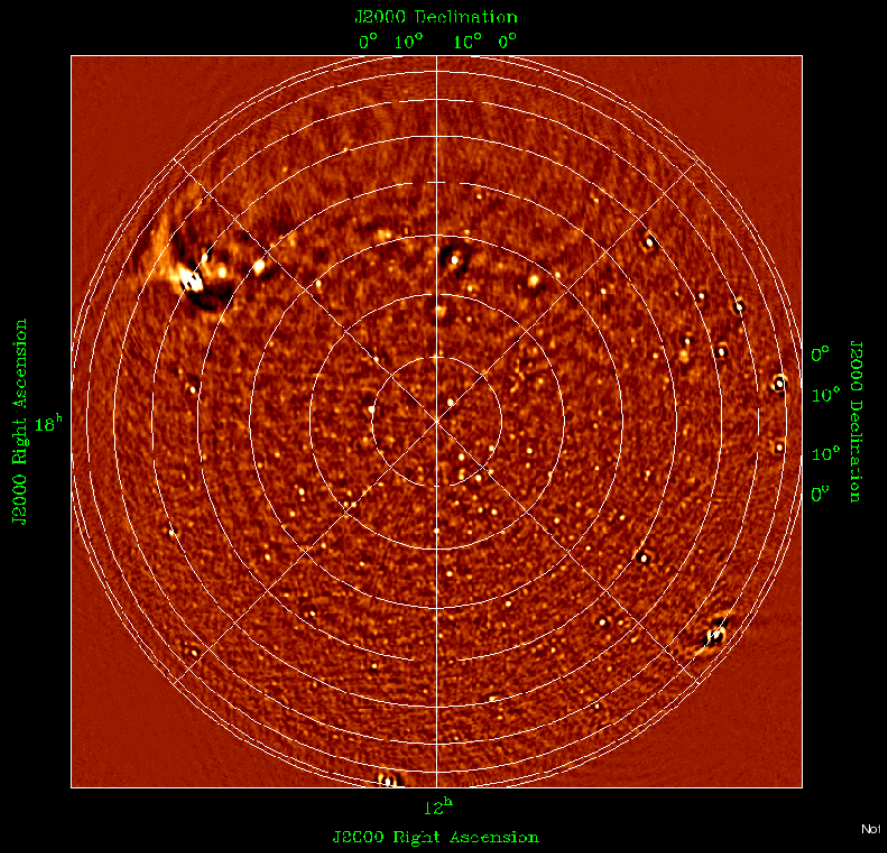
Applications of Digital Processing in LOFAR

André W. Gunst



Contents

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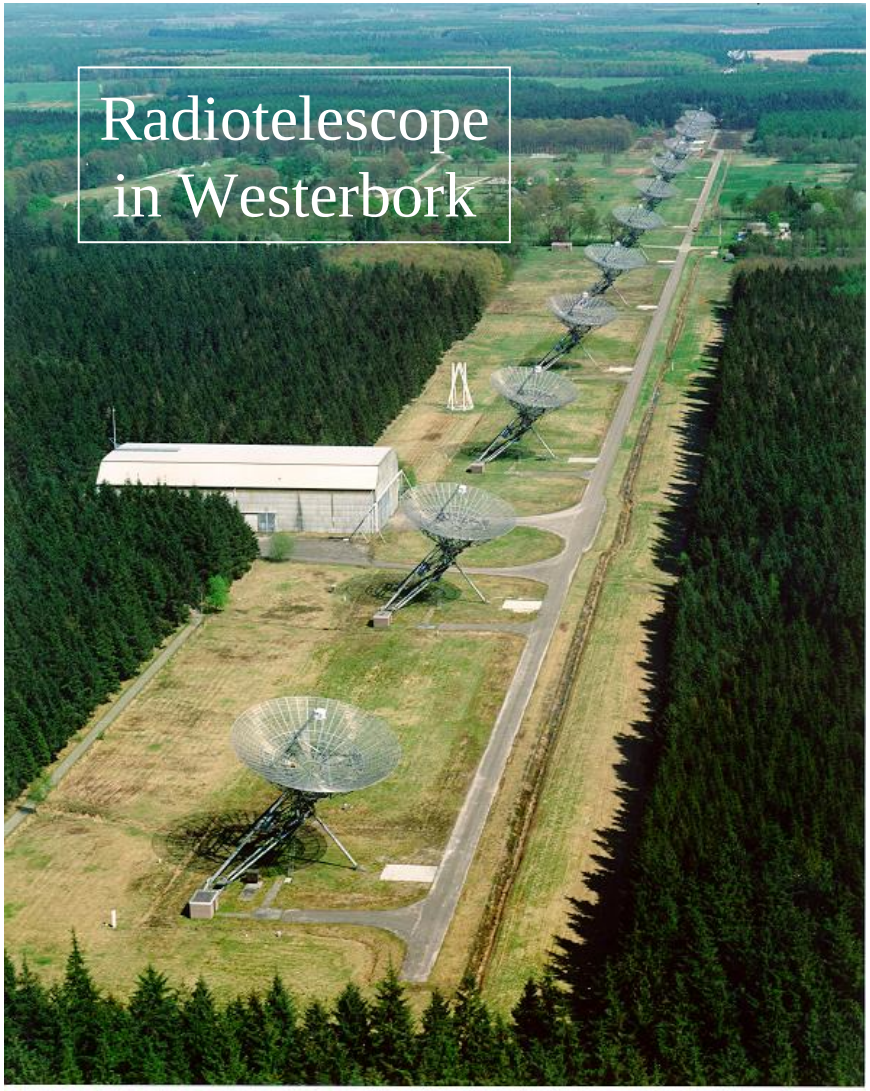
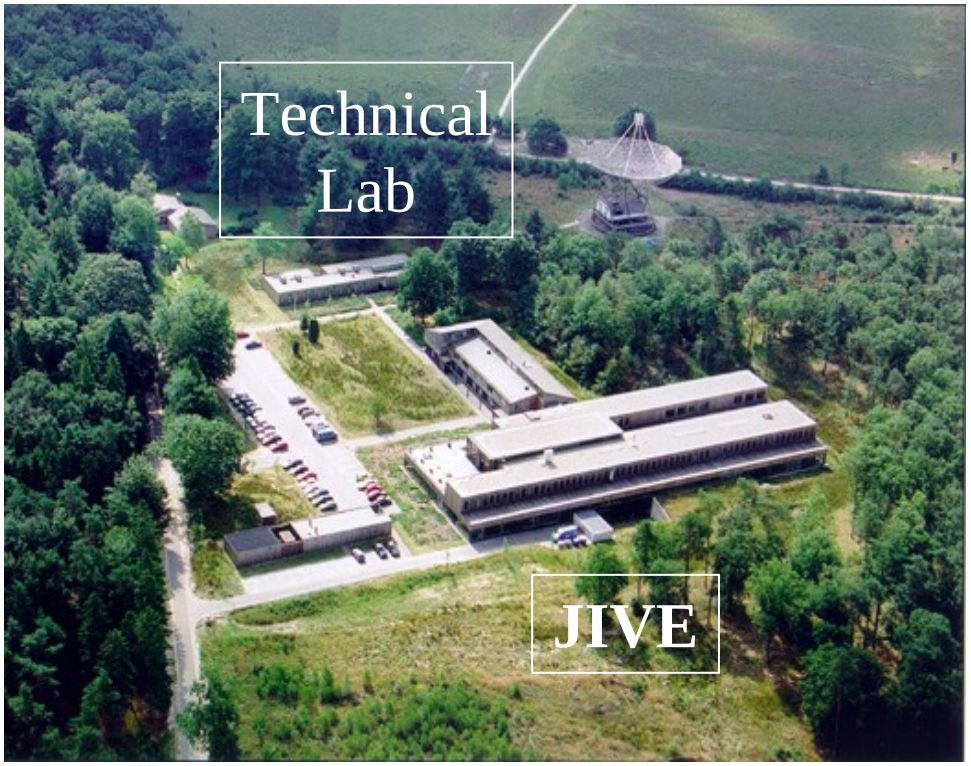
- LOFAR System Overview
- LOFAR Station Processing
- LOFAR Data Transport
- LOFAR Central Processing
- Beyond LOFAR
- Status and Conclusions

ASTRON Institute



- Radiosterrenwacht
- Technisch laboratorium
- Internationale samenwerking
  - Joint Institute for VLBI in Europe



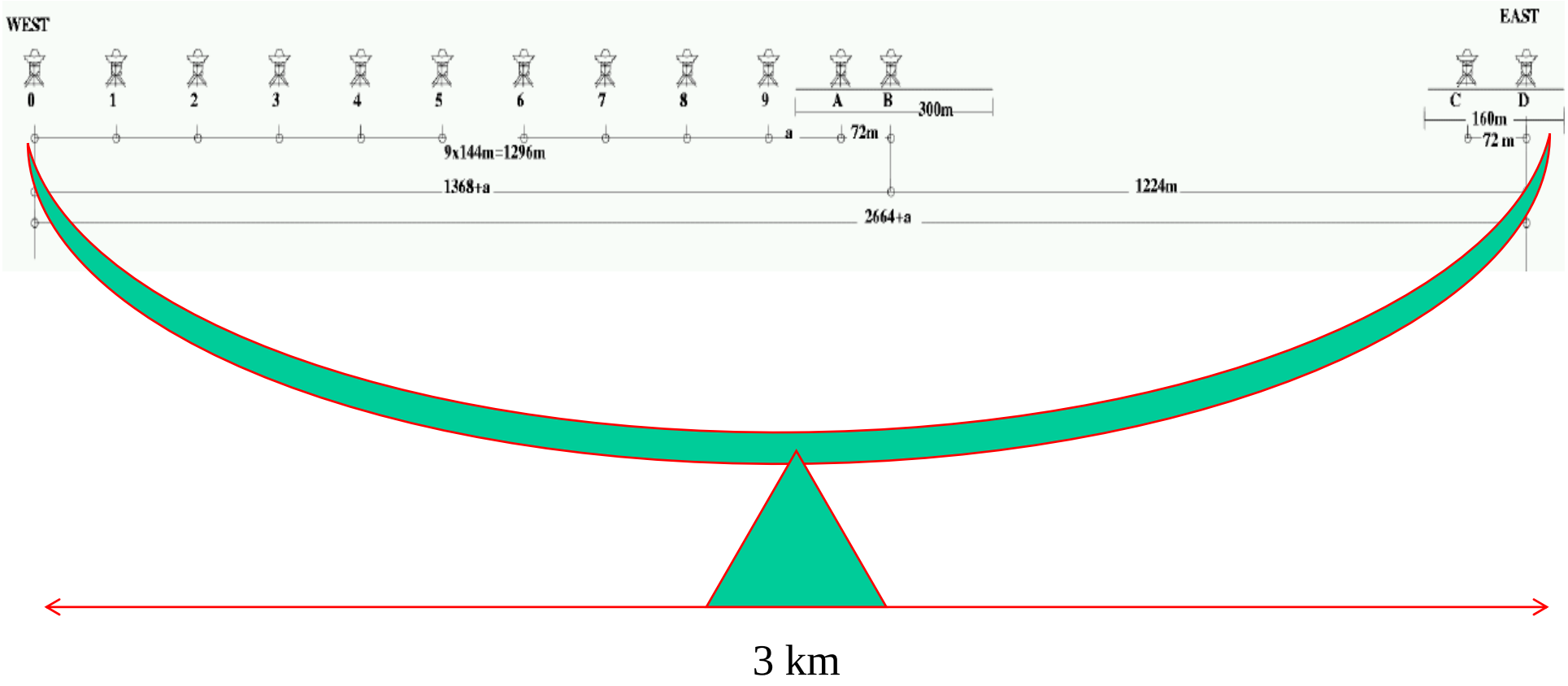
- Enabling discovery in astronomy through innovative instrumentation and facilities management.

Wish List Astronomers

- Astronomers like:
  - Better angular resolution
  - Larger field of view
  - More sensitivity
  - Larger instantanous bandwidth
  - Observe at multiple frequencies

- So, better telescopes …

Radio Synthese

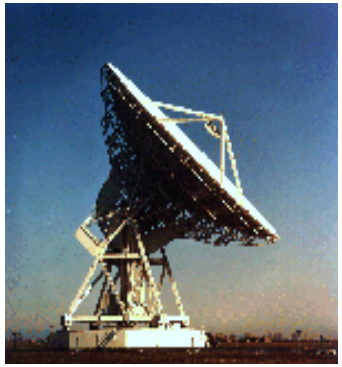


ASTRON *Westerbork Synthesis Radio Telescope*

- Diameter 3 km
- 14 telescopes

ASTRON *Joint Institute for VLBI in Europe (JIVE)*





Telescopes in Europe and China

Synchronous observations stored on tapes

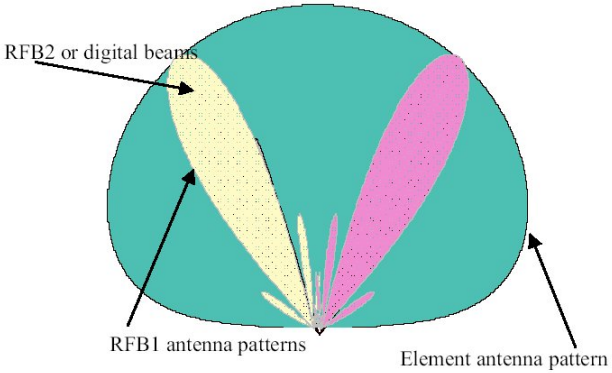
Send to supercomputer in Dwingeloo

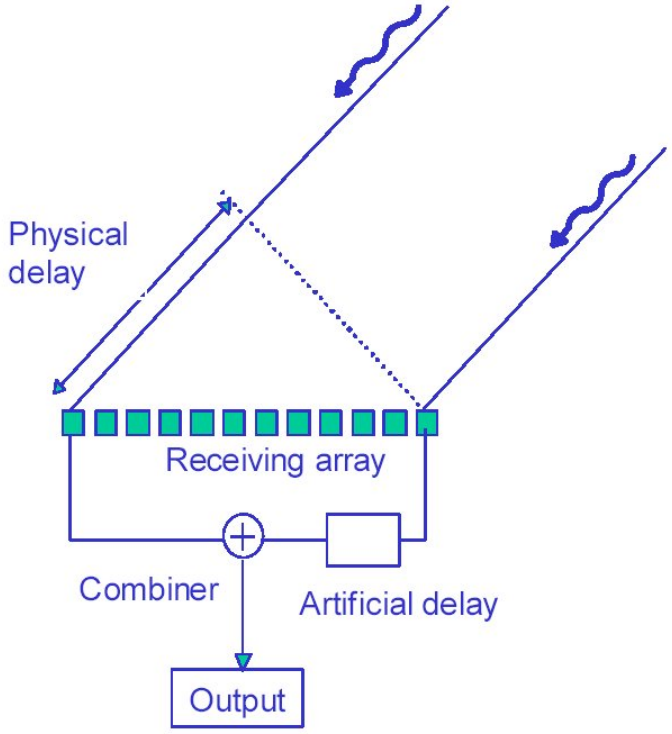
“Telescope” as large as Europe!

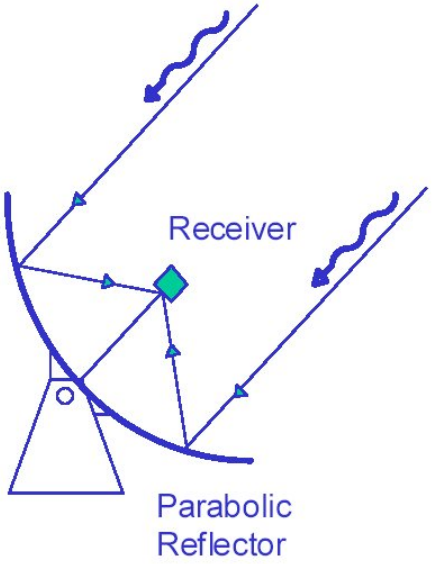
Breakthrough…

- No big dishes anymore:
  - Many small antennas
    - No maintenance, mass production
  - Electronically pointing
    - Multiple instantanous beams
    - Possibility to suppress RFI
- Now is the time:
  - Computers cheap
  - Broadband data networks available

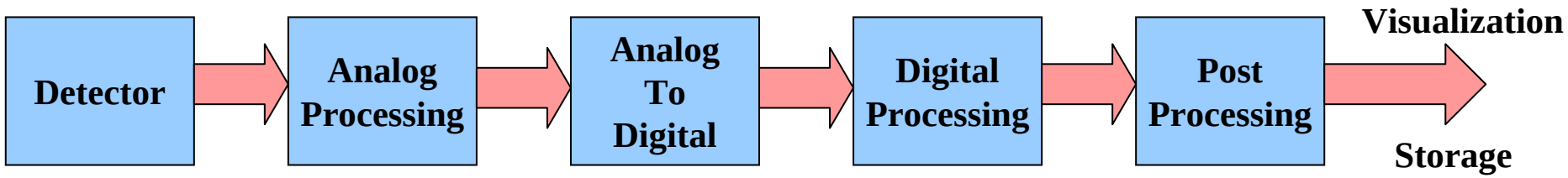
"Phased array" principe





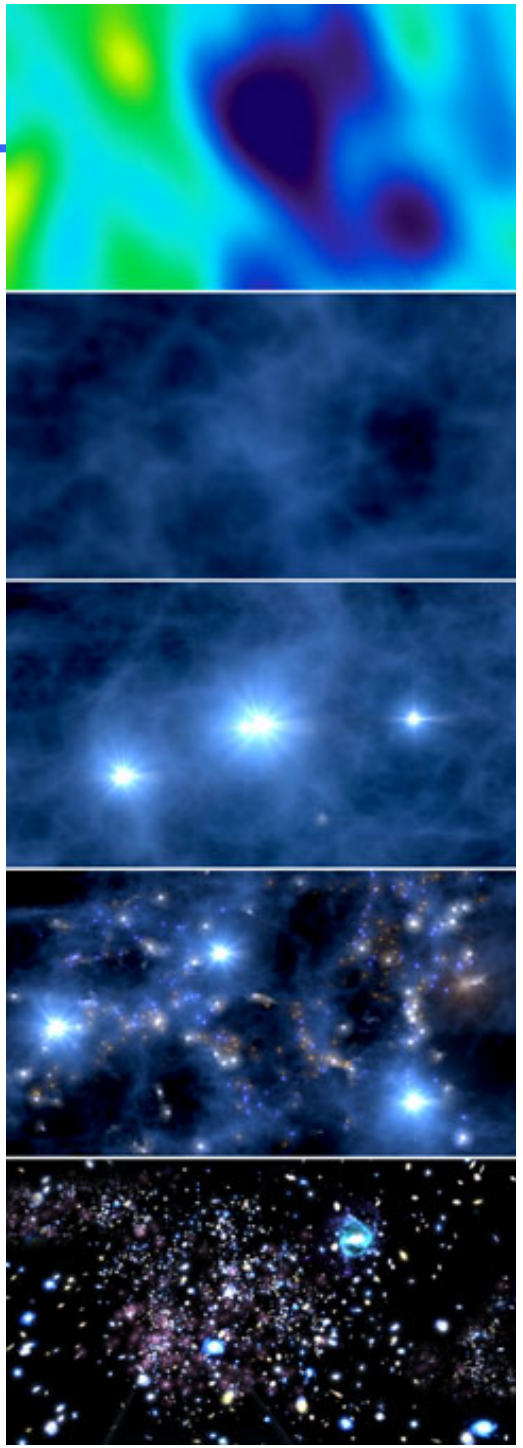


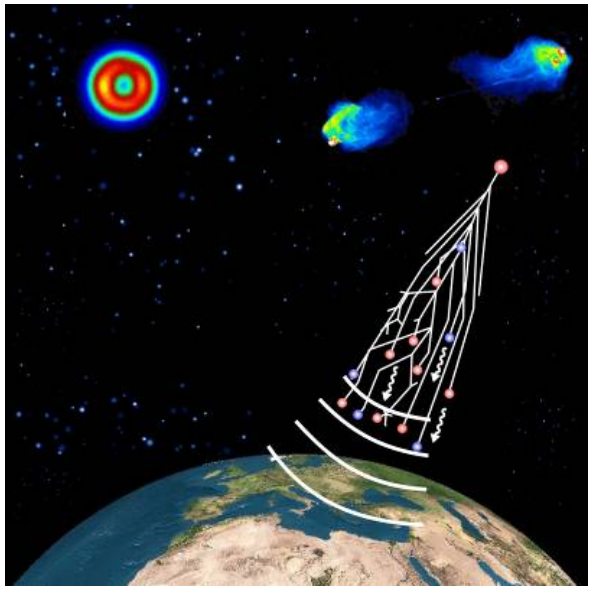
Radio Receiving System Overview

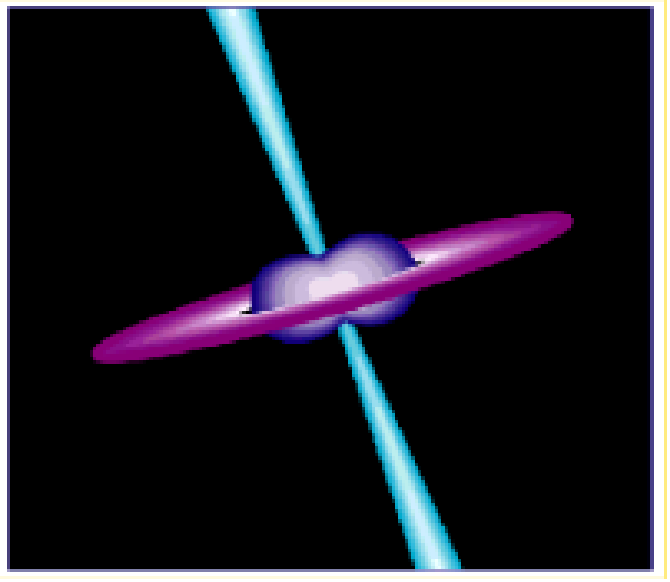


- Trend:
  - Digital hardware moves to more to the antenna

- Epoch of Reionization
- Extragalactic Surveys
- Transients and Pulsars
- Cosmic Rays
- And new discoveries …





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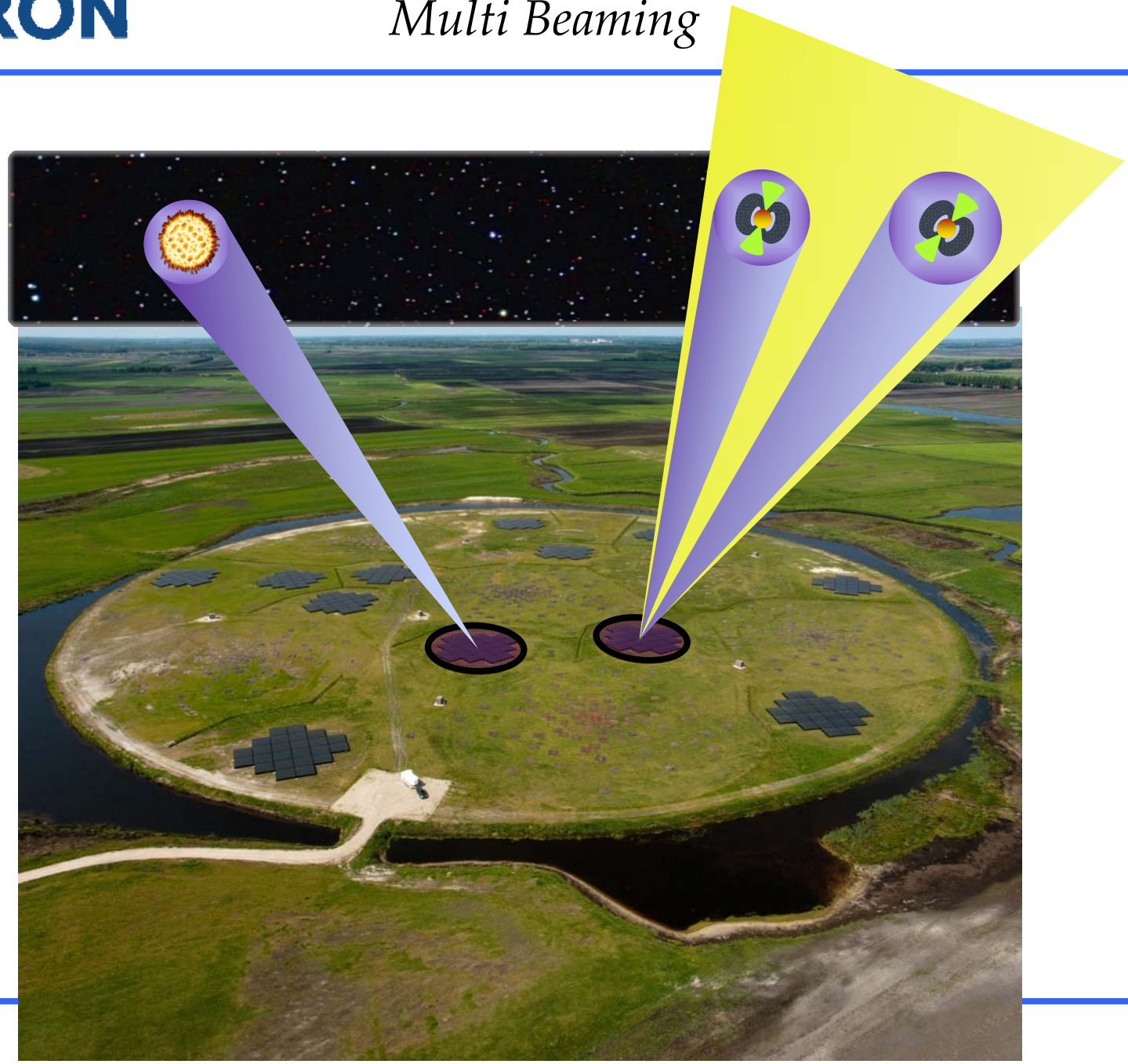
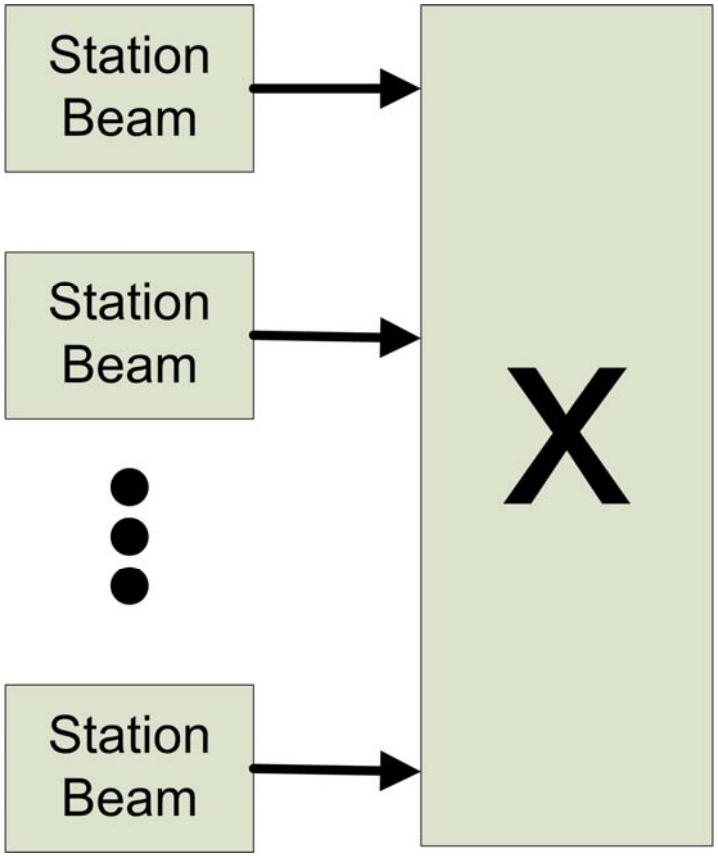
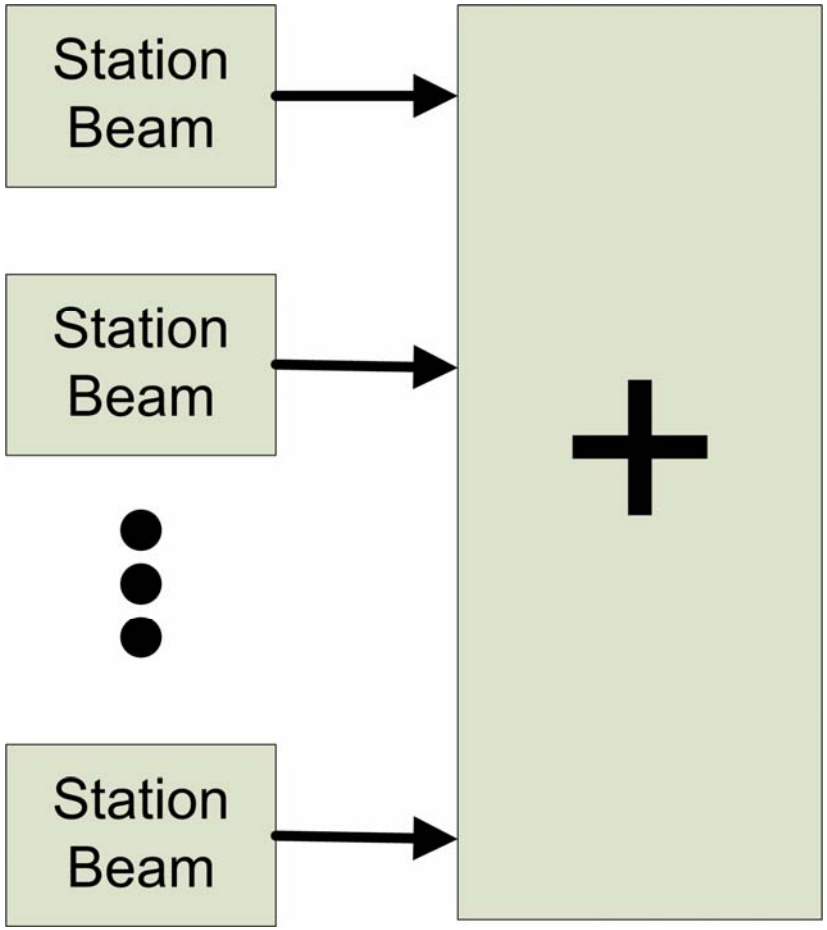
Multi Beaming

