SKA multi-beam concepts and technology

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SKA main specifications

Next giant radiotelescope (~2020) at decimetre and centimetre wavelengths

- **Collecting area: 10^6 m^2**

  line observation: sensitivity up to 100 x current designs
  continuum observation: sensitivity up to 1000 x current designs (large bandwidth)

- frequency range: 70 MHz – 25 GHz (λ 3 m - 1 cm)
- Field of view: 200 deg^2 @ f<0.3 GHz 50 deg^2 @ 1 GHz
- Nb of FoV: 1 to 4
- Baseline length: up to 3000 km
- ***Wideband, wide field of view, multi beam***
- **total construction cost ~ 1.5 · 10^9 EUR**

SKA reference design (1/6)

SKA will be a very high sensitivity instrument

=> need of a *very large collecting area*

- Very large number of dishes

and

SKA will be a general purpose instrument optimized for large surveys with high survey speed

=> need of *large FoV*

- Very large number of small dishes (Ø ~ 10m)
- Multi beam operating mode (Phased Array Feeds)

  and / or

- Large area of aperture array

SKA reference design (2/6)

Multi-beam concepts for synthesis of independent beams:

- Tied array mode with single pixel feed on dishes
  ATA (0.5 – 11 GHz) …
- Phased Array Feed on dishes
  APERTIF(0.7 – 1.8 GHz), ASKAP…
- Aperture arrays using quasi omnidirectional antenna elements
  LOFAR (30 – 240 MHz), MWA (80 – 300 MHz)
  EMBRACE (0.5 – 1.5 GHz)…

Multi-beam concept for synthesis of grid of beams:

- Spatial fourier transform from each antenna signal

Multi-beam with cluster of feeds on a dish (grid of beams):

- Cluster of corrugated horns (Parkes with 13 feeds, Arecibo with 7 feeds)

SKA reference design (3/6)

SKA will have a large frequency range and a wide instantaneous bandwidth:

- Single pixel feeds can cope with large frequency range, but are not multi-beam friendly (the tied array mode is the only way for multi beaming)

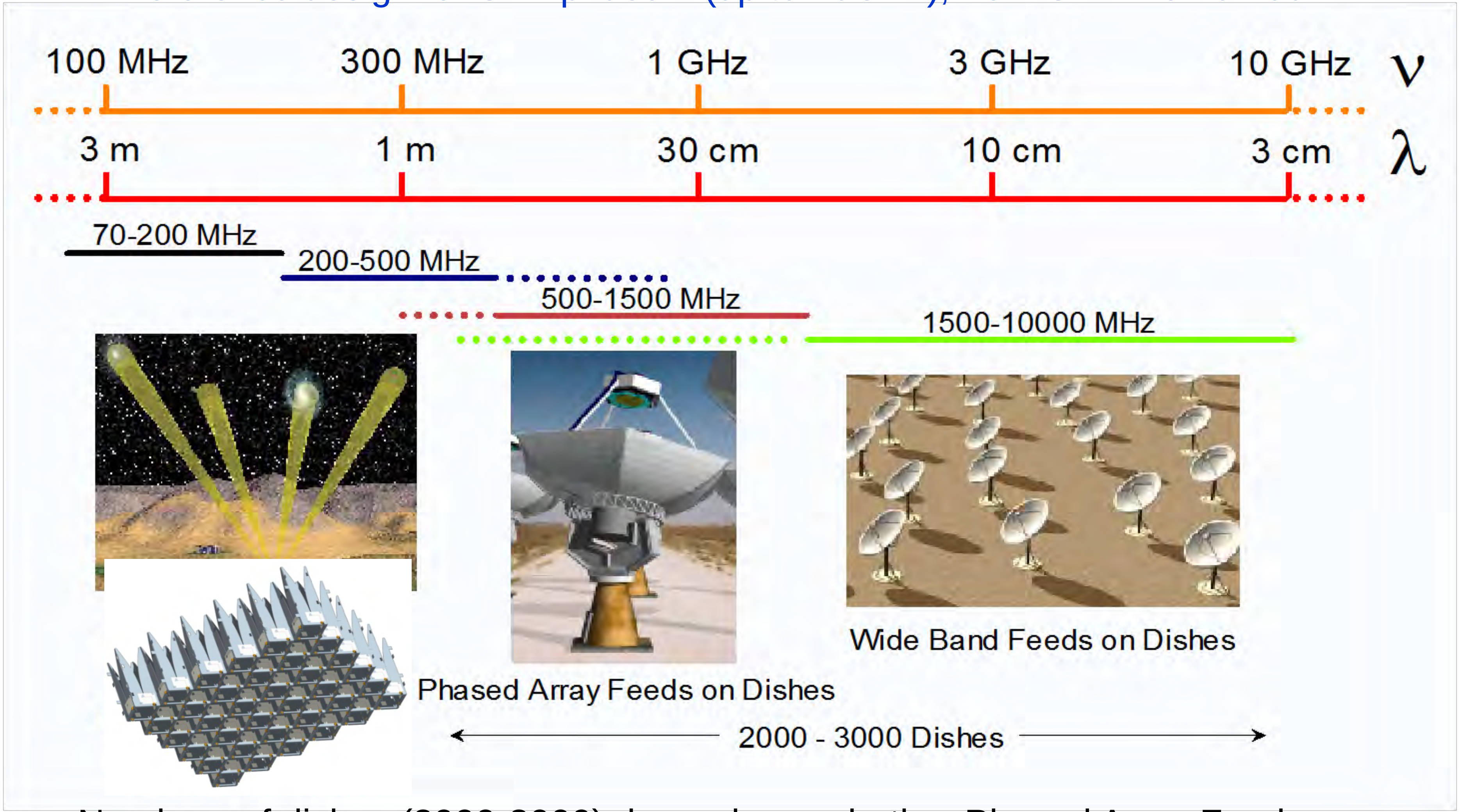
- Phased Array Feeds and aperture arrays can deliver multiple independent beams, but can't cover large frequency range

=> SKA will use a *hybrid design* with

- Small to medium dishes with either wideband single pixel feeds or phased array feeds (or both)
- Aperture arrays

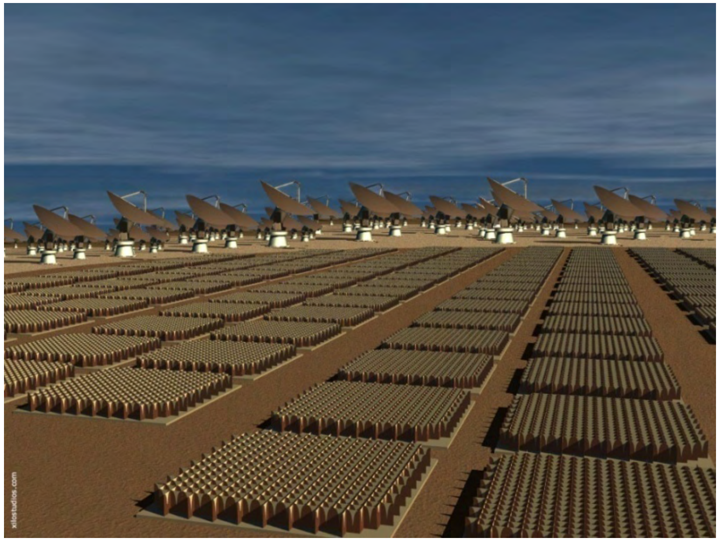
SKA reference design (4/6)

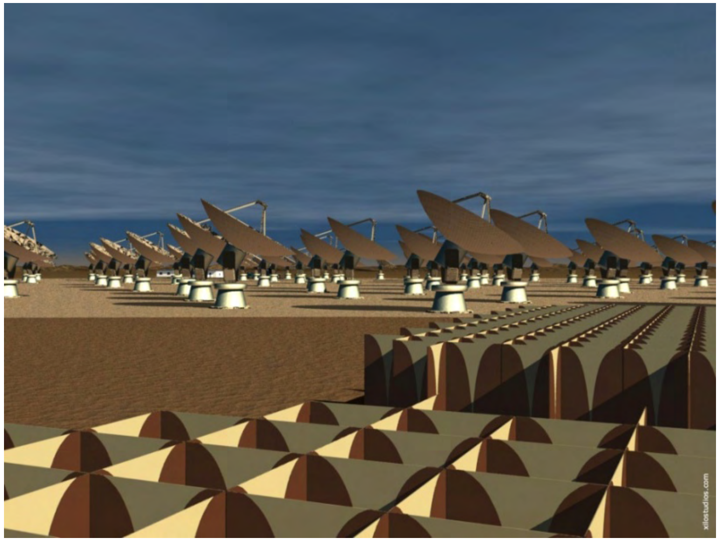
Reference design for SKA phase 1 (up to 10GHz), from SKA memo 100



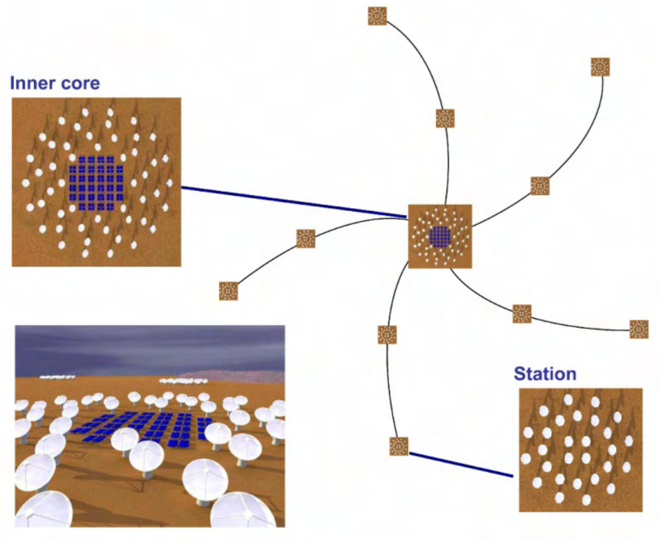
Numbers of dishes (2000-3000) depends on whether Phased Array Feeds and/or Aperture Arrays are used in the SKA.

