Station processing:
from LOFAR to EMBRACE

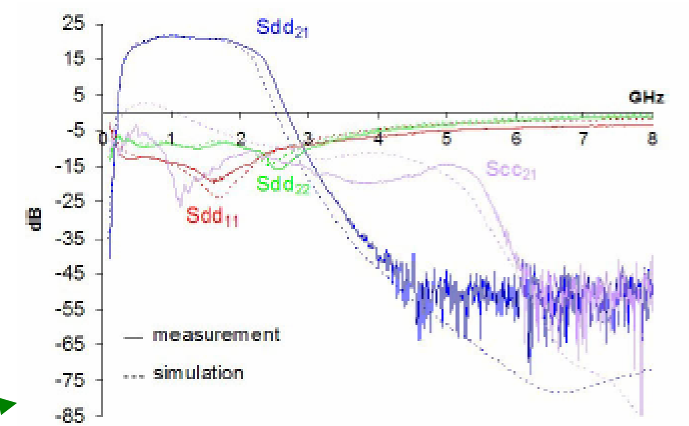
Philippe Picard
Station de Radioastronomie de Nançay

Philippe.Picard@obs-nancay.fr

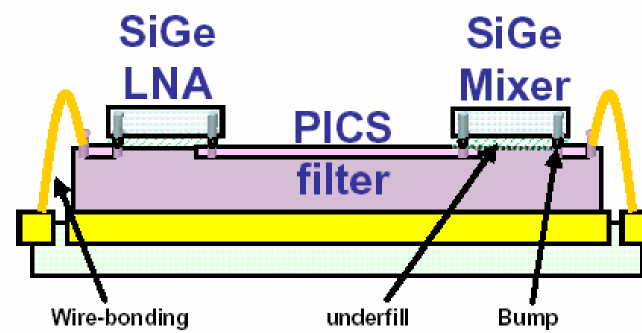
Digital processing:
Vincent Macaire (Nançay)
Rodolphe Weber (Orléans University)

Monitoring and Control software:
Patrice Renaud (Nançay)
Christophe Taffoureau (Nançay)
Ludovic Mercier (Nançay)

Paris Observatory developments in enabling technologies for SKA



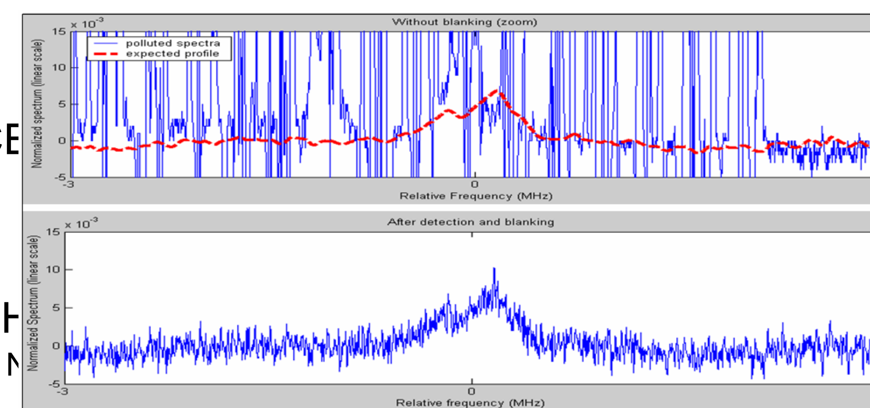
- Front-end technologies
  - **Silicon LNA**
- ➢ measured : 0.3-2.0GHz, NF<1.1dB with NXP QuBiC4G
- ➢ simulated : 0.3-2.0GHz, NF<0.6 dB with NXP QuBiC4X
  - **Substrate technology** offer high quality passives and interconnections (PICS-NXP)
- ➢ 5th order filter: 0.35-2GHz, rej. > 60dB, ripple < 0,1dB



- Integrated receiver
- ➢ measured : LNA + Filter + mixer in 0.3-2.0GHz band
- ➢ begining: direct conversion receiver in the 0.1-1.5GHz band

- Beamforming : beamformer chip for EMBRACE

- RFI mitigation
  - High dynamic, versatile digital receiver (RDH
  - Algorithms implementations

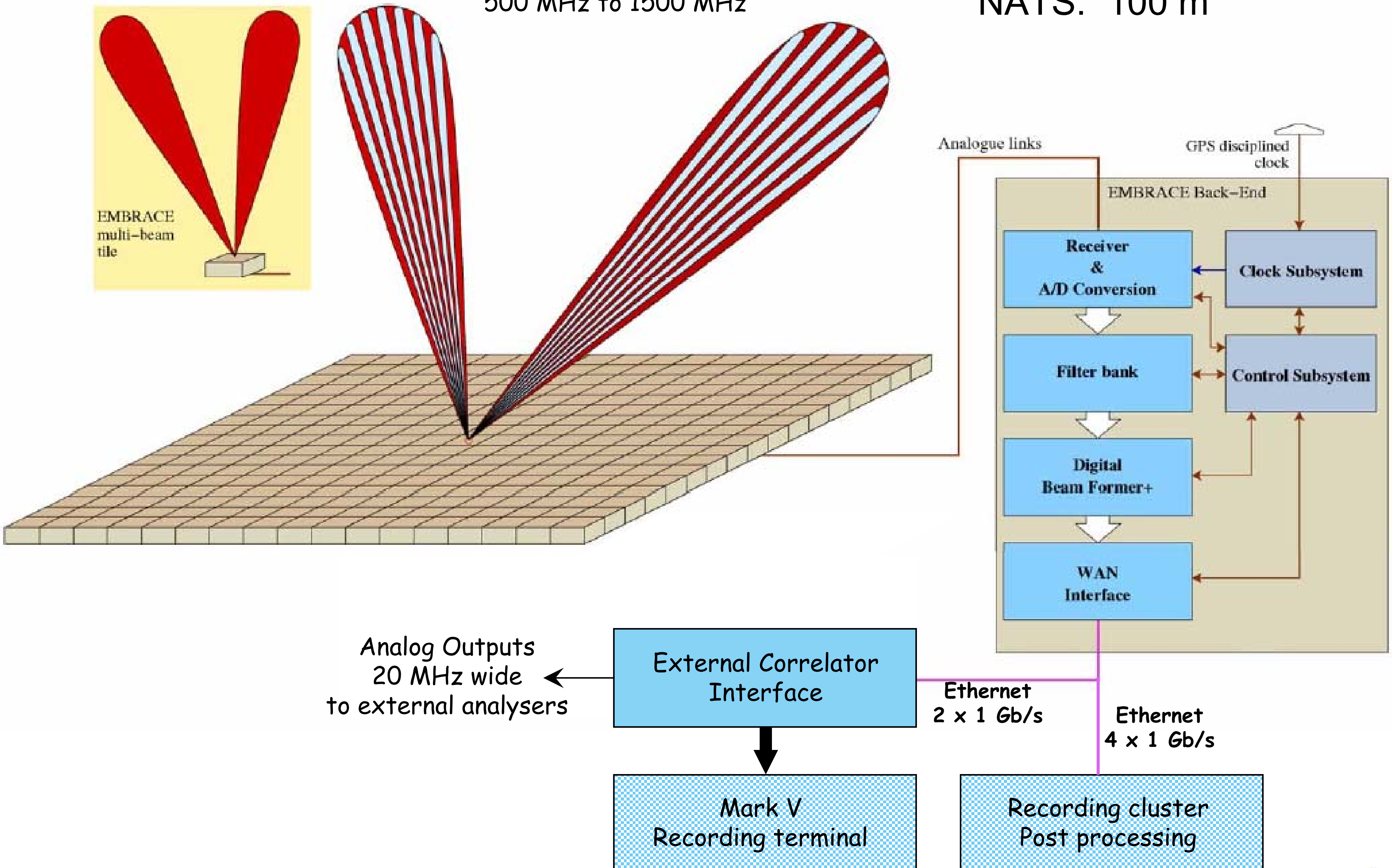


Outline

- EMBRACE overview
- Some questions about EMBRACE requirements vs LOFAR processing
- LOFAR beamforming process, beamlet concept
- EMBRACE beamformer, another beamlet concept
- LOFAR analysis filter
- EMBRACE analysis and synthesis filters
- Station processing architecture
- Conclusion