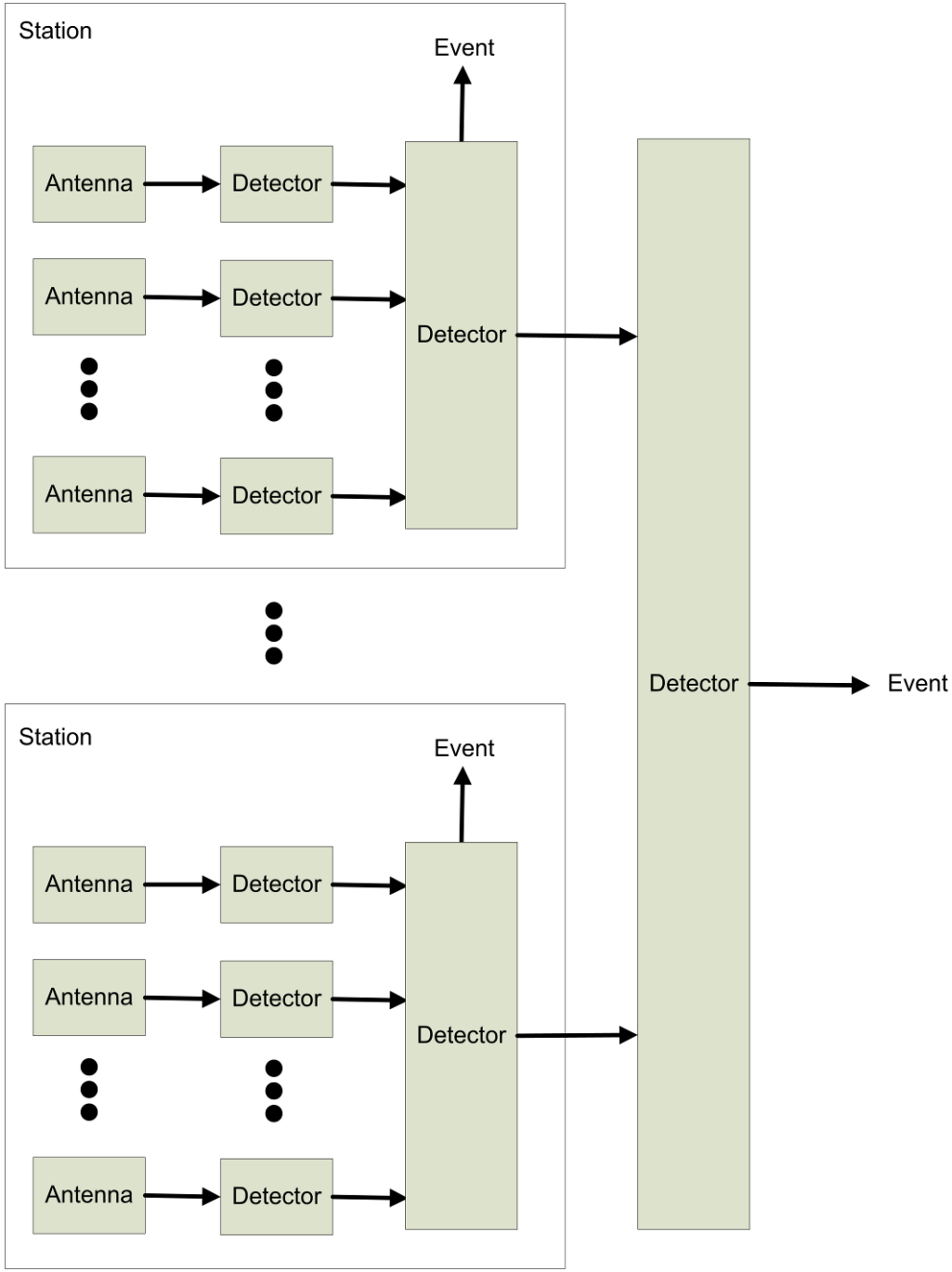


Aperture synthesis mode

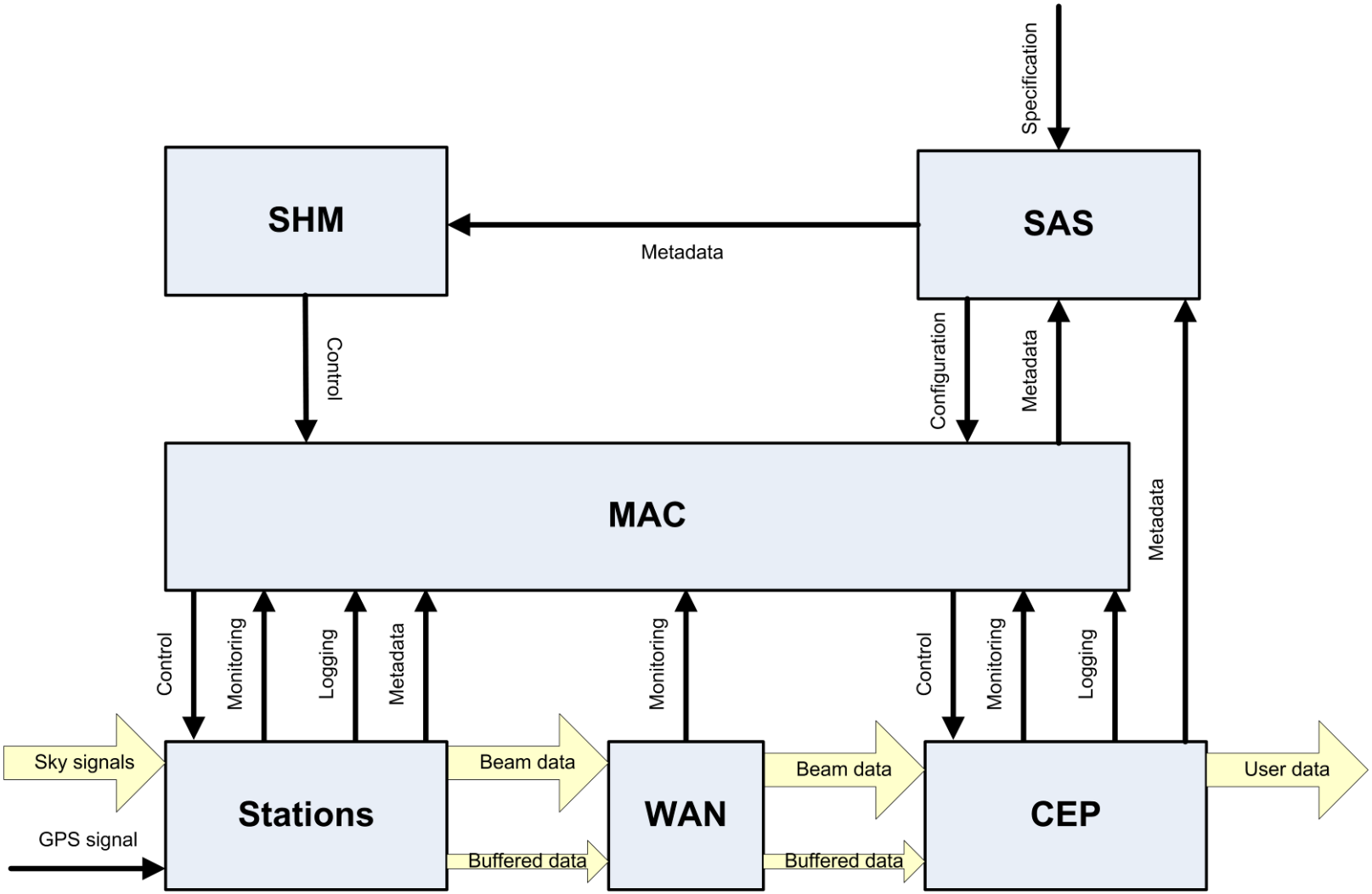


Tied-array mode

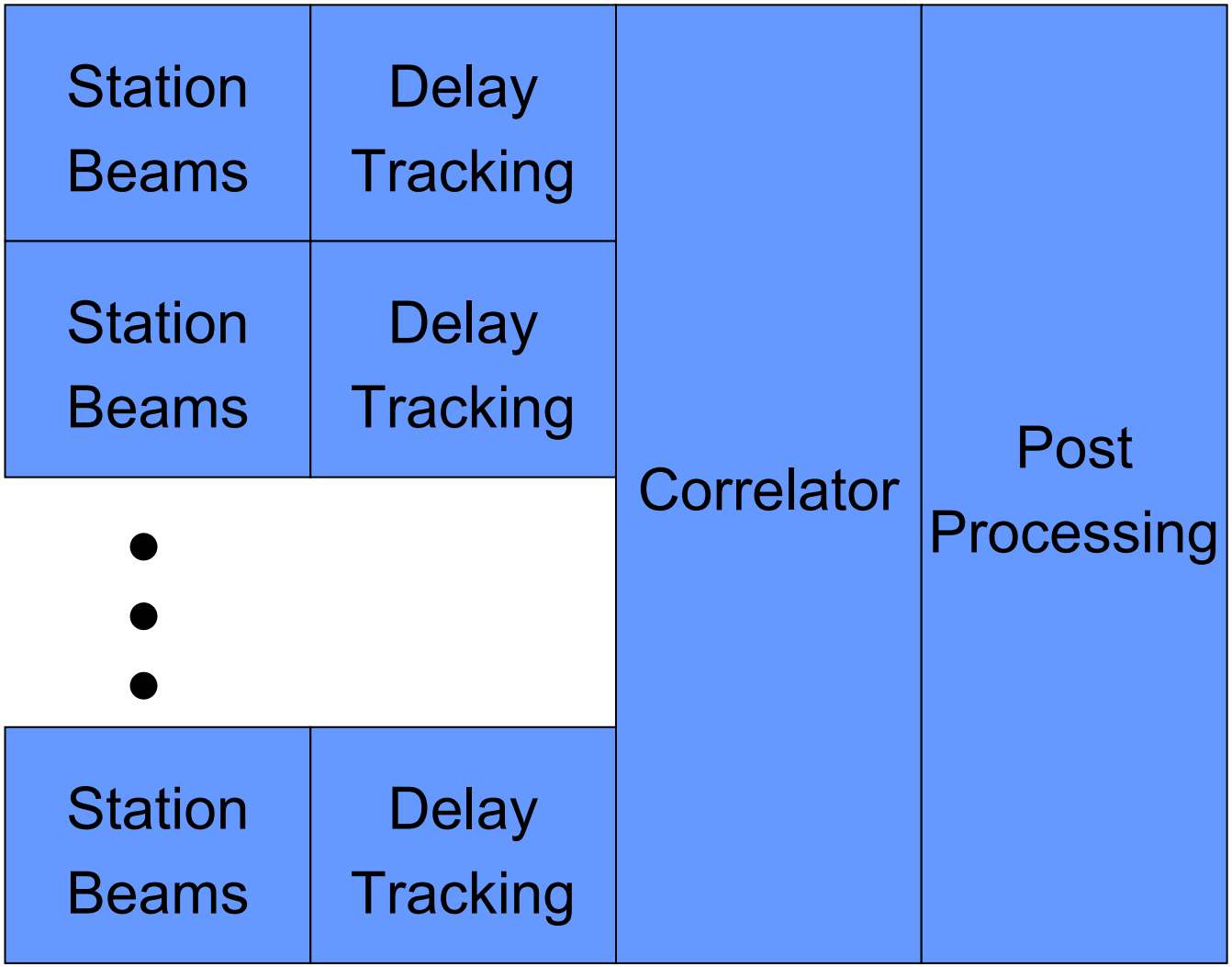



Station
Event
Antenna
Detector
Antenna
Detector
Detector
Antenna
Detector
Detector
Event
Station
Event
Antenna
Detector
Antenna
Detector
Detector
Antenna
Detector

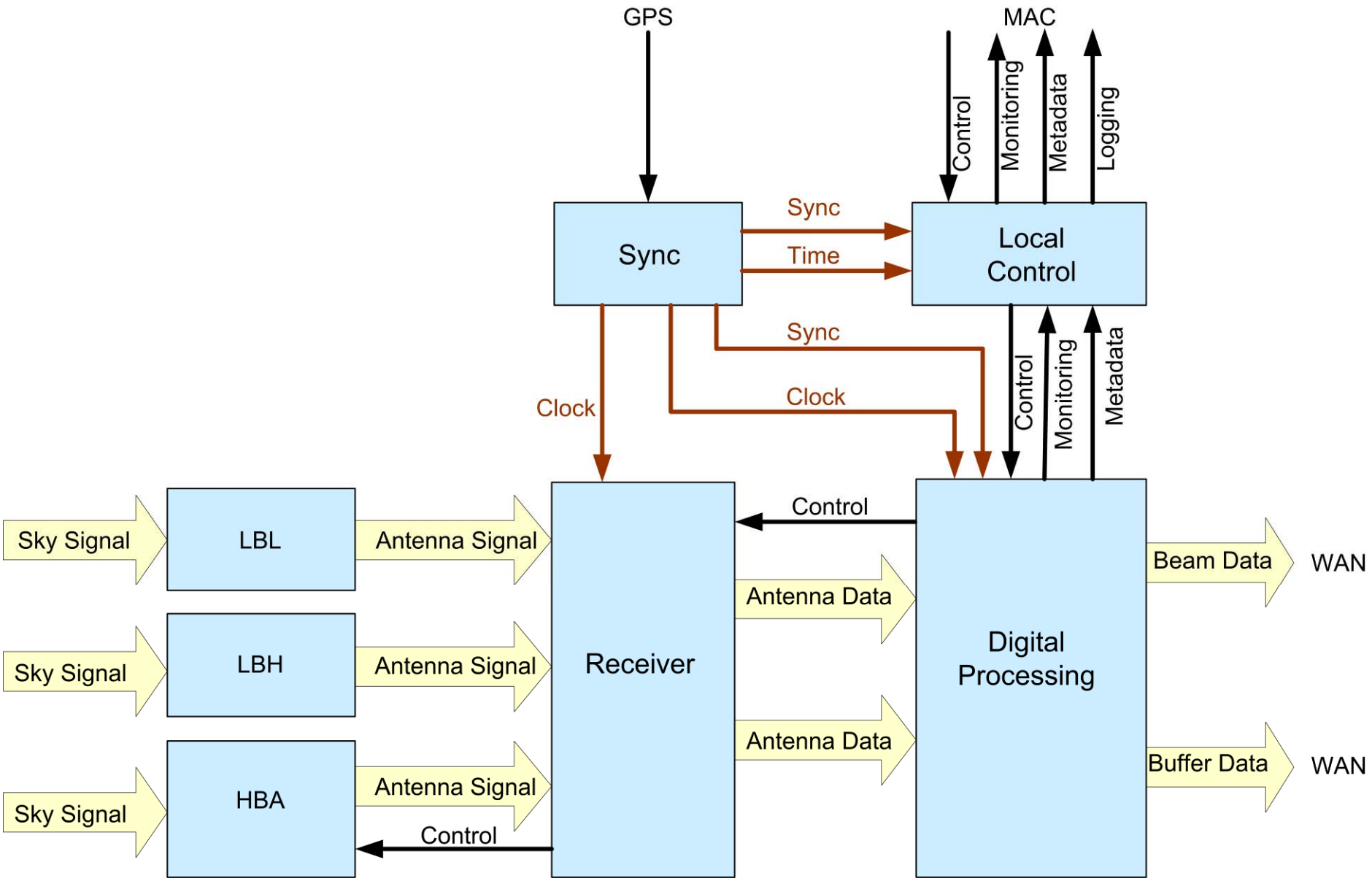
Top Level Architecture



System Data Flow



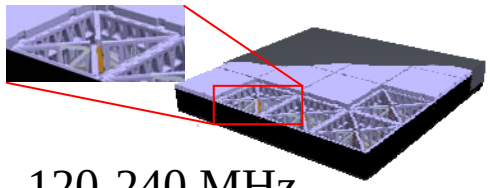
Station Architecture



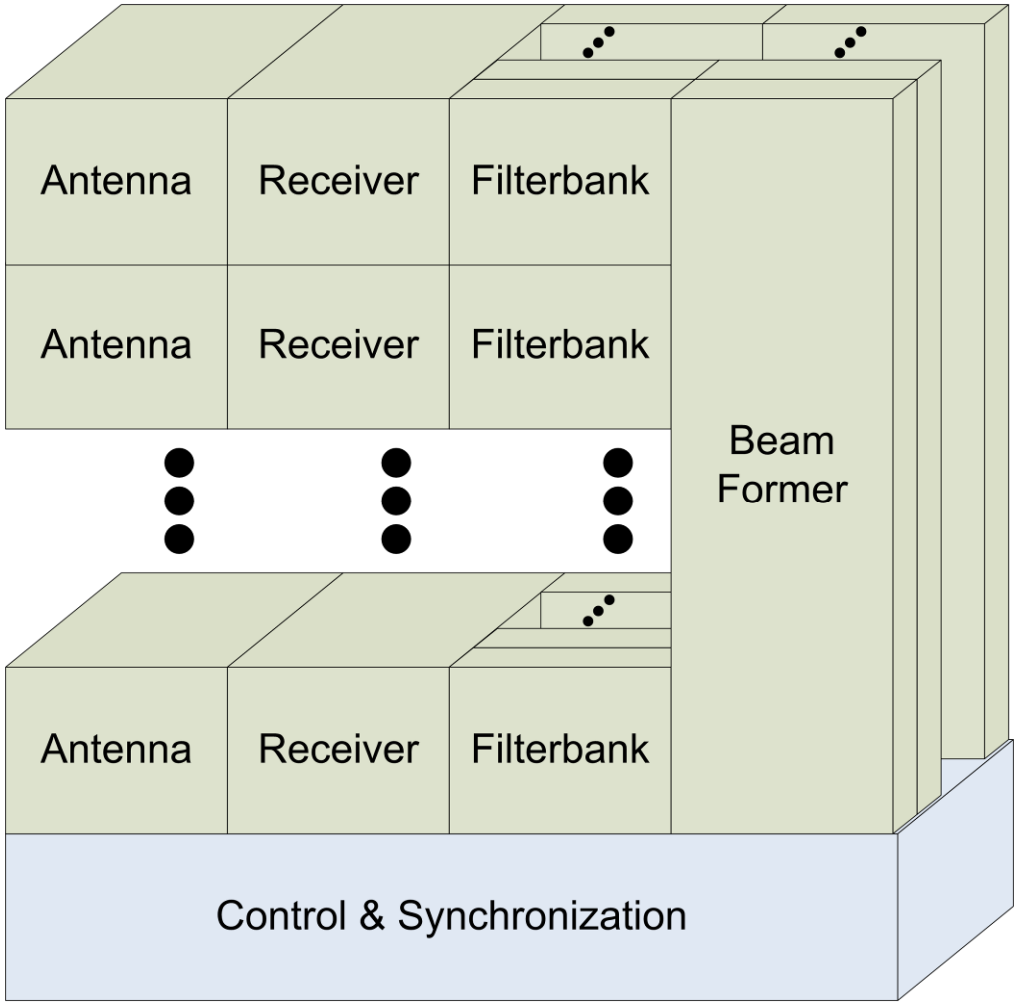
Station Signal Processing

Optional
10- … MHz

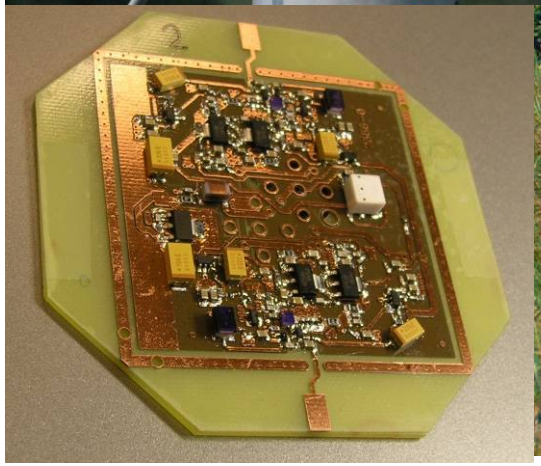
30-80 MHz

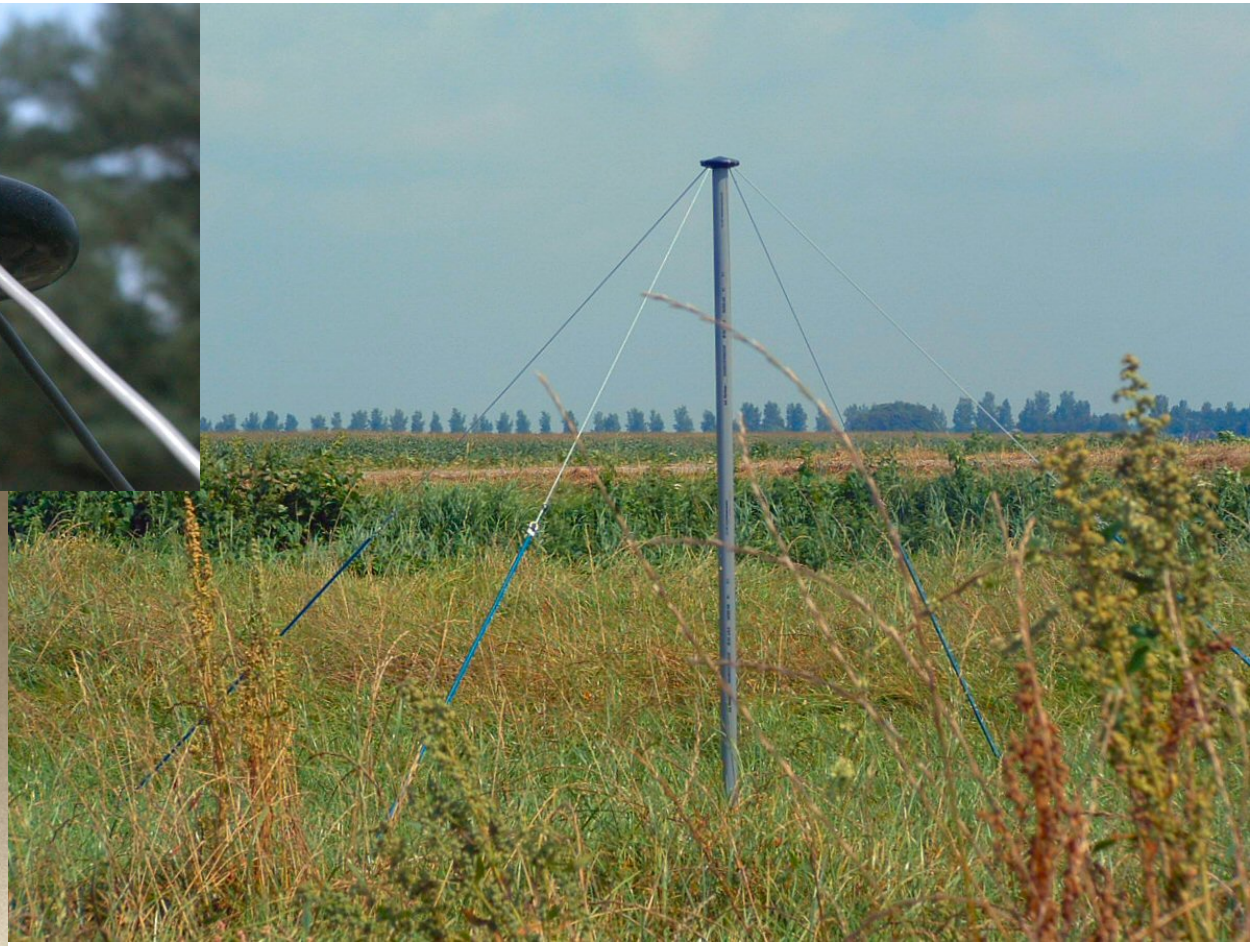


120-240 MHz

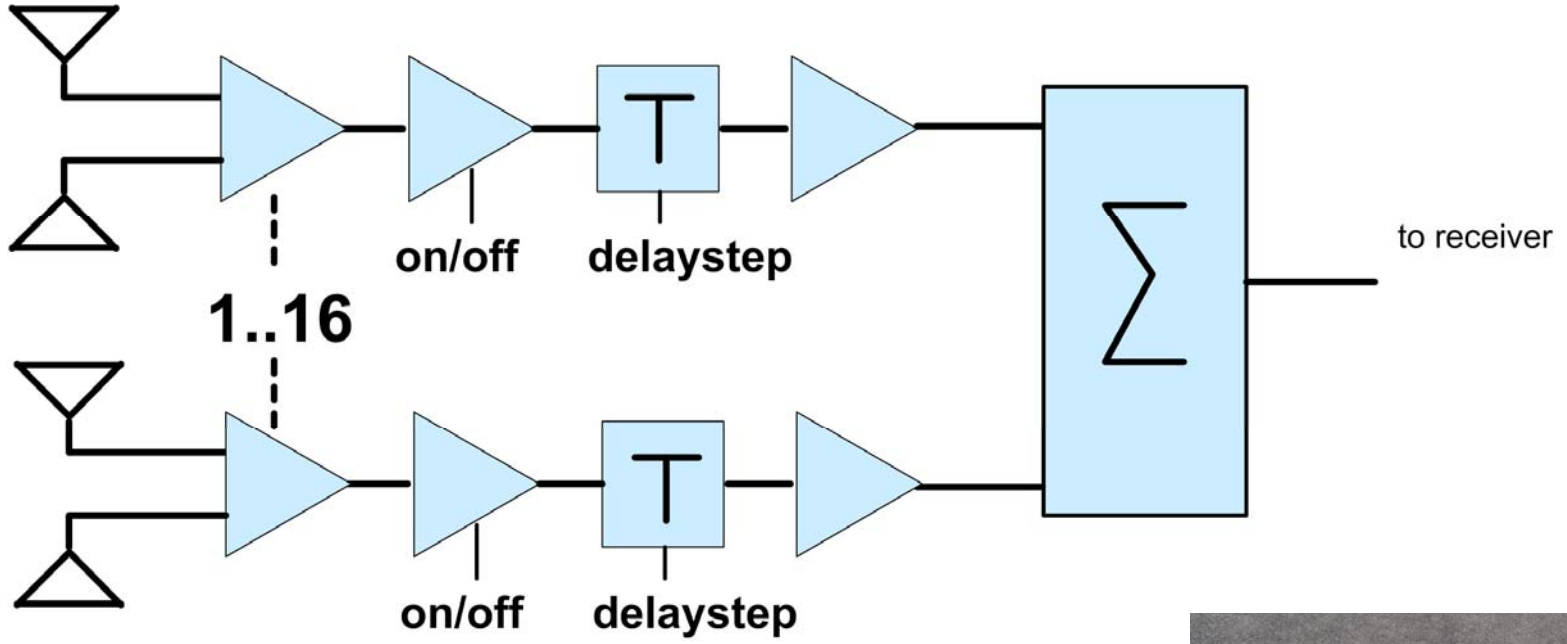


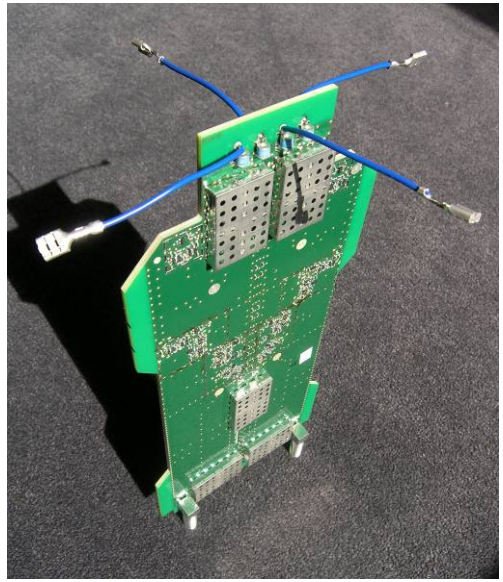
Low Band Antenna (30-80 MHz)





High Band Antenna





- Delay necessary for 1.25m and regular tile:

  3 x 1.25 x sqrt(2) = 5.3 m ➔ 17.6 ns

- 85% of that is 15.03 ns

bit	delay (ns)
0	0.47
1	0.94
2	1.88
3	3.76
4	7.51
Total	15.03

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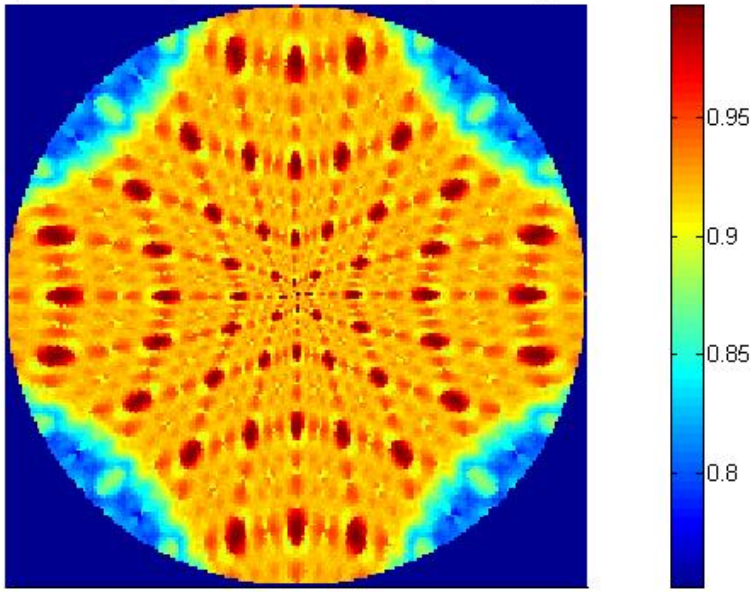
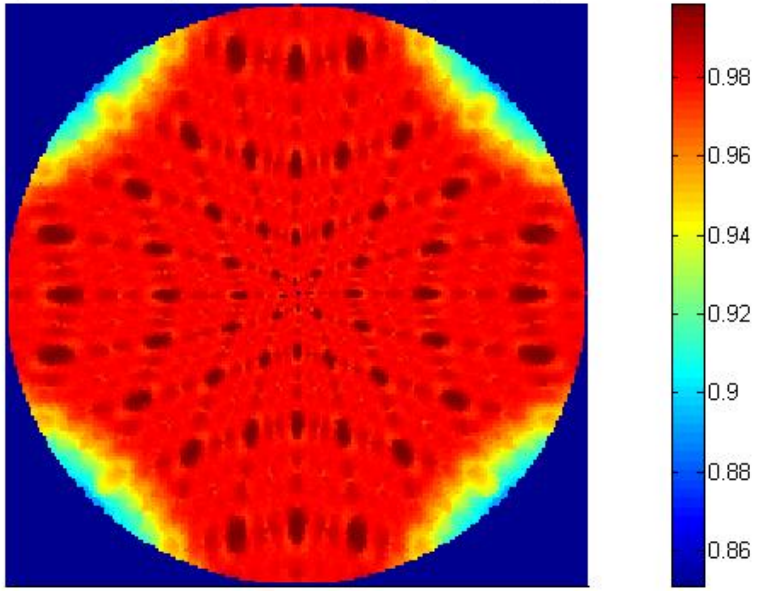
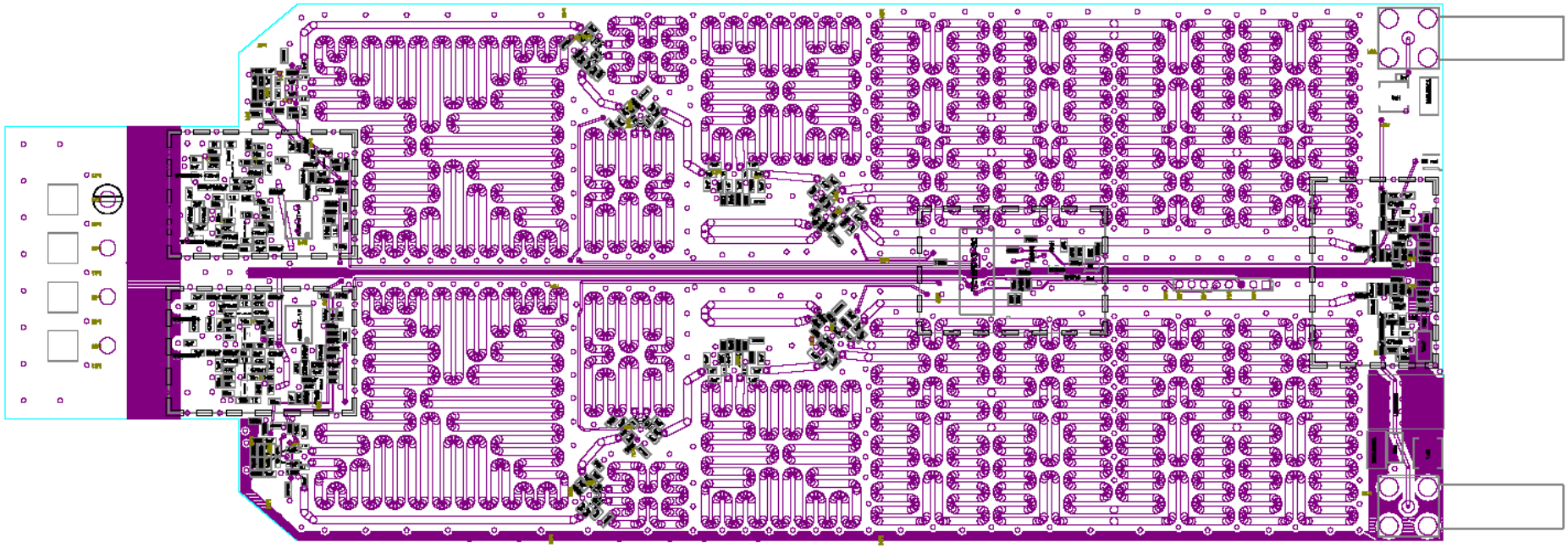
Efficiency for a time delay of 85% the maximal length for 5 bit @ 240 MHz

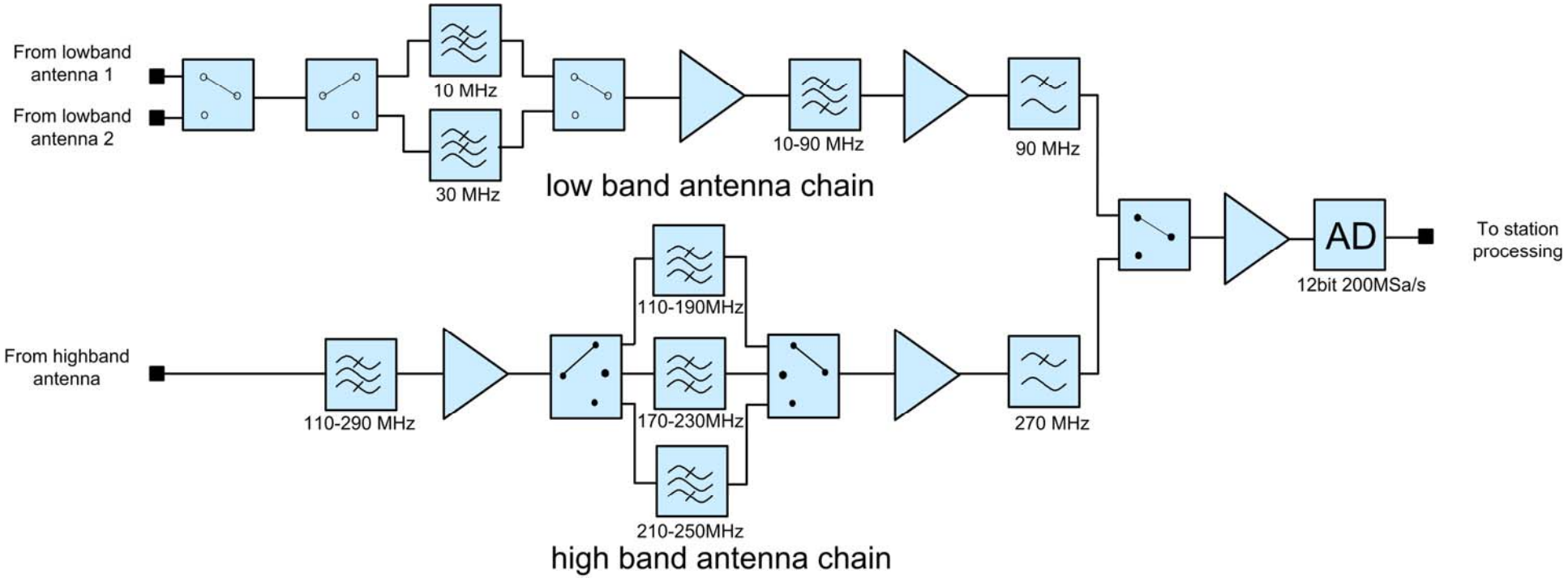


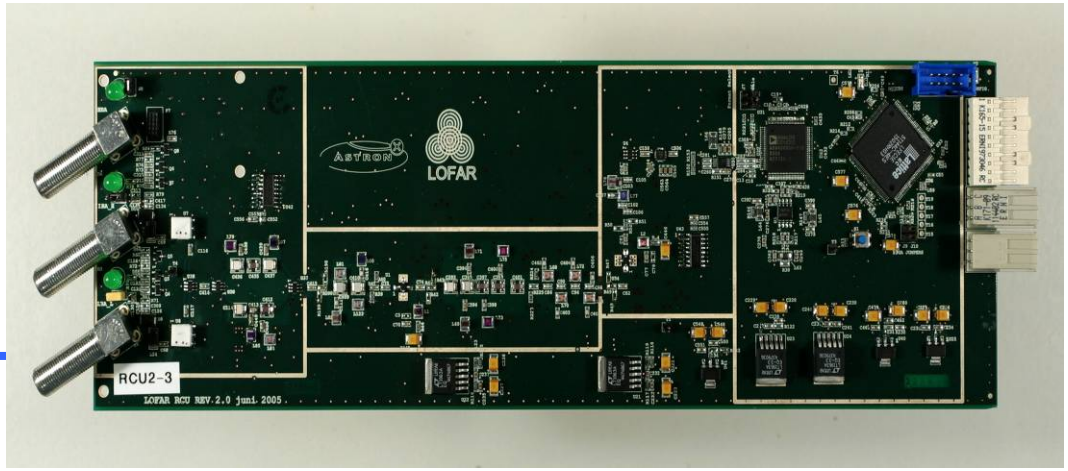
Efficiency for a time delay of 85% the maximal length for 5 bit @ 120 MHz