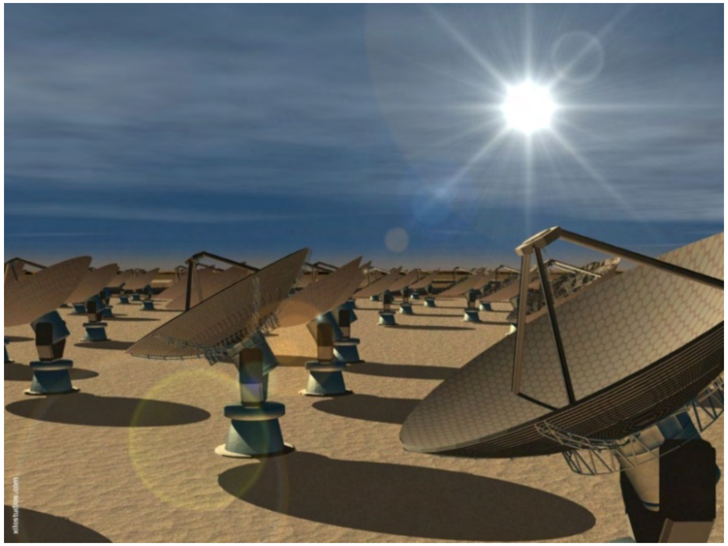
SKA reference design (5/6)





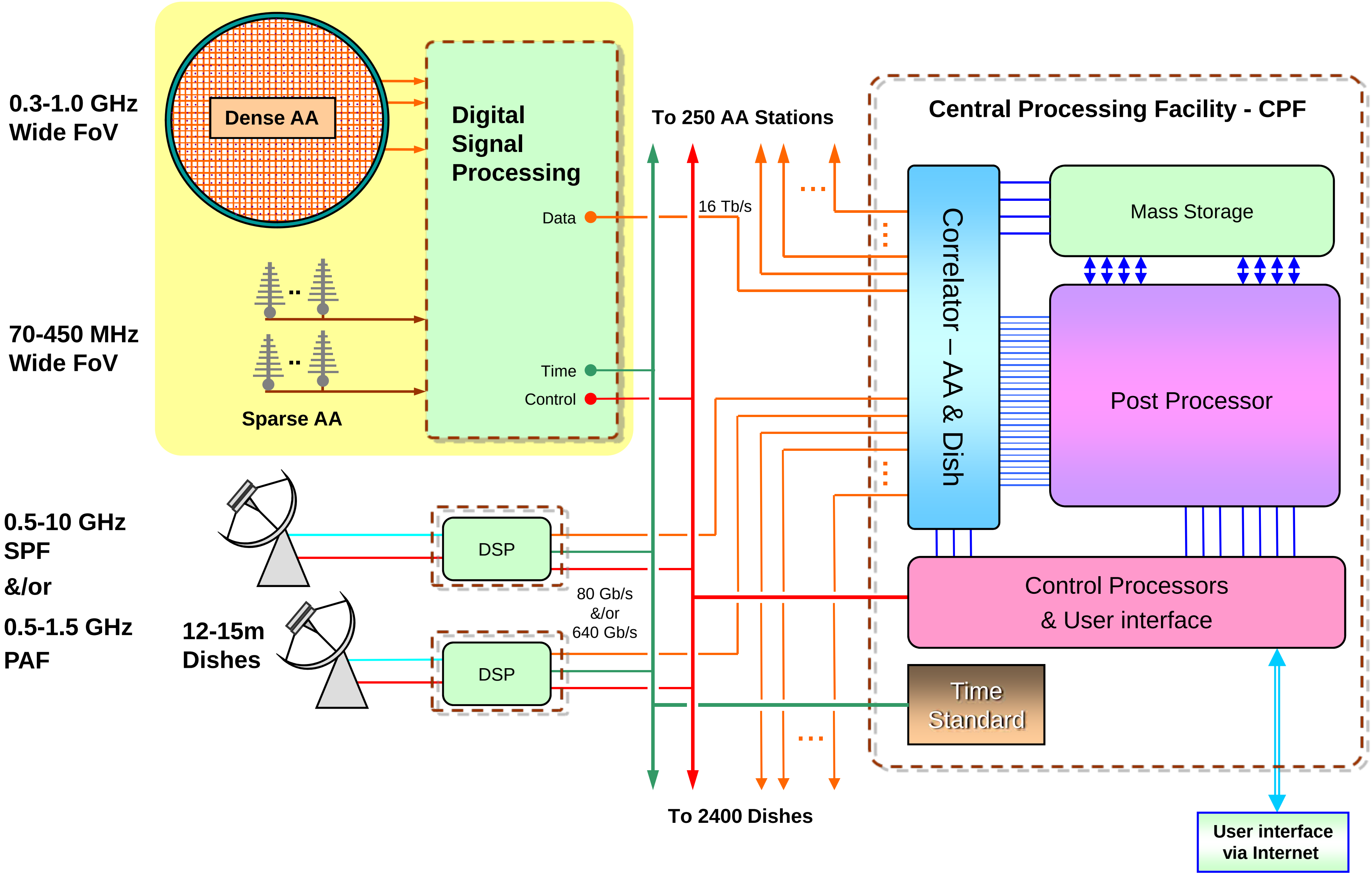
Core:
200,000 m^2 of **phased array** - tiles





Station:
parabolas with Phased Array Feed

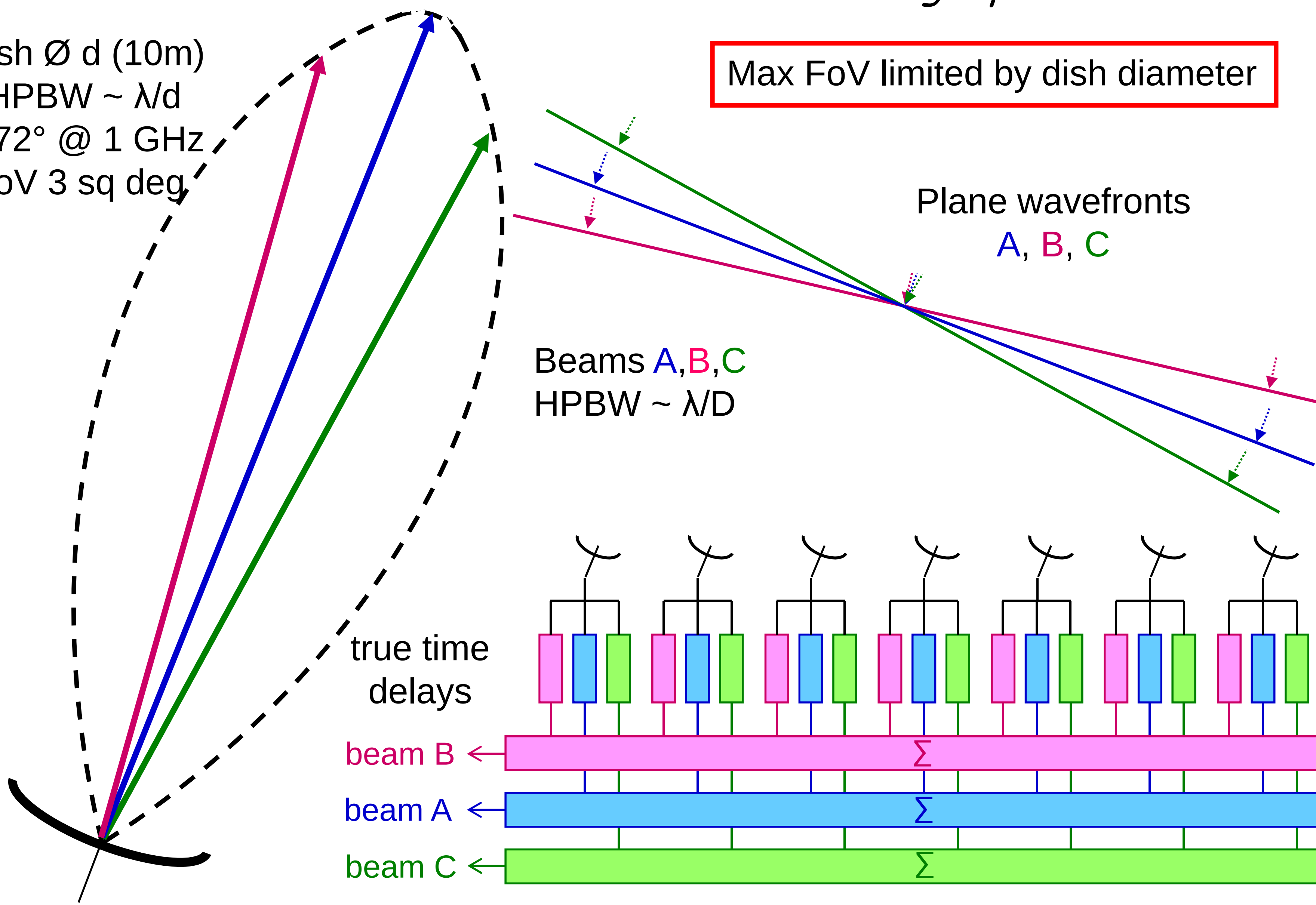
SKA reference design (6/6)



Multi beam modes (1/6)

Tied array mode and multi-beam for single pixel feeds

Max FoV limited by dish diameter



Multi beam modes (2/6)

Multi-beam mode with Phased Array Feeds:

HPBW of each beam: ~ λ/d

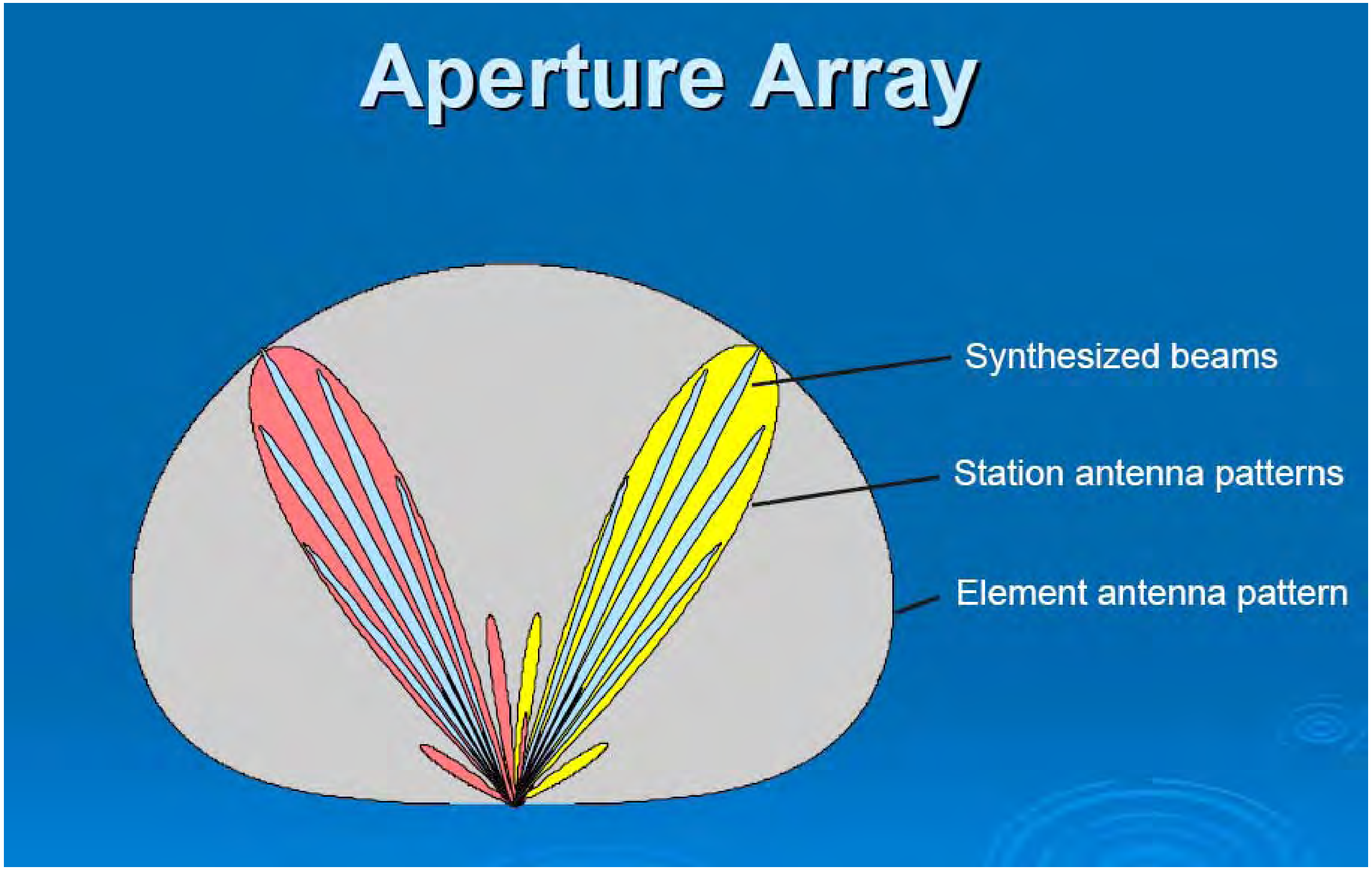
For d=12m
FoV one beam ~ 1 sq deg @ 1.4 GHz

Array of ~ 10x10 small elements with
20 beams: FoV 20 sq deg

All beams can be set independently

Phased array feeds allow access to a FoV larger than the dish FoV

Multi beam modes (3/6)



Tiles of ~1 to a few m², 8 x 8 up to 16 x 16 dual polarized antenna elements

RF analog beamforming + digital beamforming (EMBRACE demonstrator)

All digital beamforming (2-PAD demonstrator)

Multi beam modes (4/6)

Aperture Array

Engineering test of an EMBRACE tile (Nançay lab)

Multi beam modes (5/6)

Phased Array Feeds:

To date, there is no interferometer instrument using phased array feeds on a large scale, the SKA precursor ASKAP is the first one.

Aperture Arrays:

Emerging instruments such as LOFAR and MWA use aperture arrays on a large scale, only in low frequency domains: 30 to 240 MHz and 80 to 300 MHz

For SKA design, Aperture Arrays and Phased Array Feeds are higher risk designs than wideband single pixel feeds, but they allow access to large FoV, specially under 2 Ghz (a cluster of corrugated horns under 2 GHz would be too big to operate on a small dish).

Multi beam modes (6/6)

Aperture Array and Phased array feeds challenging parameters:

Limited bandwidth: currently 3:1, achievable 4:1

Grating lobes if elements spacing larger than $\lambda_{min}/2$

Scan angle: radiation pattern changes with scan angle, defined at broadsight

Cross polarization may be high

High power requirements due to high number of elements and associated electronics

See the DS4T4 SKADS deliverables about antenna technology for Aperture Arrays: Wideband Integrated Antenna

Technology challenges

Technology and operation challenges:

Small dish with wideband single pixel feed:

• mature technology to be optimized for low cost

• Front end cooling system

Phased array feed and aperture arrays:

• System noise ? (no use of cooled front ends)

• Bandwidth limited to 4:1

• Very high digital bandwidth for digital signal processing (Tb/s)

• Very high power requirement

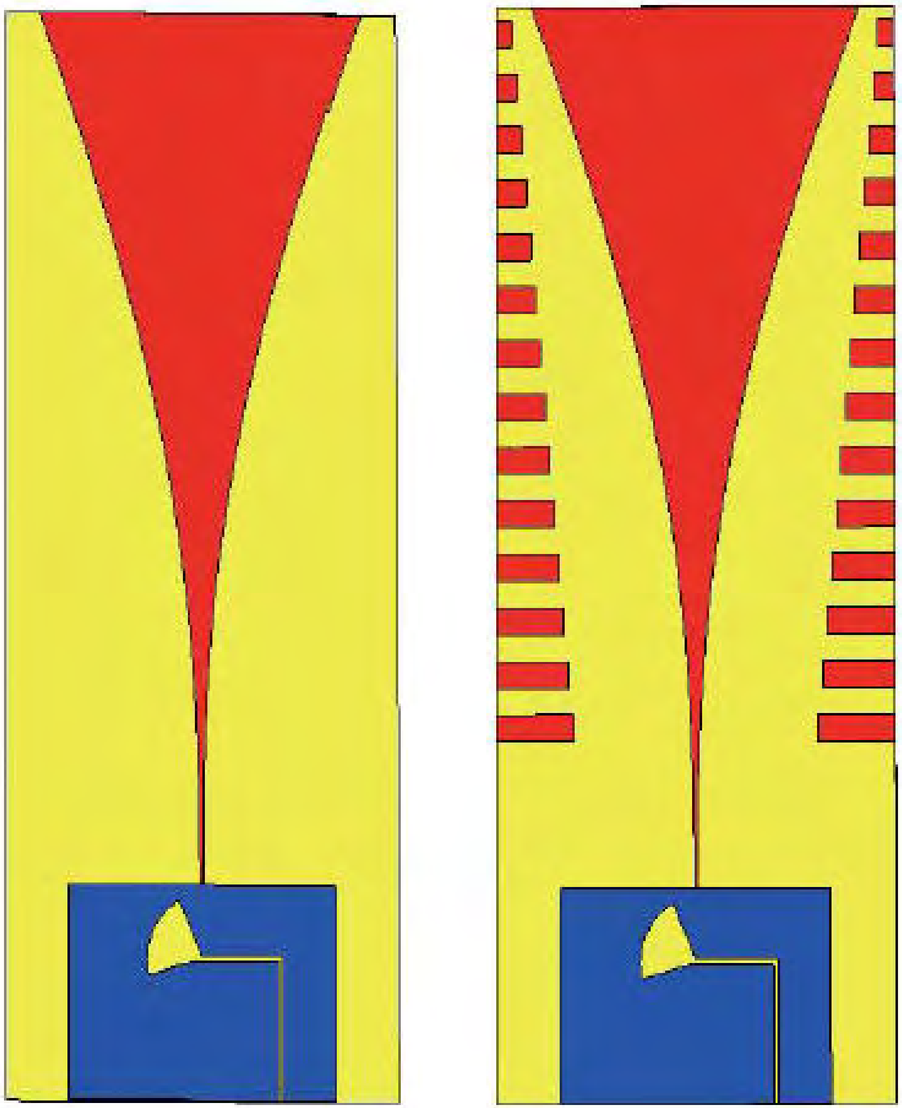
Output data flow from SKA:

• Tera bytes of data…

• Availability of raw data? (10 min., 1 hour, 3 days?)