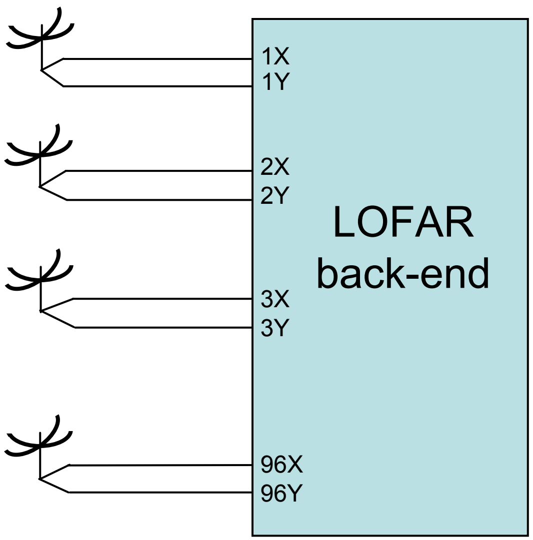
WATS: 300 m²
NATS: 100 m

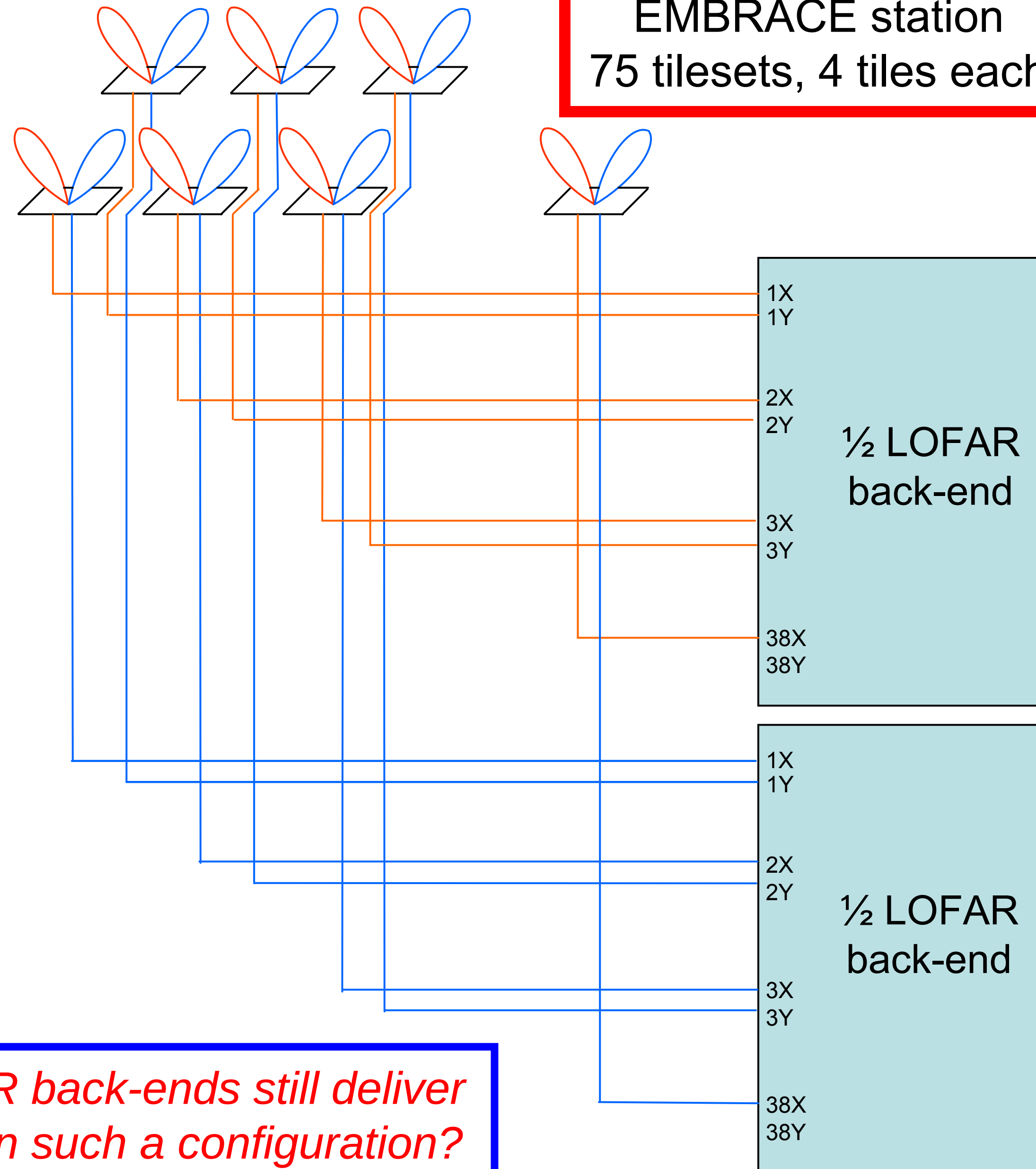
RF bandwidth
500 MHz to 1500 MHz



LOFAR station
96 antennas, 2 polarizations

EMBRACE station
75 tilesets, 4 tiles each

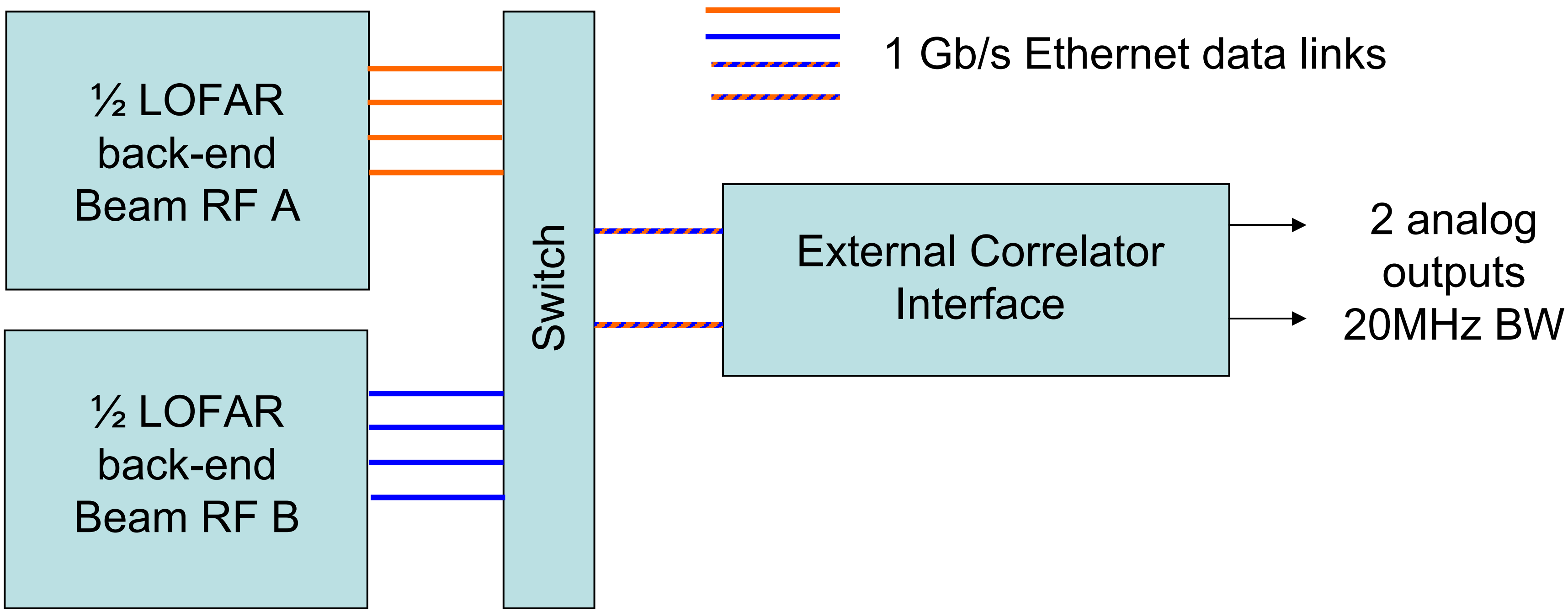




Question 1: can the LOFAR back-ends still deliver synthetised digital beams in such a configuration?