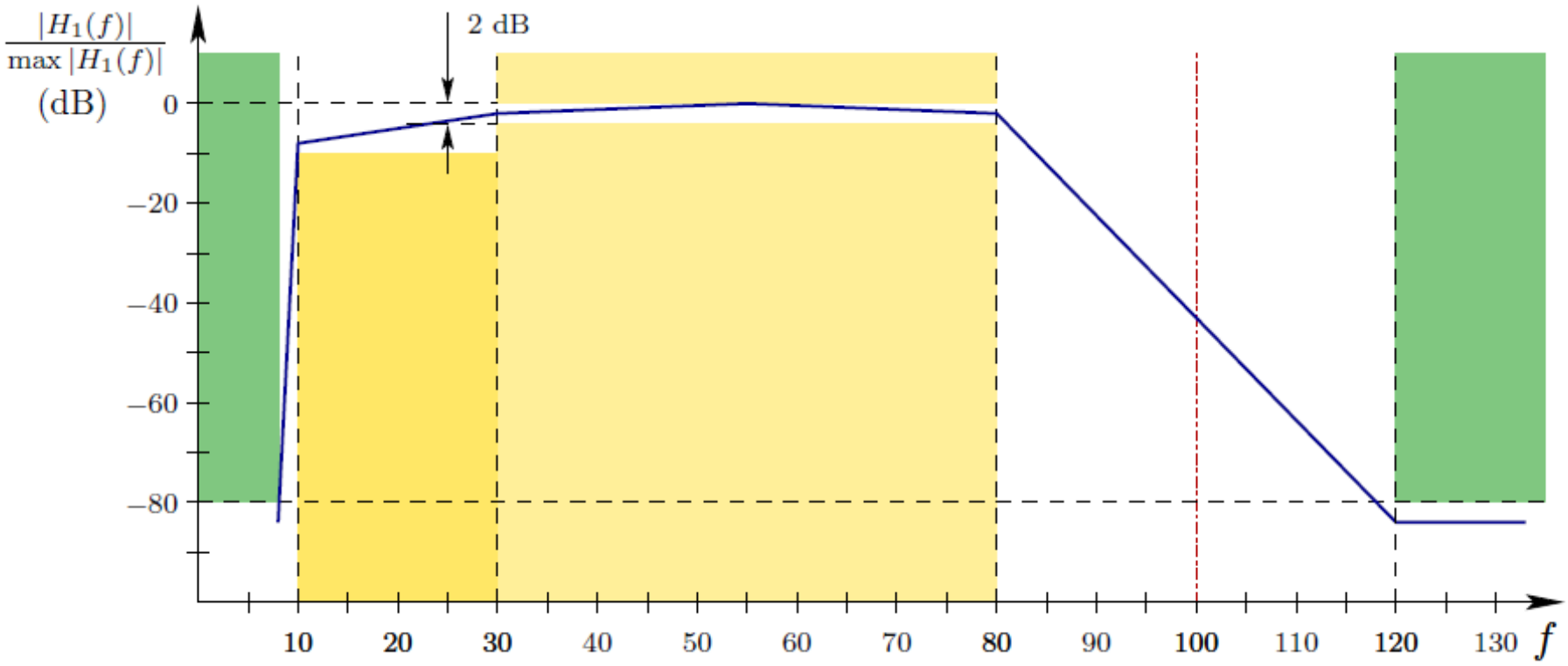


Receiver

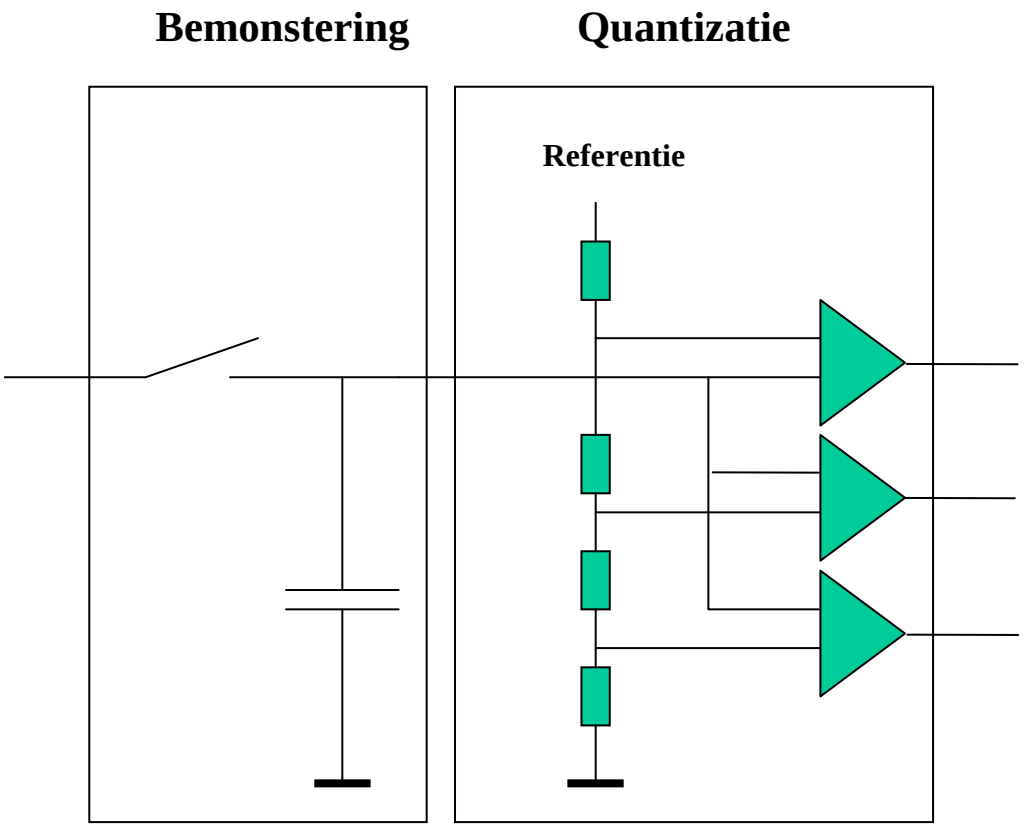

From lowband antenna 1
From lowband antenna 2
10 MHz
30 MHz
10-90 MHz
90 MHz
low band antenna chain
AD
12bit 200MSa/s
To station processing
From highband antenna
110-290 MHz
110-190MHz
170-230MHz
210-250MHz
270 MHz
high band antenna chain


ASTRON
LOFAR
RCU2-3
LOFAR RCU REV.2.0 juni 2005

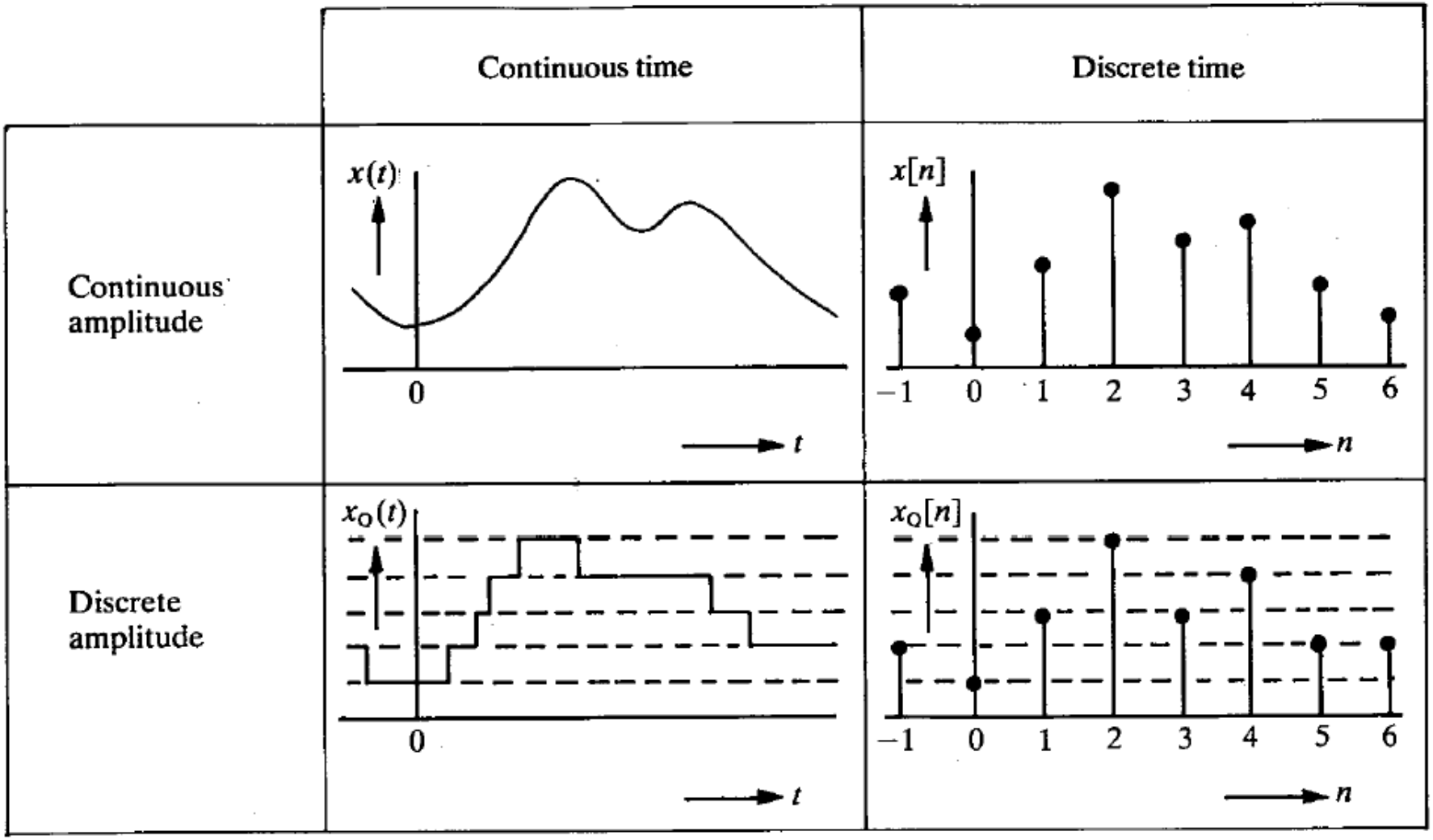
Anti-alias filter



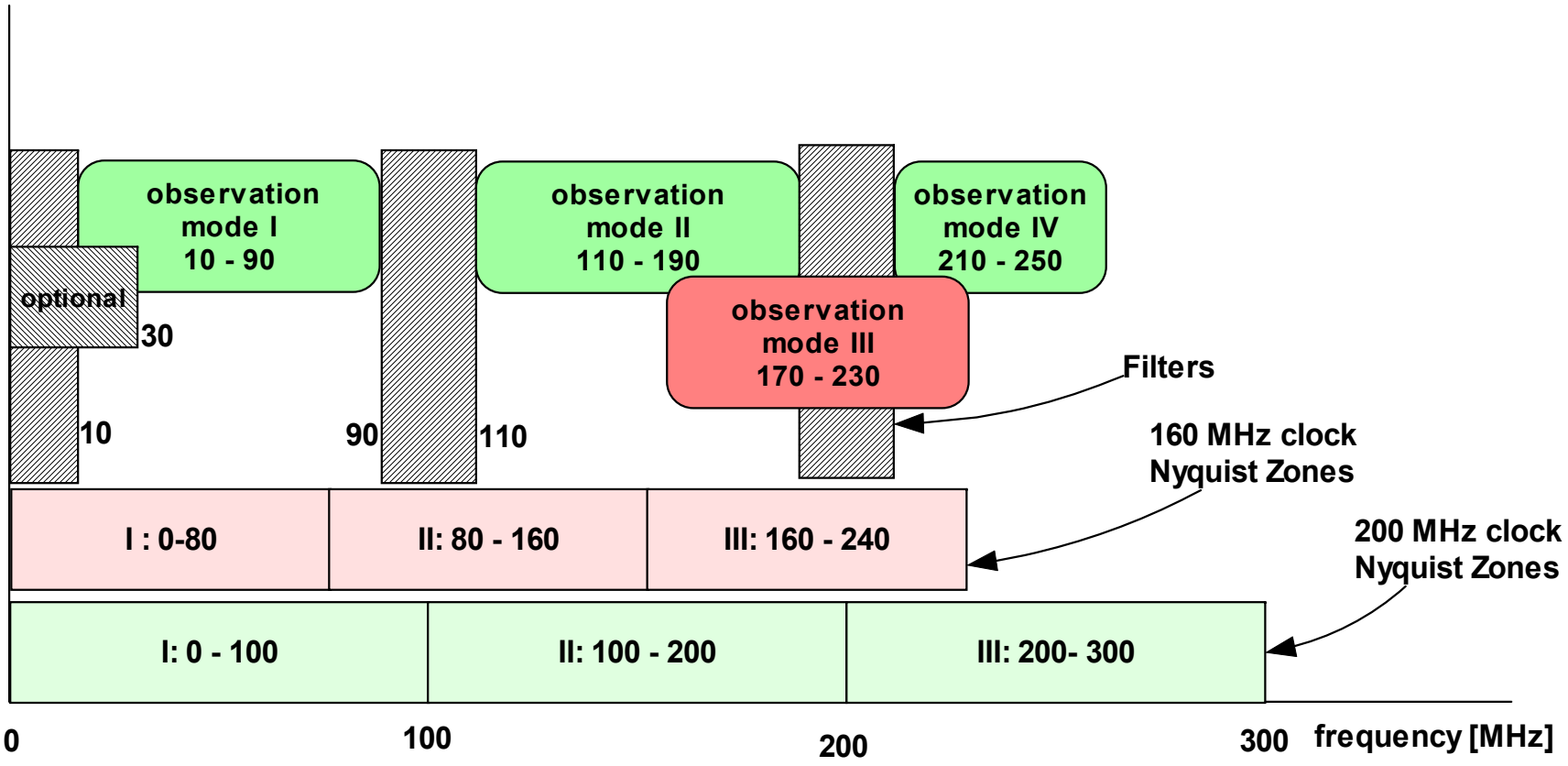
A/D Conversion



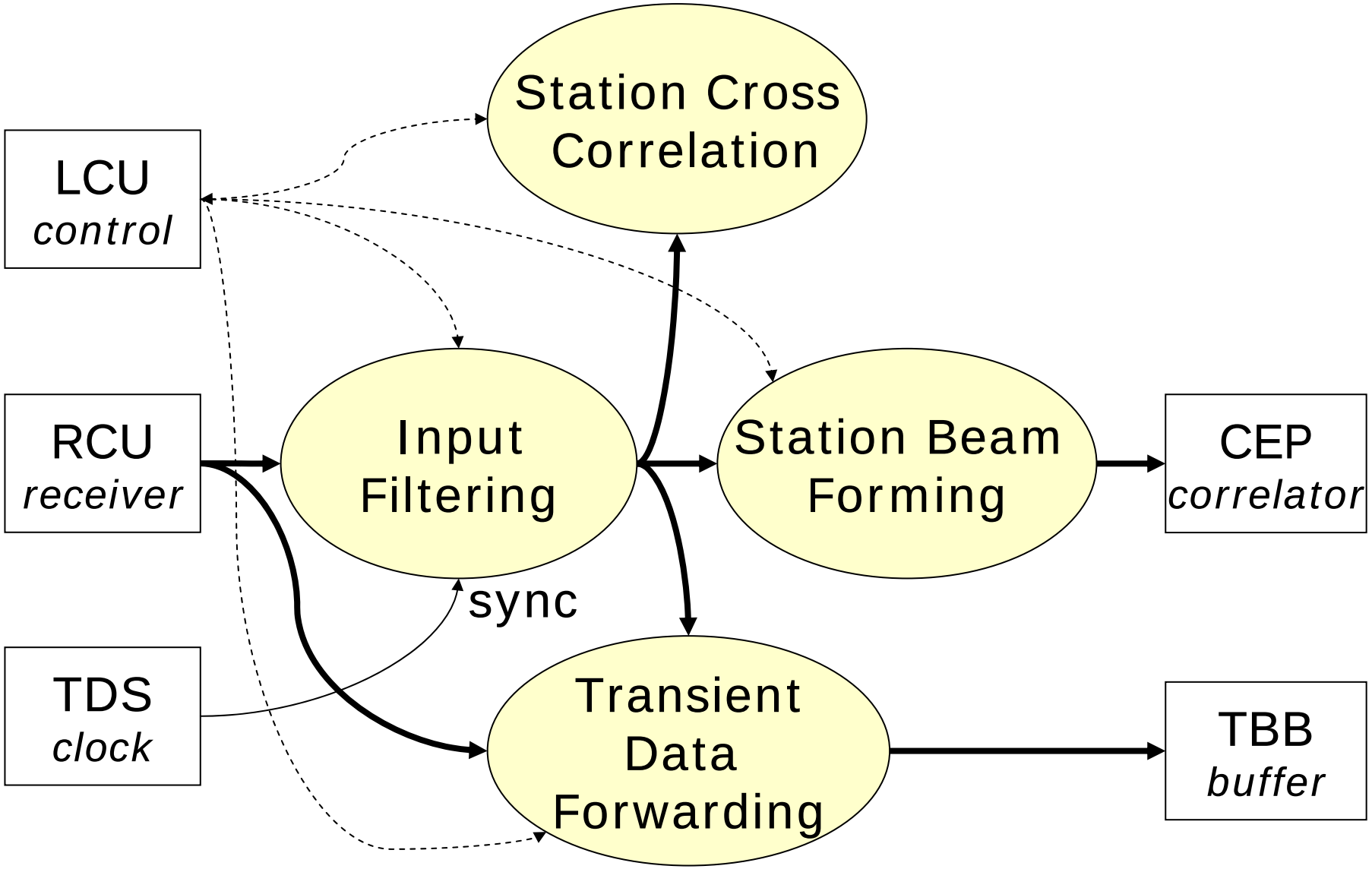
- Number of bits: 12
- Sampling frequency: 200 MHz / 160 MHz


Continuous time
Discrete time
Continuous amplitude
Discrete amplitude
x(t)
0
t
x[n]
−1 0 1 2 3 4 5 6
n
x_Q(t)
0
t
x_Q[n]
−1 0 1 2 3 4 5 6
n

Modes



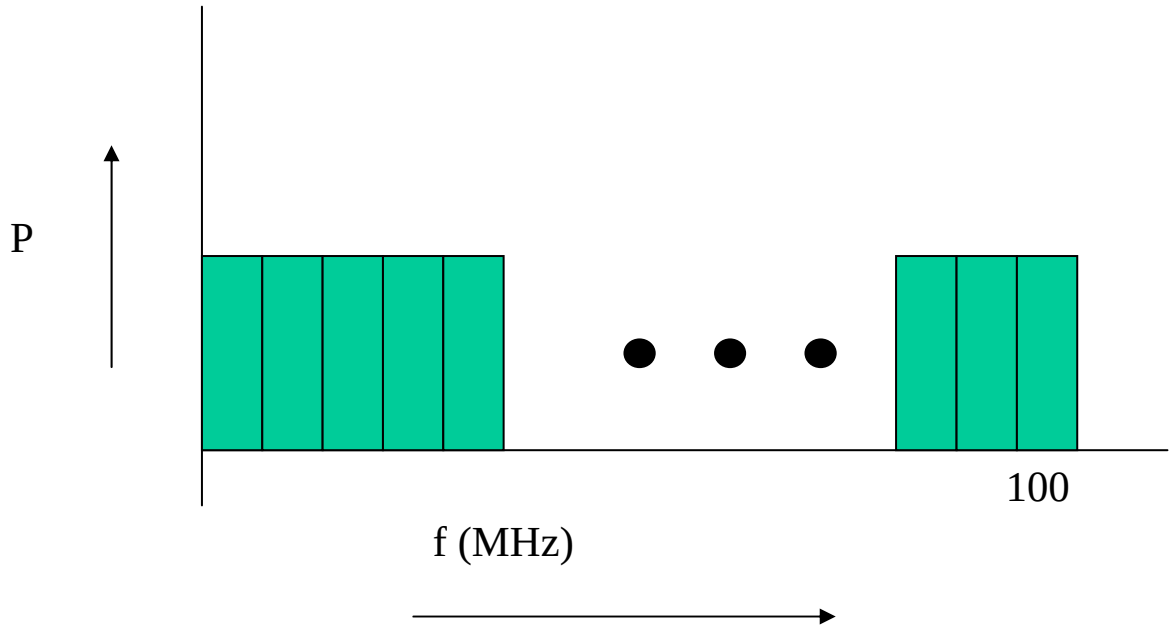
Processing functions



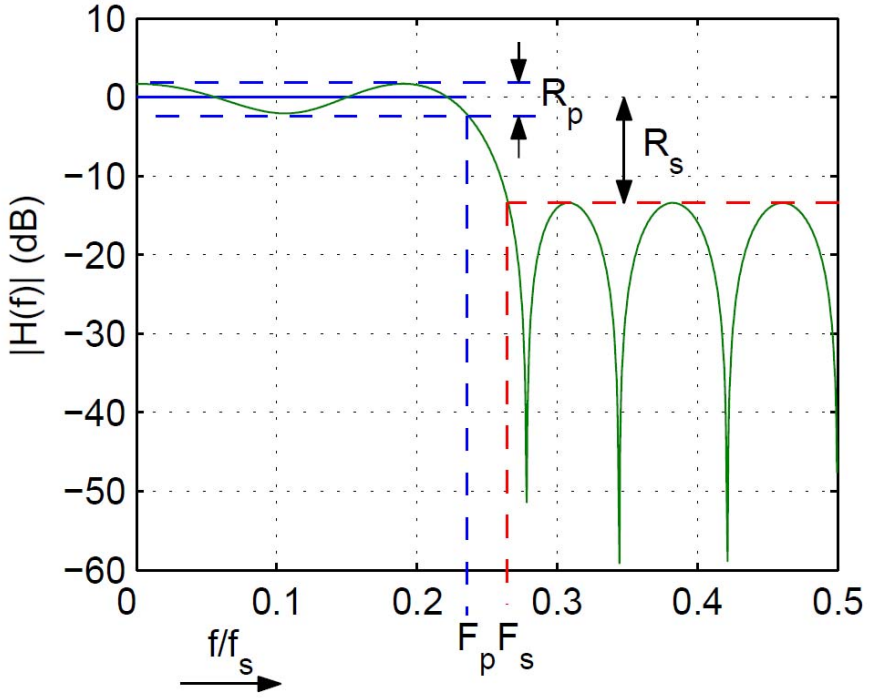

LOFAR
ALTERA
Stratix II
PMC
ASTRON

Digital filter bank

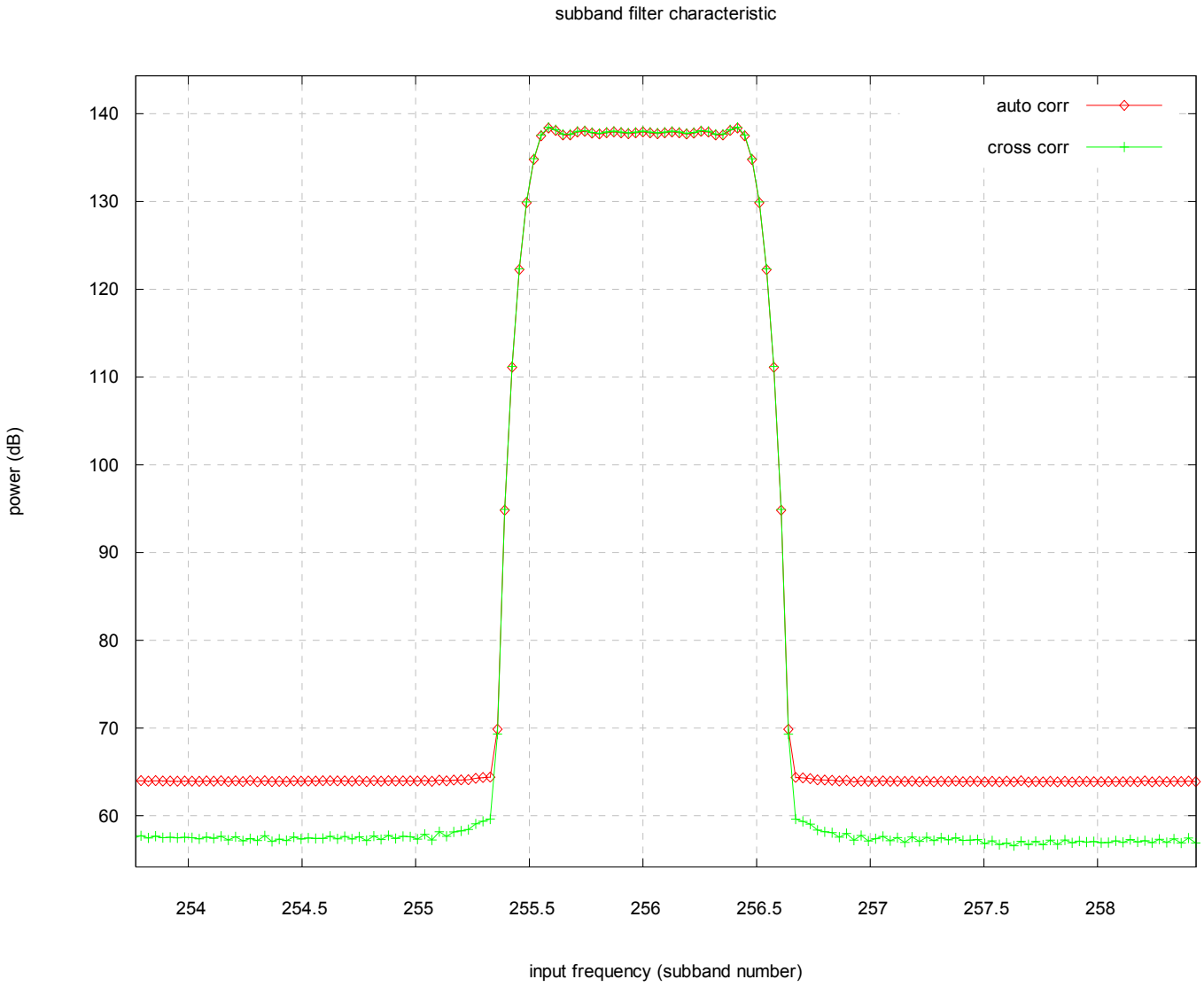
- Sample rate max. 200 MHz
- Number of taps: 4096
- Number of subbands: 512



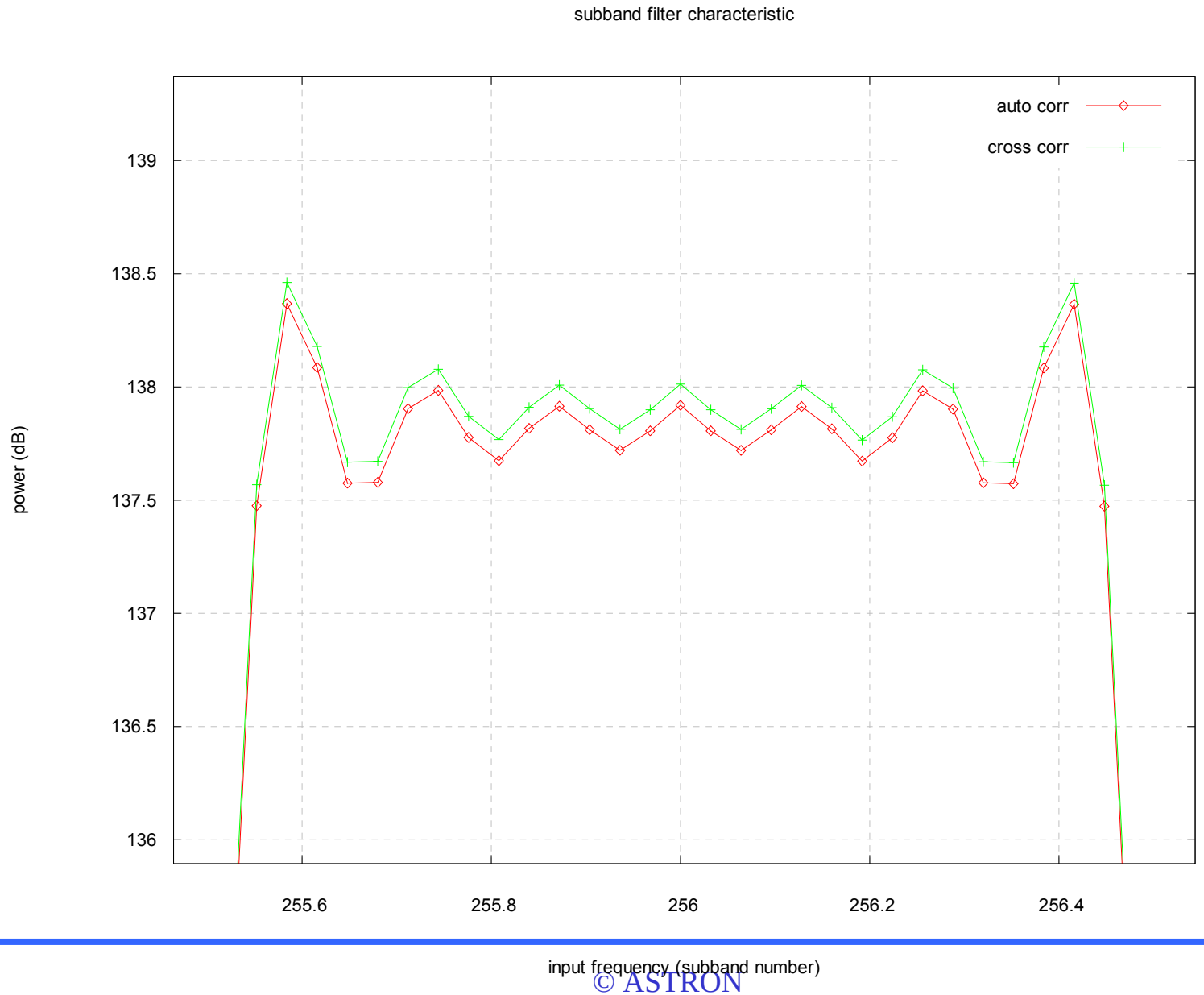
- Stopband attenuation: 80 dB
- Ripple: 0.45 dB
- Transition region: 0.2 subband