• Data archive

Technology challenges, antenna (1/3)

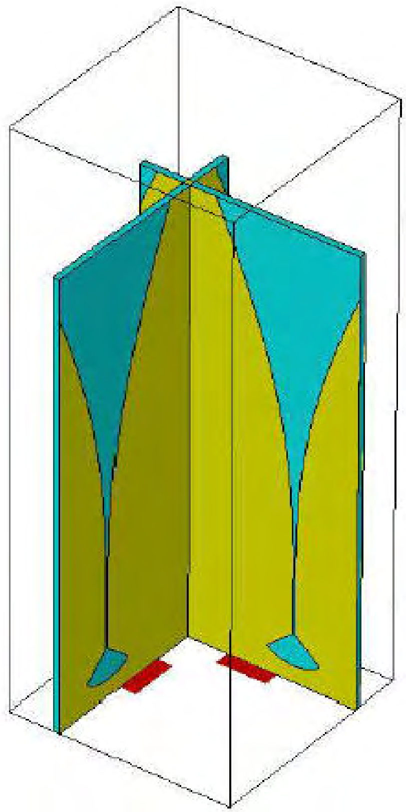


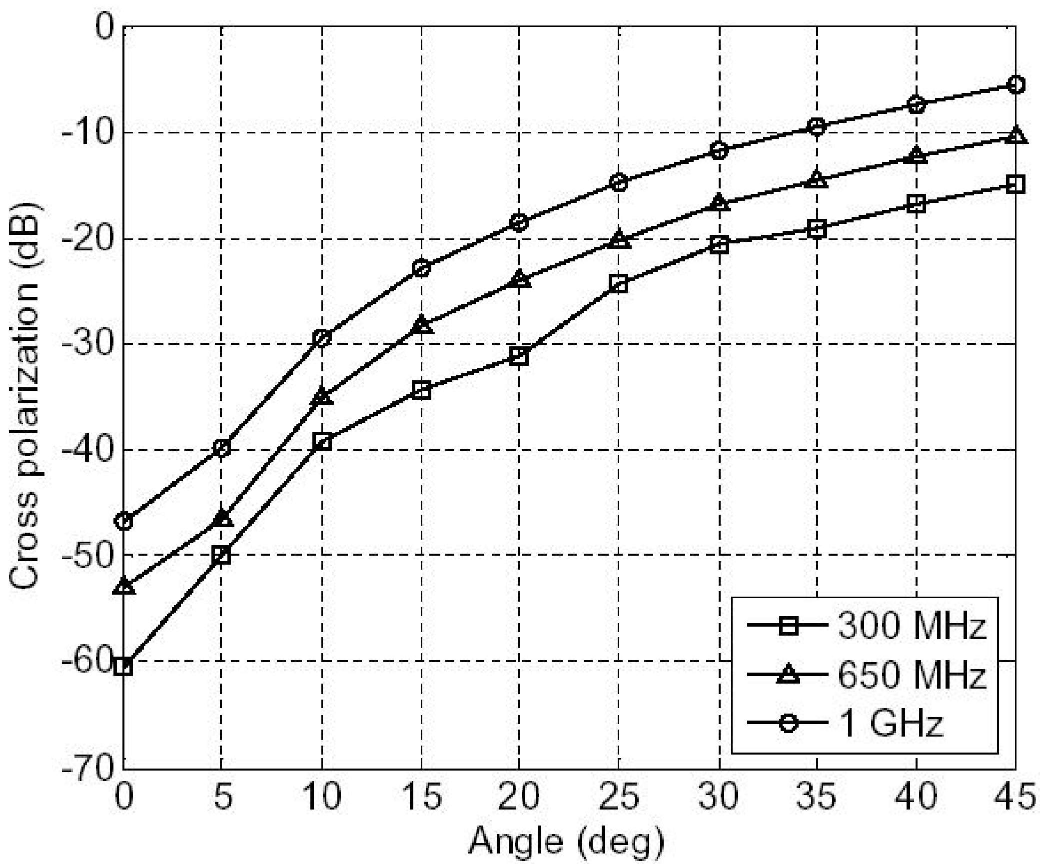
Vivaldi antenna (left)
and
Combline Vivaldi antenna (right)

- Usefull bandwidth 3:1
- Single ended devices
- HPBW > 130° when used above a ground plane

Corrugated comb-lines enhance the scan stability (less scan blindness) and improve the cross polarization performance

Technology challenges, antenna (2/3)





Cross polarization characteristic of a dual pol Vivaldi antenna in the diagonal plan

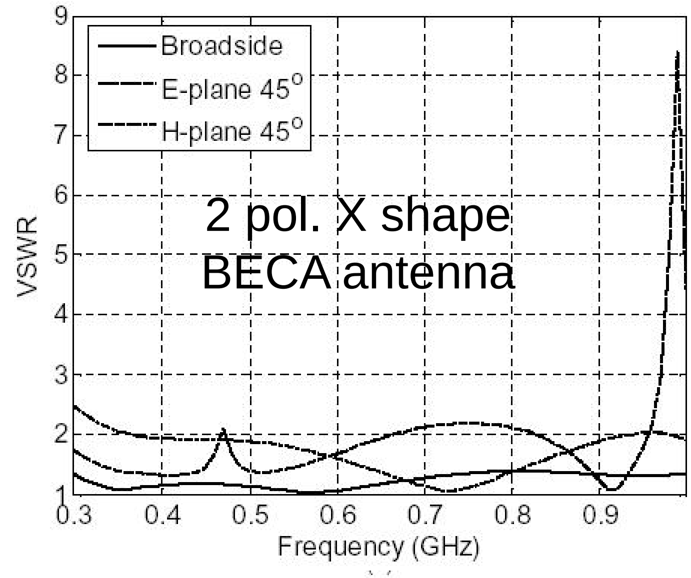
High cross polarization in the diagonal plan at high scan angles

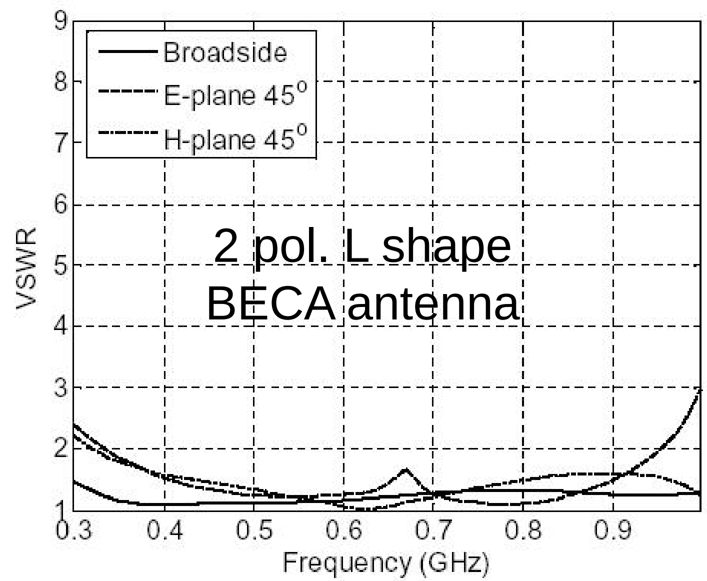
Technology challenges, antenna (3/3)

Bunny Ear Combline Antenna (BECA)

Shorter depth than Vivaldi for the same bandwidth and better cross-polarization performance

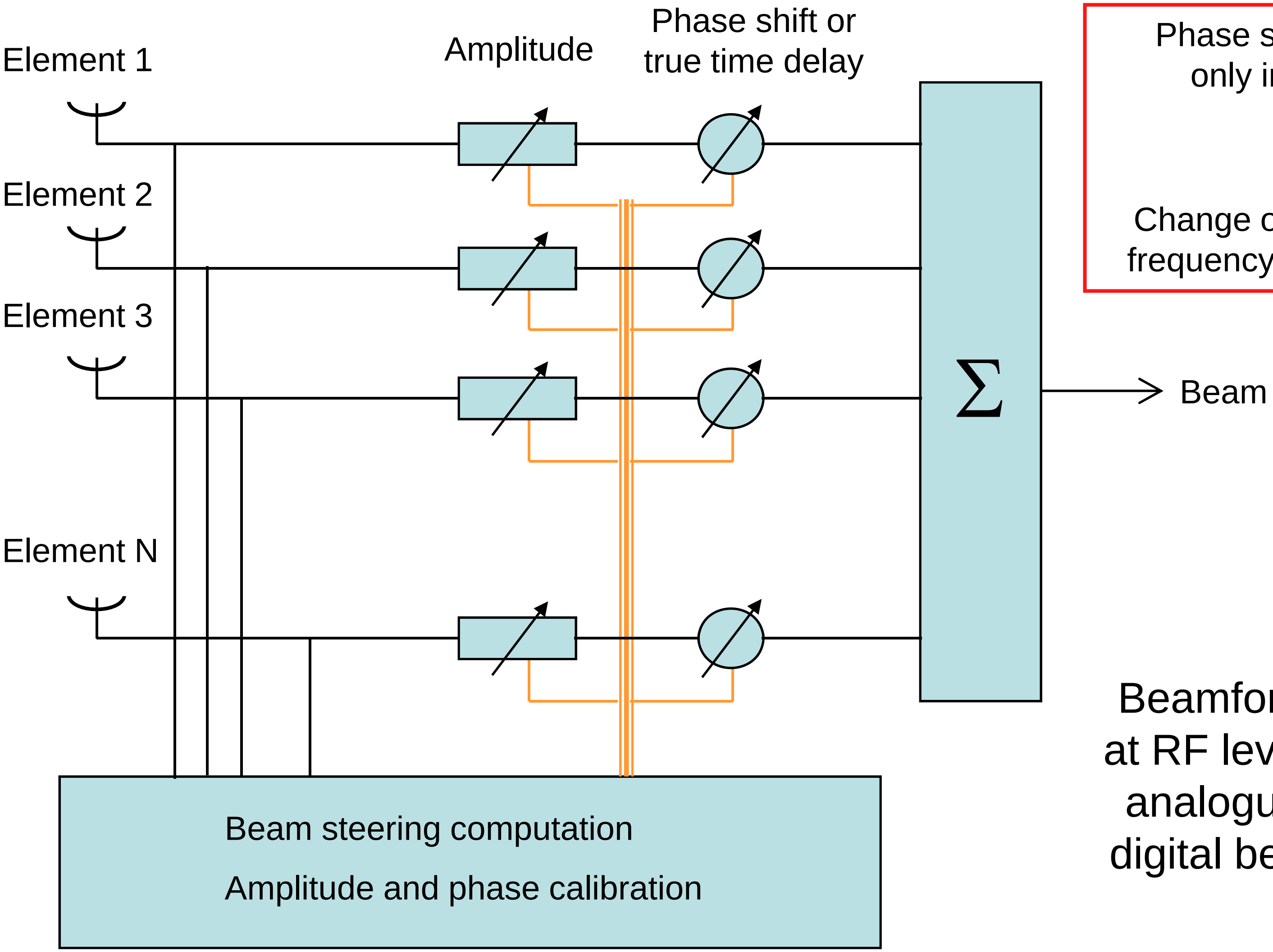
Balanced structure for differential feeding





Technology challenges, beamforming (1/3)

