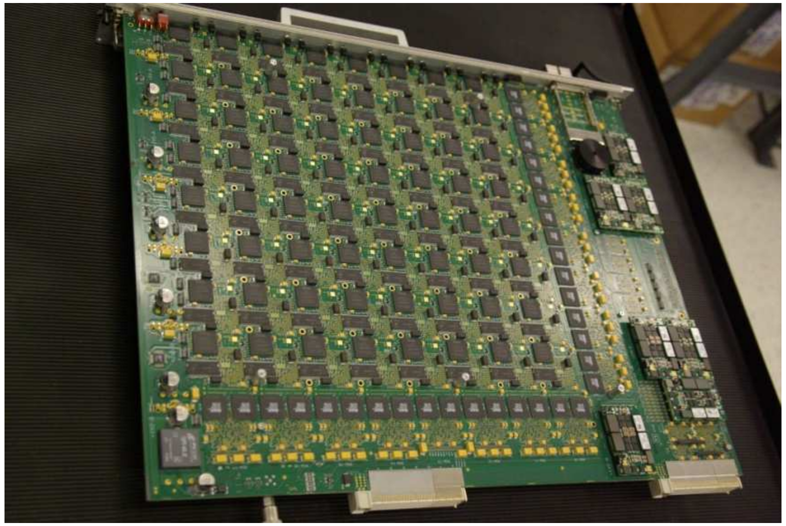
Full Custom ASIC vs FPGA

- 10 times faster
- 508 times the density
- 42 times more power efficient

From ref 1, 2, 3 & 4

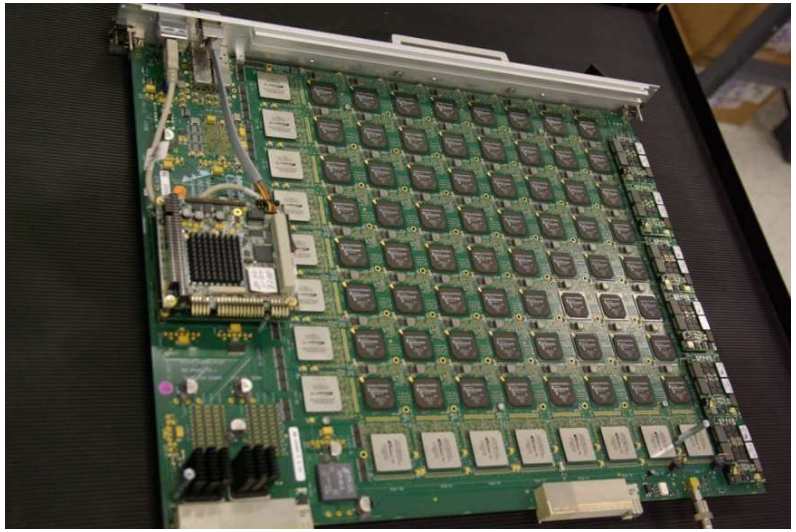
What would F or X unit look like?

SPDO



Baseline Board (rear)

Station Board



Baseline Board (front)

<u>EVLA style boards might be an optiton ?</u>

64 ASICS or FPGAs on board (~1.5 kW card)

~ 190 boards for Dense AA ASIC correlator

14 cards per shelf -> 14 shelves

Is production yield an issue?