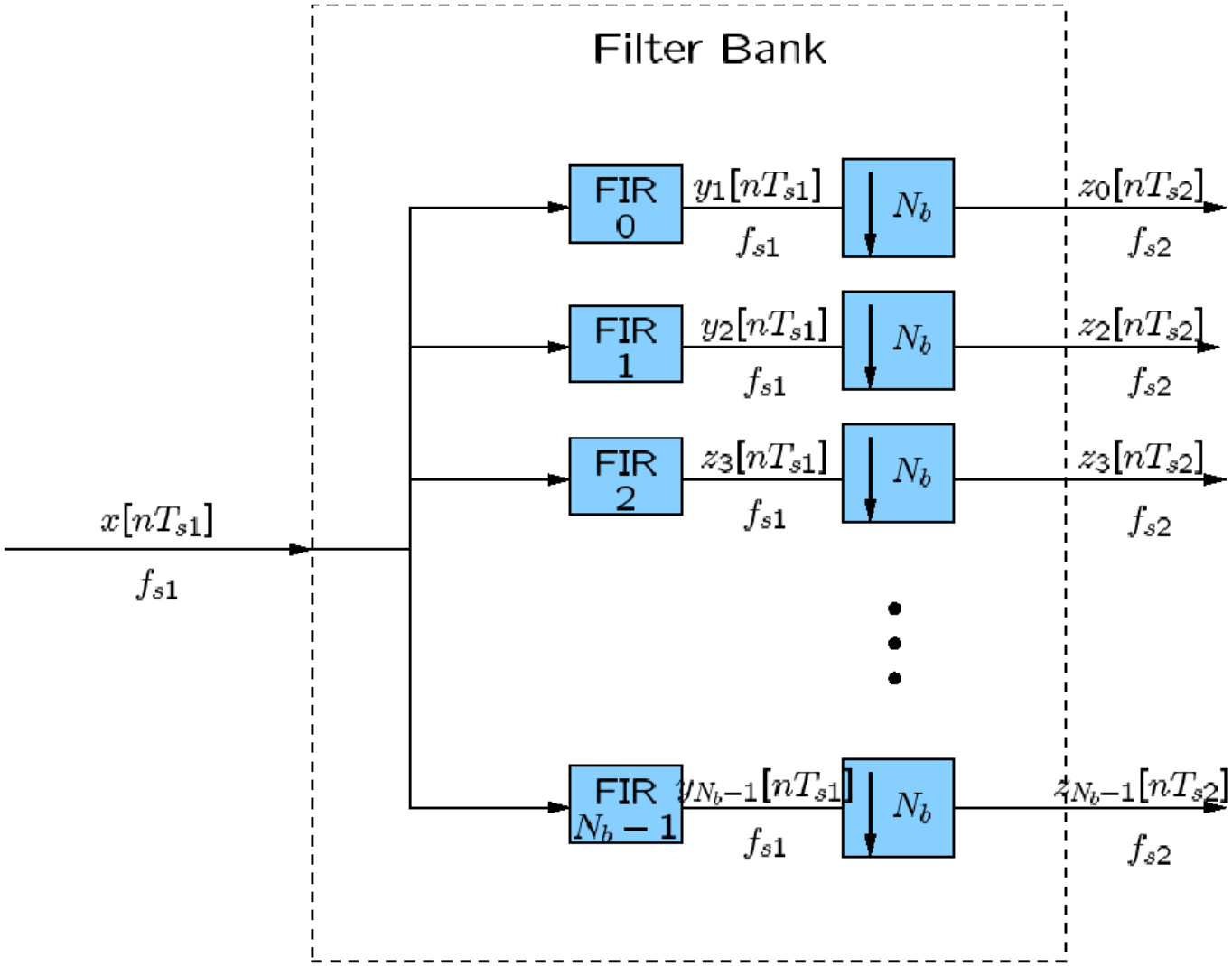
Measured Frequency Characteristic



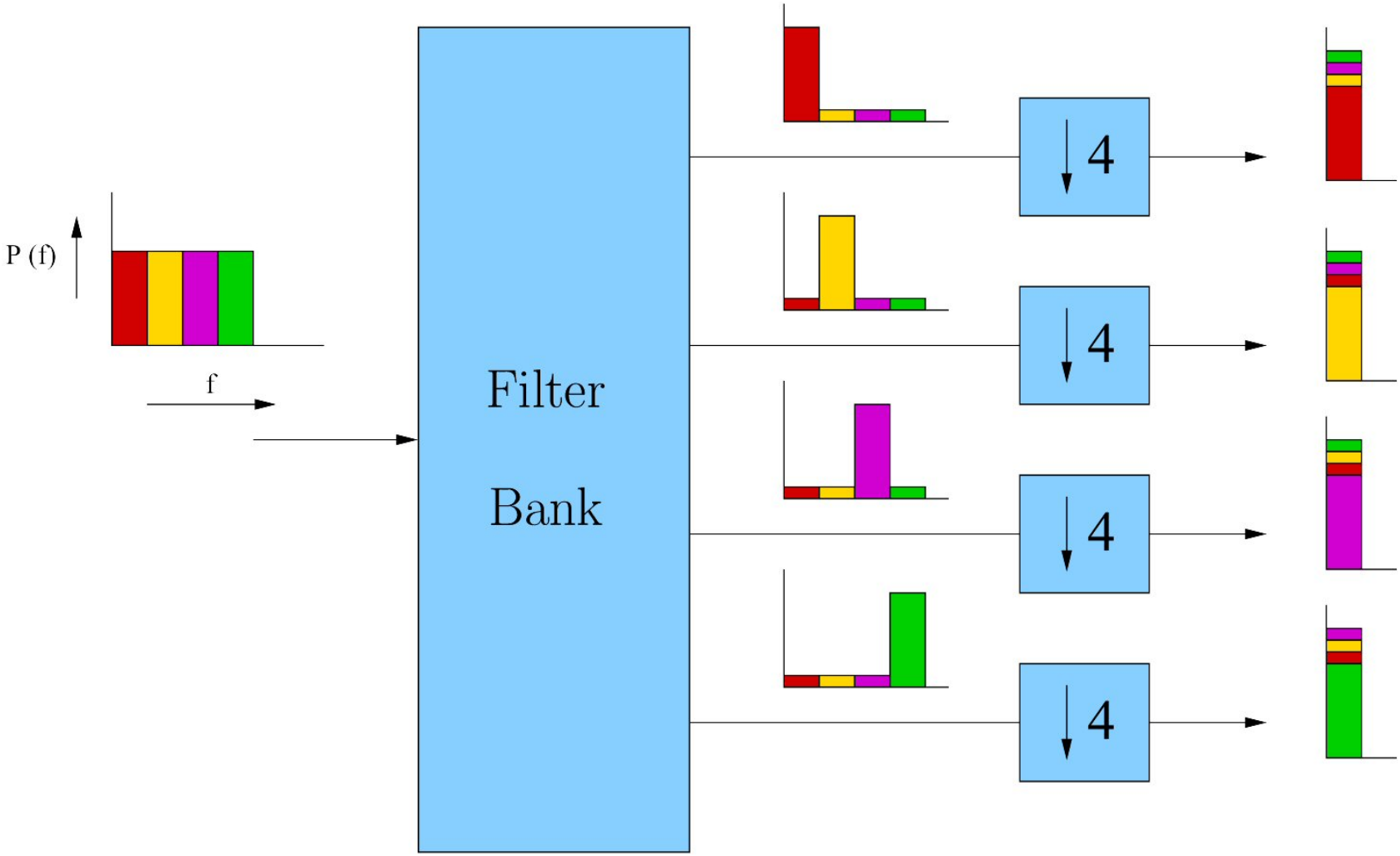
Measured Ripple of the Passband



Straightforward Filter bank

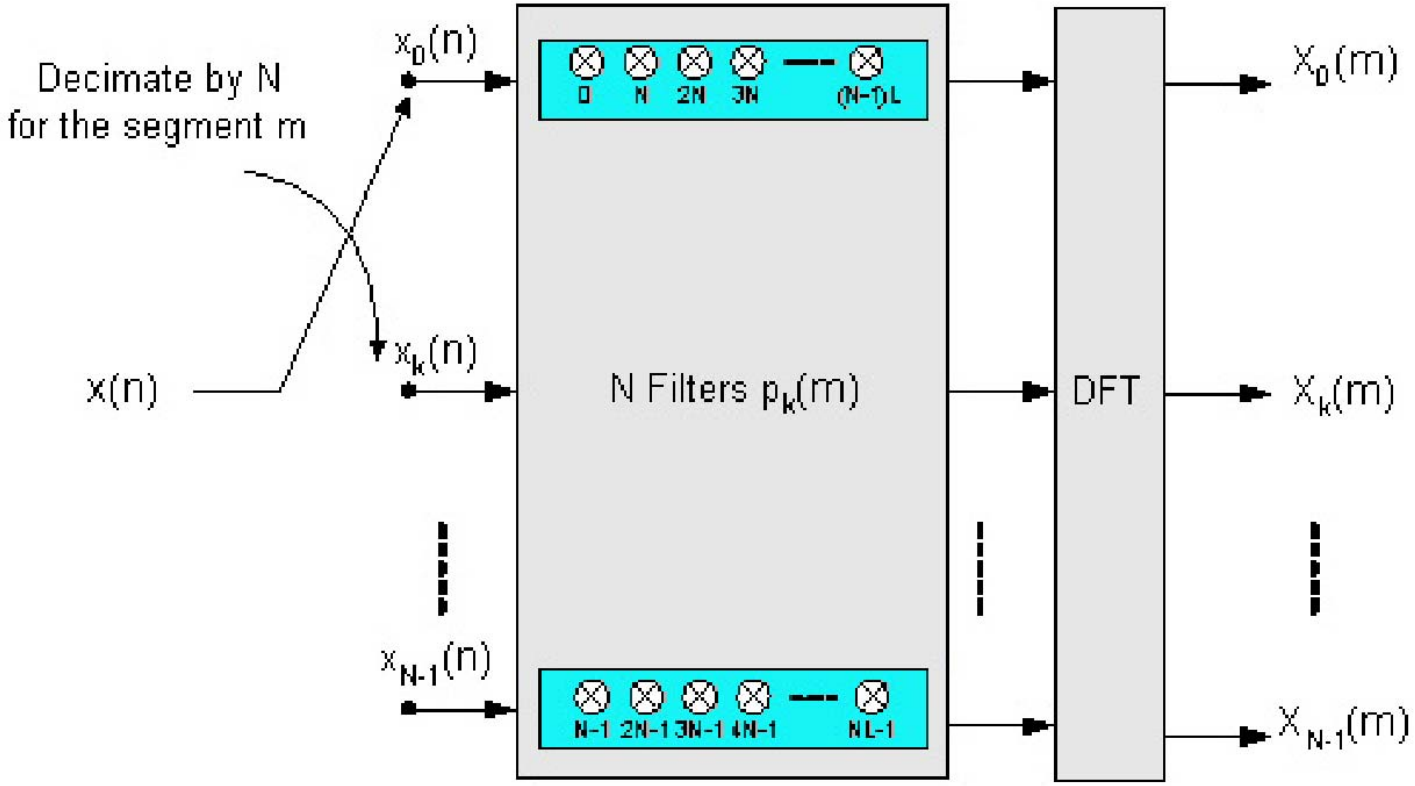


Example for Four Subbands



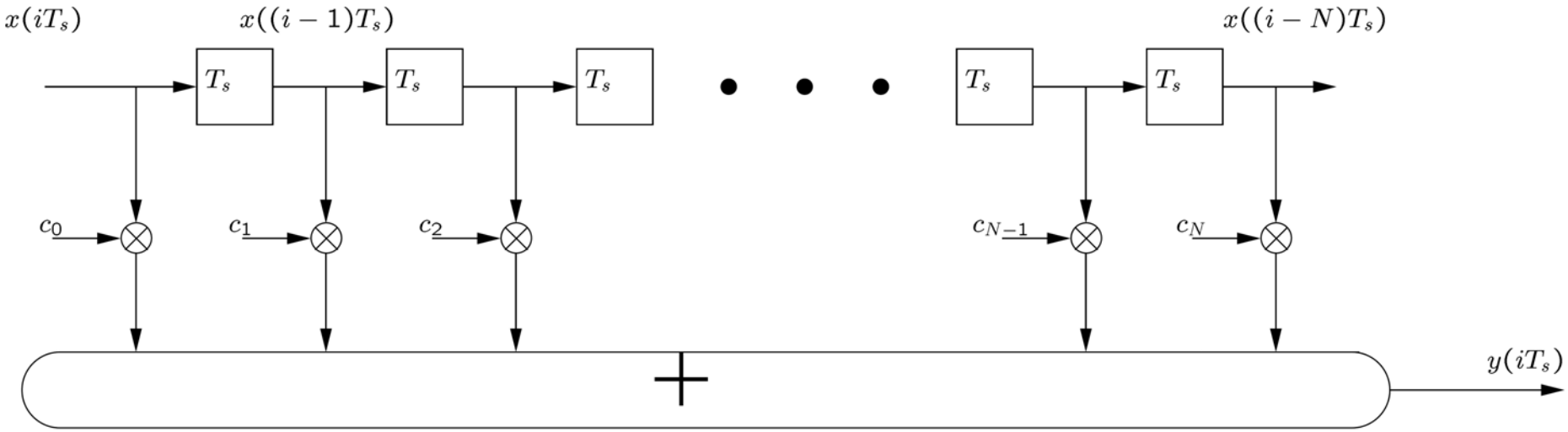
Poly phase filter

- Why multiplying signals, which are thrown away
- Number of required resources much smaller



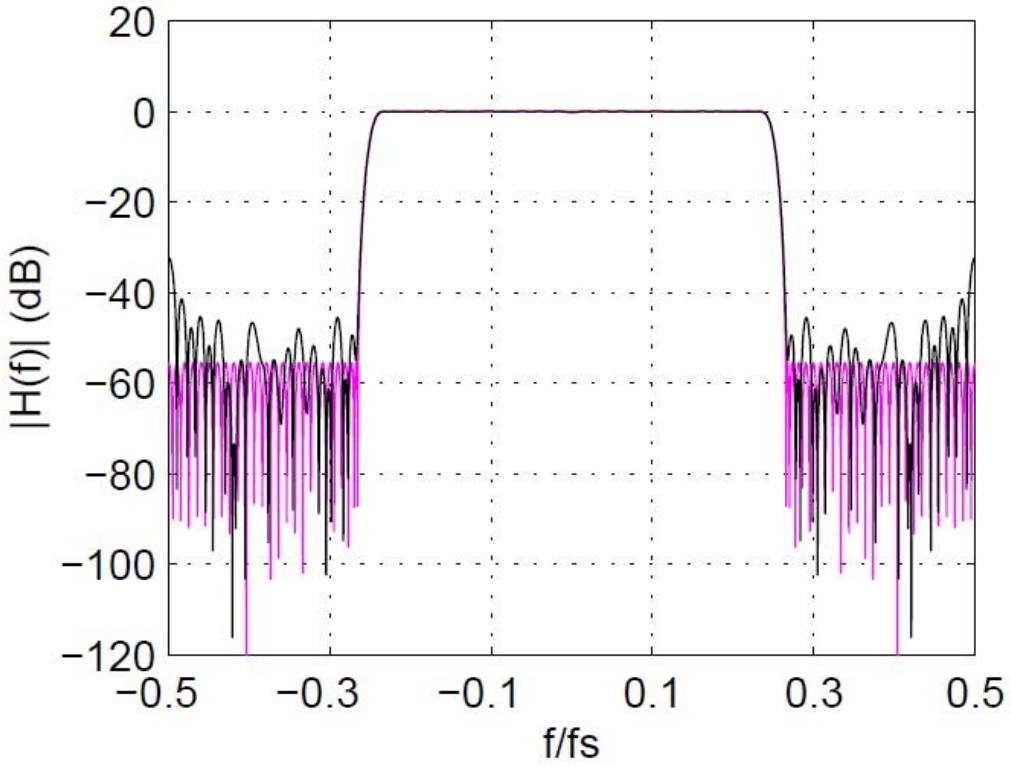
FIR Filter

$$y(iT_s) = \sum_{j=0}^{N} x((i-j)T_s)c_j$$



Limited Amount of Bits

$$y(iT_s) = Q_e \left\{ \sum_{j=0}^{N} Q_b \left[Q_s \left(x((i-j)T_s) \right) Q_c \left(c_j \right) \right] \right\}$$



- Small amount of operations on a large amount of data
- Not much chips required (< 10 k chips)

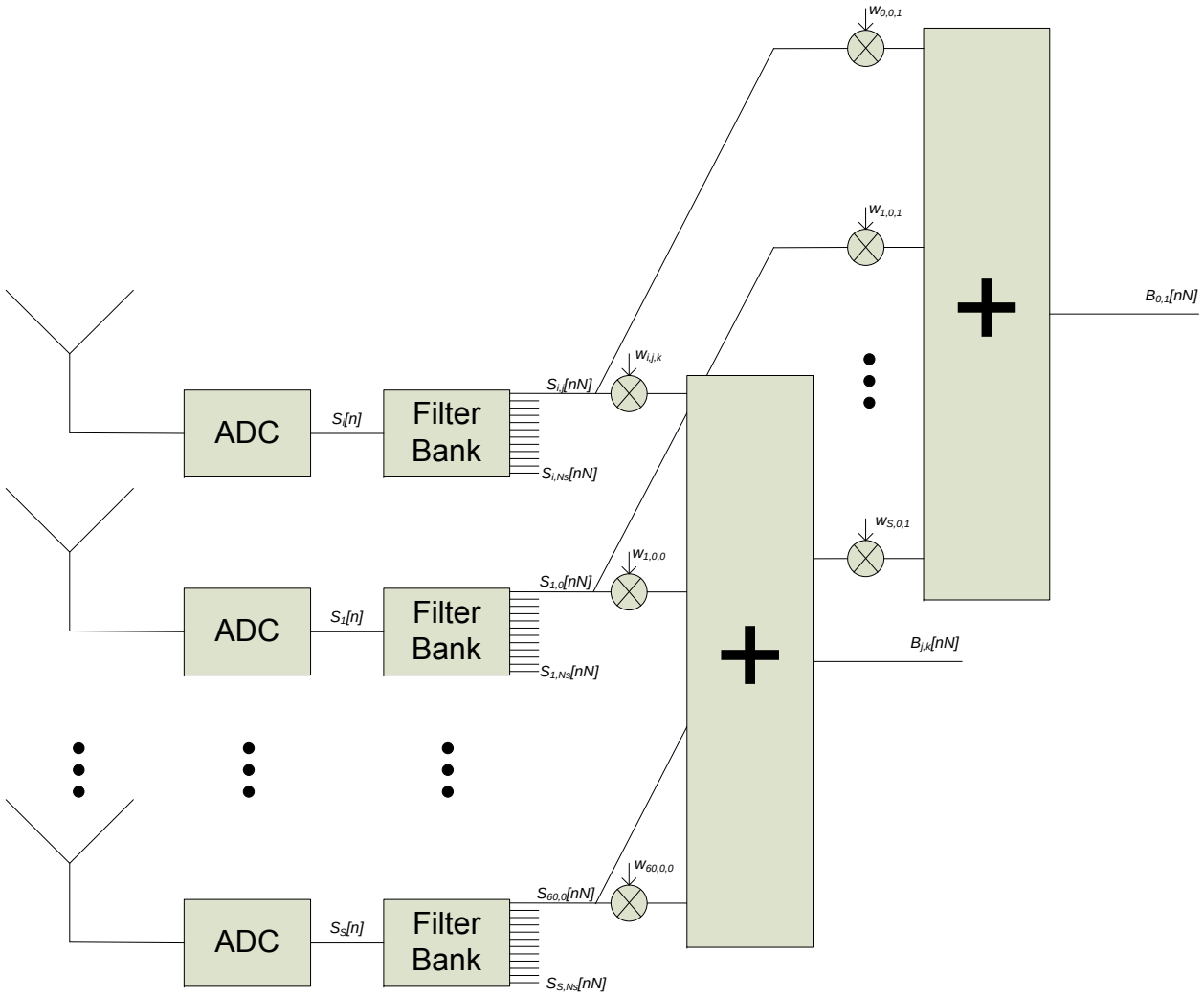
Therefore FPGA's are used to implement the digital functionality

Current trend in FPGA land is to embedd:

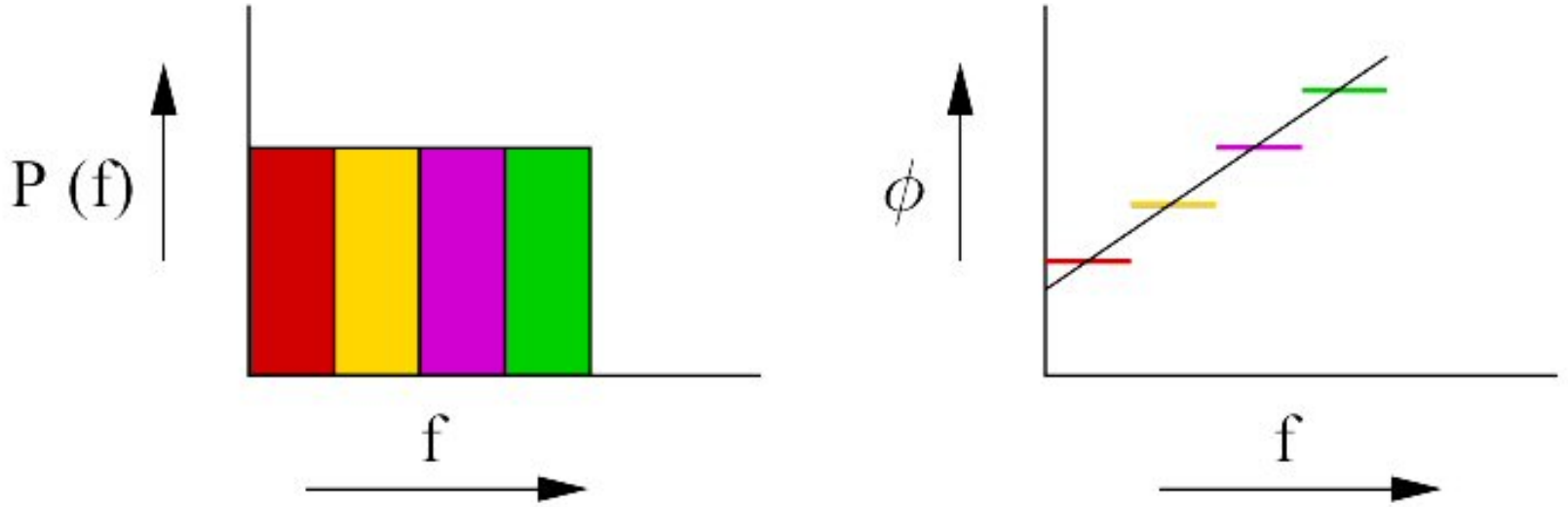
- Multipliers
- Memory
- On chip microprocessor cores

instead of logical elements only

Digital Beamforming



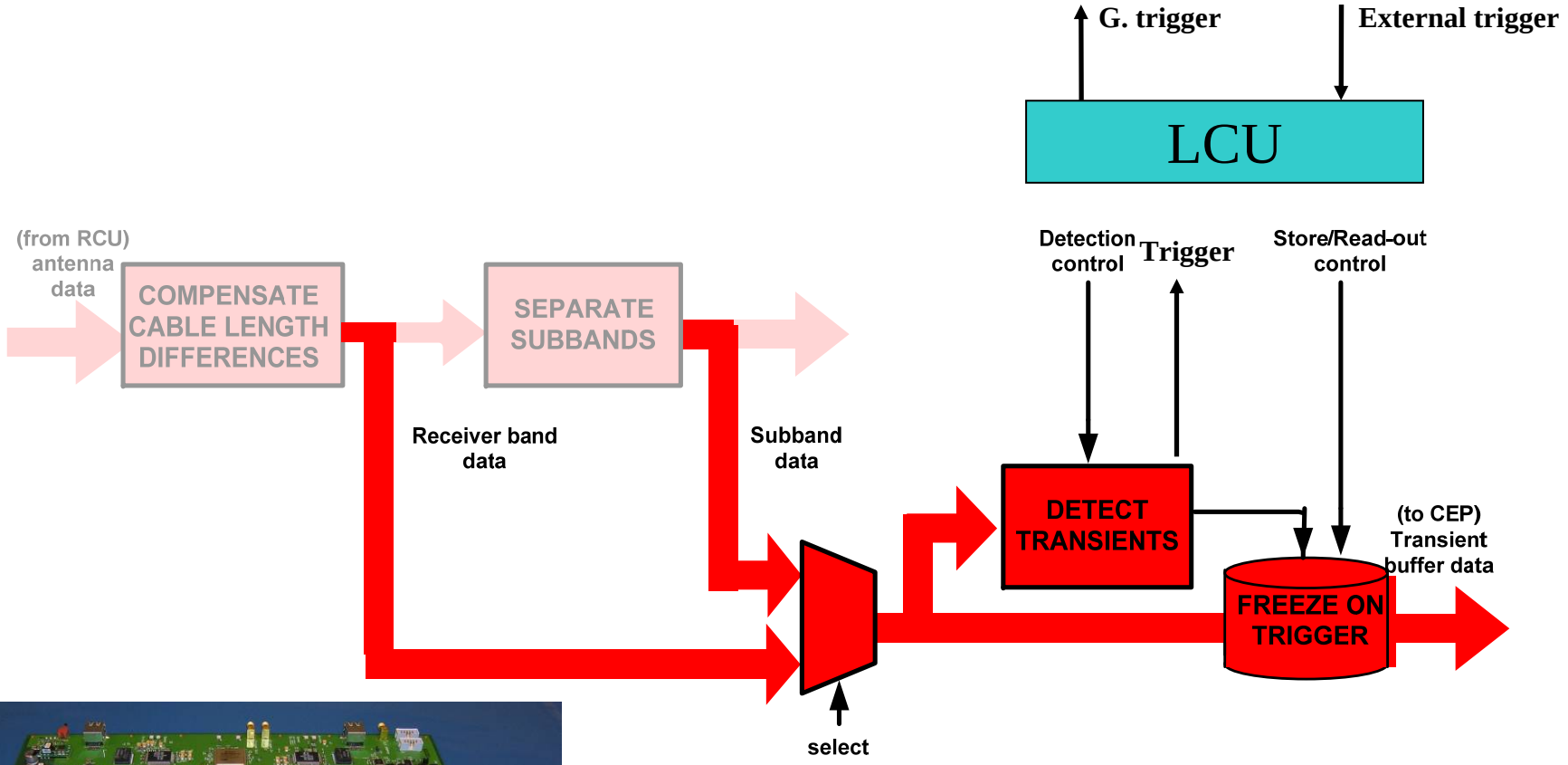
Representing Time Shifts by Phases

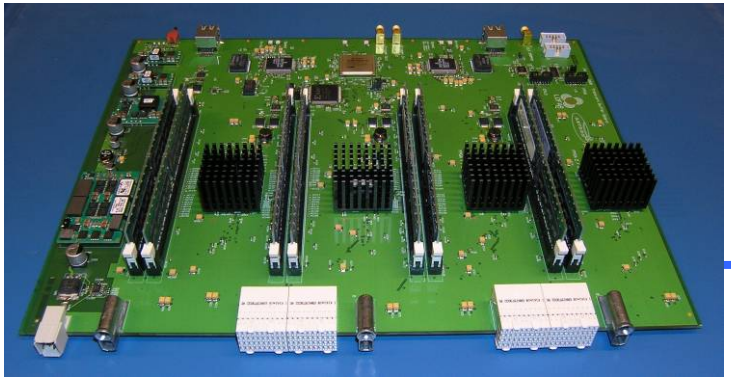


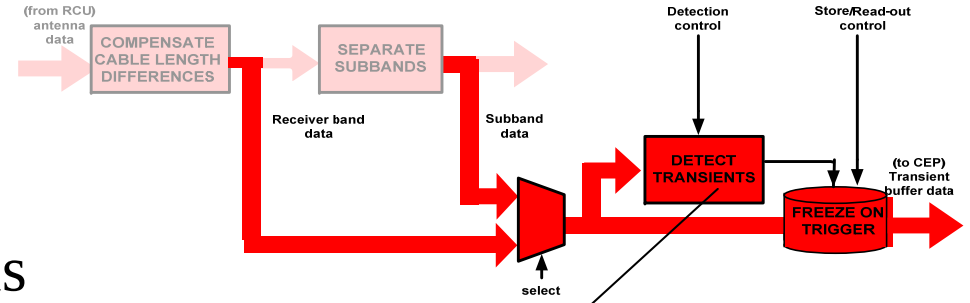
Stations Numbers

- Input data stream: 230 Gbps (6 DVDs/s)
- Output data stream: 3-6 Gbps
- Memory: 48 GByte
- Processing capacity: 750 Gmul/s
- 20 kilometer coax cable

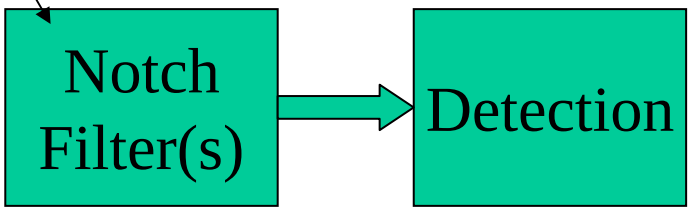
Transient Buffering







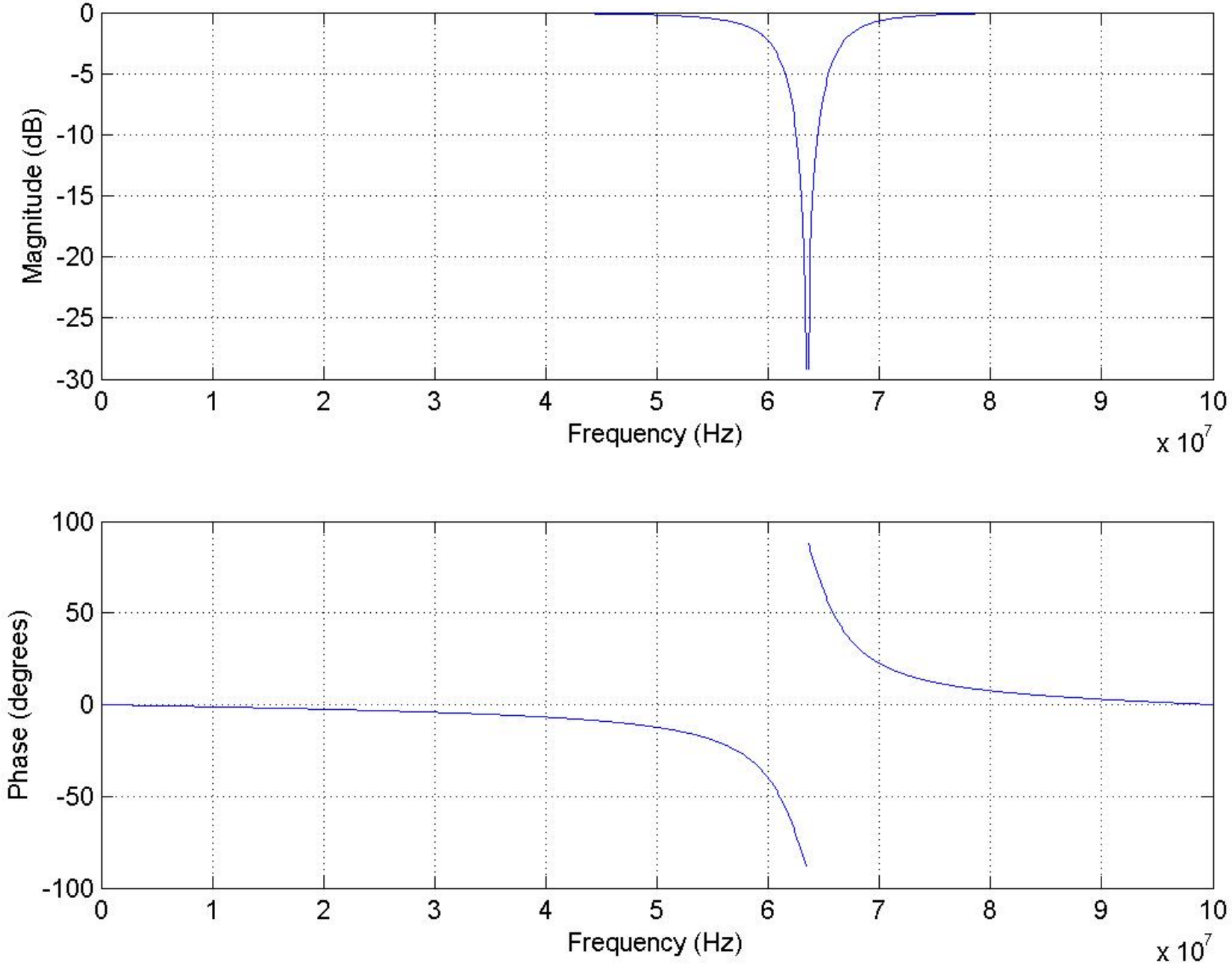
to suppress strong RFI signals
at fixed locations

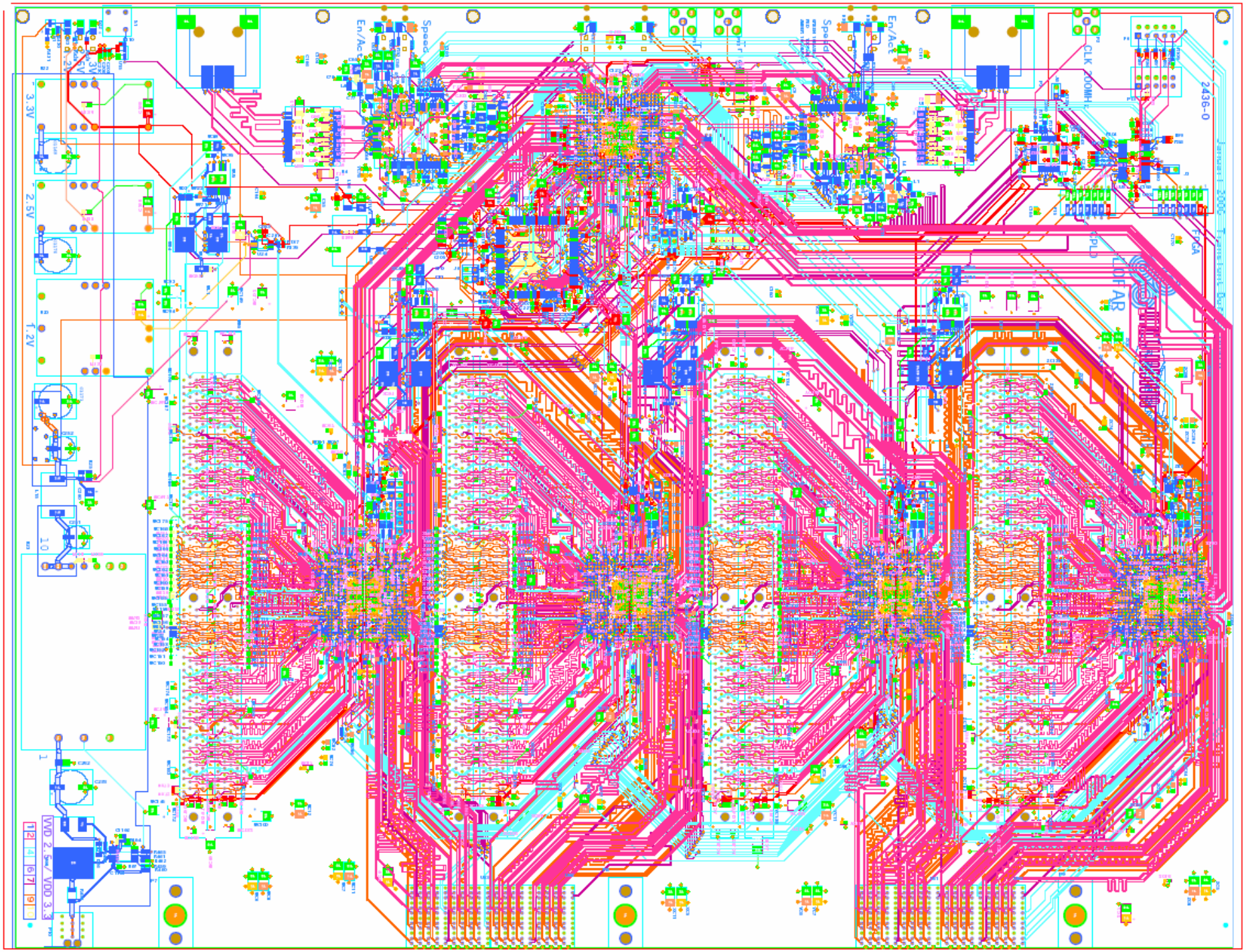


Detection only possible on the stored signals

- Properties Infinite Impulse Response Filters:
  - Advantage: cheap
  - Disadvantage: non-linear phase

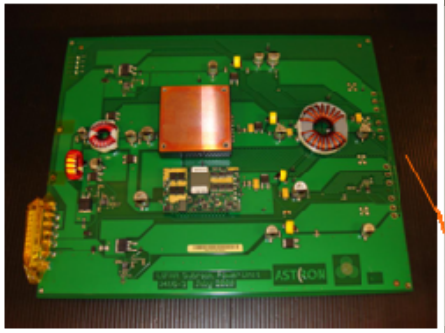
- Example of a 3th order IRR filter:
  - centre frequency: 63.5 MHz
  - bandwidth: 2 MHz
  - 4 multipliers required


Magnitude (dB)
0
-5
-10
-15
-20
-25
-30
0
1
2
3
4
5
6
7
8
9
10
Frequency (Hz)
x 10^7
Phase (degrees)
100
50
0
-50
-100
0
1
2
3
4
5
6
7
8
9
10
Frequency (Hz)
x 10^7