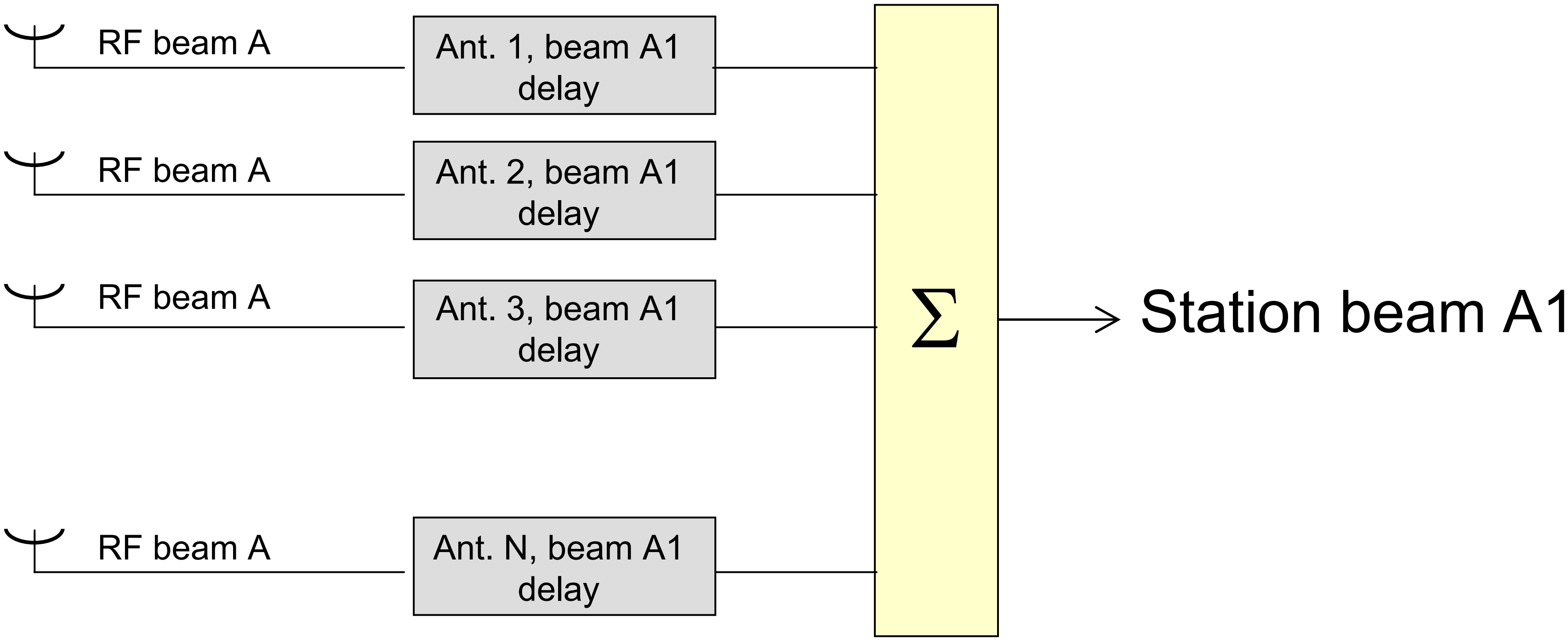
Data output from a LOFAR back-end: narrow beamformed subbands

EMBRACE tests require acces to external analysers with analog inputs, 20 MHz BW



Question 2: given the LOFAR analysis filters, can we design an inverse filter in the ECI to agregate subbands for 20 MHz output bandwidth?

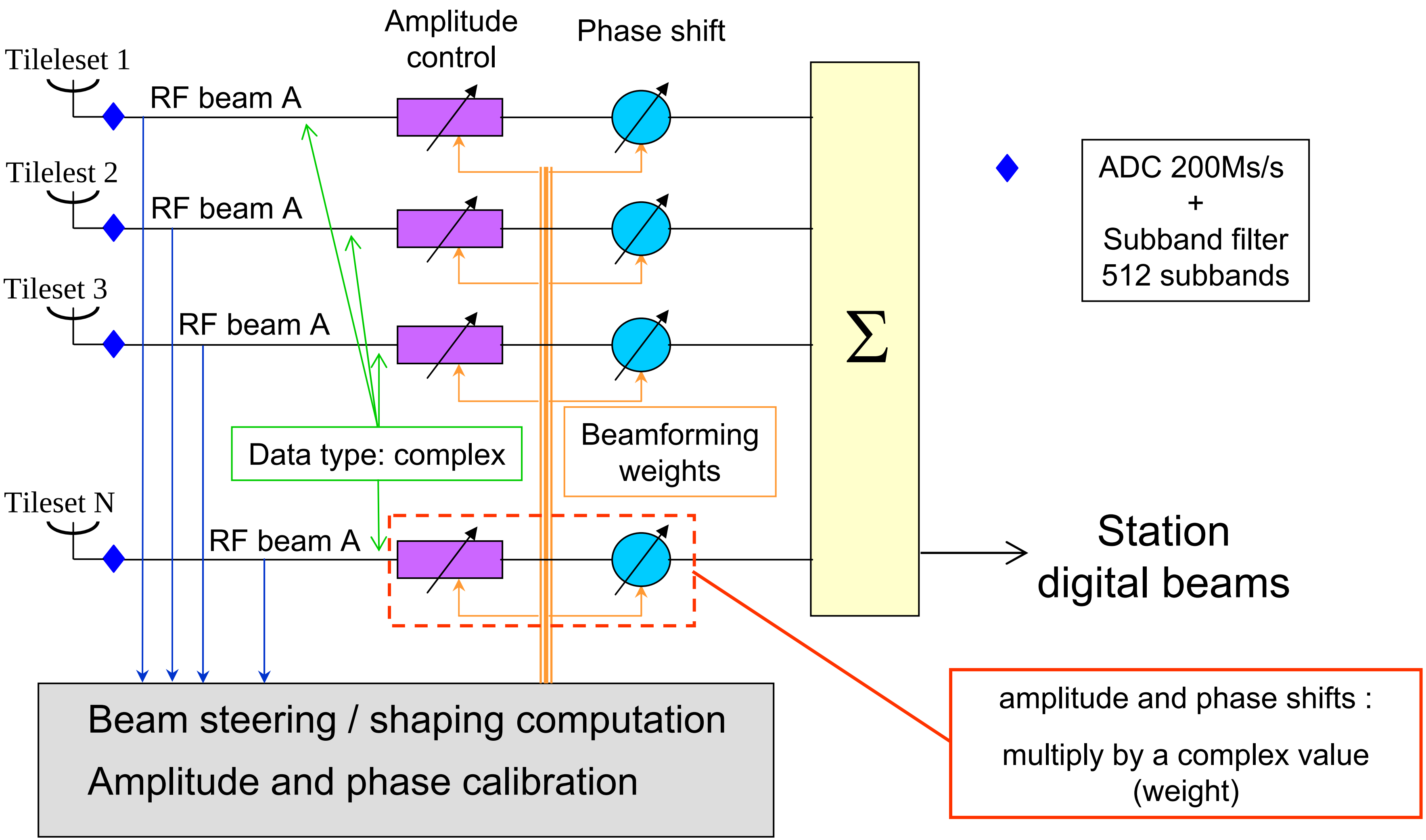
Sum of delays beamforming for wideband arrays



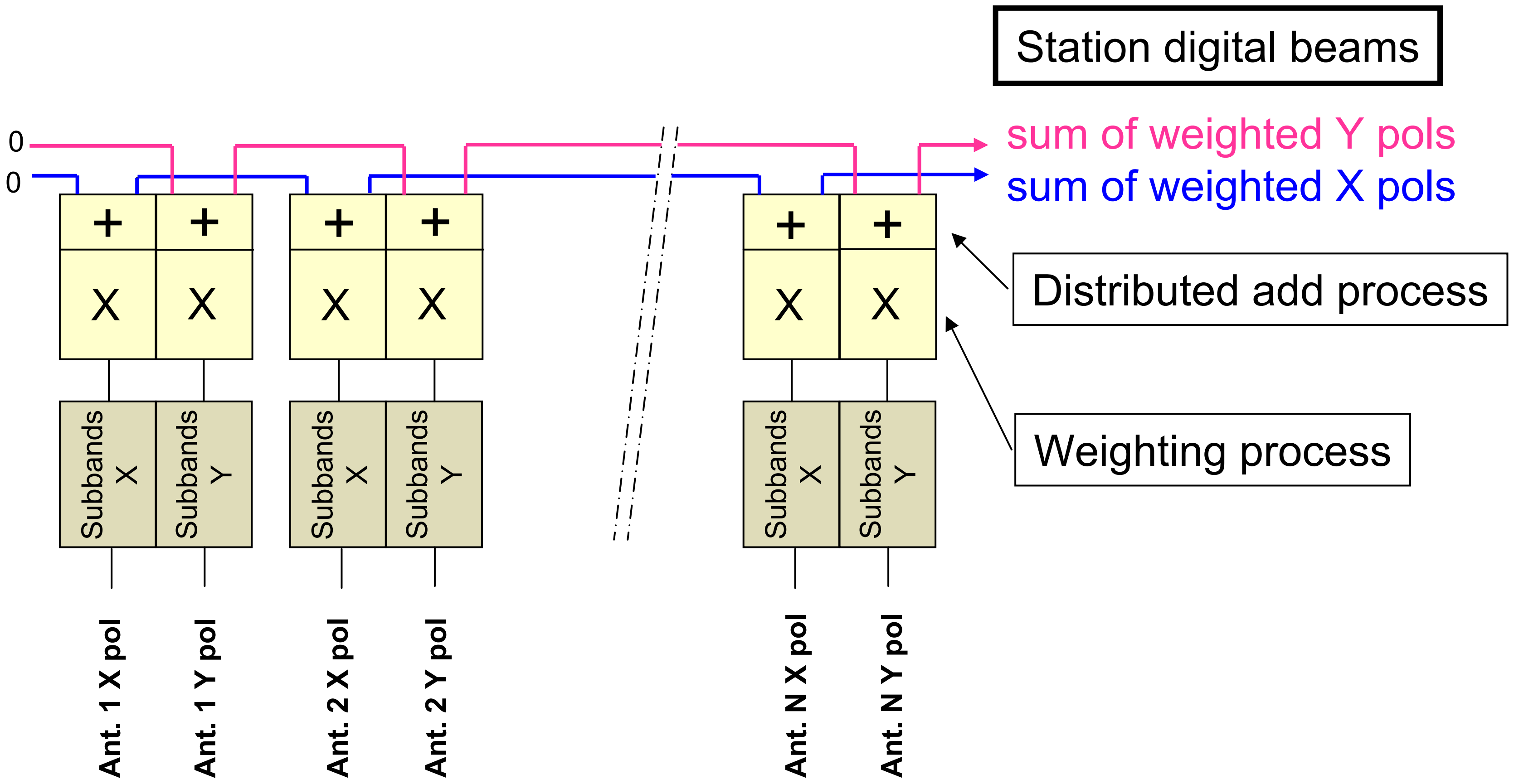
For k station beams (A1 to Ak): k-fold duplicate of the sum of delays
For m RF beams / antenna: k.m-fold duplicate