<u>Could use smaller 8 processor chip board</u>

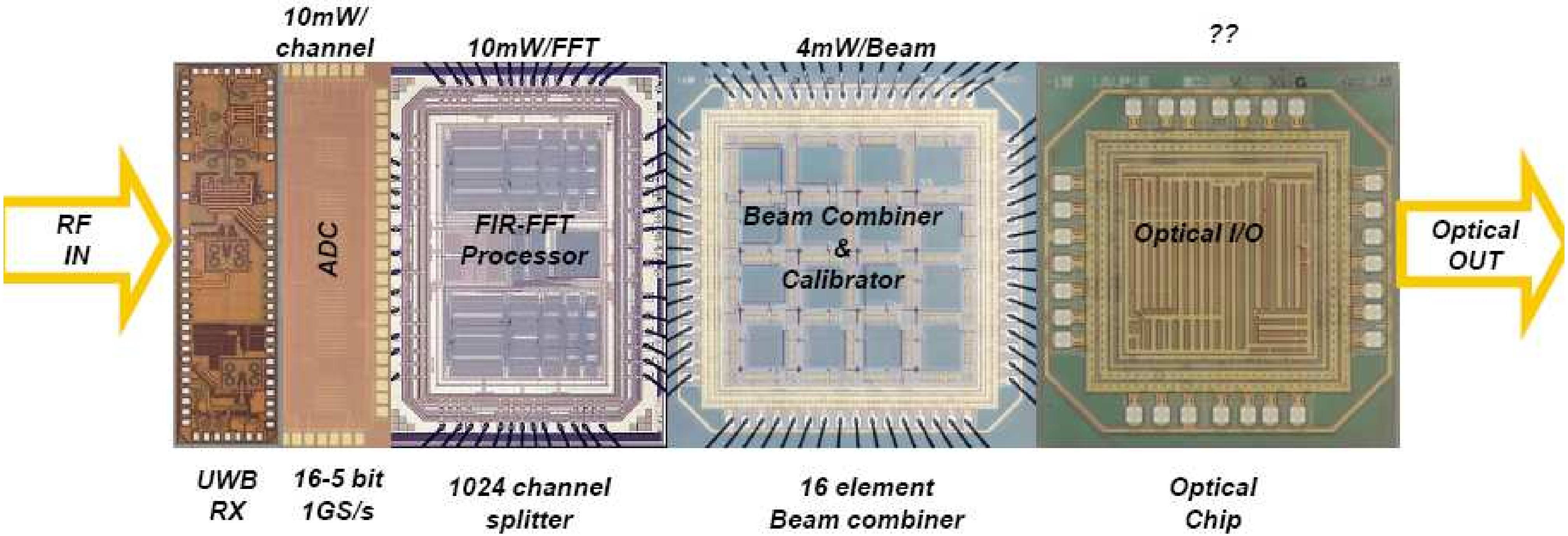
As per ASKAP or Uniboard

Inter-board Communication links increase

Pictures courtesy Brent Carlson

Multichip Module

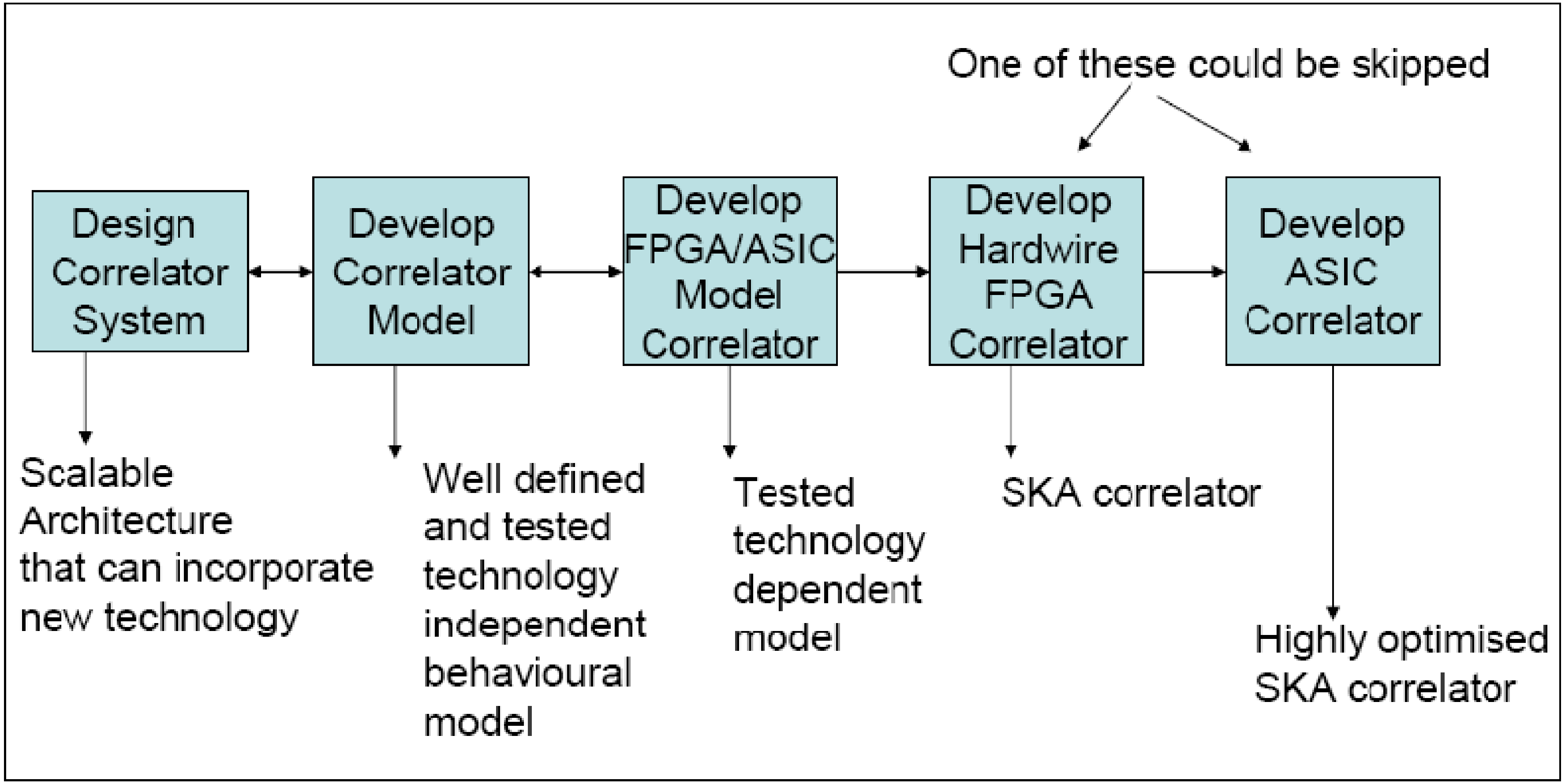
•SKADS have developed a promising Multichip Module:
4 x 4 antenna array currently,
Current RFI Protection shows -57dB per M (in air)



Could be developed and used in several areas of the SKA
(Note that the key components are ADC and Optical I/O, although the others could be useful in some applications.)