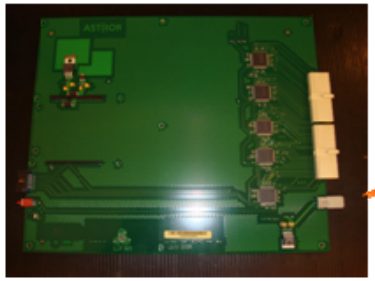

3.3V
2.5V
1.2V
CLK 200MHz
FPGA
CPLD
LOFAR
2436-0

Station Subrack

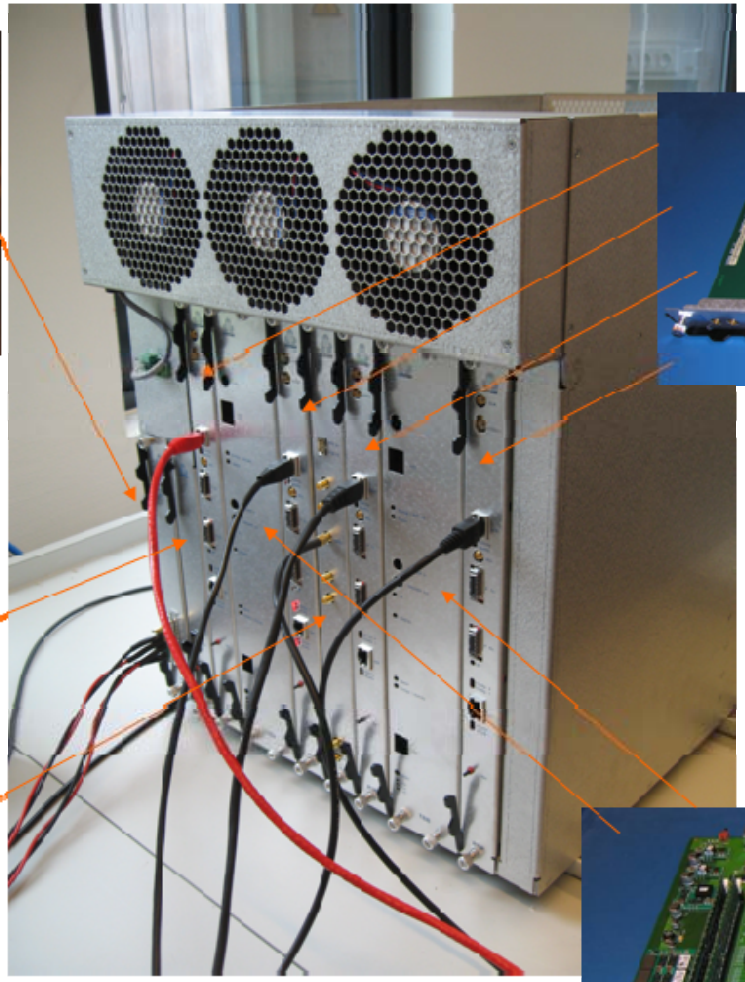
SPU



JTB

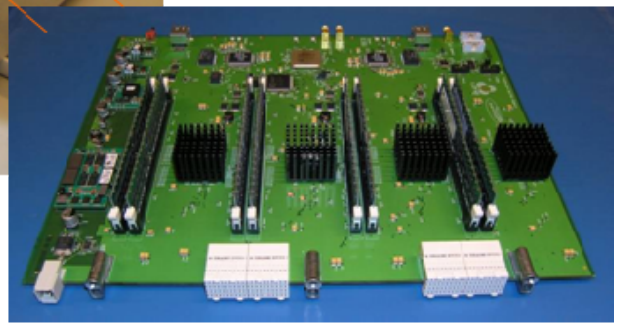


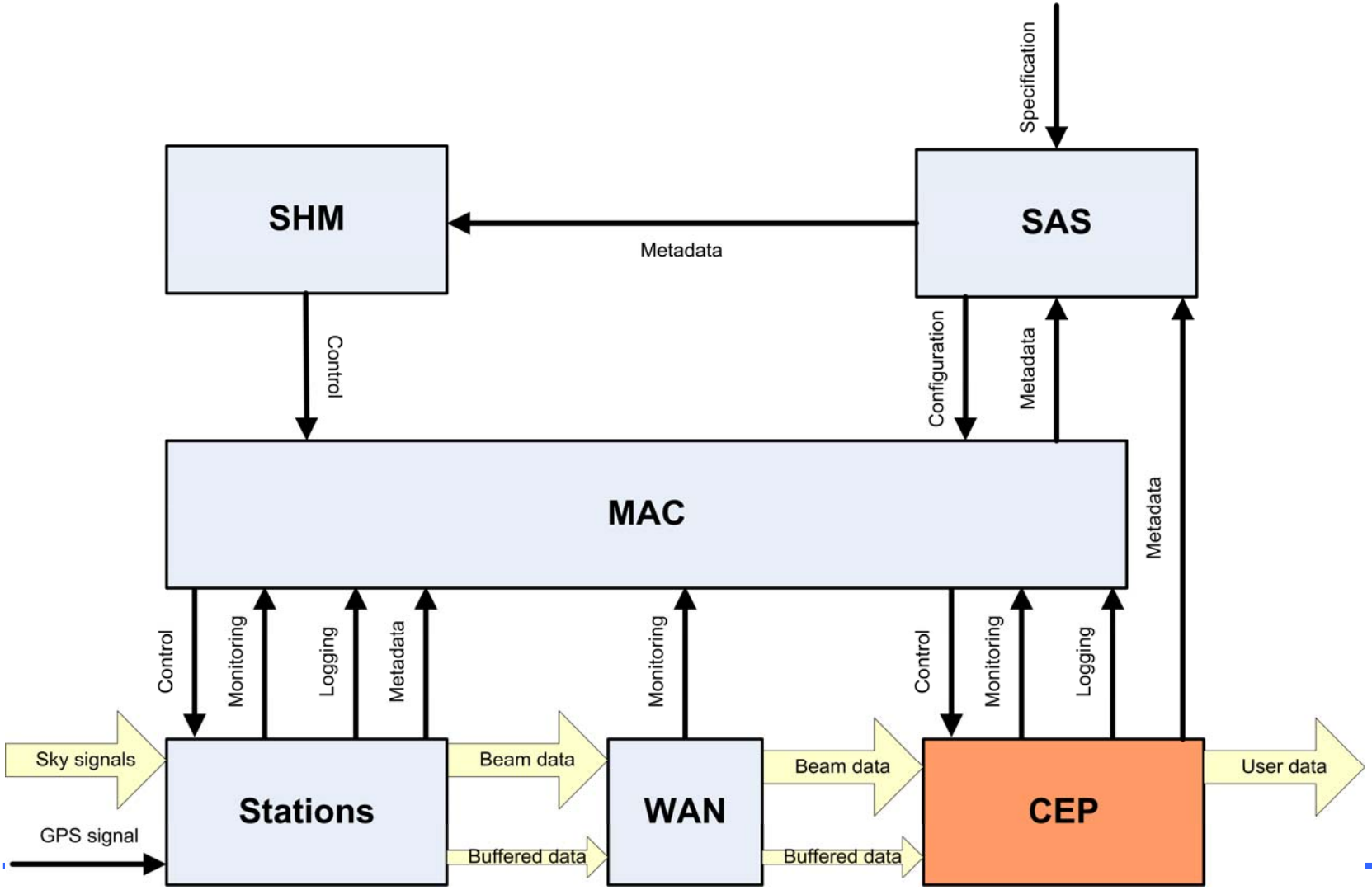
TDS



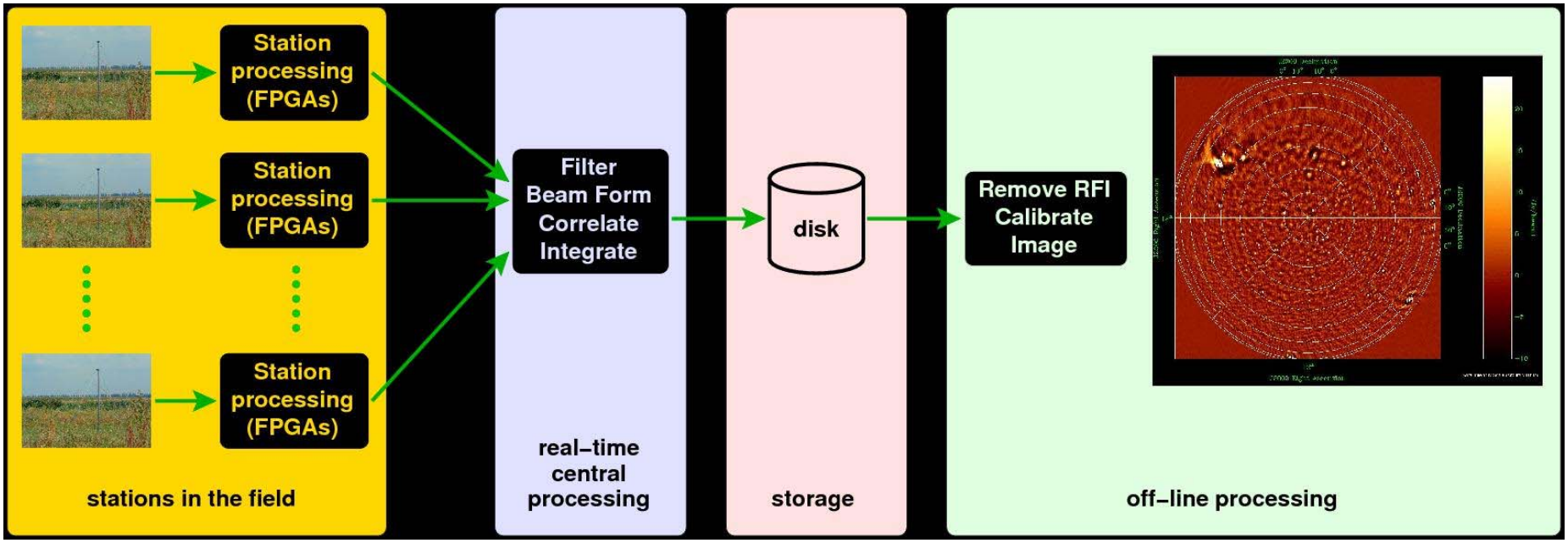
RSP

TBB

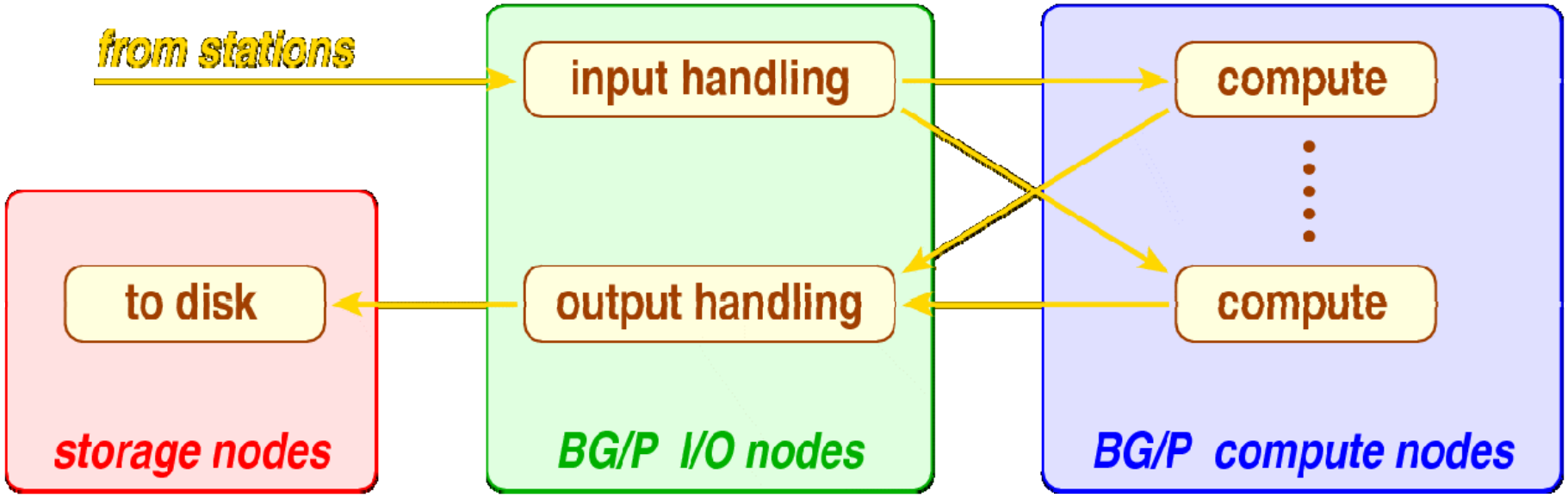



Specification
SHM
Metadata
SAS
Control
Configuration
Metadata
MAC
Metadata
Control
Monitoring
Logging
Metadata
Monitoring
Control
Monitoring
Logging
Sky signals
GPS signal
Stations
Beam data
Buffered data
WAN
Beam data
Buffered data
CEP
User data

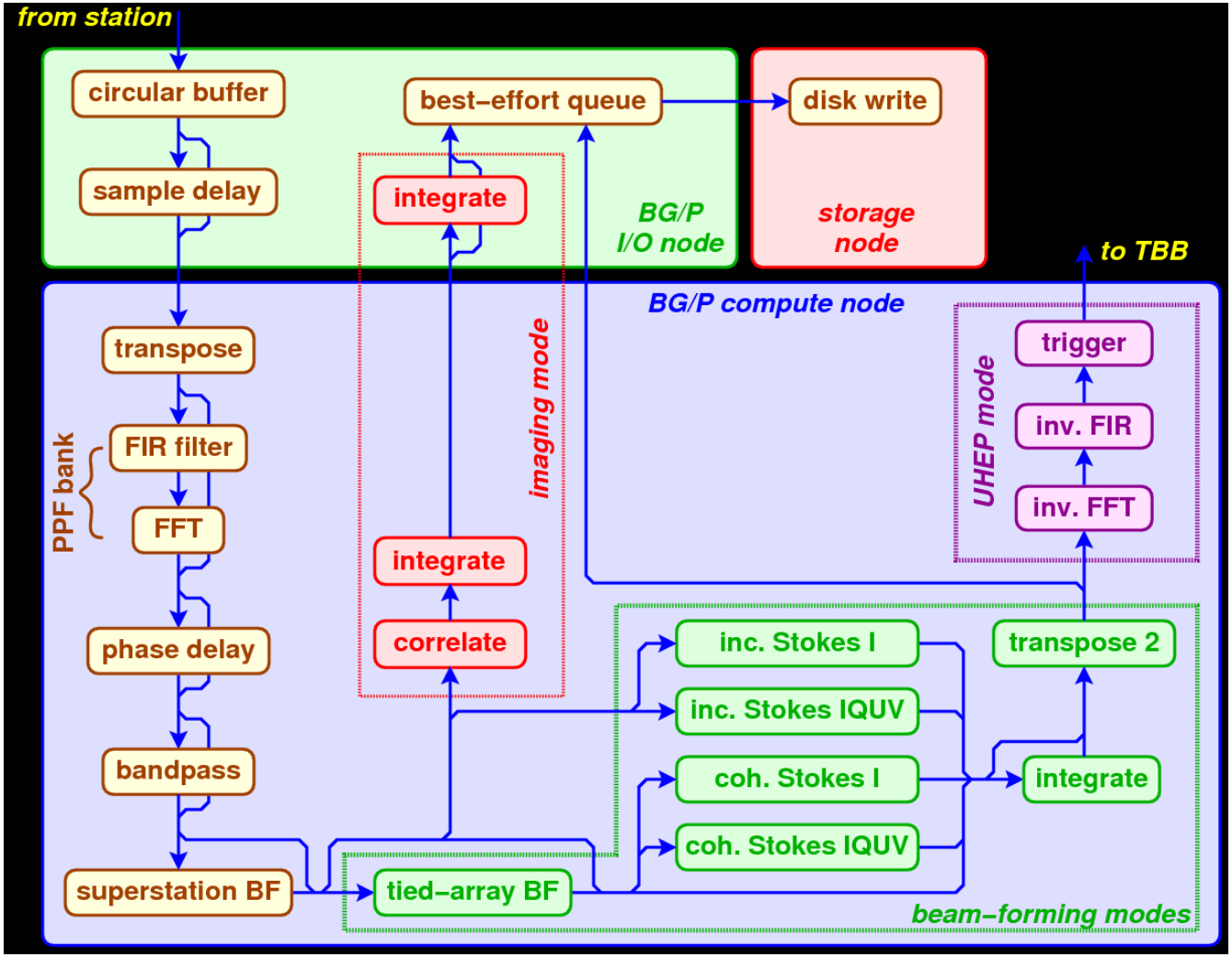
Centrale processing



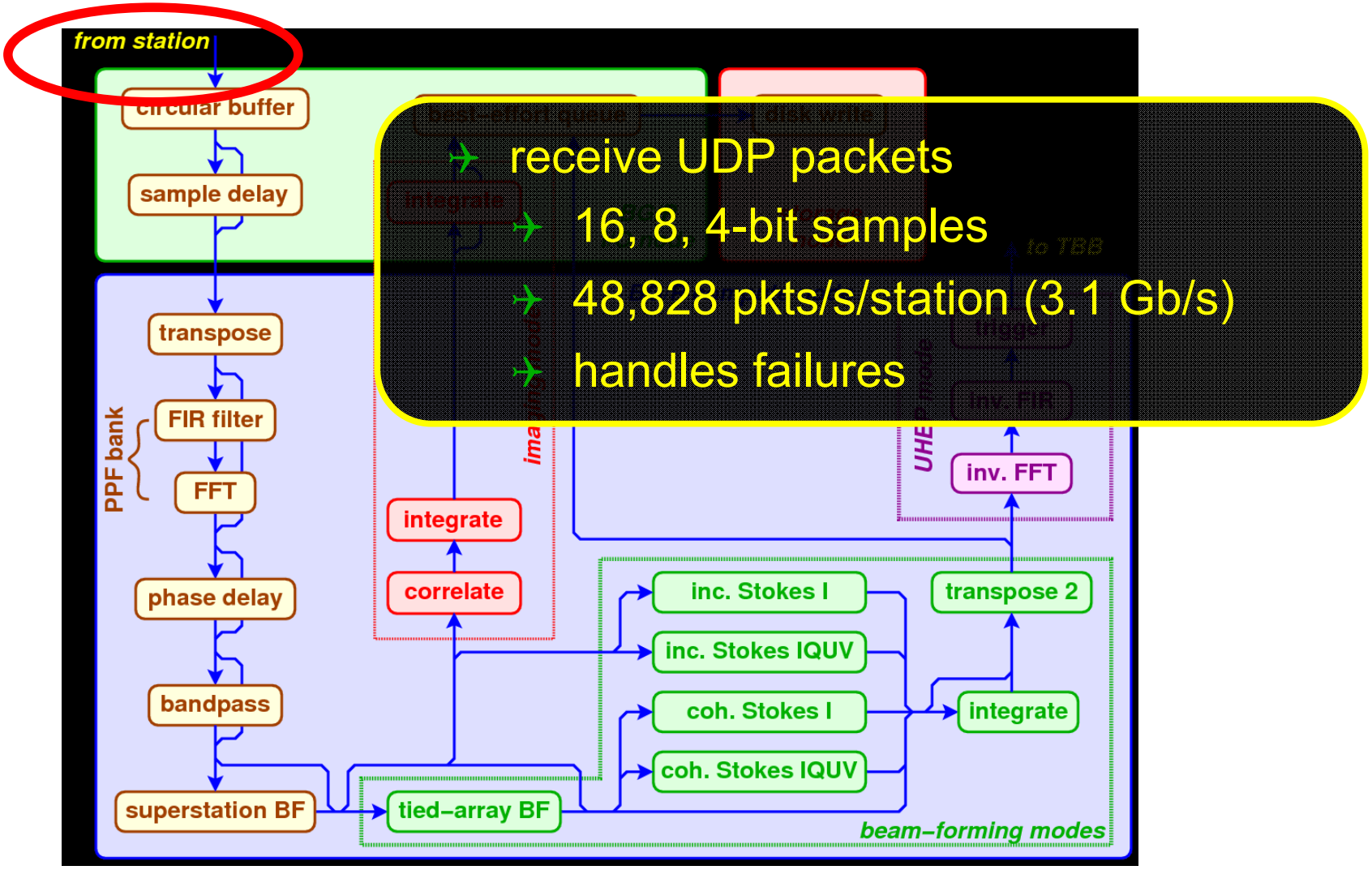
The BG/P Correlator



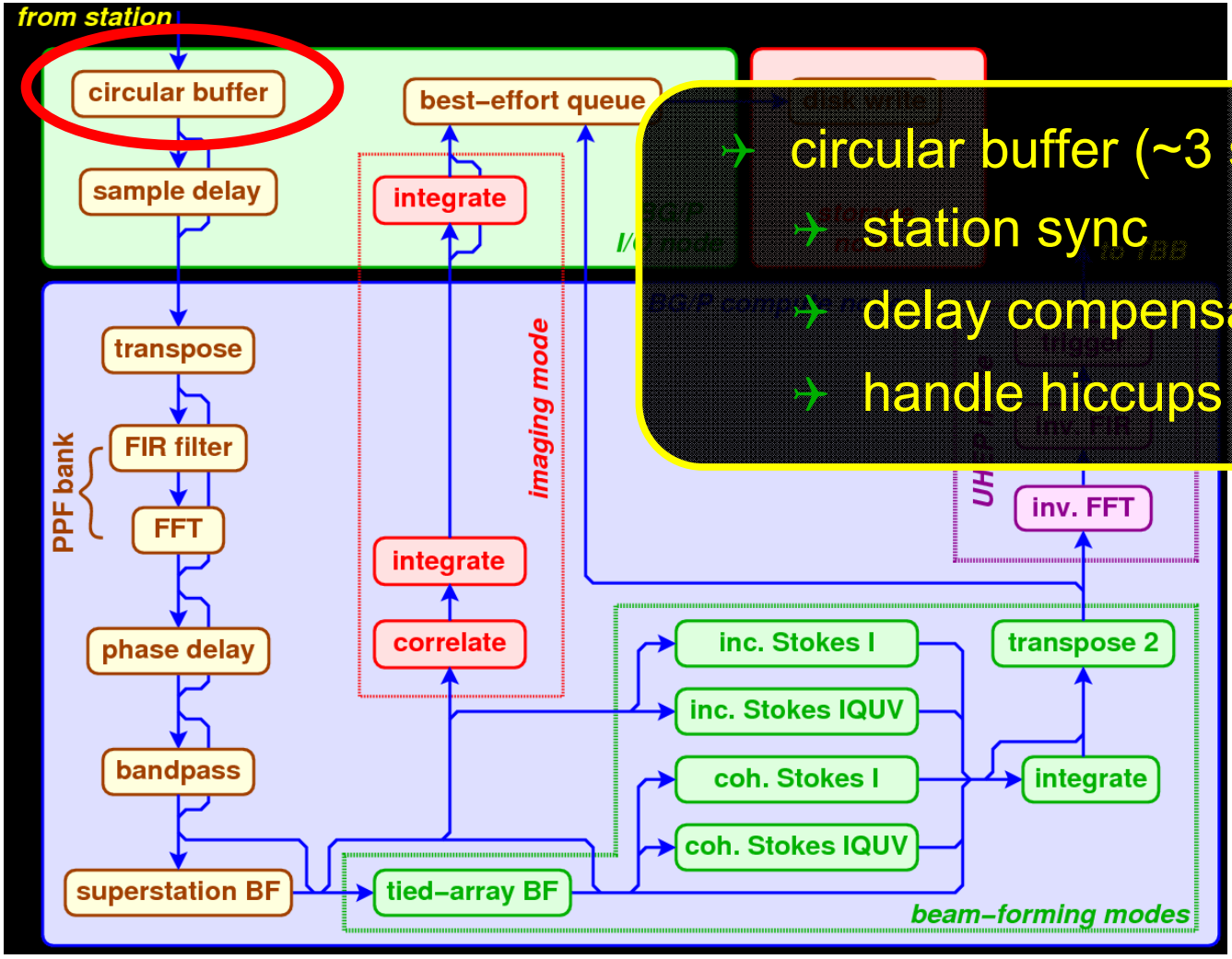
Pipeline Overview



Station Data Receipt

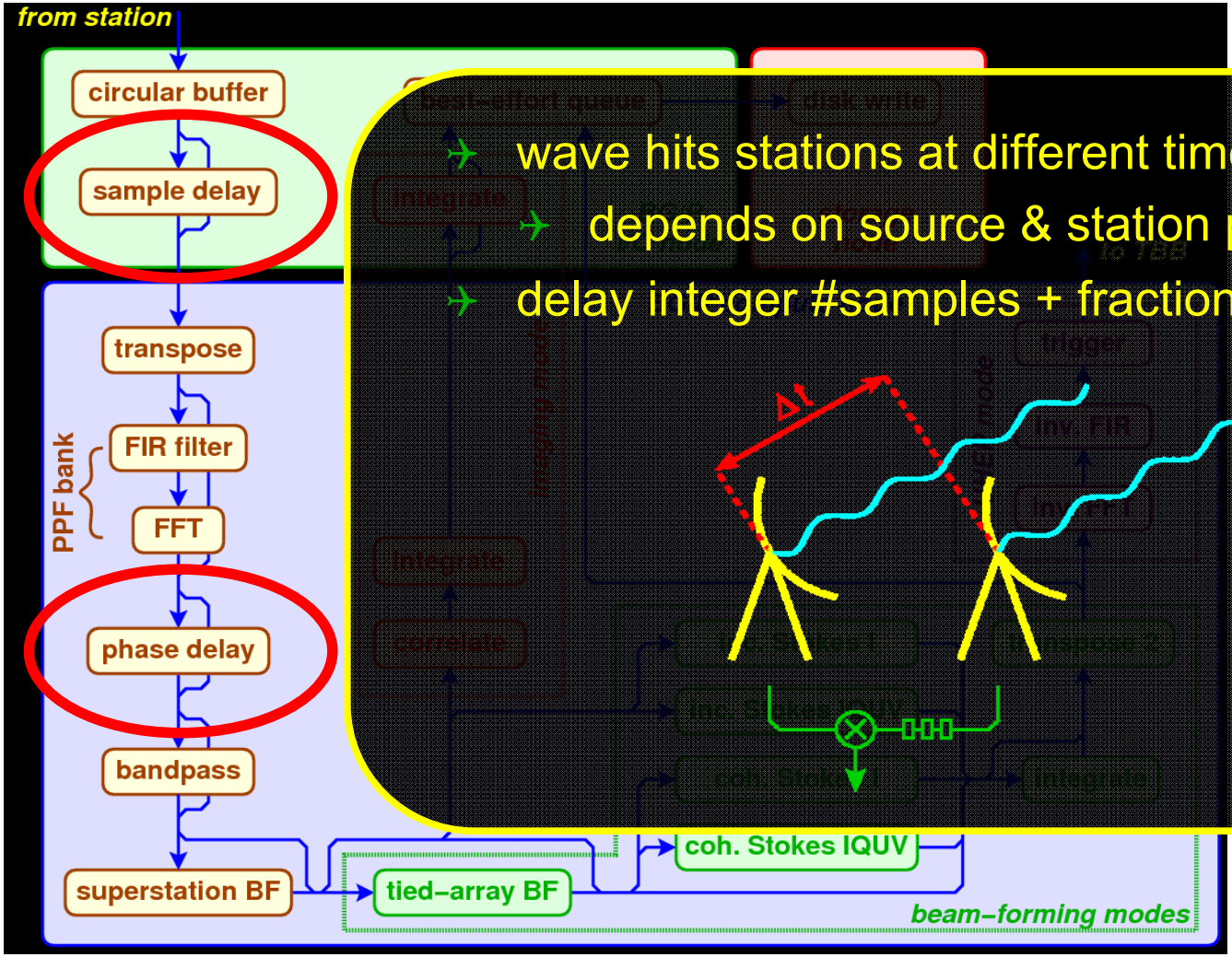


Circular Buffer



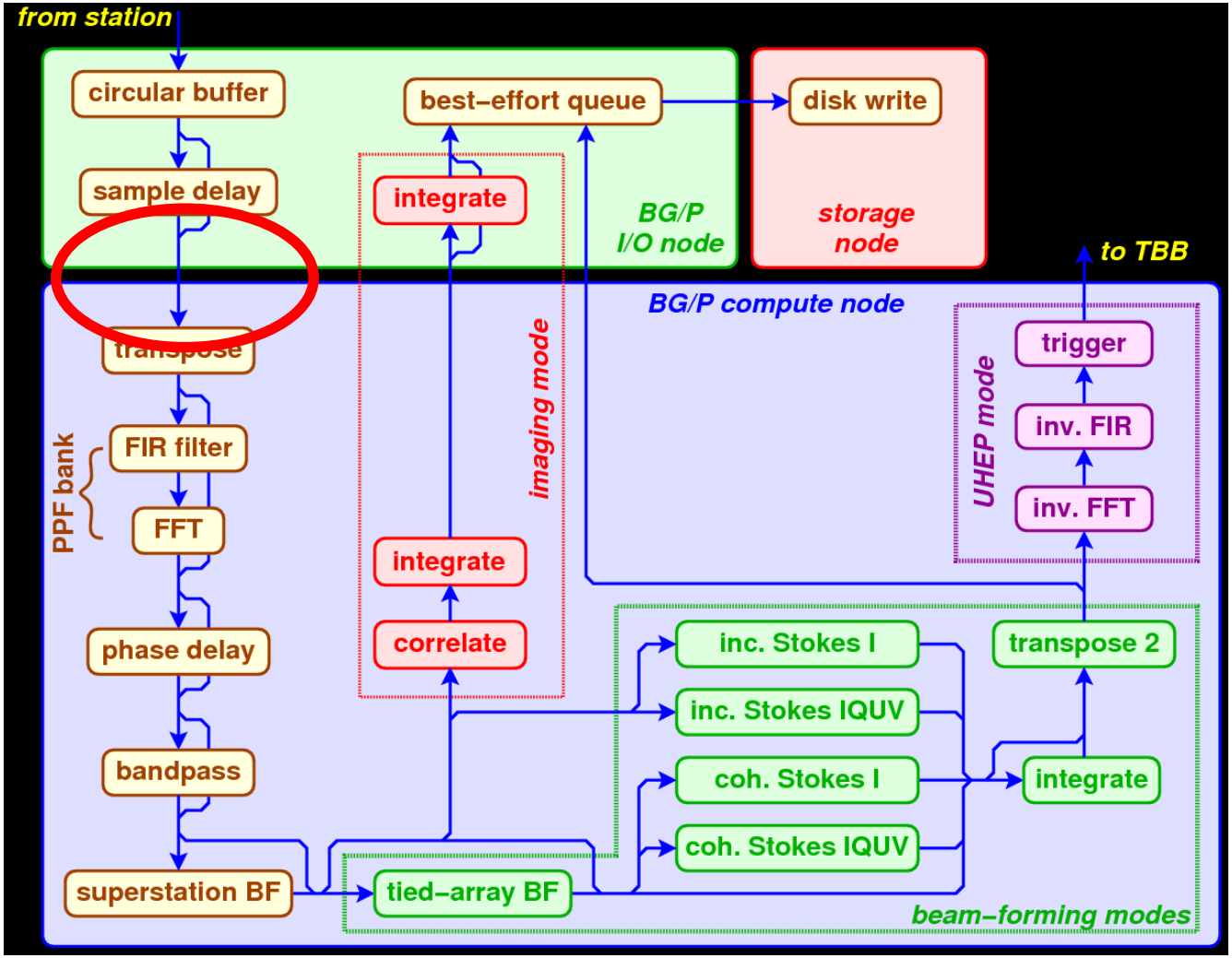
- circular buffer (~3 sec)
- station sync
- delay compensation
- handle hiccups

Delay Compensation

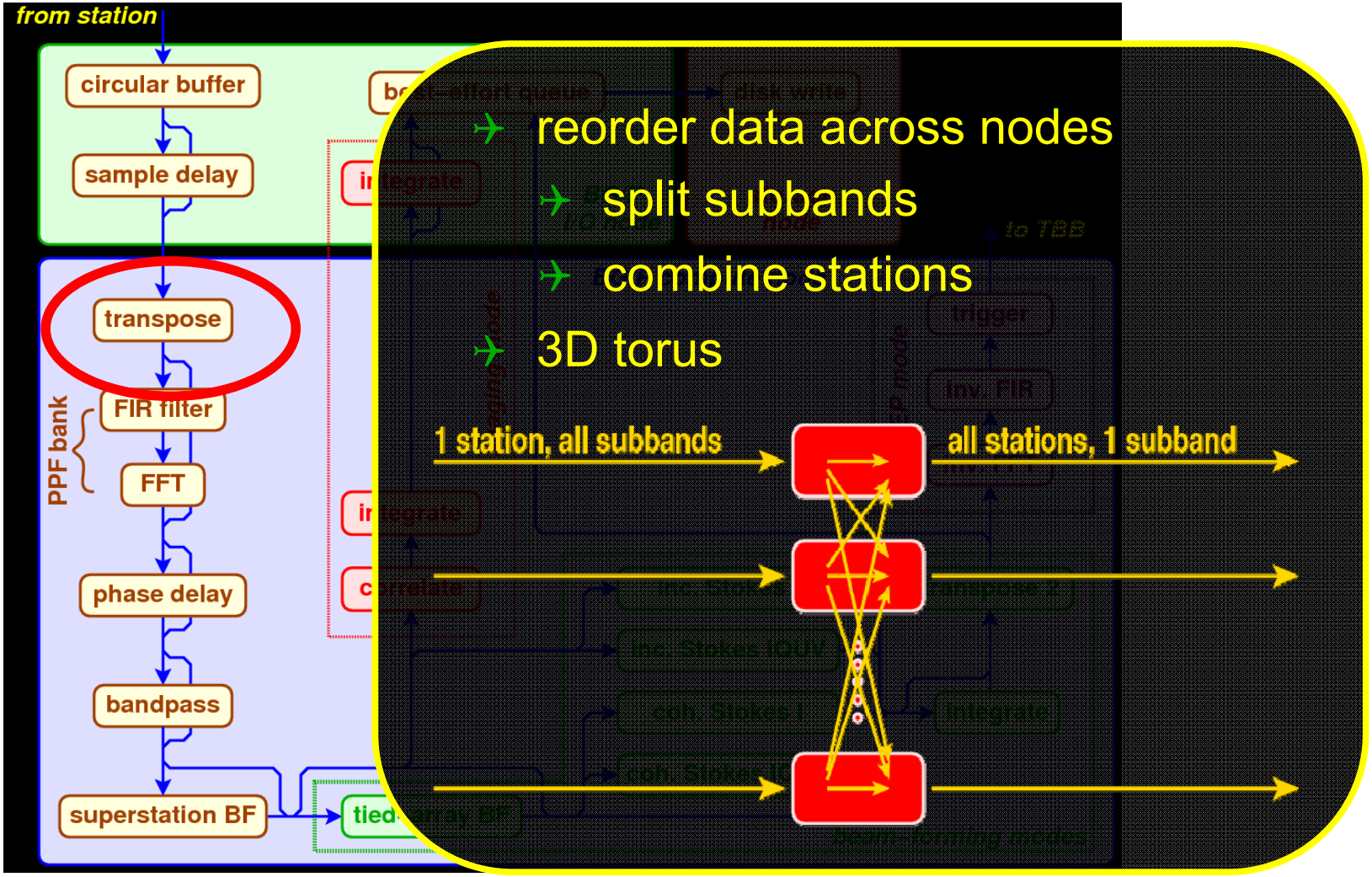


- wave hits stations at different times
- depends on source & station positions
- delay integer #samples + fractional delay