Rather than delays, phase shifts beamforming can be used (cost, compactness)
Phase shifts beamforming works only on narrow frequency bands => subbanding

Digital beamforming using phase shifts



LOFAR beamformer topology: parallel / serial processing



LOFAR weighting process:

For one antenna and two polarizations x and y:

- data after X and Y filter banks for one subband s: $X_s re + jX_s im$, $Y_s re + jY_s im$
- LOFAR beamlet concept associates one subband s and one direction (θ, φ) for the 2 polarizations
- data after beamformer transform for one subband: X' sre + jX' sim, Y' sre + jY' sim
- Subband for beamlet b: from Subband Select map
- Beamformer weights for beamlet b : from weights matrix (4x4) => (θ, φ) for subb. s, ant. a

$$\begin{vmatrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{vmatrix}_a = \begin{vmatrix} WXR(b)Xre & WXR(b)Xim & WXR(b)Yre & WXR(b)Yim \\ WXI(b)Xre & WXI(b)Xim & WXI(b)Yre & WXI(b)Yim \\ WYR(b)Xre & WYR(b)Xim & WYR(b)Yre & WYR(b)Yim \\ WYI(b)Xre & WYI(b)Xim & WYI(b)Yre & WYI(b)Yim \end{vmatrix}_a * \begin{vmatrix} X_s re \\ X_s im \\ Y_s re \\ Y_s im \end{vmatrix}_a$$

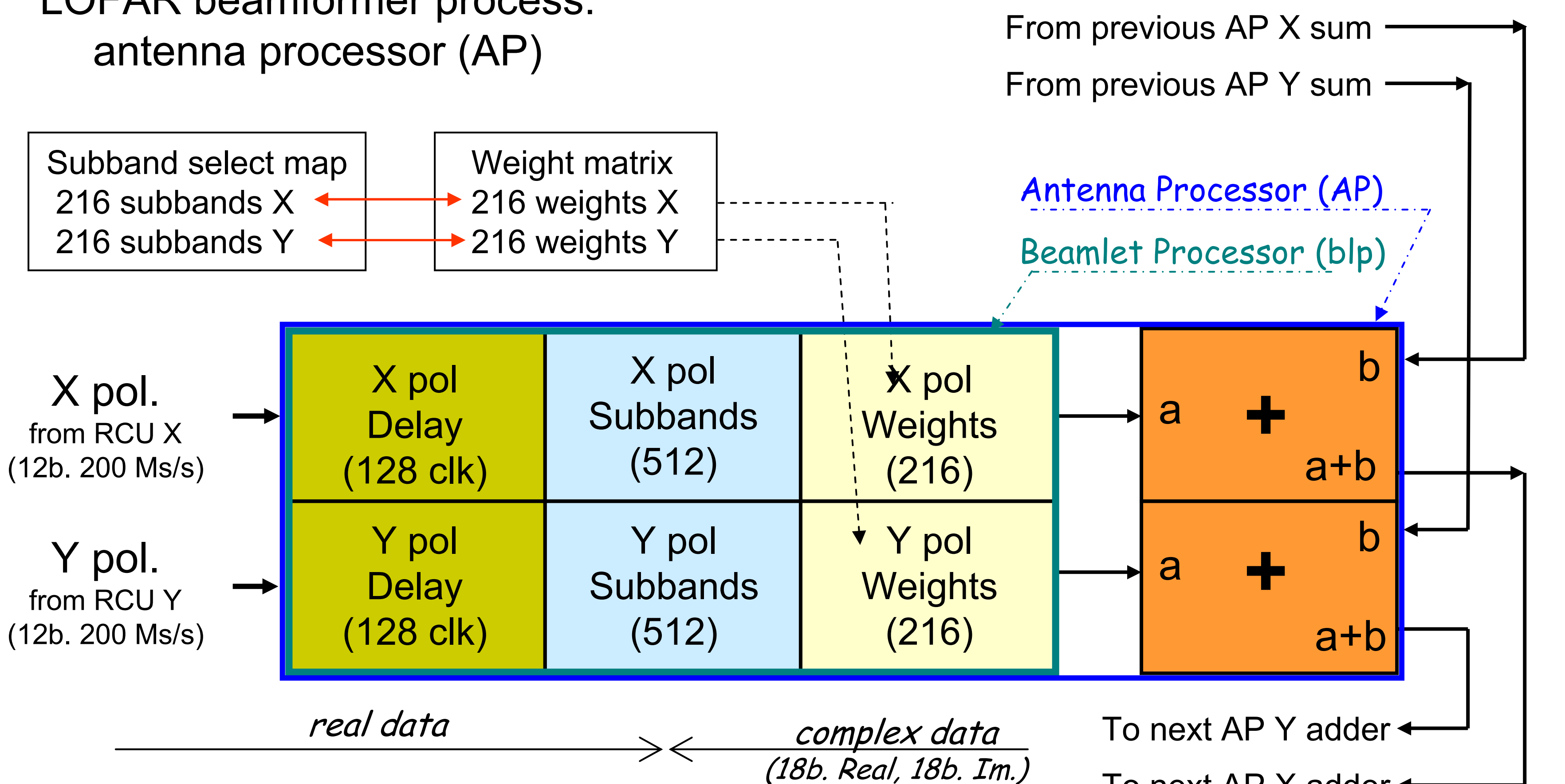
black weights = 0 if no orthogonalization process (or beam rotate)

Station data for beamlet b, N antennas, subband s, (θ, φ) :

$$\begin{vmatrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{vmatrix}_{N,s} = \sum_{a=1}^{N} \begin{vmatrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{vmatrix}_{a,s}$$

A LOFAR back-end delivers 216 beamlets
one subband, (θ,φ), pol. X, Y

LOFAR beamformer process: antenna processor (AP)