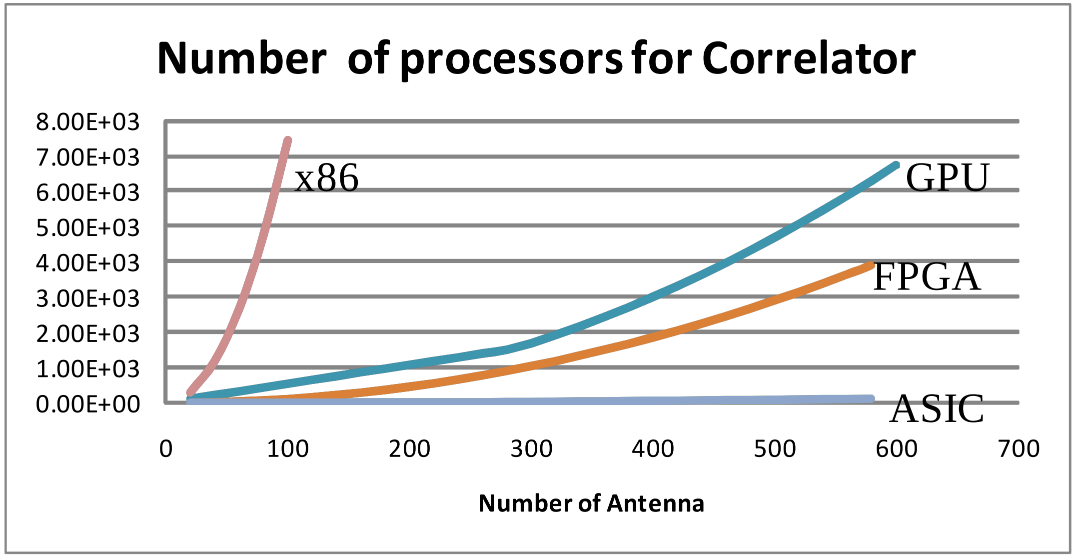
Picture courtesy of Kris Zarb Adami

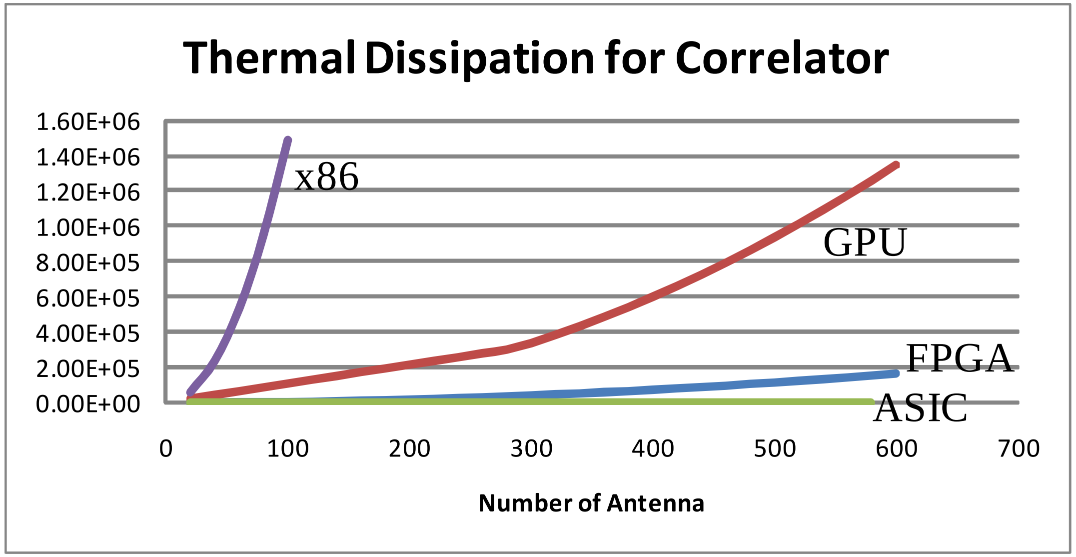
Development Path



Phase 1 Correlator

SPDO





Assumes: 60% usage x86 & GPU, 80% FPGA, 100% ASIC
GPU I/O capability ~ 240 G bits/s : Needs to Benchmarked

Example: Nvidea GPU

~ 1.2k€ per GPU
~ 4k€ per hosting server
~ 0.3k€ Infiniband HCA
(10 G bit Ethernet could also be used but is more expensive)

Phase 1
300 SPF dishes (1GHz to 8GHz)
~ 1 Peta Op X correlation
~ 10 T samples/s net
~ **350 kW** dissipation
~ **2 M€** for the processing hardware
47 Schroff Cabinets

An equivalent x86 correlator:
13MWatts
269M€
1900 Cabinets

Development time for ASICS too long for Phase 1

References

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