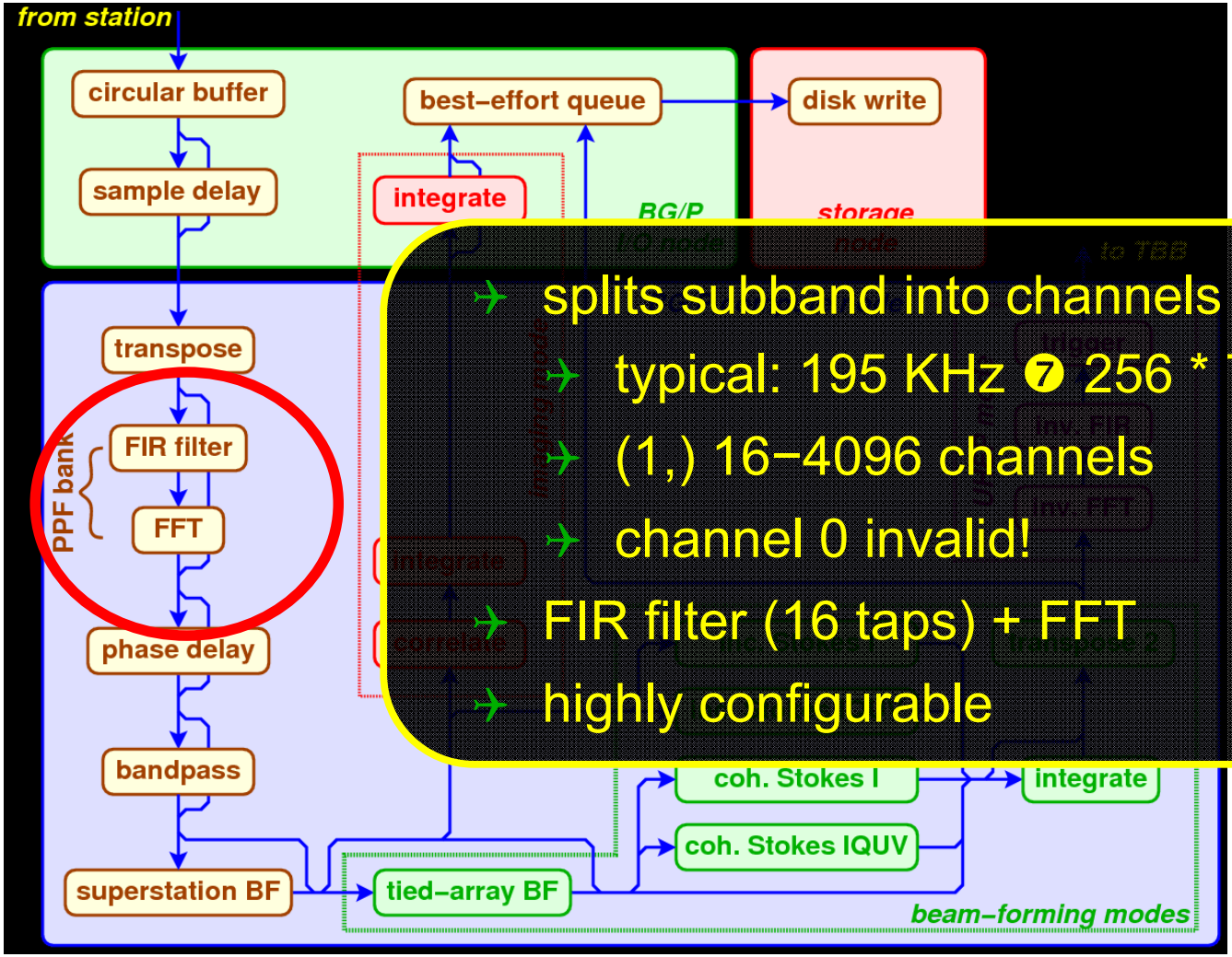
I/O Node → Compute Node



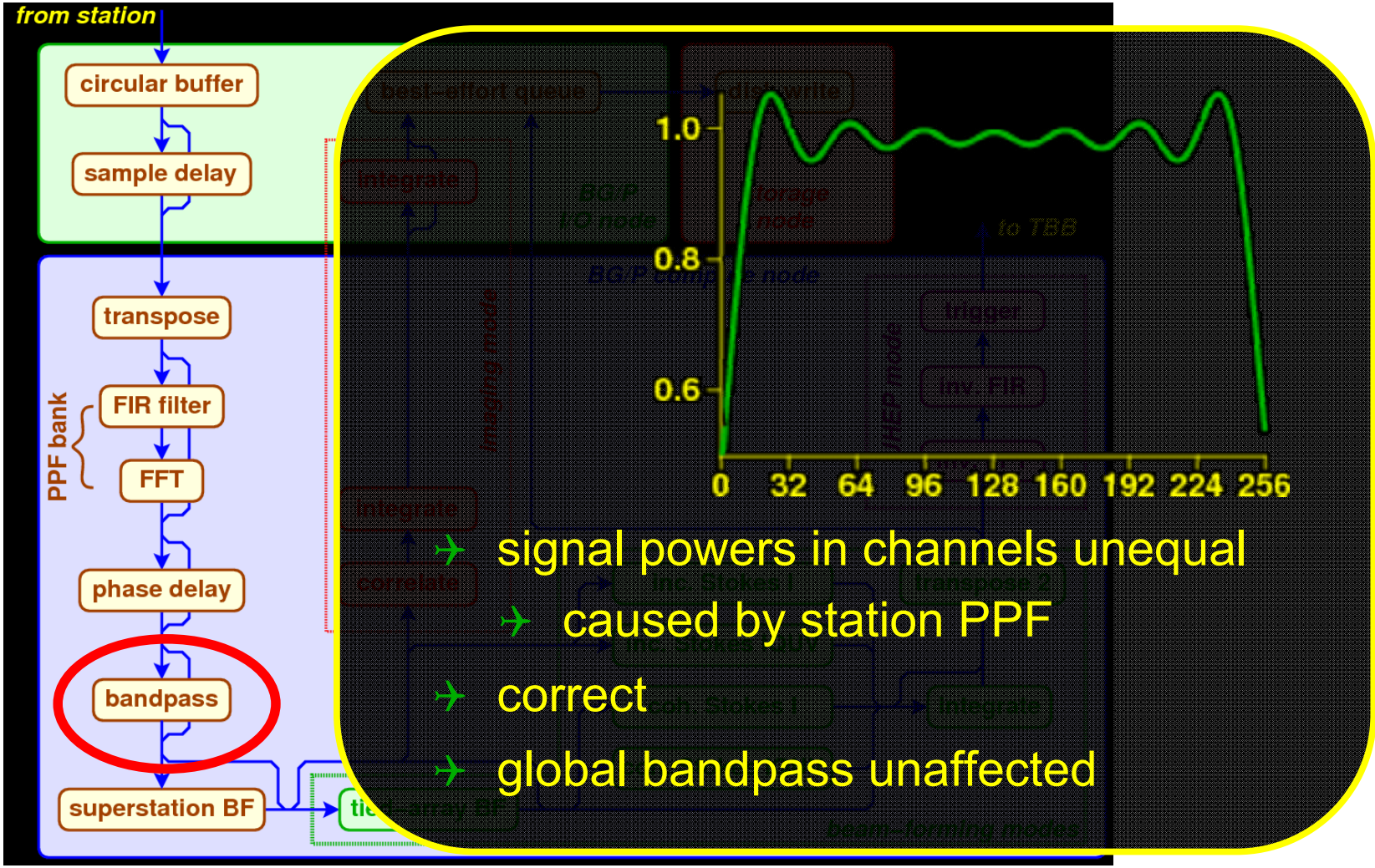
Transpose



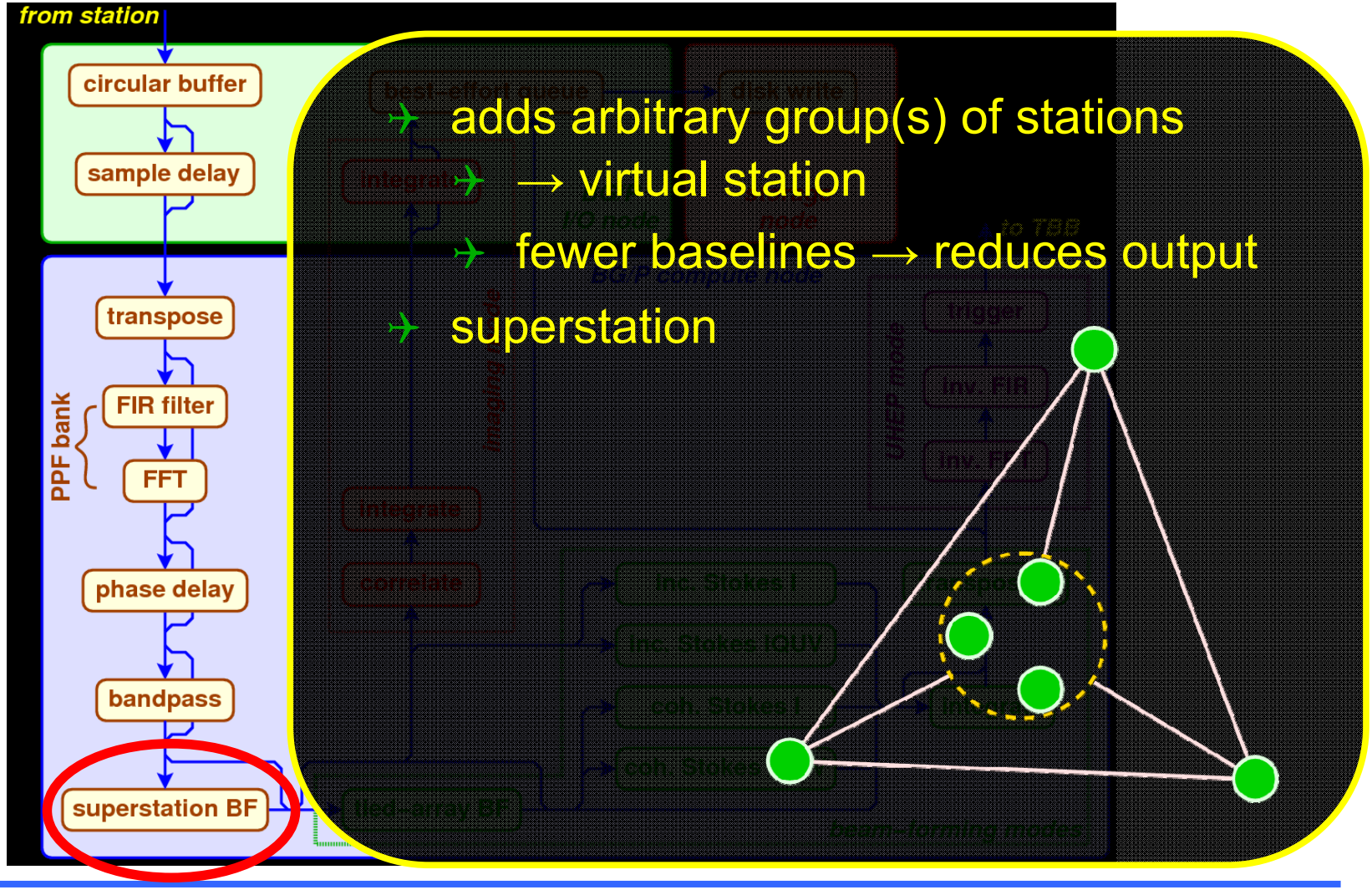
Poly-Phase Filter Bank



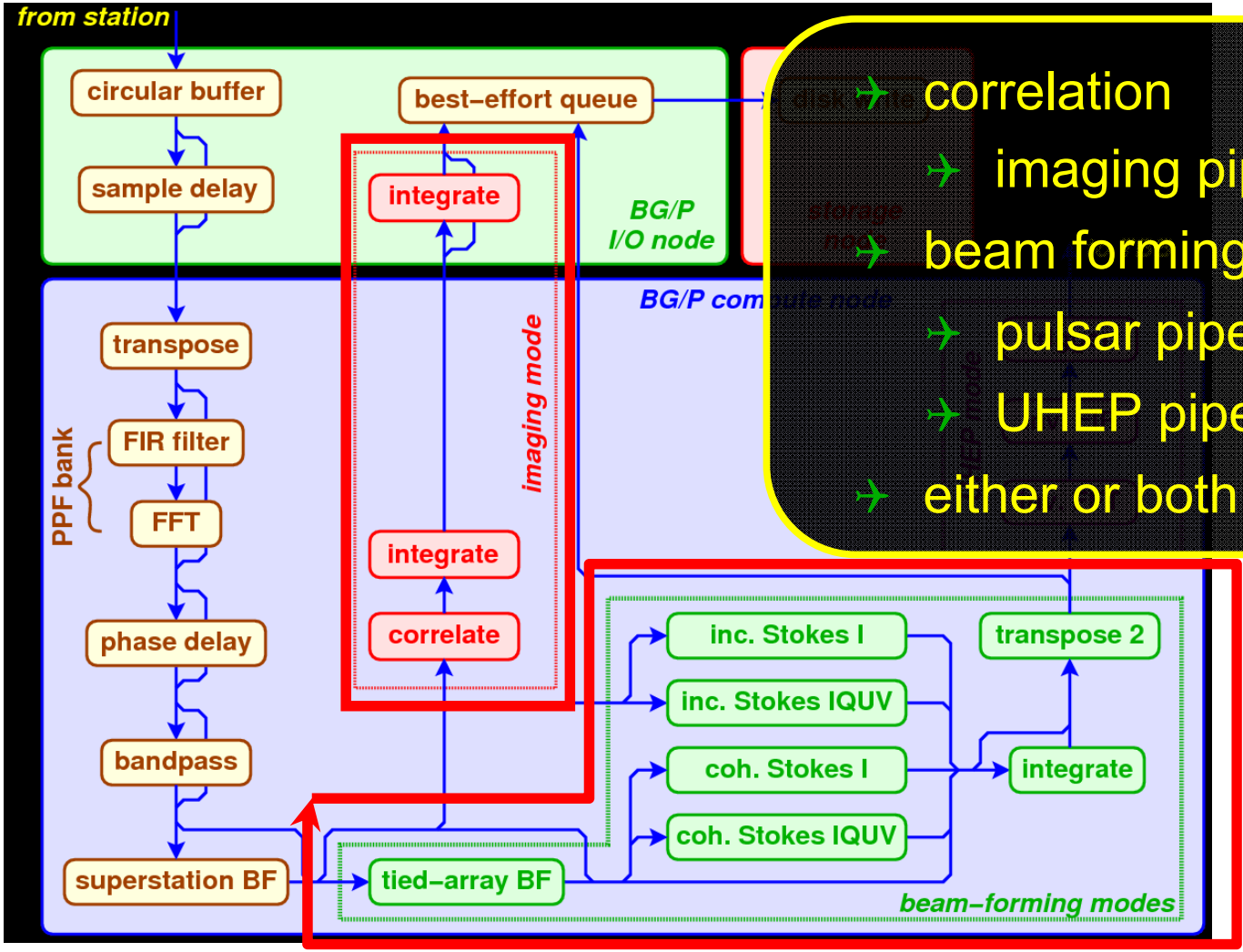
Bandpass Correction



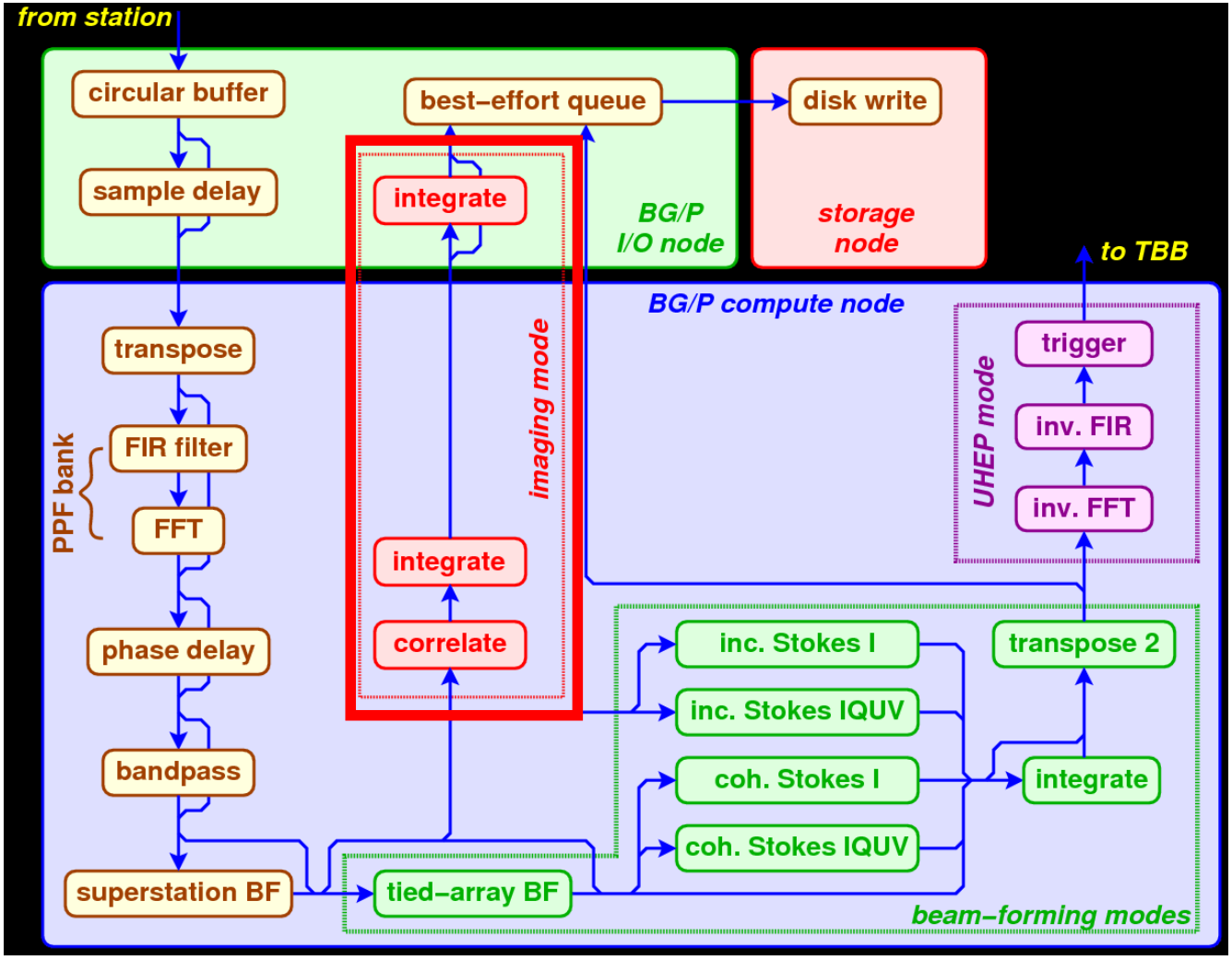
SuperStation Beam Forming



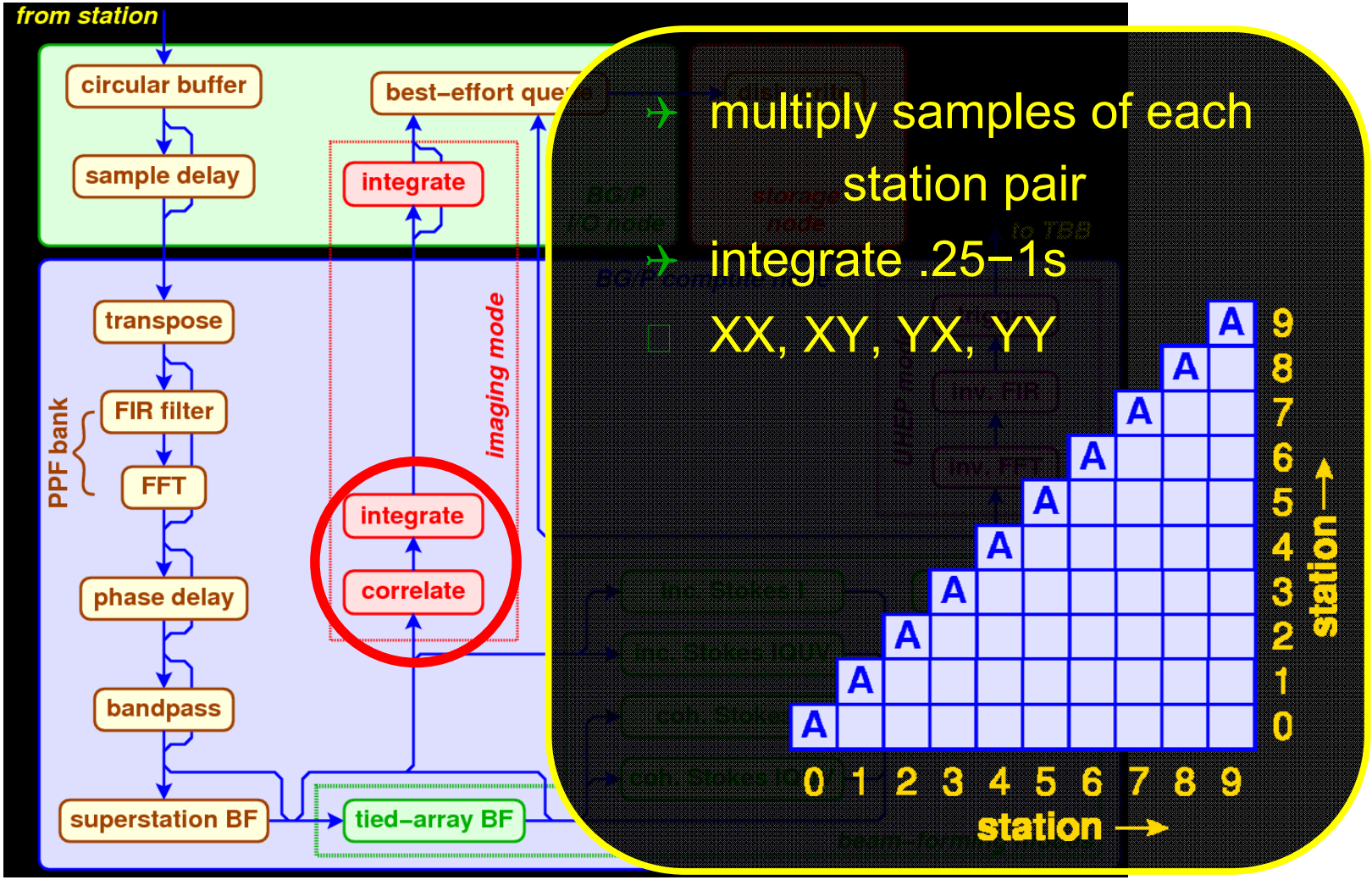
Pipeline diversion



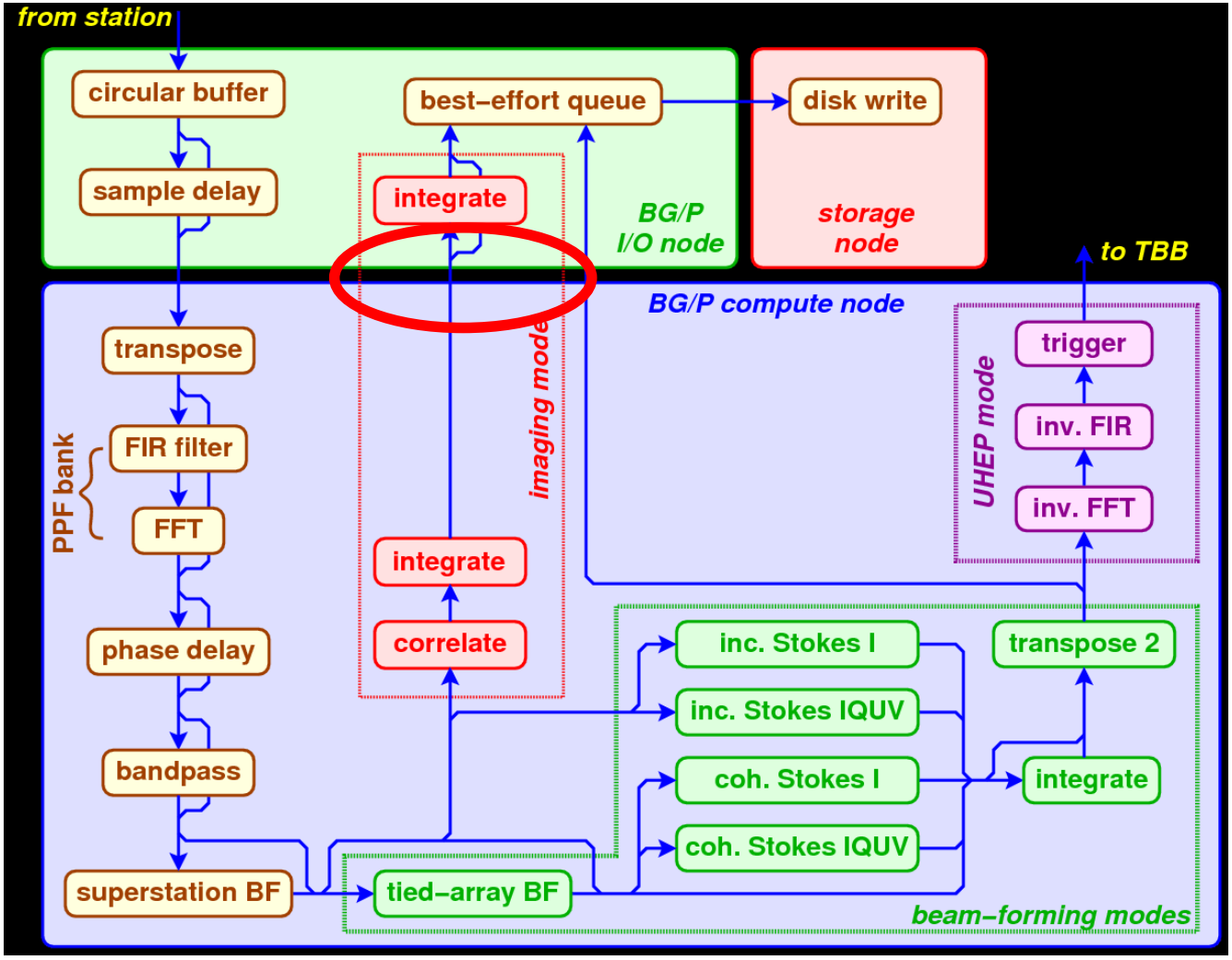
Correlation Pipeline



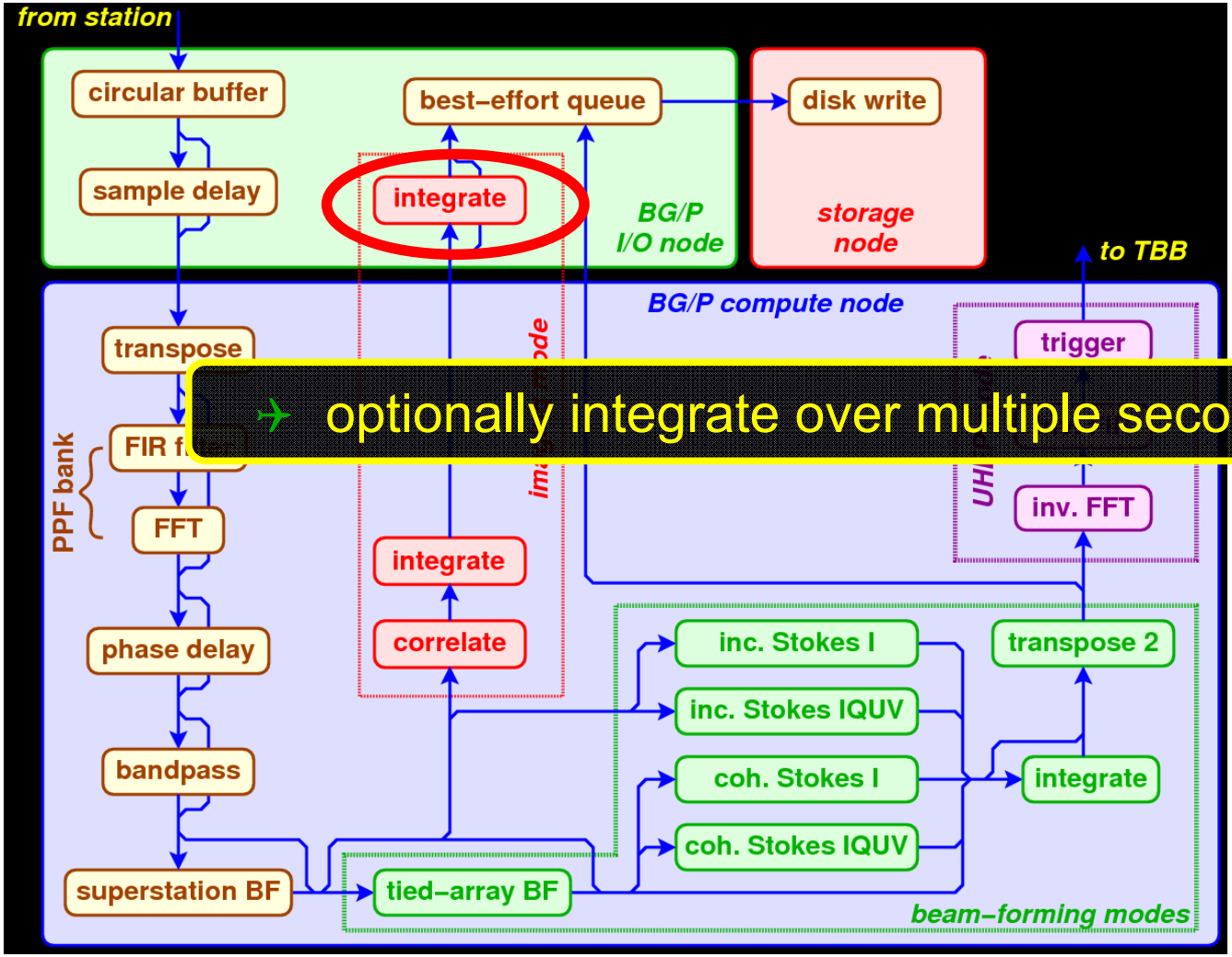
Correlation



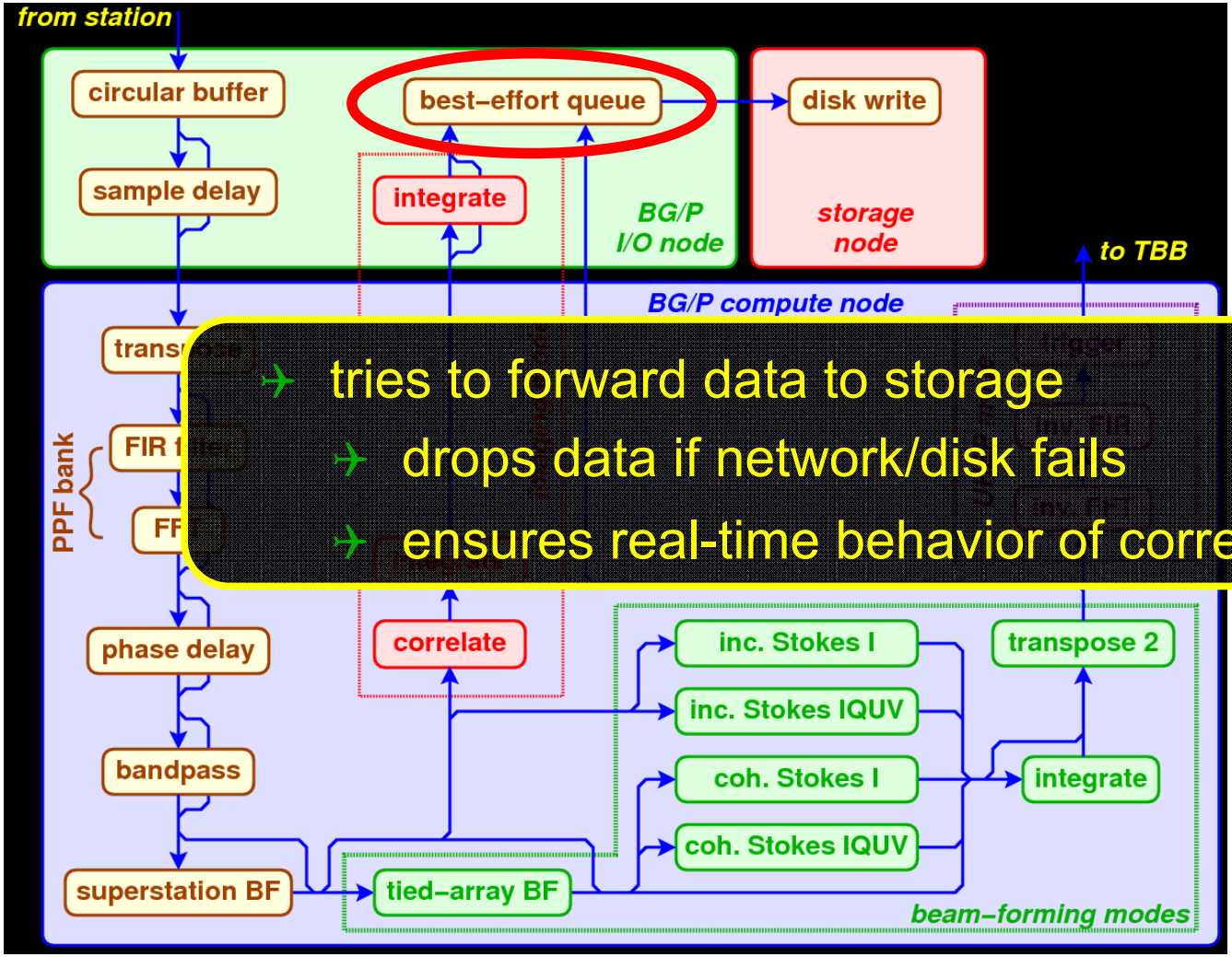
Compute Node → I/O Node



Further Integration

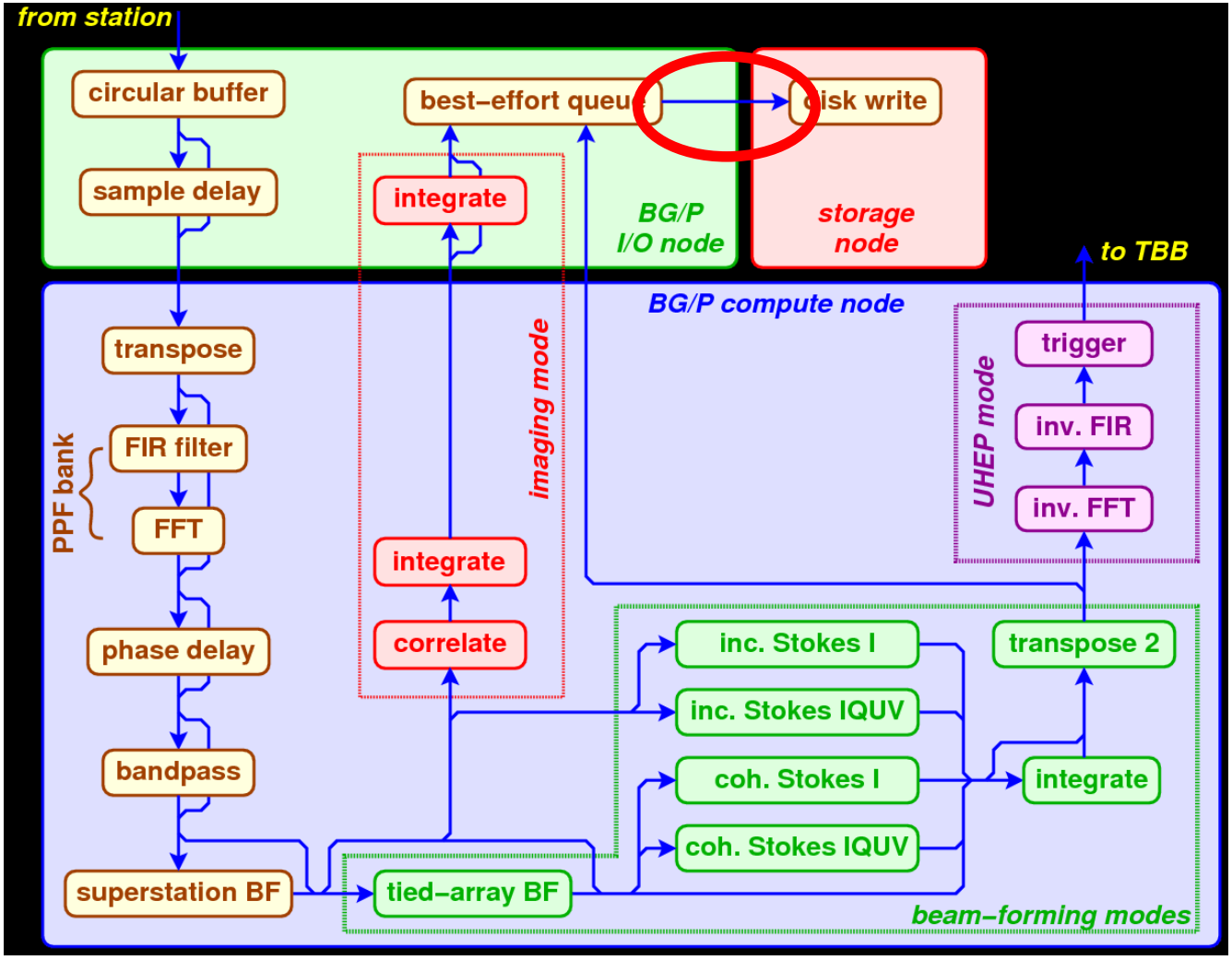


Best-Effort Queue

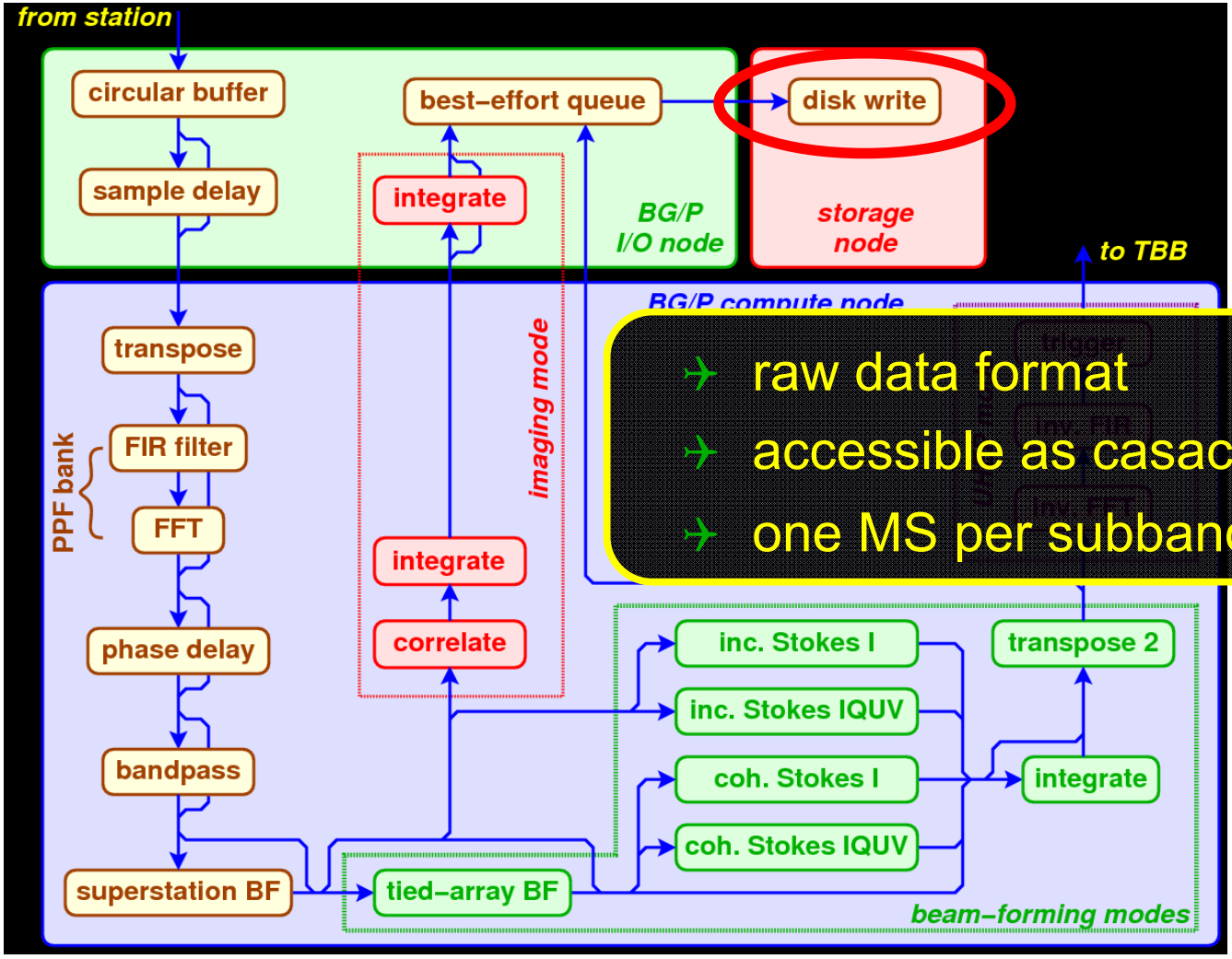


- tries to forward data to storage
  - drops data if network/disk fails
  - ensures real-time behavior of correlator

I/O Node ❼ Storage Node



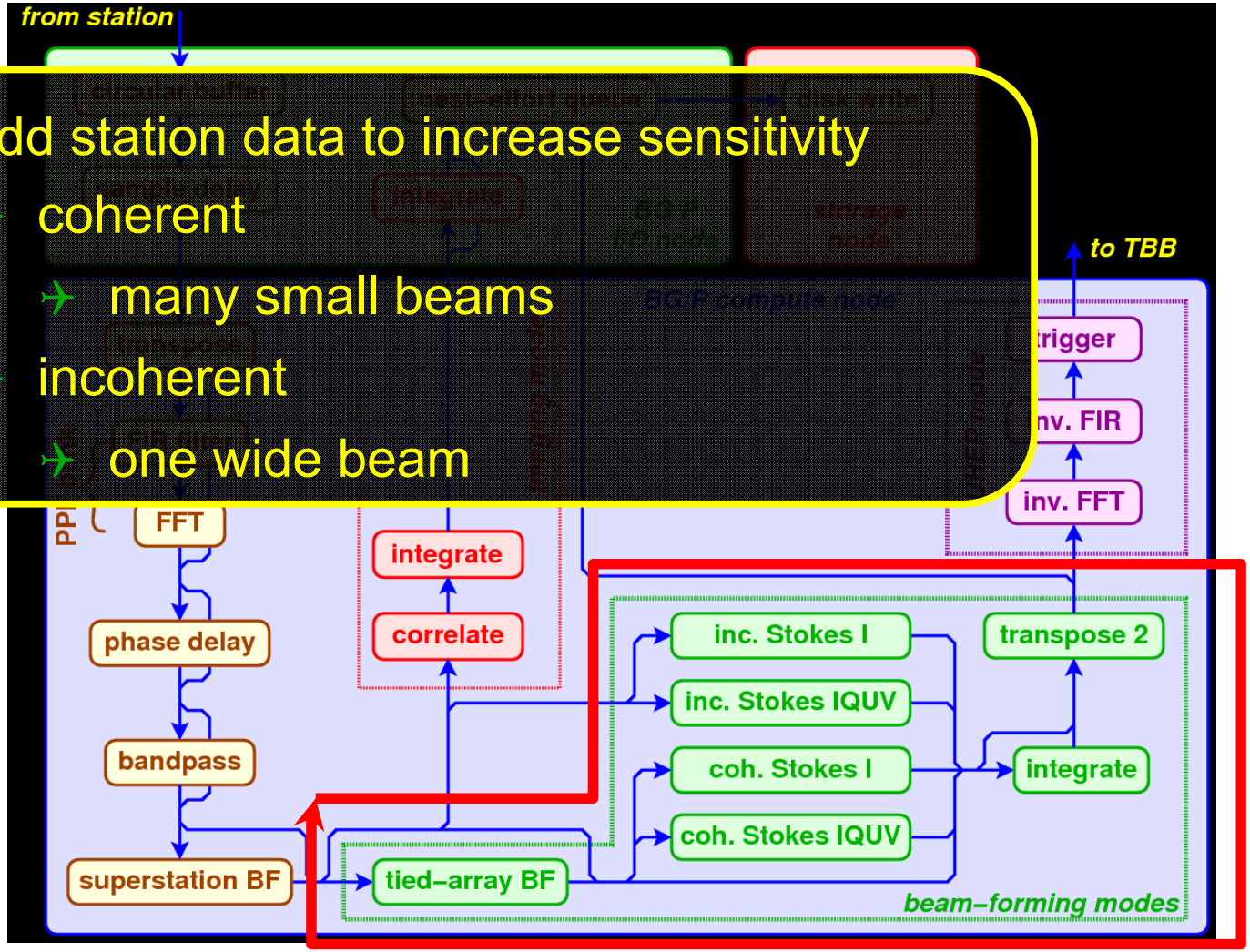
Write to Disk



- raw data format
- accessible as casacore MS
- one MS per subband