Generic beamforming



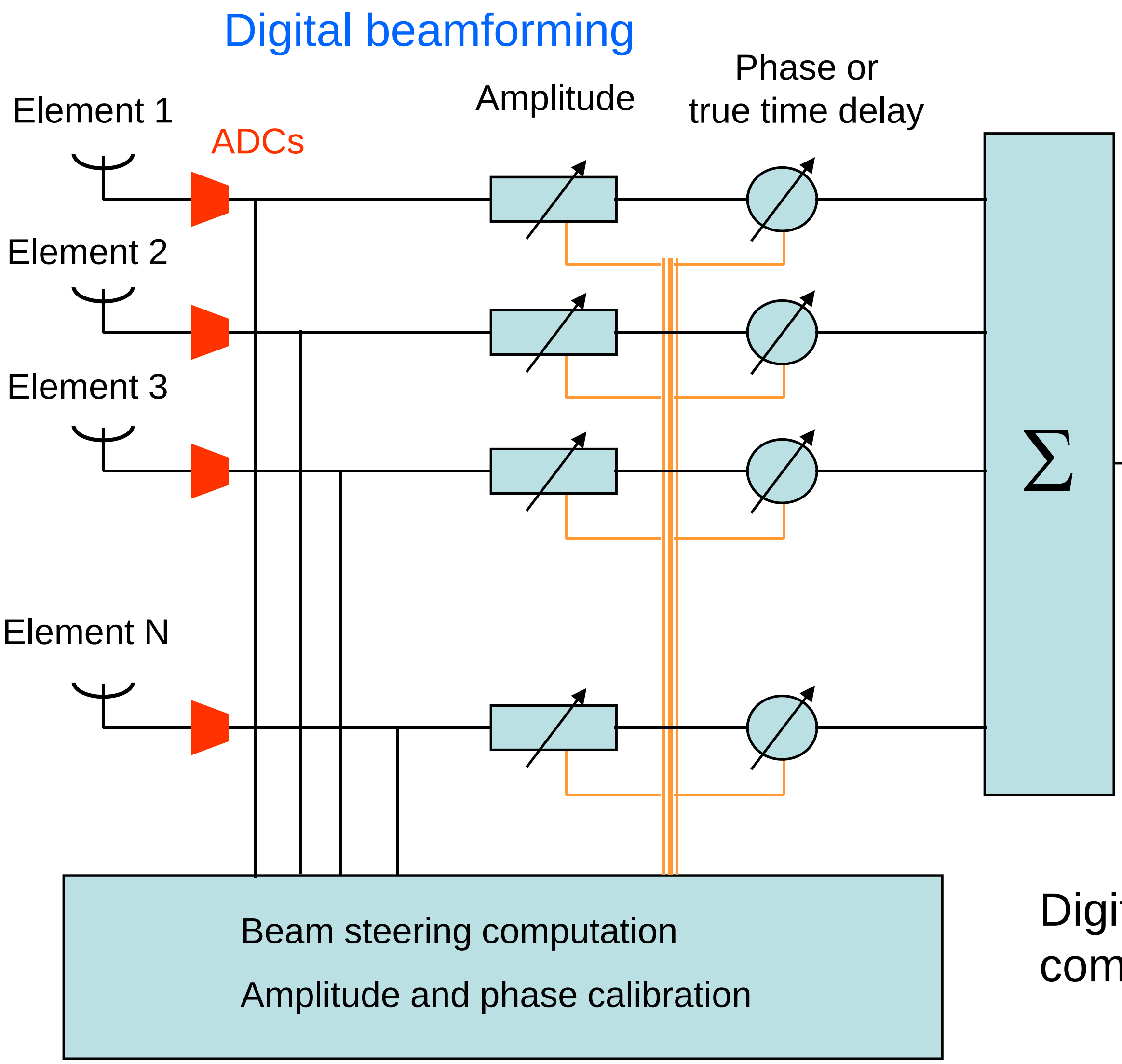
Phase shift ≈ true time delay only in narrow bandwidth

→

Change of beam steering versus frequency when using phase shift

Beamforming can be done at RF level or IF level, using analogue beamforming or digital beamforming or both

Technology challenges, beamforming (2/3)



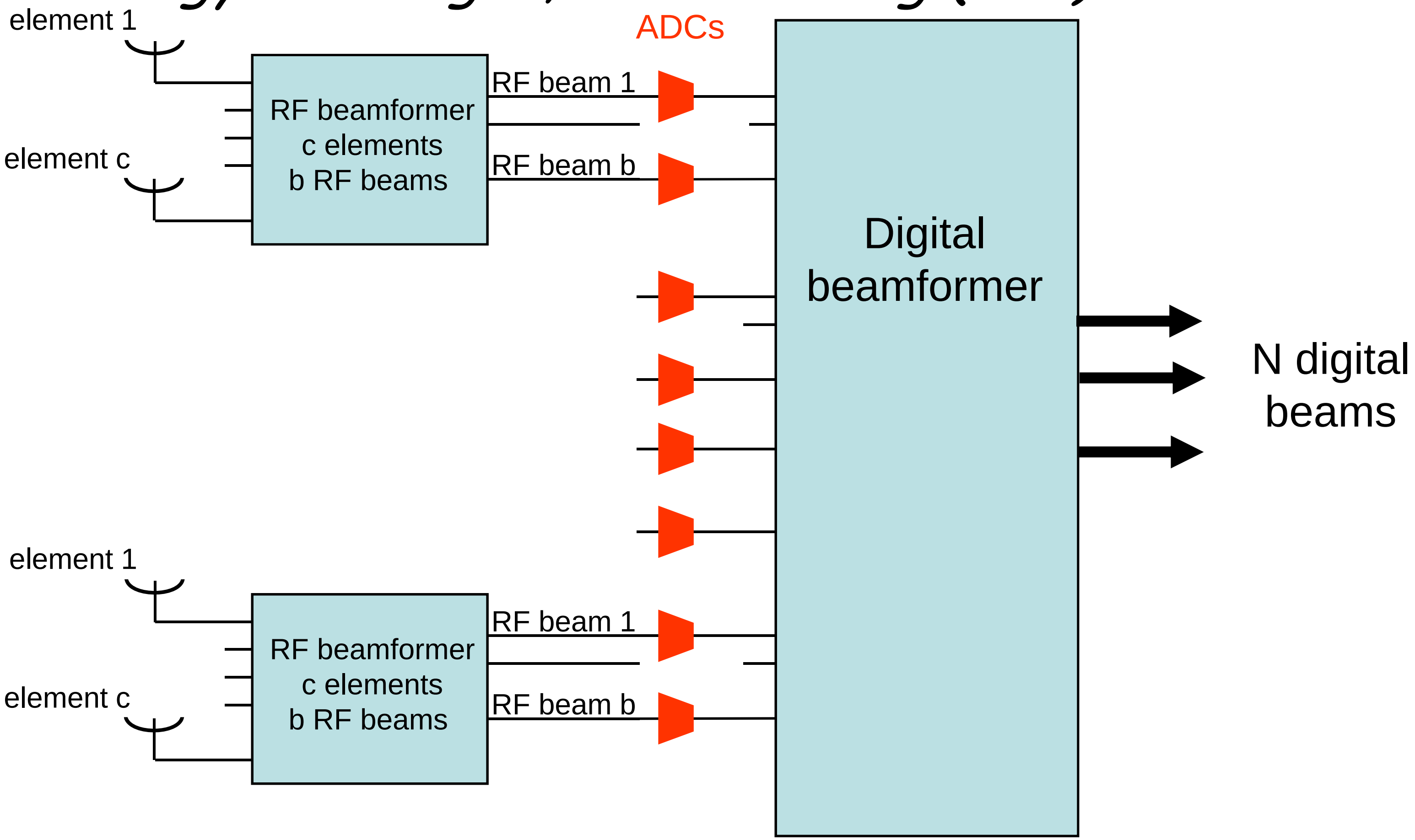
Phase shift ≈ true time delay
only in narrow bandwidth

→

Apply phase shift on narrow subbands

Digital phase shift: multilpy by a complex value

Technology challenges, beamforming (3/3)



Hierachical beamforming: RF beamforming followed by digital beamforming

Used in EMBRACE demonstrators with b=2   c= 72 or 4x72   N= 8 to 496

Technology challenges, DC power in AA (1/5)

DC power requirement is a driving parameter for yearly recurrent operating cost and could be very high for AA systems with millions of antenna elements and associated digital processing

Need of ultra low power design wherever it can apply

All digital system:

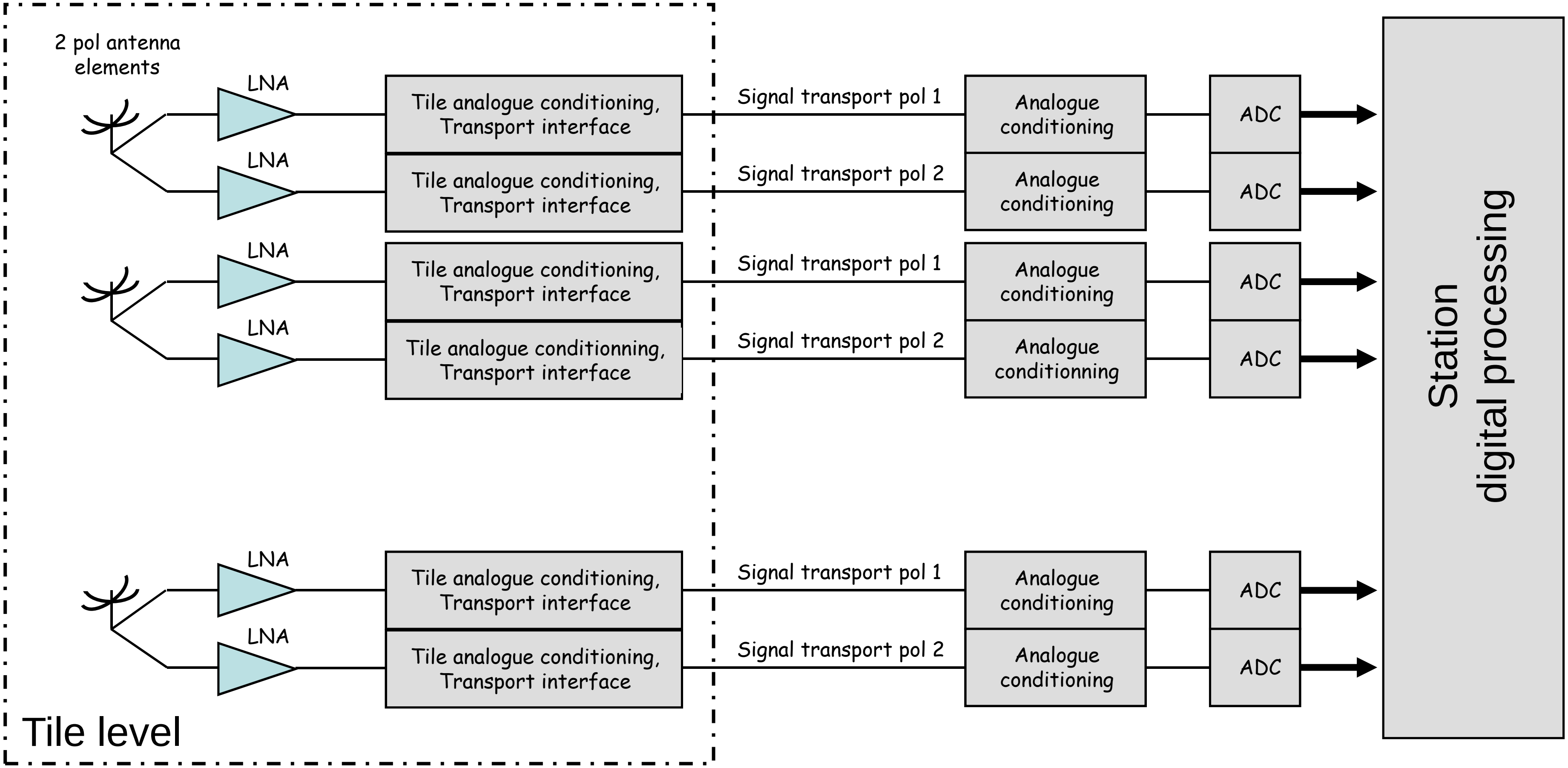
- the most flexible system
- « max. instantaneous FoV » ~ antenna element FoV
- calibration parameters apply at the antenna element level

System with front end RF combining:

- « max. instantaneous FoV » reduced by the combining factor
- not so easy to calibrate compared to an all digital system
- may be an efficient way to reduce power requirements

Technology challenges, DC power in AA (2/5)

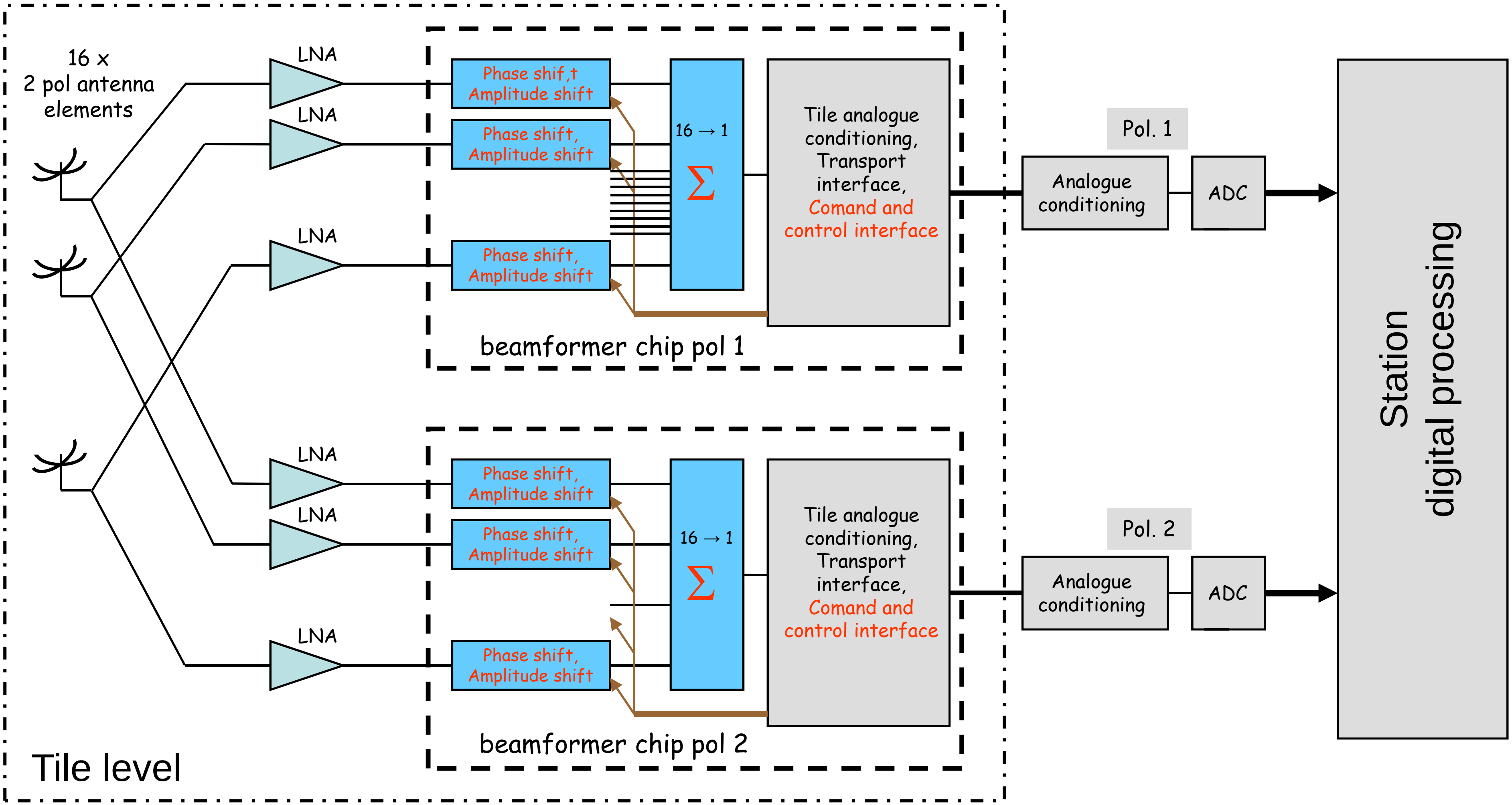
AA all digital system: generic design



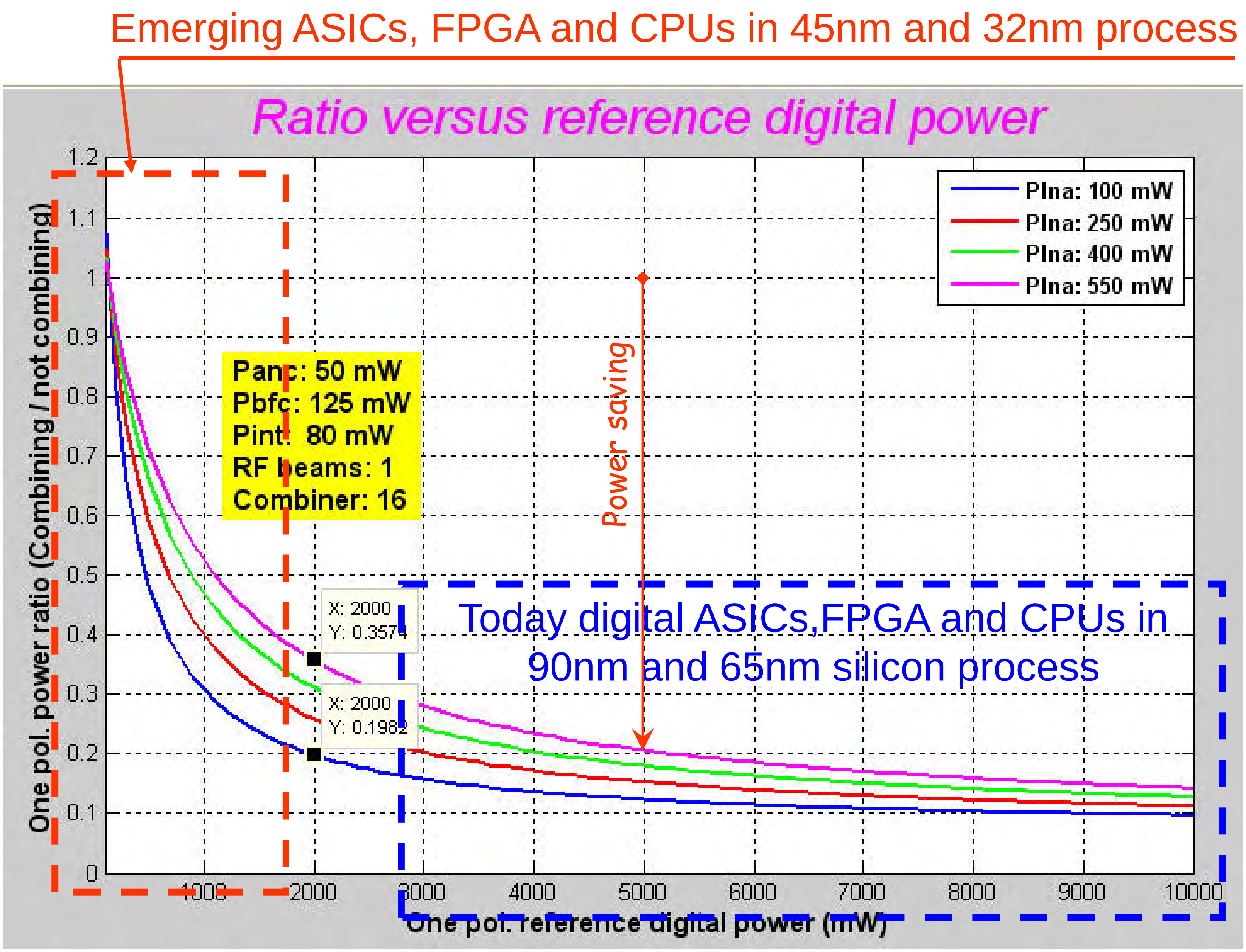
Reference digital power = DC power for one antenna one pol electronics chain