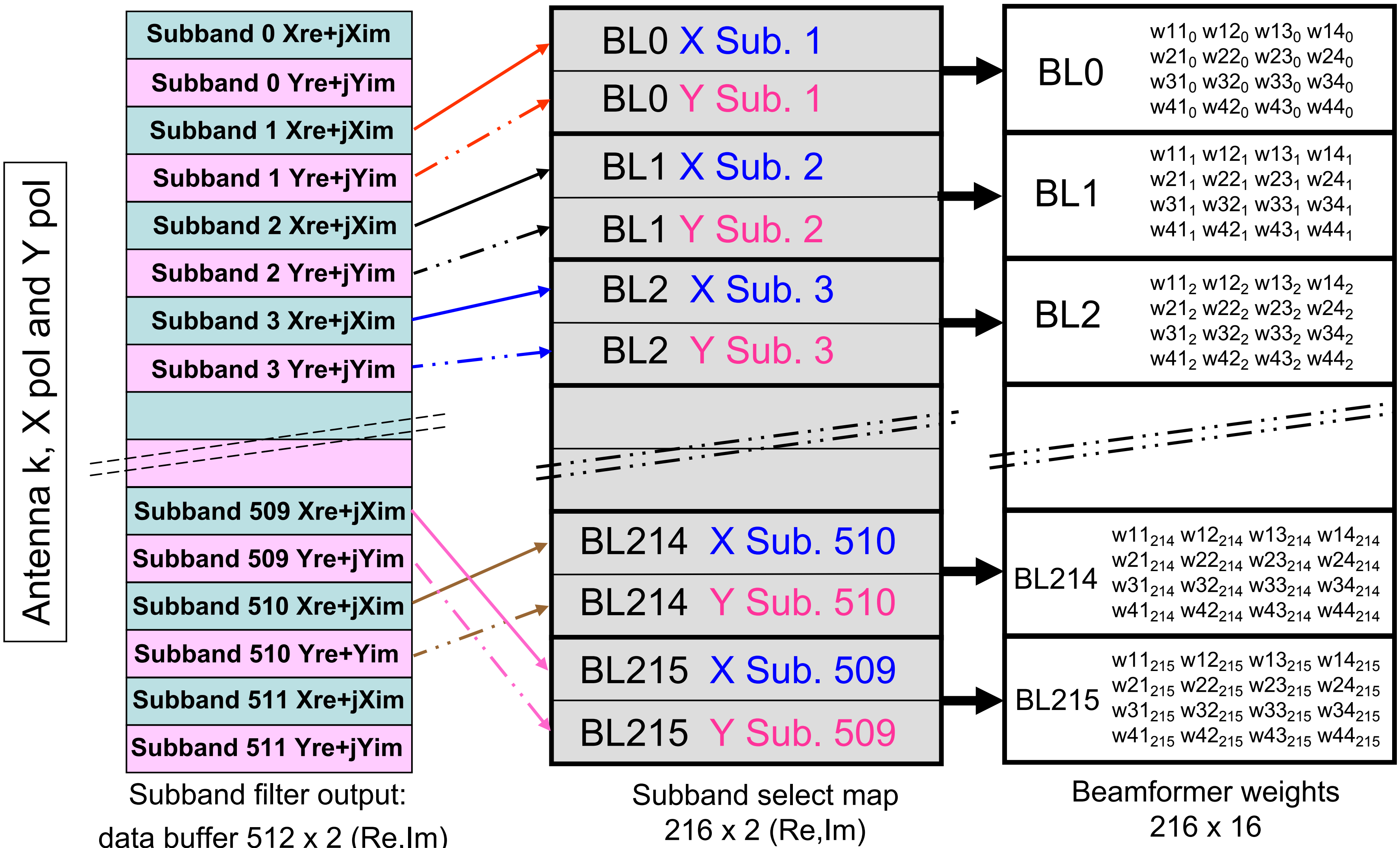
The last AP output gives the weighted sum for 216 beamlets

EMBRACE can use this process as is, but:

LOFAR antenna:	1 RF beam, 2 pol.
EMBRACE antenna (tile or tileset):	2 RF beams, 1 pol.

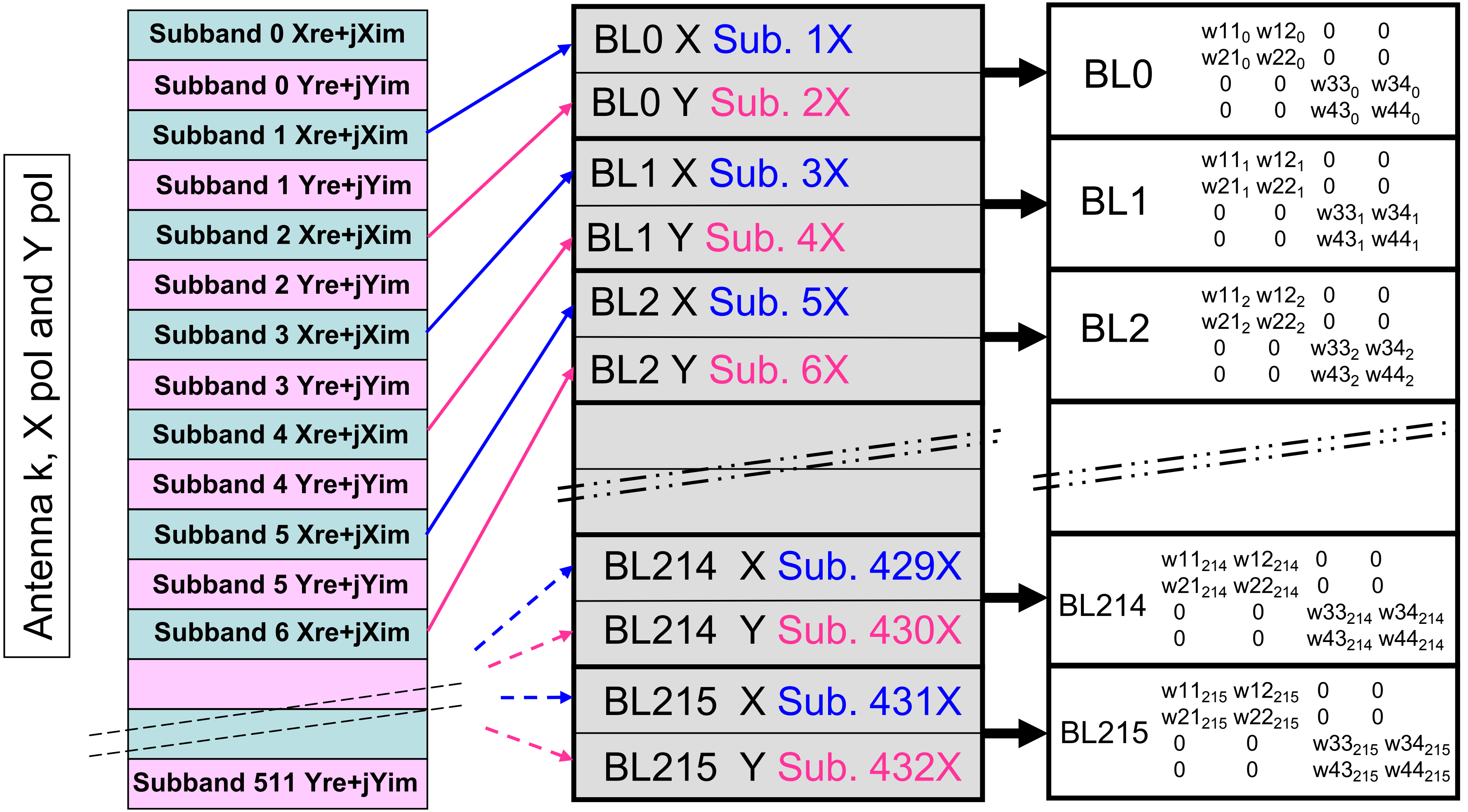
LOFAR antenna processor
Subband select map and weights matrix for 216 beamlets

All subbands / beamlets / weights associations are valid for this process



A nice way to double the bandwidth in LOFAR Back-end:

Using only one polarization and specific subband select map and weights matrix:
Max band for one polarization = 432 subbands (64 MHz or 84 MHz in LOFAR station)