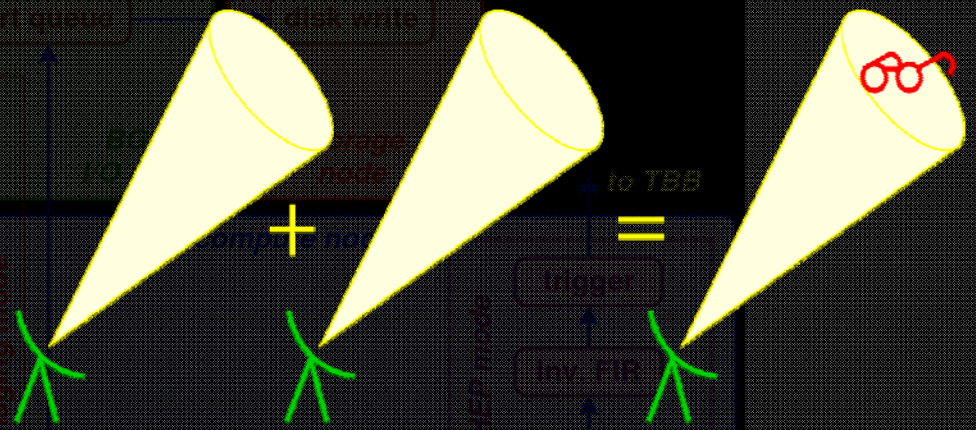
Beam Forming Pipelines

- add station data to increase sensitivity
  - coherent
    - many small beams
  - incoherent
    - one wide beam

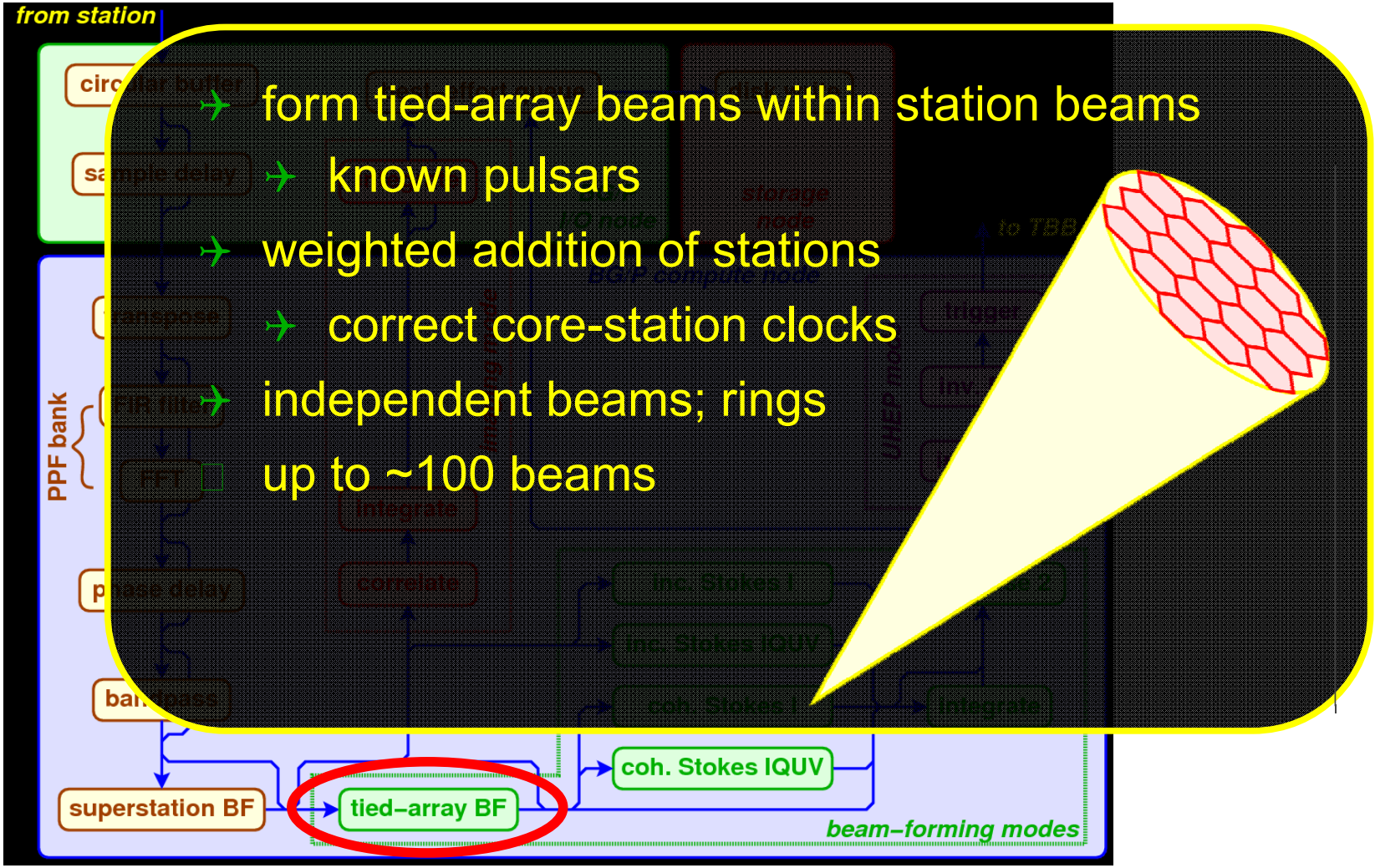


Incoherent Beam Forming

- add station powers
- one wide beam
  - pulsar search
- Stokes I or IQUV

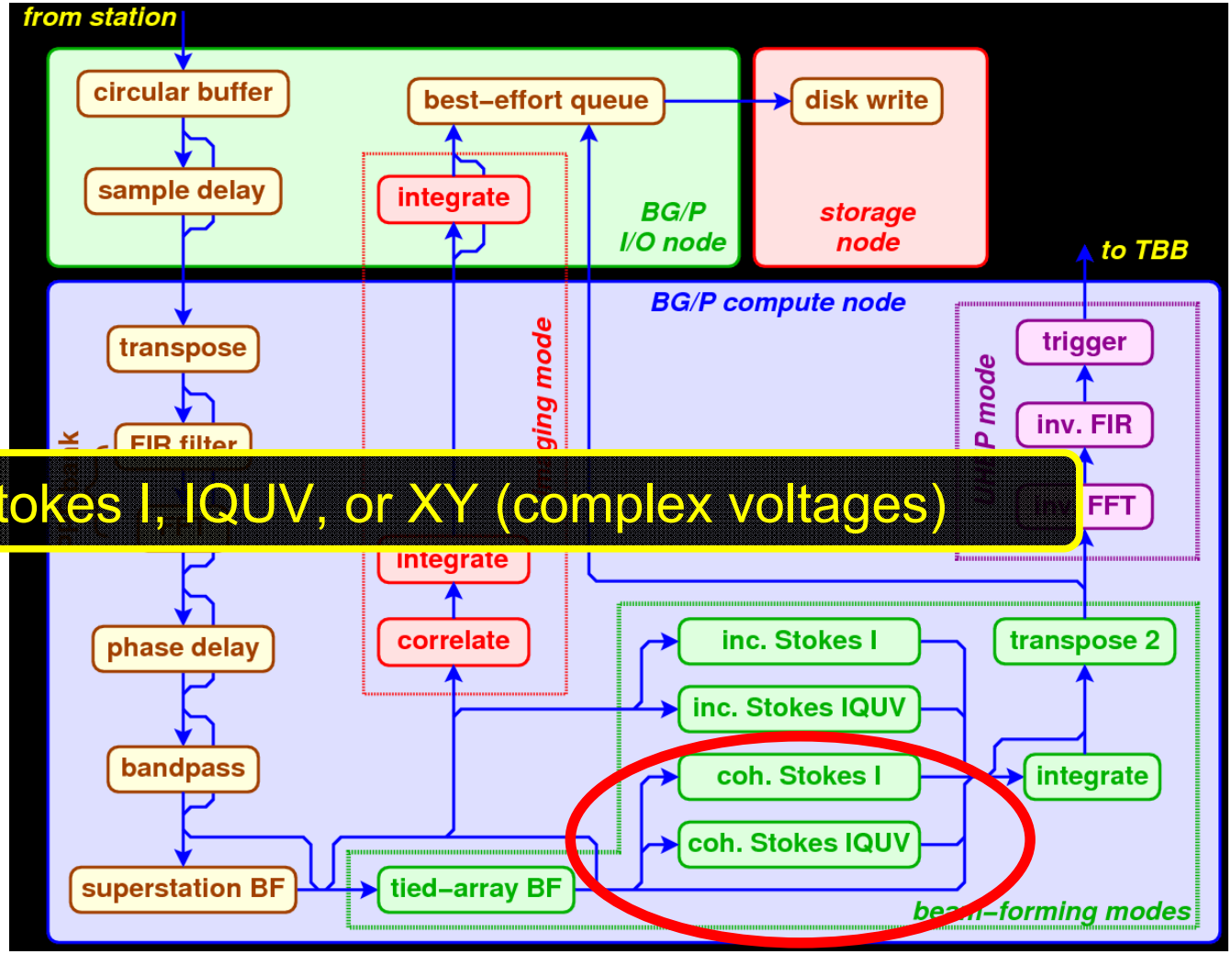


Coherent Beam Forming



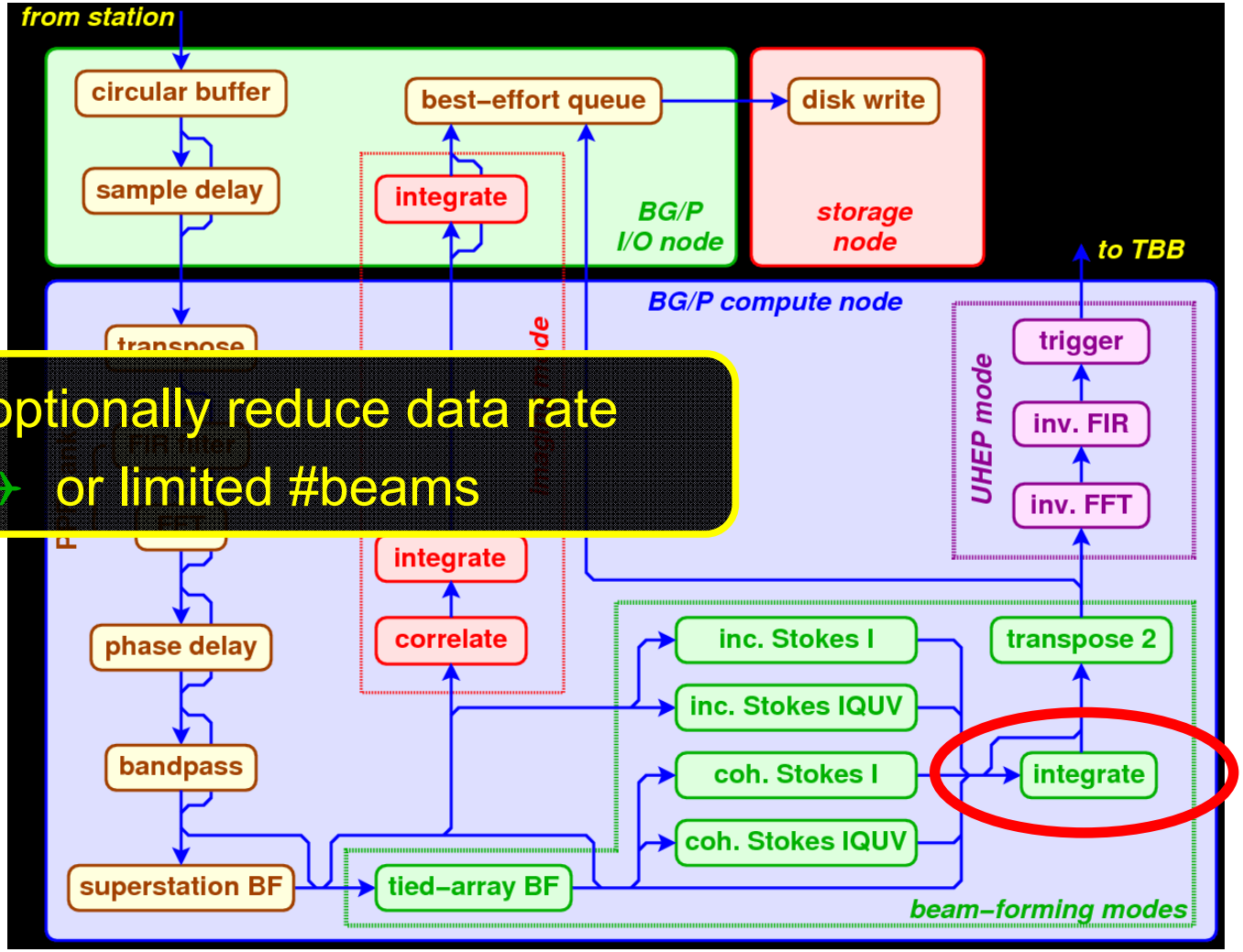
- form tied-array beams within station beams
  - known pulsars
  - weighted addition of stations
  - correct core-station clocks
- independent beams; rings
- up to ~100 beams

Coherent Beam Forming



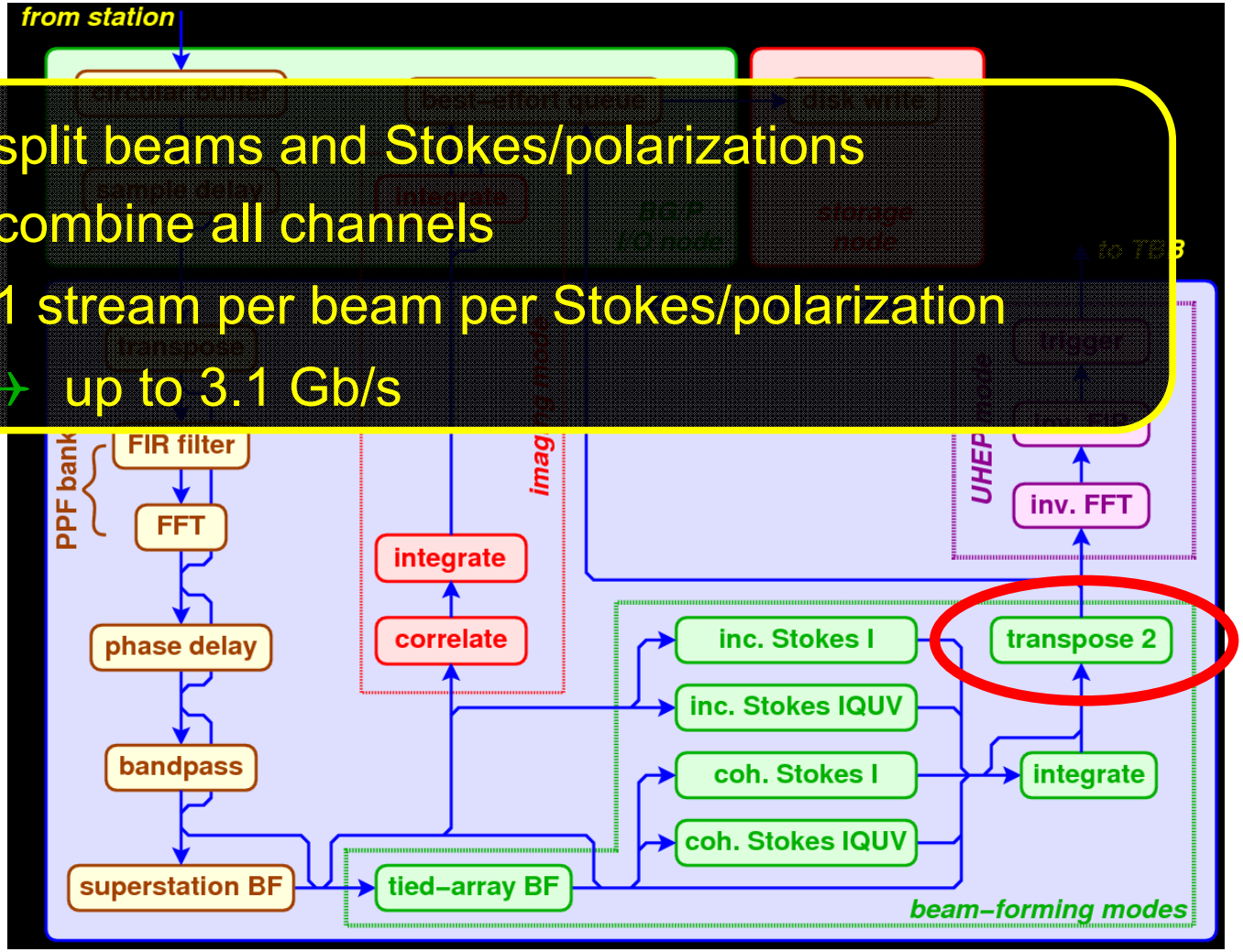
- Stokes I, IQUV, or XY (complex voltages)

Integration



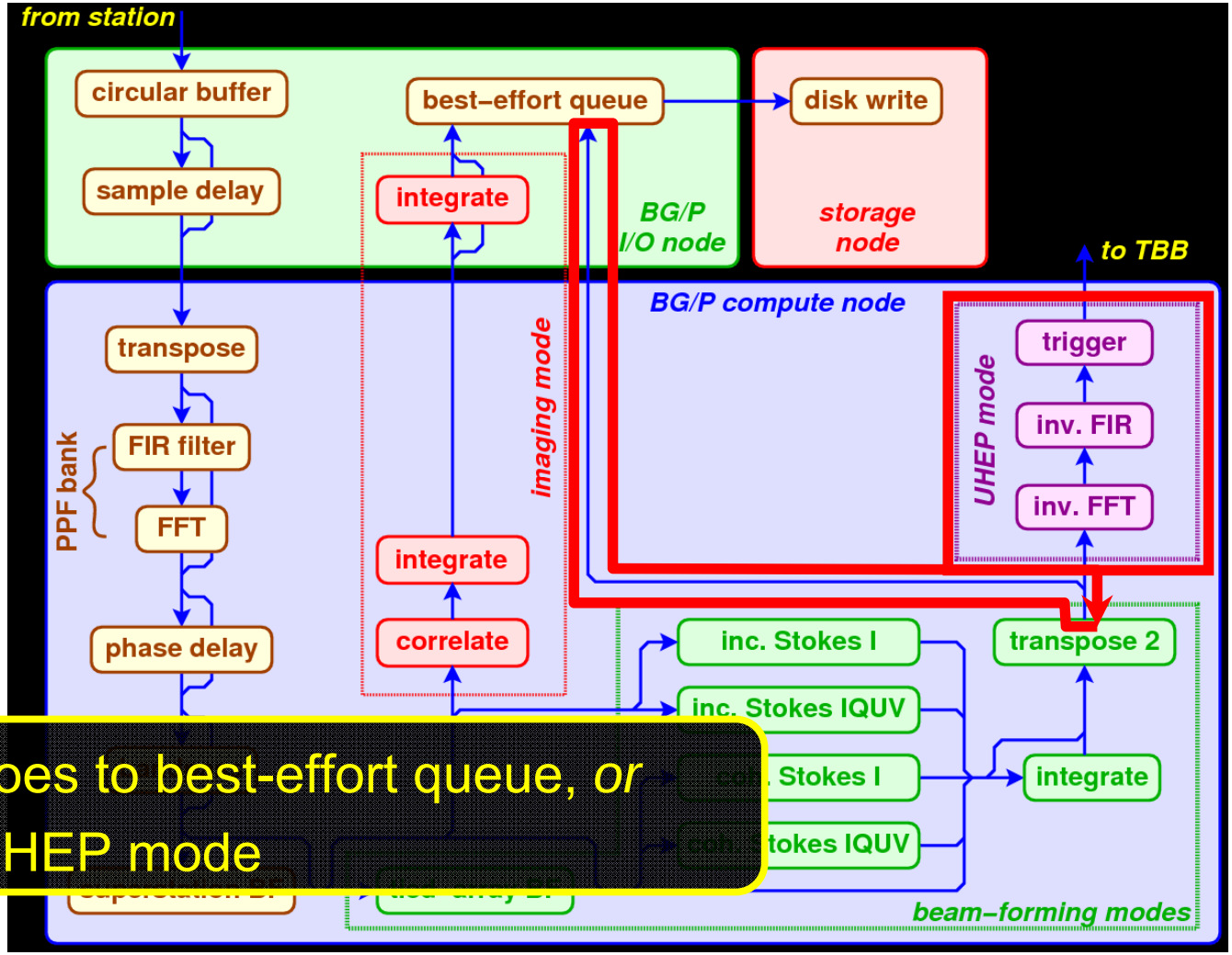
- optionally reduce data rate
- or limited #beams

2nd Transpose



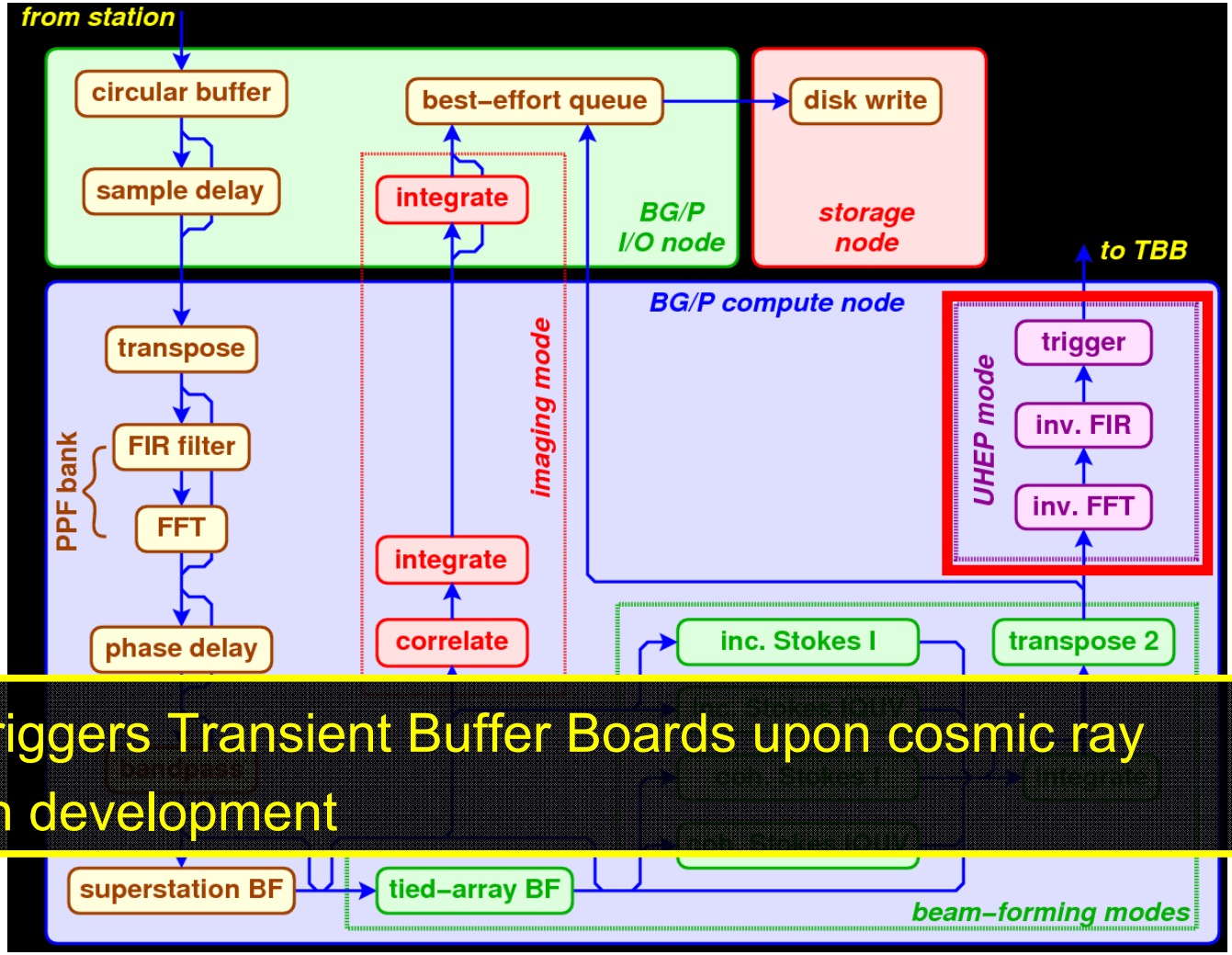
- split beams and Stokes/polarizations
- combine all channels
- 1 stream per beam per Stokes/polarization
  - up to 3.1 Gb/s