Technology challenges, beamforming (3/5)

AA with RF combining: generic design

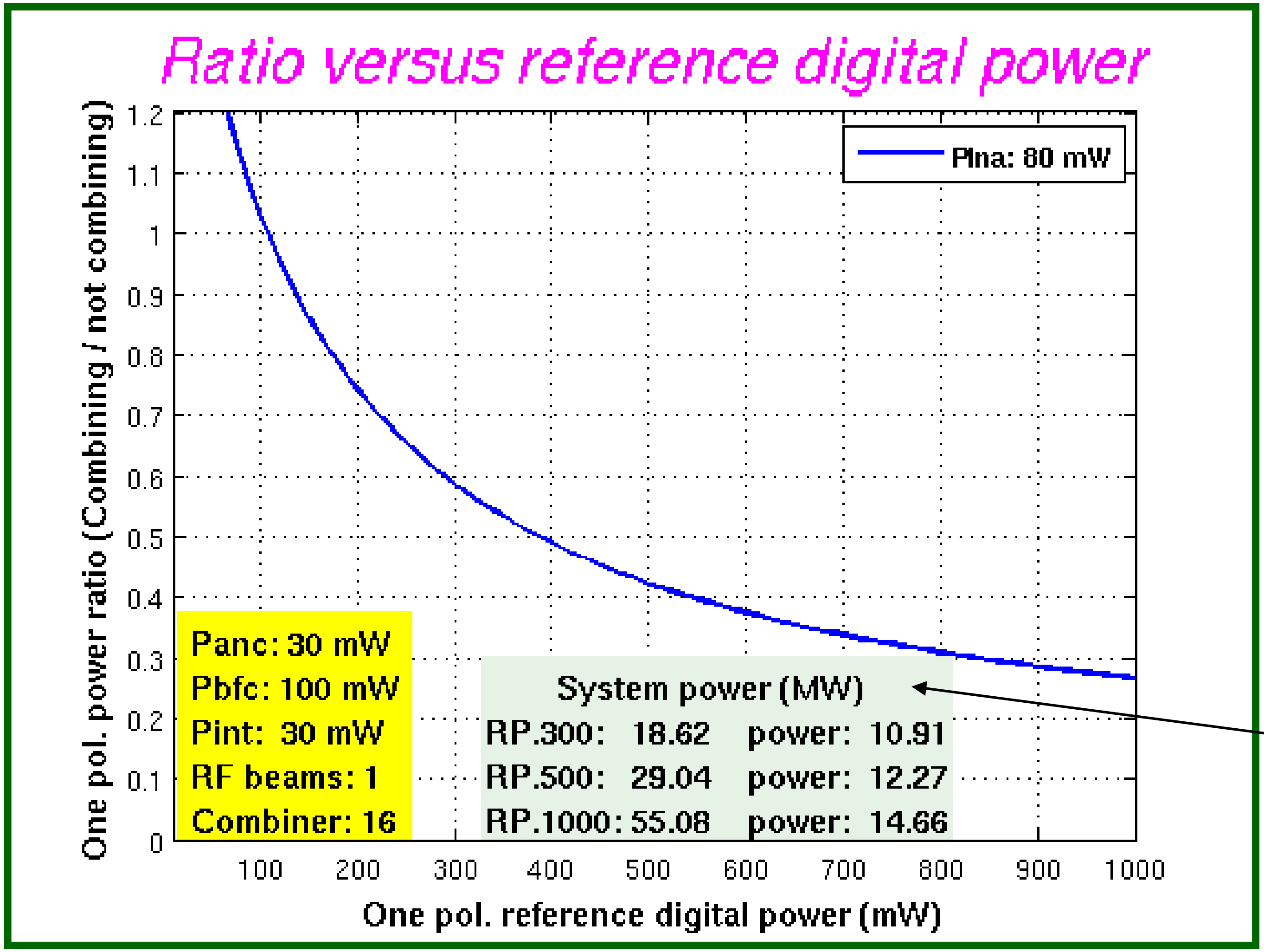


Technology challenges, DC power in AA (4/5)



RF combining efficiency for DC power

Technology challenges, DC power in AA (5/5)



N=75000 antennas
S=250 stations
2 pol.

RF combining efficiency for DC power

Technology challenges, LNA

Aperture Arrays and Phased Array Feeds concepts require a very high number of low power uncooled LNAs with noise figure < 0.35dB.

Here are some simulations results showing the need of futher developments to achieve SKA minimum requirements (from SKADS DS4 deliverable):

Technology	CMOS 90 nm	GaAs 0.5 µm pHEMT	InGaAs-InAlAs pHEMT 1 µm	SiGeC 0.25 µm
Bandwidth (GHz)	0.7 – 1.4	0.6 – 1.6	0.3 - 2	0.5 – 1.7
Power dissipation (mW)	45	852	110	50
Noise Figure (dB)	0.35	0.5	0.45	0.7
IP3 (dBm)	7.5	15.4	14	9
Gain (S21) dB	20.5 – 16.3	29.3 – 20.9	26	17.0 – 16.2

Technology challenges, ADC

For Aperture Arrays and Phased Array Feeds, main parameters for ADCs are:

- Sampling rate: minimum 2.5 Gs/s
- Dynamic range: minimum 4 bits (if RFI free site)
- Very low power
- Low cost (= high manufacturing yield => specific design)

From SKADS DS4-T1 deliverable 11, preliminary results from two suppliers (simulation work) for power requirement are:

e2v report (using SiGe 0.35 µm process):

- 35 mW for ADC core
- 185 mW for full ADC including all Dmux and LVDS circuitry

IBM report (using Cmos 65 or 45 nm process):

- 35 to 45 mW for ADC core
- to be integrated on the same die as the processing chip to avoid large IO power requirements

Technology challenges, signal processing (1/7)

Front end signal processing (station processing):

Subbanding (mainly with polyphase filters)

Apply beamforming weights

Cross correlations

Station Data transport to back-end centre

Back-end signal processing:

Receive data from stations

Internal data routing (refering to operating modes)

Subbanding

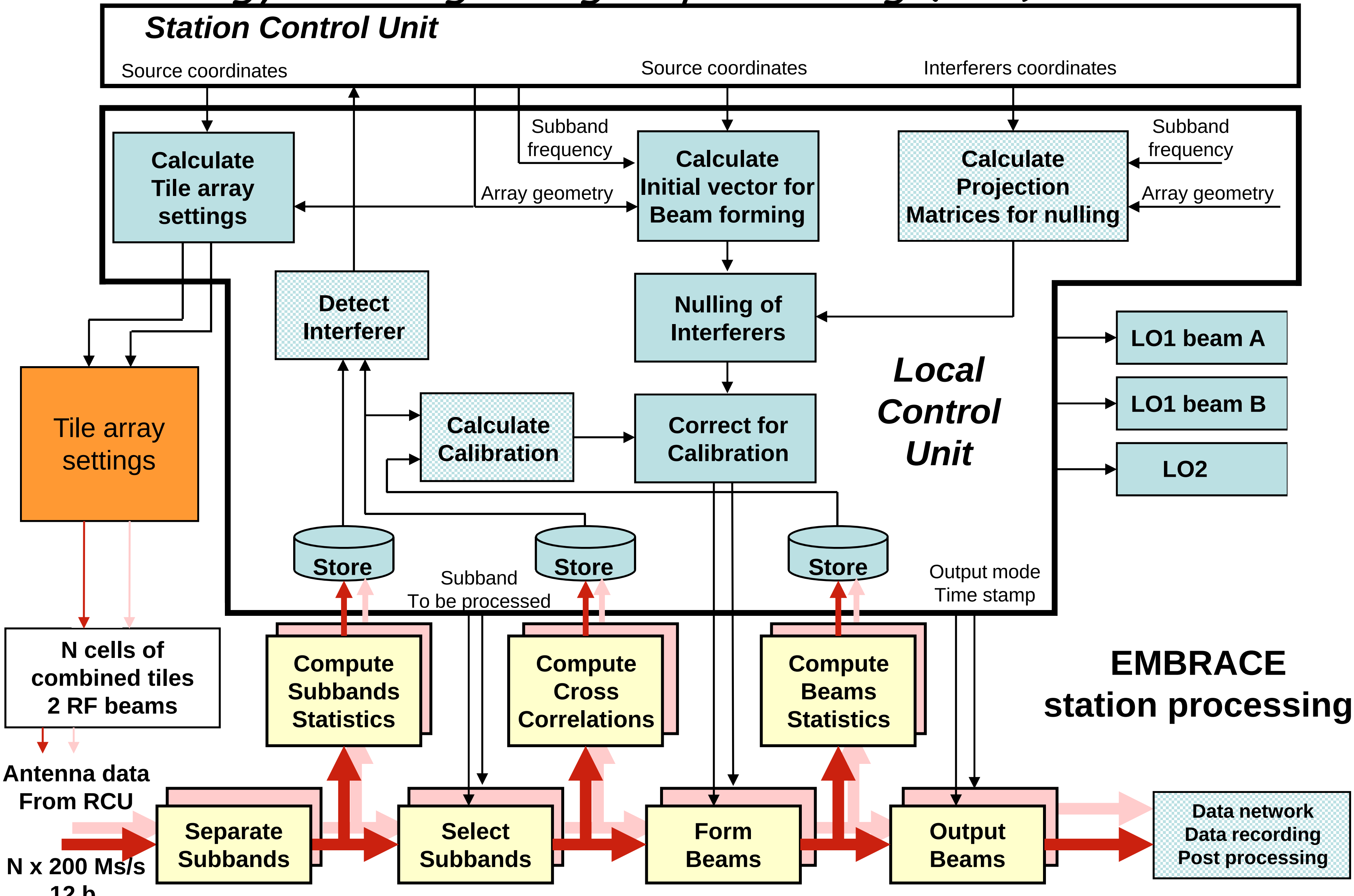
+ RFI mitigation ?