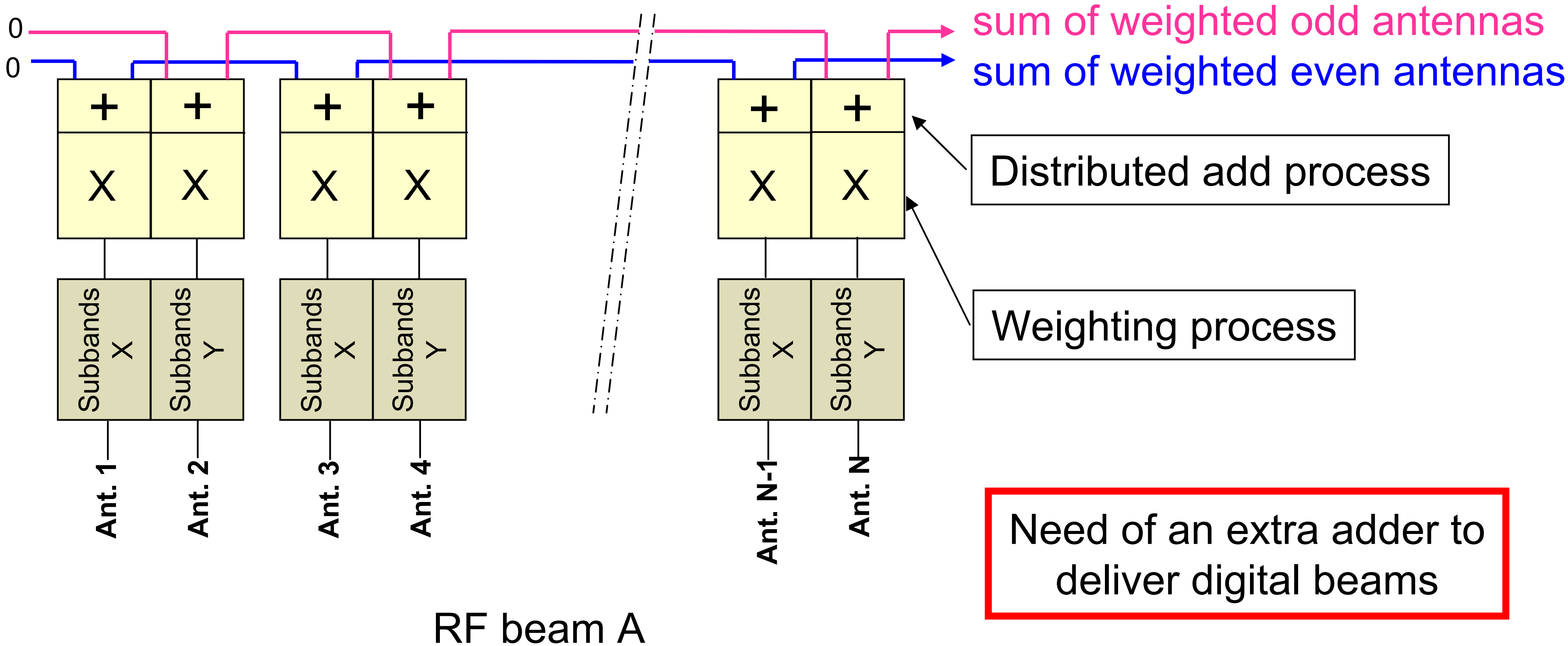


Subband filter output:
data buffer 512 x 2 (Re,Im)

Subband select map
216 x 2 (Re,Im)

Beamformer weights
216 x 16

EMBRACE beamformer using LOFAR antenna processors, ½ back-end



Need of an extra adder to deliver digital beams

EMBRACE weighting process using an antenna processor:

for two antennas and RF beam A :

- used data from X an Y filter banks for one subband s: $A_a re + jA_a im$, $A_{a+1} re + jA_{a+1} im$
- Subband for beamlet b: from Subband Select map
- Beamformer weights for beamlet b: from weights matrix

Beamformer transform in EPA firmware for 2 antennas, one subband, one RF beam:

$$\left| \begin{matrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{matrix} \right|_{a,a+1,s} = \left| \begin{matrix} WXR(b)Xre & WXR(b)Xim & WXR(b)Yre & WXR(b)Yim \\ WXI(b)Xre & WXI(b)Xim & WXI(b)Yre & WXI(b)Yim \\ WYR(b)Xre & WYR(b)Xim & WYR(b)Yre & WYR(b)Yim \\ WYI(b)Xre & WYI(b)Xim & WYI(b)Yre & WYI(b)Yim \end{matrix} \right|_{a,a+1} * \left| \begin{matrix} A1_a re \\ A1_a im \\ A2_{a+1} re \\ A2_{a+1} im \end{matrix} \right|_s$$

θ1,φ1

θ2,φ2

This specific weighting provides us with the additional add of X part and Y part

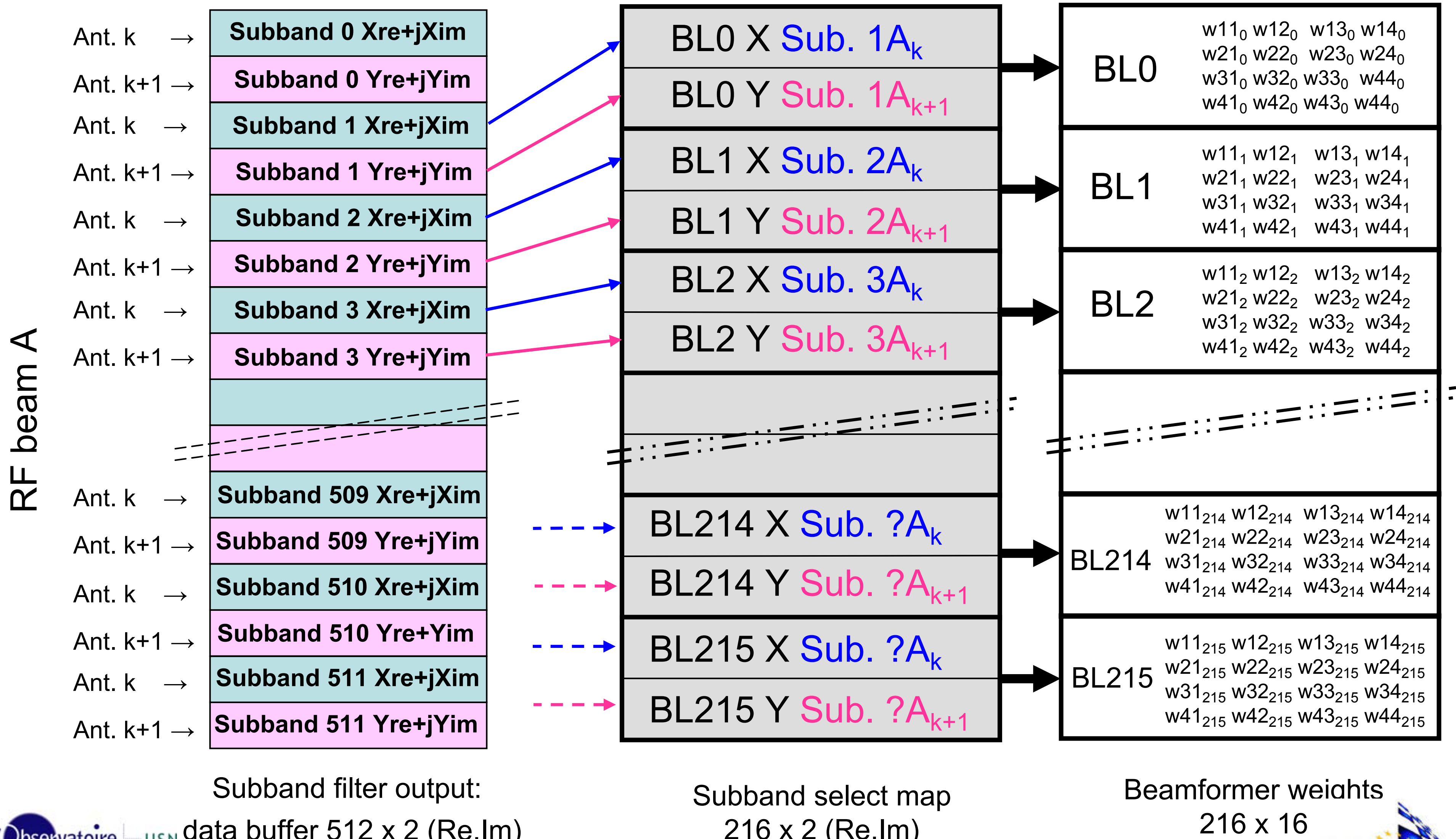
Station data for beamlet b, N antennas, RF beam A, using ½ back-end:

$$\left| \begin{matrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{matrix} \right|_{N,s} = \sum_a \left| \begin{matrix} X'(b)re \\ X'(b)im \\ Y'(b)re \\ Y'(b)im \end{matrix} \right|_{a,a+1,s}$$