Beam Formed Data



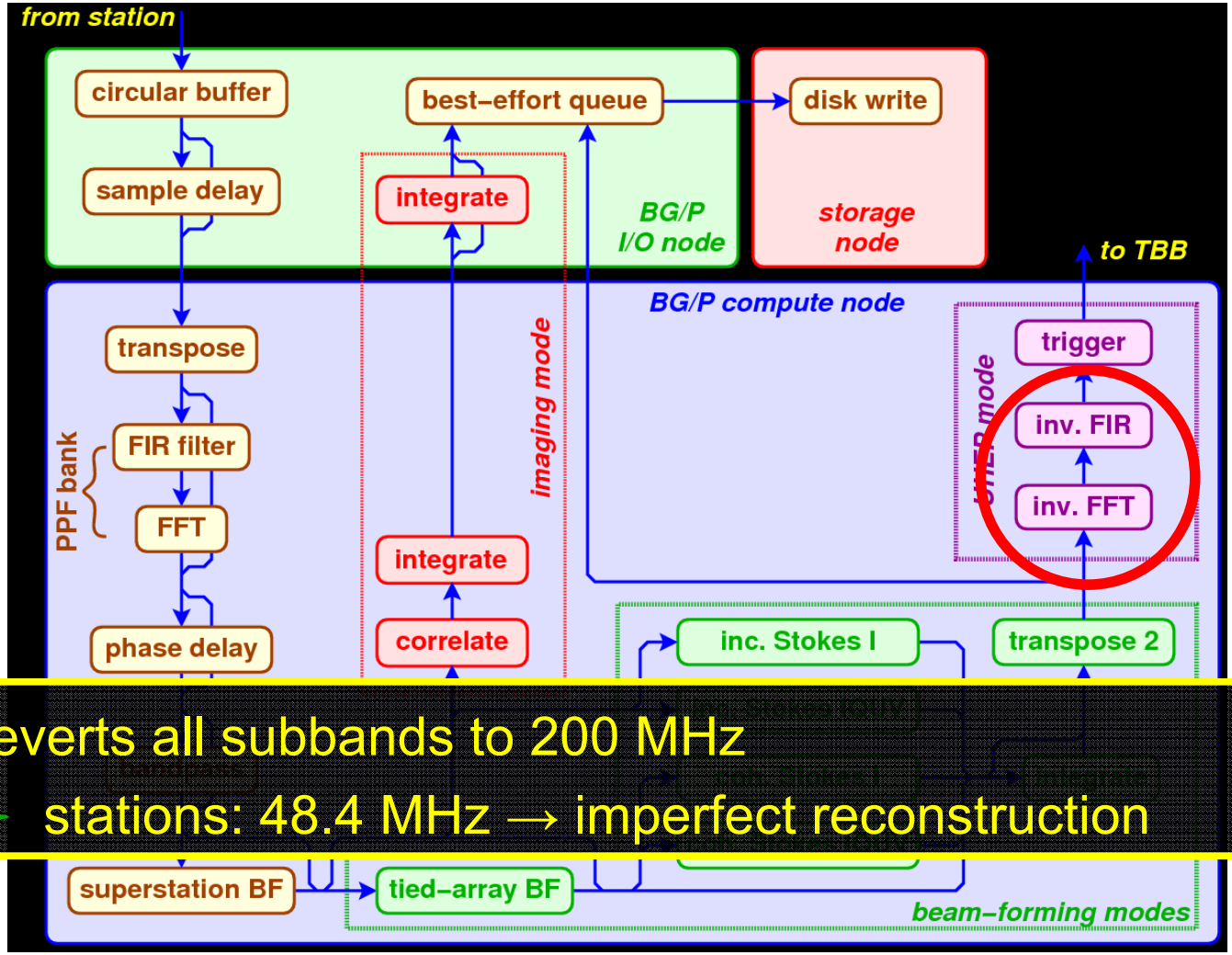
- goes to best-effort queue, *or*
- UHEP mode

Ultra-High Energy Particles Mode



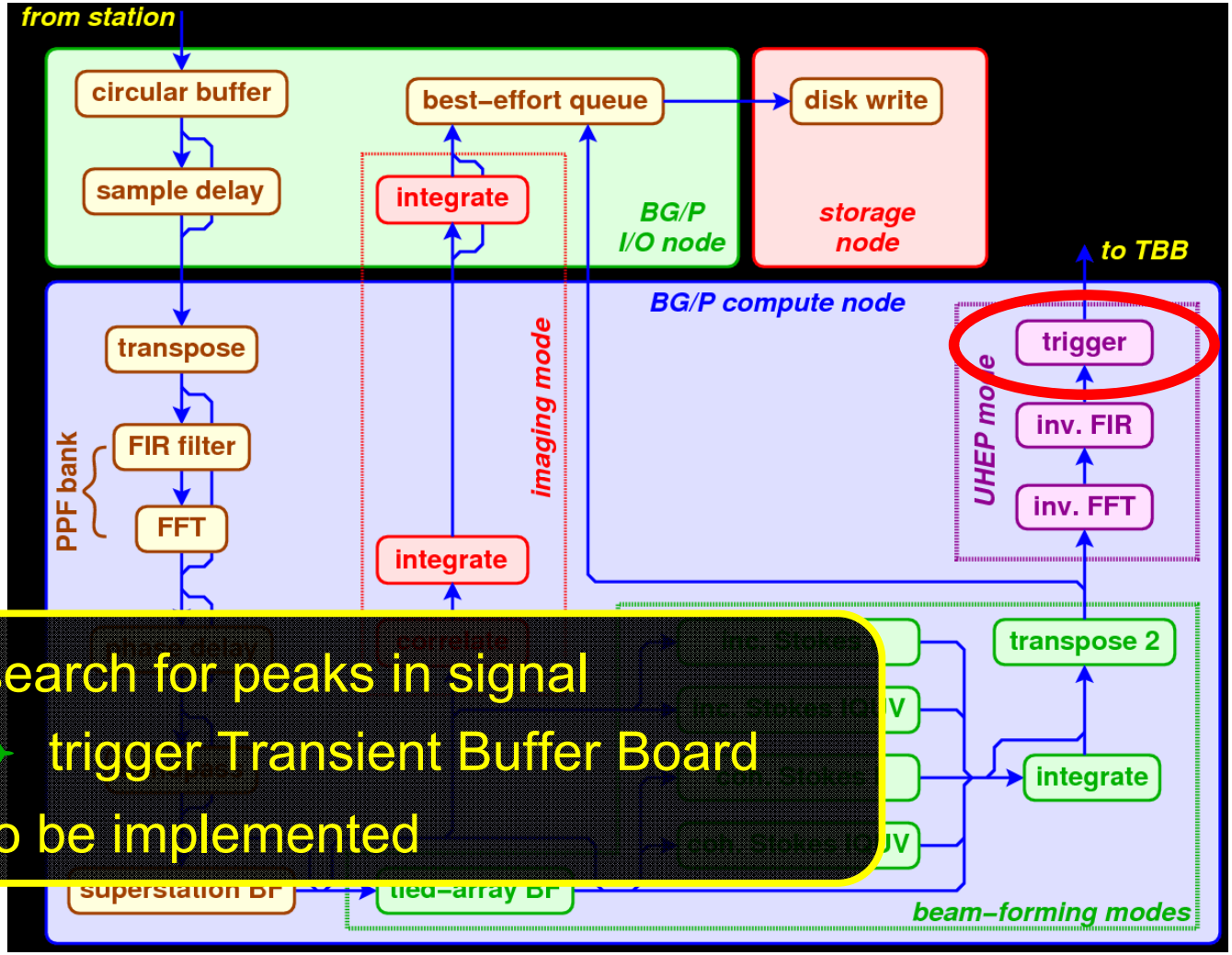
- ✈ triggers Transient Buffer Boards upon cosmic ray
- in development

Inverse PPF



- reverts all subbands to 200 MHz
- stations: 48.4 MHz → imperfect reconstruction

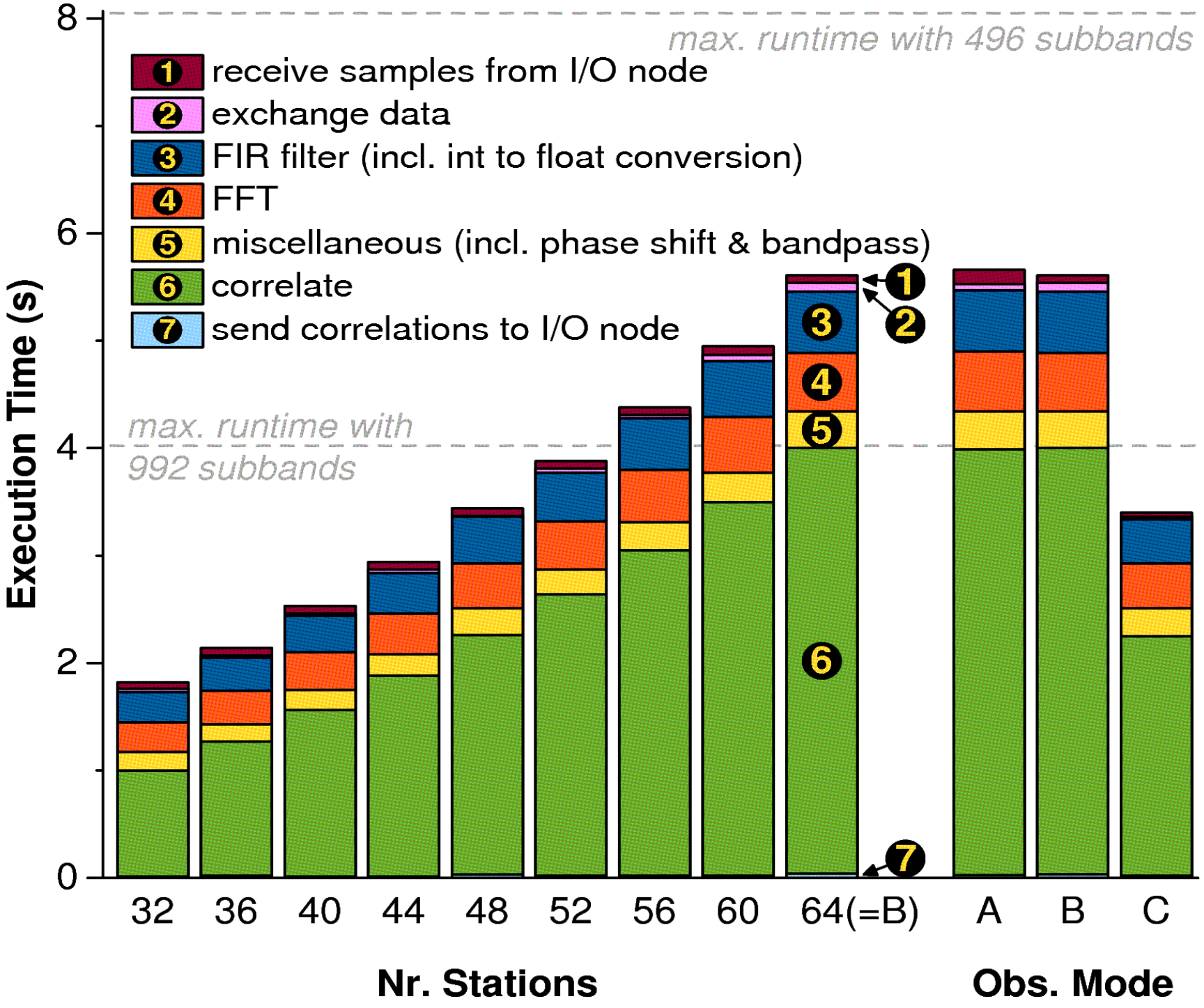
Trigger Algorithm

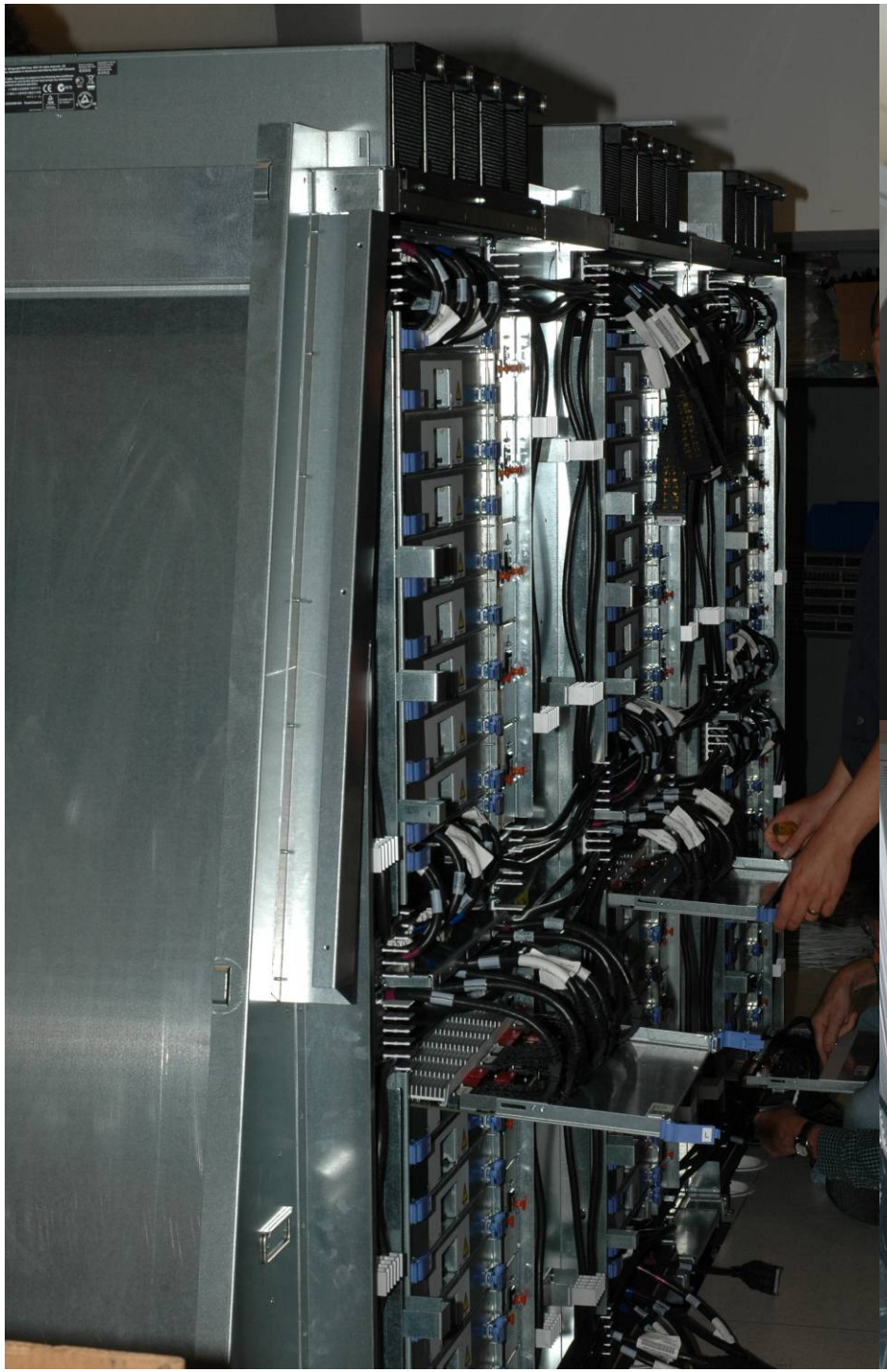


- search for peaks in signal
  - trigger Transient Buffer Board
- to be implemented

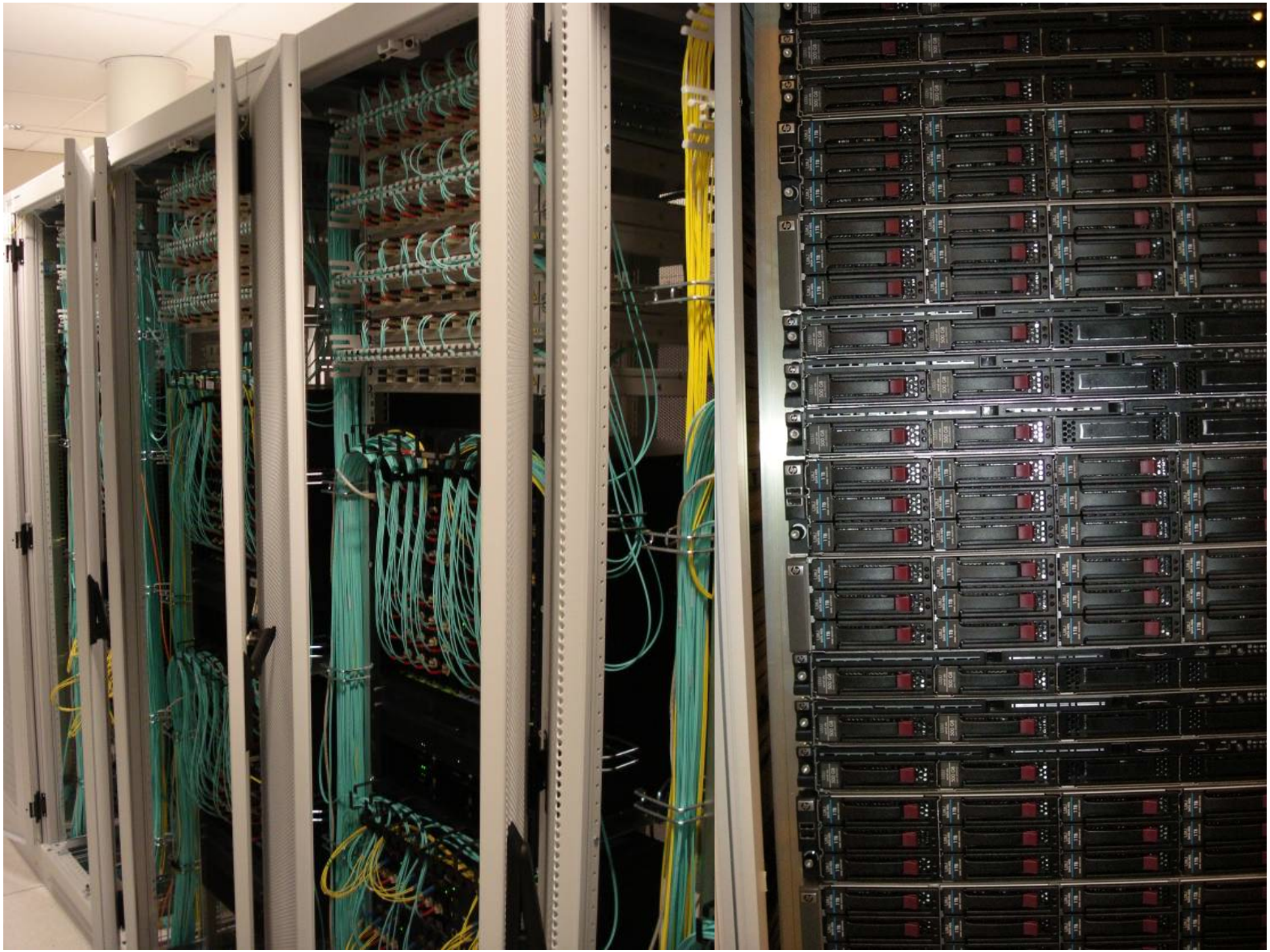
Optimizations

- Required: high bandwidth, performance and real-time
- Assembly used 96% of FPU peak)
  - Network protocol optimized
  - OS modified


max. runtime with 496 subbands
1 receive samples from I/O node
2 exchange data
3 FIR filter (incl. int to float conversion)
4 FFT
5 miscellaneous (incl. phase shift & bandpass)
6 correlate
7 send correlations to I/O node
max. runtime with 992 subbands
Execution Time (s)
0
2
4
6
8
32
36
40
44
48
52
56
60
64(=B)
A
B
C
Nr. Stations
Obs. Mode




Blue Gene/P



- Combined compute and storage cluster
  - 102 compute nodes of which 100 storage nodes
  - 2 CPUs with 12 cores (2.1 GHz klok freq.)
  - 20 TByte per storage node

- Total capacity: 20 TFlop and 2 PByte

Status

ASTRON

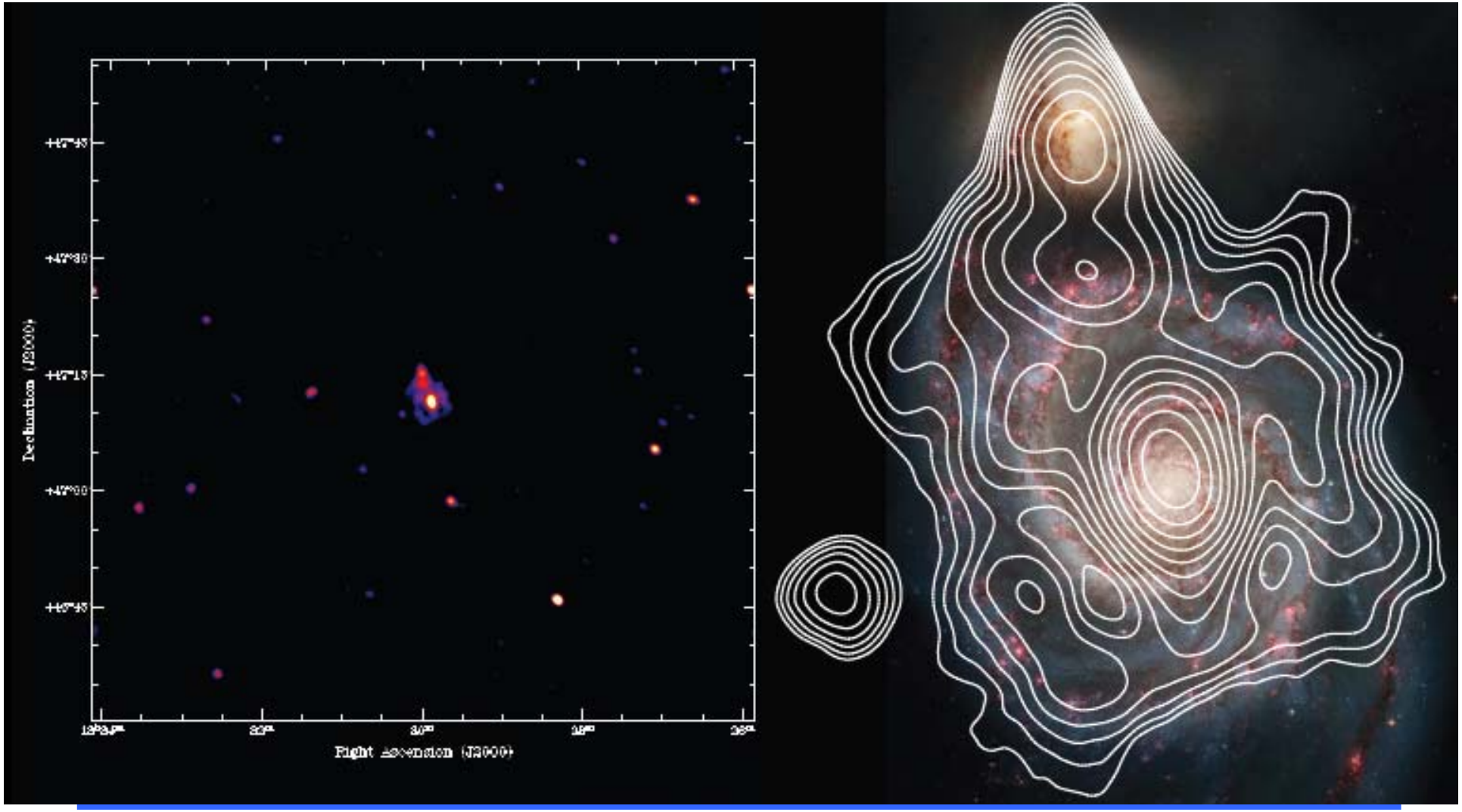
LOFAR Opening 12 June 2010

ASTRON

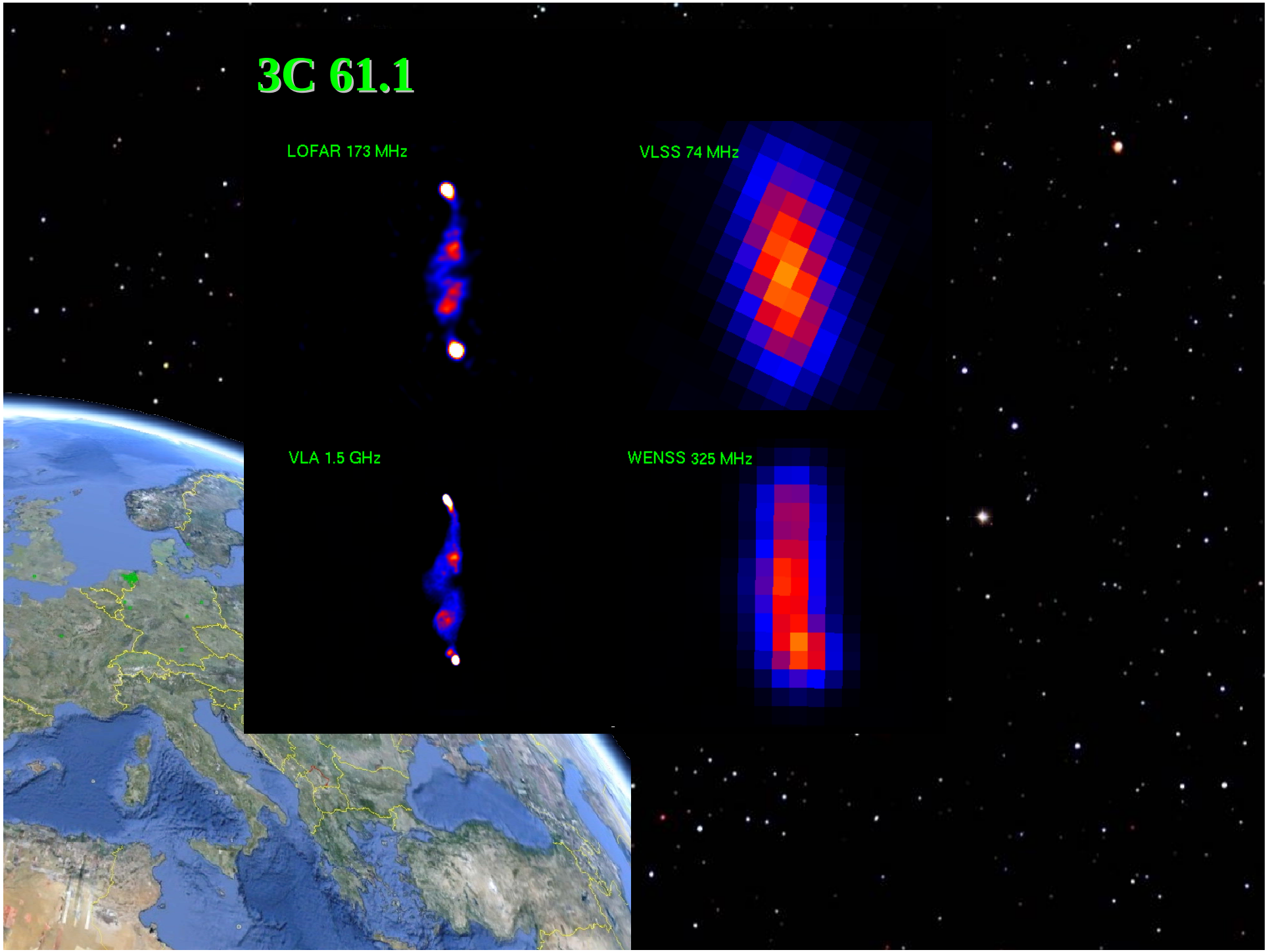
- LBA fields: 40
- HBA fields: 40
- Fiber conn.: 36
- In operation: 34

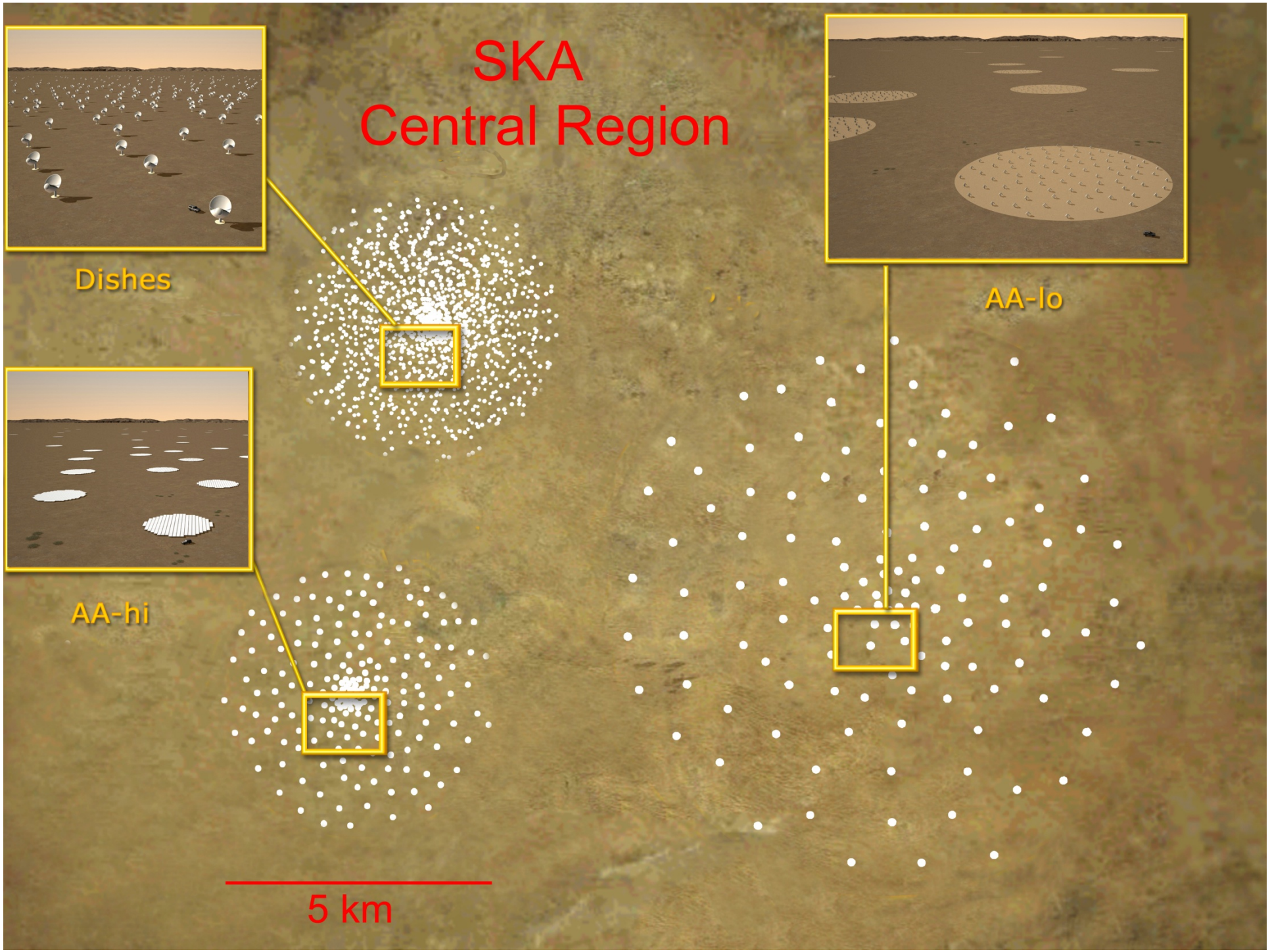
Station/Item	Cabinet	LBA	HBA	Fibre	CEP connection	Validated
CS302						
RS307						
RS503						
RS106						
RS208						
CS030						
CS401						
CS021						
CS032						
RS306						
CS301						
CS501						
RS509						
CS103						
CS001						
CS002						
CS003						
CS004						
CS005						
CS006						
CS007						
CS024						
CS201						
CS101						
CS026						
RS205						
CS017						
CS011						
CS013						
CS028						
CS031						
RS305 (RS104)						
RS210						
RS310						
RS404						
RS406						
RS407						
RS409						
RS410						
RS508						
Effelsberg						
Tautenburg						
Garching						
Potsdam						
Juelich						
Nancay						
Onsala						
Chilbolton						
Totals	40	40	40	36	35	34

LOFAR Results (M51)



3C 61.1

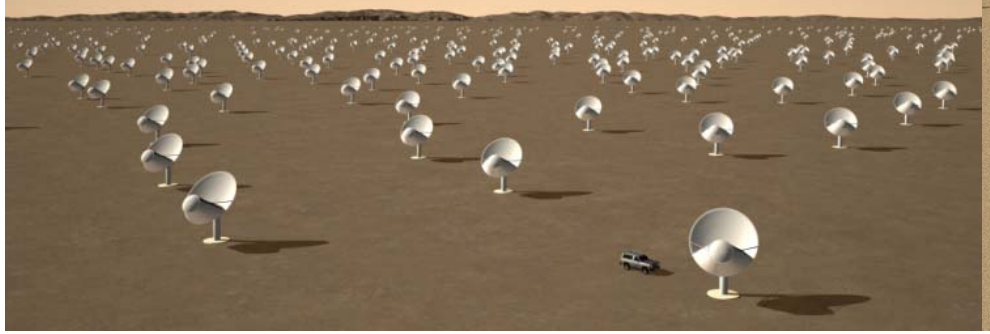



SKA
Central Region
Dishes
AA-lo
AA-hi
5 km

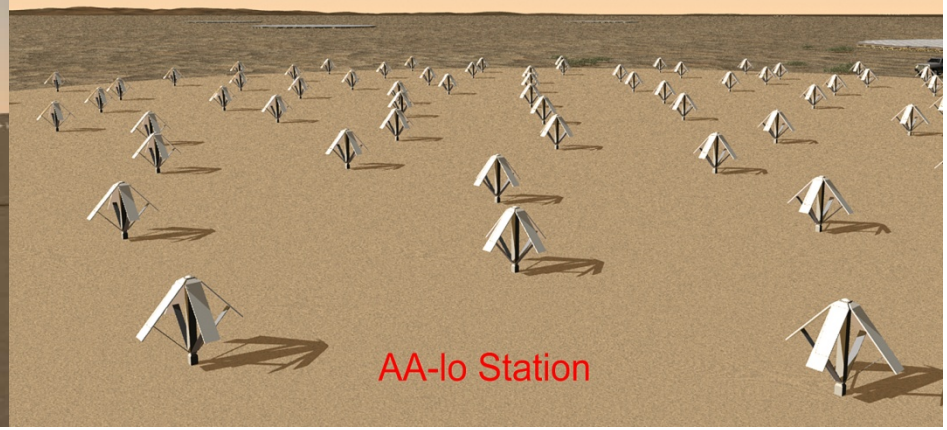
Possible telescope configuration

1500 dishes (15m diameter) in central ~5 k

+1500 from 5 km to 3000+ km



Sparse aperture arrays



Conclusions

- LOFAR full of digital signal processing functionality
- Multiple technologies used in one system
- Digital systems tend to move to the antennas