Beamforming: compute / apply beamforming weights

Cross correlations

Data output to data centres

Technology challenges, signal processing (2/7)



Technology challenges, signal processing (3/7)

With high number of antenna elements and wide operating bandwidth, signal processing requirements for SKA will be more than one magnitude larger than emerging instruments such as LOFAR or ALMA.

The table (next slide) shows signal processing requirements for emerging instruments and comes from the SKADS DS3-T6 deliverable D1/M9

Used parameters are:

Number of stations	# stations
Number of Fiels of View	# FoV
Instantaneous correlator / beamformer bandwith per FoV	B/FoV
Number of frequency channels	fchan
Number of tera complex multiply-add computation	TCMACS
Power requirements	Power
Technology used	Technology

Technology challenges, signal processing (4/7)

	# stations	# FoV	B / FoV (MHz)	# fchan	TCMACS	Power (kW)	Technology
LOFAR RSP (remote station)	96 (antennas)	160 (248)	0.2	1	0.6	3	FPGA 90nm
LOFAR compact	32	24	32	32000	1.6	40	PowerPC 130nm
eVLA	32	4	2000	2000	16.4	100	ASIC 130nm FPGA 90nm
ALMA	64	4	2000	2000	65.5	100	ASIC FPGA
SKA high F	300	2	2000	32000	720	?	?
SKA low F	300	20	200	32000	720	?	?

Processing requirements of emerging instruments

Technology challenges, signal processing (5/7)

Plenty of chip technologies are available for digital processing, main parameters to choose the optimum one for specific application are listed below:

- Amount of processing power (Gop/s)
- IO bandwidth (GB/s)
- Flexibility to change algorithms
- Power consumption (W)
- Cost
- Development time

The following table coming from the SKADS DS3_T2 deliverable summarizes the advantages and disadvantages of main computing technologies

Technology challenges, signal processing (6/7)

	Op/s	IO bandw.	Flexibility	Watts	Volume	Cost	Time
CPU	+ -	- -	+ +	- -	- -	+ +	+ +
GPU	+ -	- -	+ -	- -	- -	+ +	+ +
DSP	+ -	+ -	+ -	- -	- -	+ -	+ -
FPGA	+ +	+ +	-	+ -	+ -	-	-
FPGA for high volume	+ +	+ +	- -	+	+	-	-
ASSP	+ +	+ +	- -	+ +	+ +	-	--
ASIC	+ +	+ +	- -	+ +	+ +	- -	- -
CELL	+	+ -	+	-	-	- -	+ -
Supercomputer	+	+ -	+	-	-	- -	+

"Software solutions", high flexibility, low cost and short development time

"Hardware solutions", no flexibility, low power, high to very high development time

Of the shown solutions, Supercomputer is at system level, others are at chip level

Technology challenges, signal processing (7/7)

Emerging interconnect technologies

High data rate interconnections are required at various system levels:

Chip to chip interconnections

Total data rate from 15 GB/s up to 50 GB/s are available in emerging chips

Board to Board interconnections

Backplane with 20 GB/s data rate are emerging

Cabinet to Cabinet interconnections

Ethernet 10Gb/s over copper or optical, from a few meters up to a few kilometers
Infiniband 40Gb/s over copper, a few meters, low latency and low power
SONET/SDH long distance optical link and interface standard, current data rate 40Gb/s, 80 and 160 Gb/s to come

E.C. developments towards SKA (1/3)

Ongoing developments under SKADS (E.C. FP6) and PrepSKA (E.C. FP7):

- Antenna elements for aperture arrays and phased array feeds
- LNA (Cmos, SiGe, AsGa)
- Low cost front ends (aperture array tiles)
- Cooling system for phased array feeds
- RF beamforming: Beamformer chip
- Digital beamforming
- Array layout
- Signal transport
- Calibration

E.C. funded developments to promote the Aperture Array concept

E.C. developments towards SKA (2/3)

AA technology demonstrators under SKADS program, 2005-2009

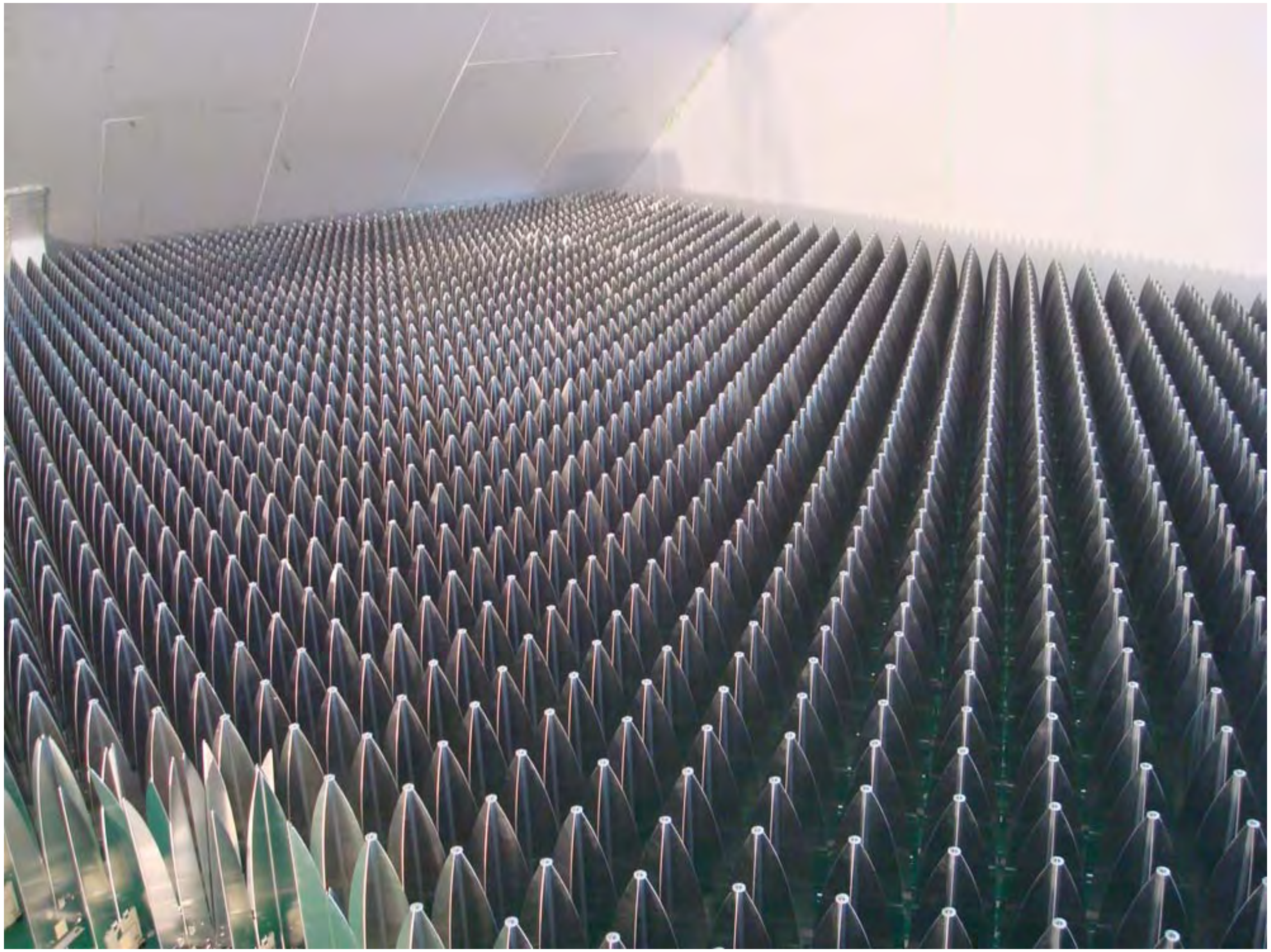
2-PAD
AA tiles using all digital beamforming, a few m² (UK)
0,2 to 0,5 GHz

EMBRACE
160m² (WSRT, NL) and 90 m² (Nançay, FR) AA stations
1,06 x 1,06 tiles, 2x72 Vivaldi elements (only one pol. electronics)
0,5 to 1,5 GHz

BEST
Linear Array at cylindrical reflector focus (Northern Cross, Medicina IT)
408 MHz

AA science demonstrator under AAVP program (2010-2012):
2000 to 3000 m² AA

E.C. developments towards SKA (3/3)



60 AA tiles at Westerbork EMBRACE station (less than half final array)

SKA pathfinder and precursors (1/2)

ATA (USA) - Pathfinder

Up to 350 dishes, Ø 6m
Feed: Wideband single pixel
Frequency range: 0.5 to 11 Ghz

Max. baseline: a few km
Operation: ATA 42 since end of 2007 – future enlargement?

MeerKAT (South Africa)

Up to 80 dishes, Ø12m
Feed: 2:1 corrugated horns + wideband feeds ?
Frequency range: 0.7 to 10 GHz
Instantaneous bandwidth: 1 GHz

Max. baseline: 8 km ; with flexible beam size (6-60 arcsec)
Fully operational by 2013

Beta phase KAT-7: 7 antennas on site by the end of 2009

SKA pathfinder and precursors (2/2)

ASKAP (Australia)

Array of 36 dishes Ø12m with Phased Array Feed

- Frequency range 0.7 to 1.8 GHz
- Instantaneous bandwidth 300 MHz
- T_{sys} 50 K after beamforming
- 30 independent beams of 1 sq deg each @ 1.4 GHz
- Cross correlation on a per beam basis
- FoV: 30 sq deg @ 1.4 GHz
- Max. baseline 6 km (optimized for beam size of 30 arcsec)

Western Australia site (Murchison Radio Observatory), very low RFI environment

Digital beamforming per antenna: ~100 dual pol elements
After sub-banding, beamforming in each subband by a weighted sum of all elements, up to 30 beams in each subband.
Cross correlation of all same beams for all antennas

Beta phase of six antennas by 2011
Fully operational by 2013

Thank you