EMBRACE beamlet:
one subband, two directions

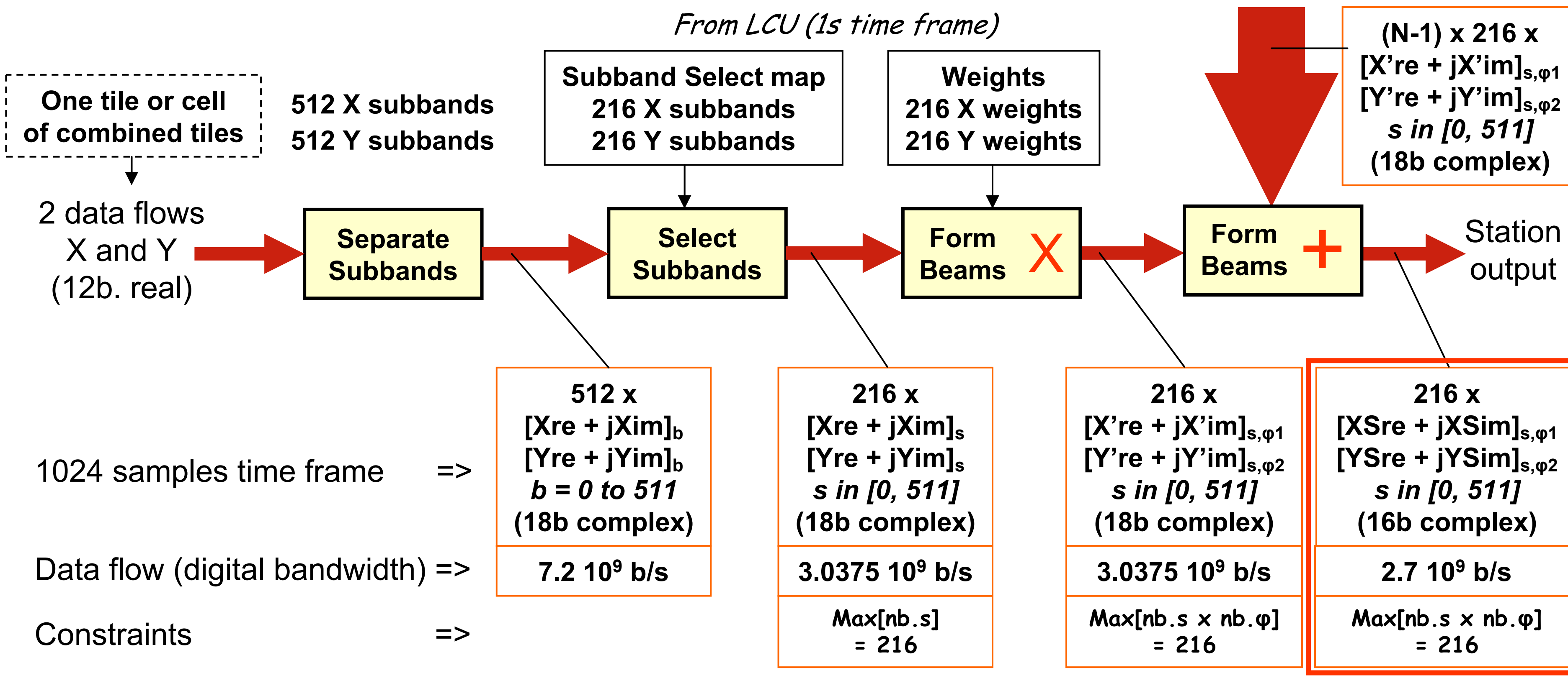
And we can do the same way for RF beam B, using second half of the back-end

EMBRACE antenna processor:
Subband select map and weights matrix for 216 beamlets



Digital beam = sum of all phase shifted antenna data to point at source position (θ,φ)

Subband width: 195.3125 Khz at 200 Ms/s (156.25 KHz at 160 Ms/s for LOFAR LBA)



Station digital beam = collection of $[XSre + jXSim]_{s,(\varphi 1,\theta 1)}$, $[YSre + jYSim]_{s,(\theta 2,\varphi 2)}$ for the required number of subbands

RF beam A

Separate beams	Separate spectral windows	Window width (MHz)
2	1	42
4	2	21
2 4	1 2	21 10.5
8	4	10.5
.	.	.
48	24	1.75
.	.	.
2 72	1 36	7.03125 0.9765625
.	.	.
432	216	0.1953125

RF beam B

Separate beams	Separate spectral windows	Window width (MHz)
2	1	42
4	2	21
2 4	1 2	21 10.5
8	4	10.5
.	.	.
48	24	1.75
.	.	.
2 72	1 36	7.03125 0.9765625
.	.	.
432	216	0.1953125

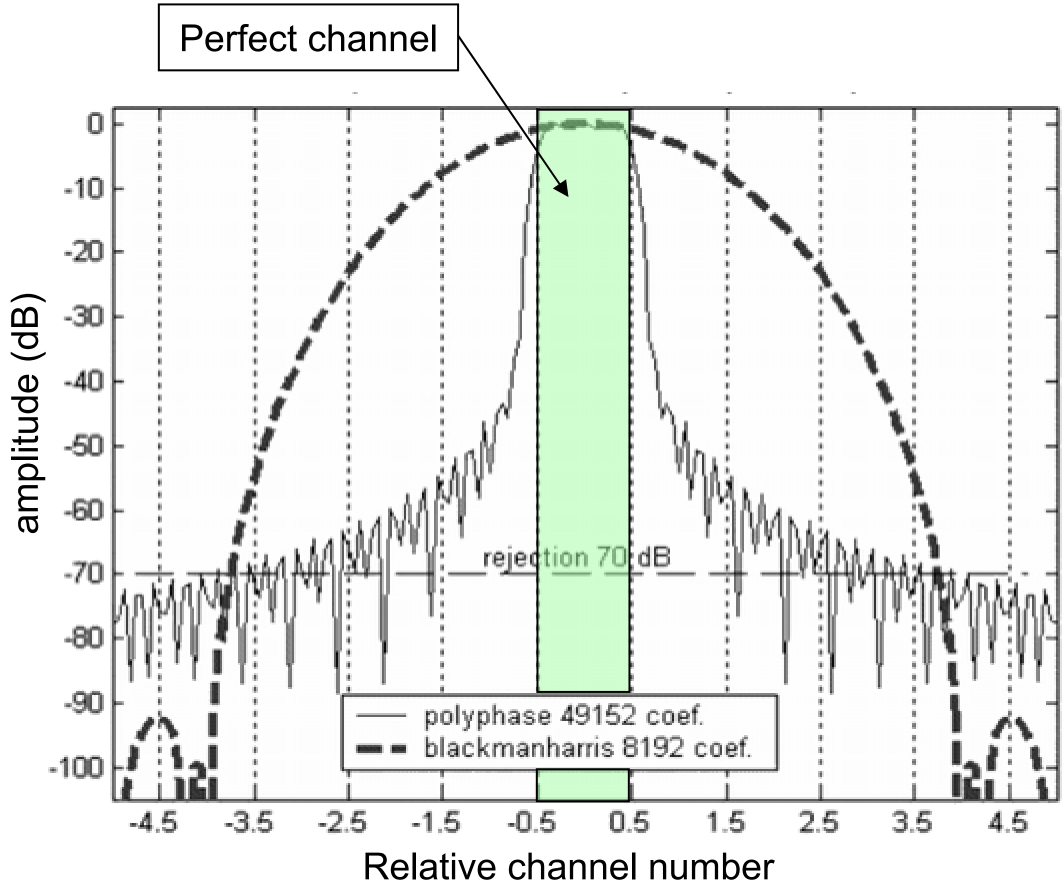
At this point answer to question 1 is:

We can use the LOFAR back-end to deliver synthetised digital beams for the EMBRACE configuration without any change in the embedded processes.

This is obtained via specifics subbands select maps and associated weights matrices.

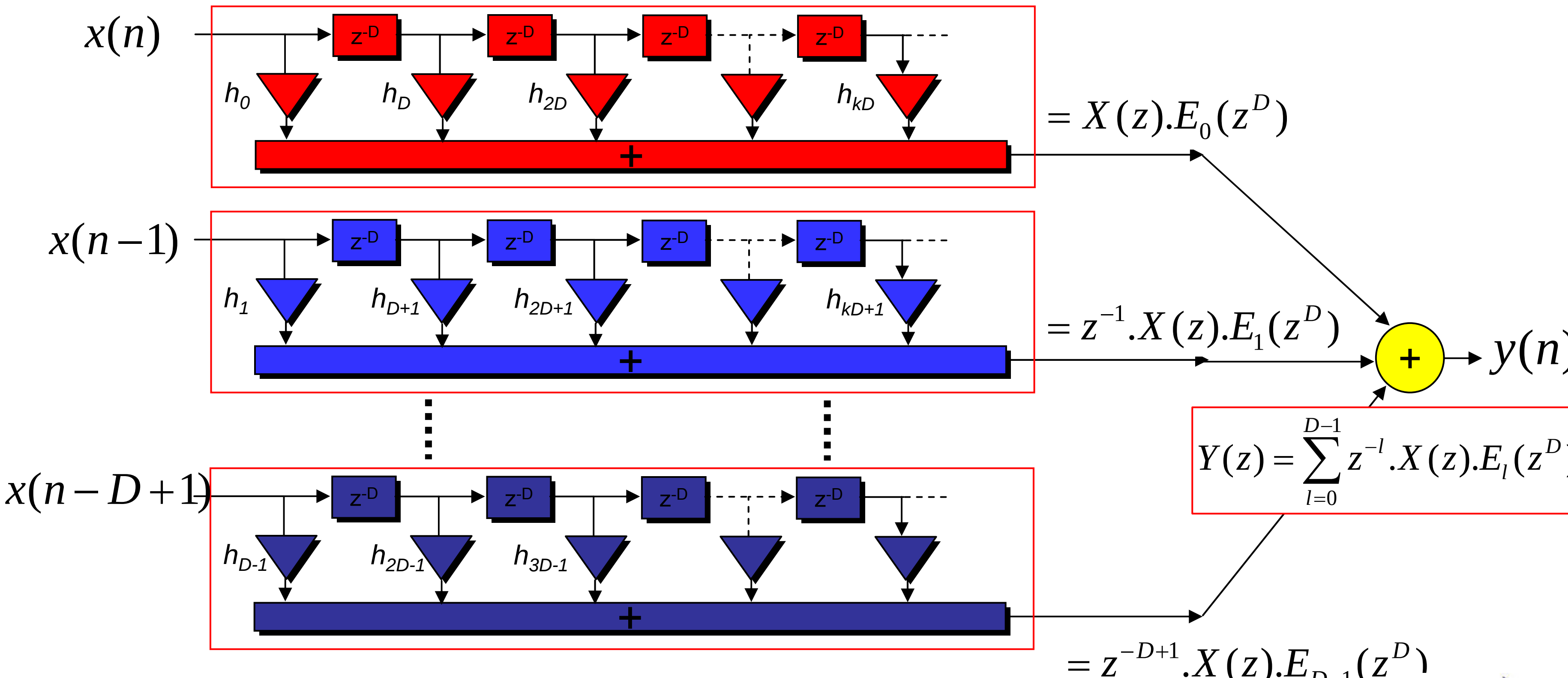
The beamlet concept evolves in « one beamlet = one subband, two directions »

Subbands filter: analysis filter



Polyphase structure

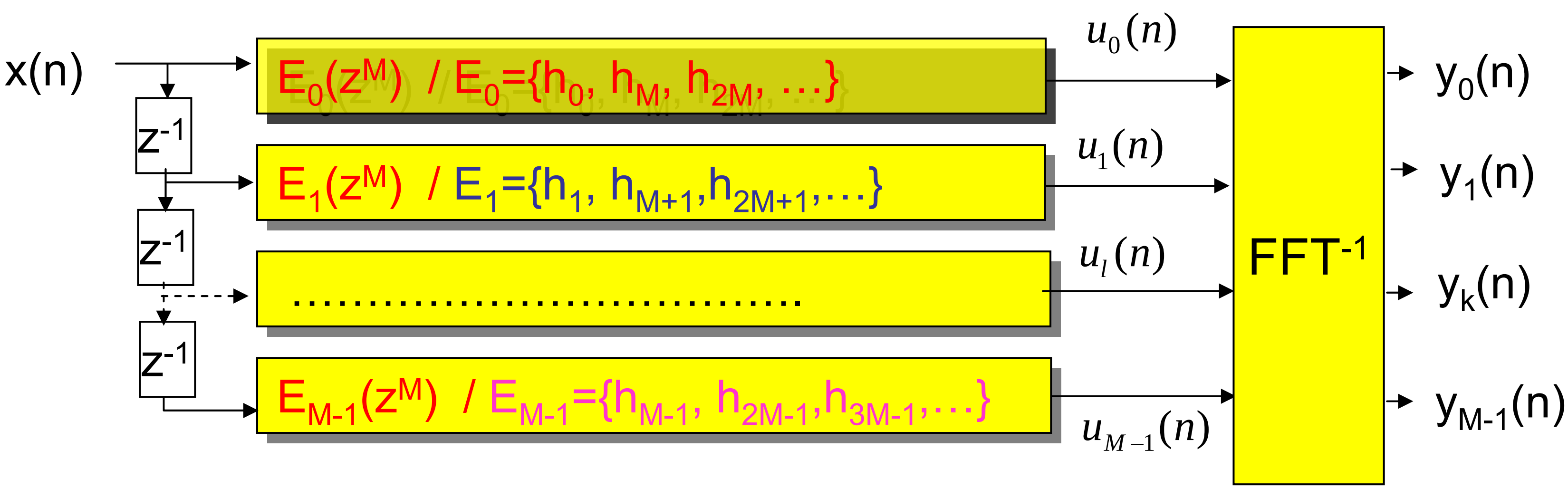
$$y(n)=\sum_{k=0}^{N.D} h_k x(n-k) = \begin{cases} h_0 x[n] + h_D x[n-D] + h_{2D}x[n-2D]+\cdots+h_{kD}x[n-kD]\ldots \\ +h_1 x[n-1]+h_{D+1}x[n-D-1]+h_{2D+1}x[n-2D-1]+\cdots+h_{kD+1}x[n-kD-1]\ldots \\ \vdots \\ +h_{D-1}x[n-D+1)]+h_{2D-1}x[n-2D+1)]+h_{3D-1}x[n-3D+1)]+\cdots+h_{(k+1)D-1}x[n-(k+1)D+1)]\ldots \end{cases}$$



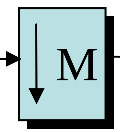
Polyphase filter bank

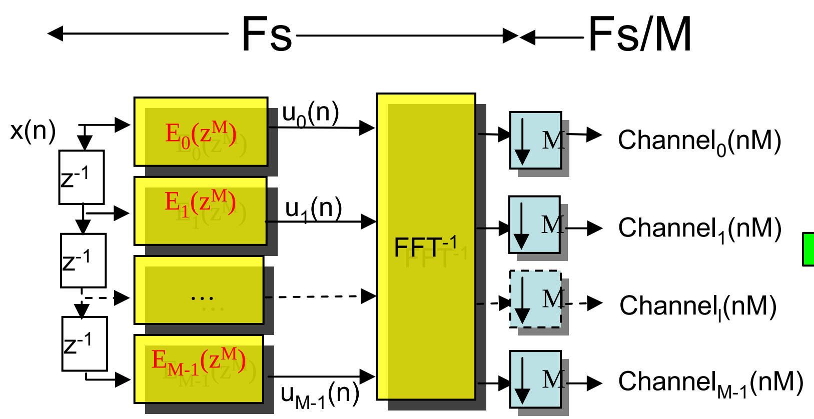
1) $U_l(z) = z^{-l}.X(z).E_l(z^M)$ for $l = 0,\dots,M-1$

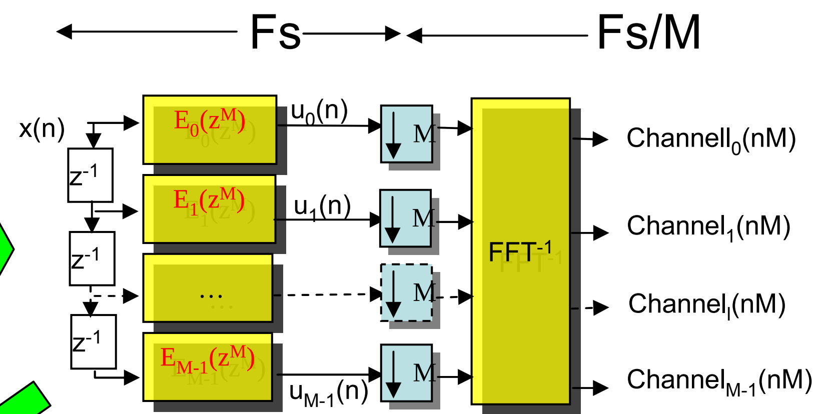
2) $Y_k(z) = FT^{-1}(U_{l=0,\dots,M-1}(z))$ at frequency $\dfrac{k}{M}$



Output channels have narrow bandwidth: we can use decimation

Decimation factor : $s(n) \rightarrow$  $\rightarrow s(nM)$



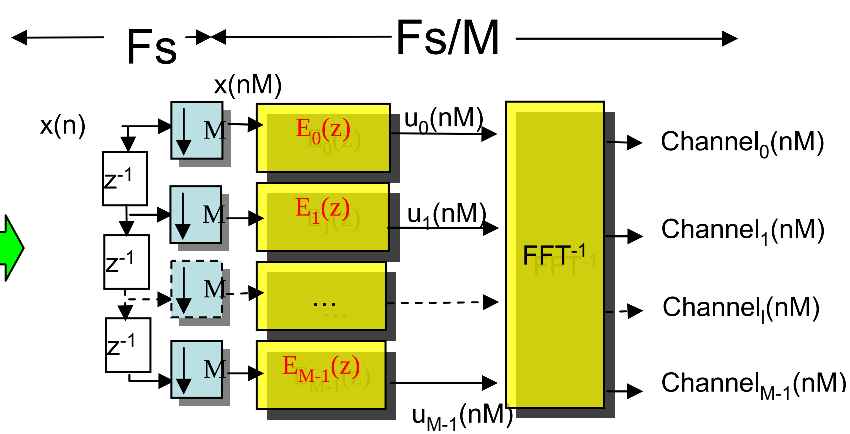


Fs : sampling frequency

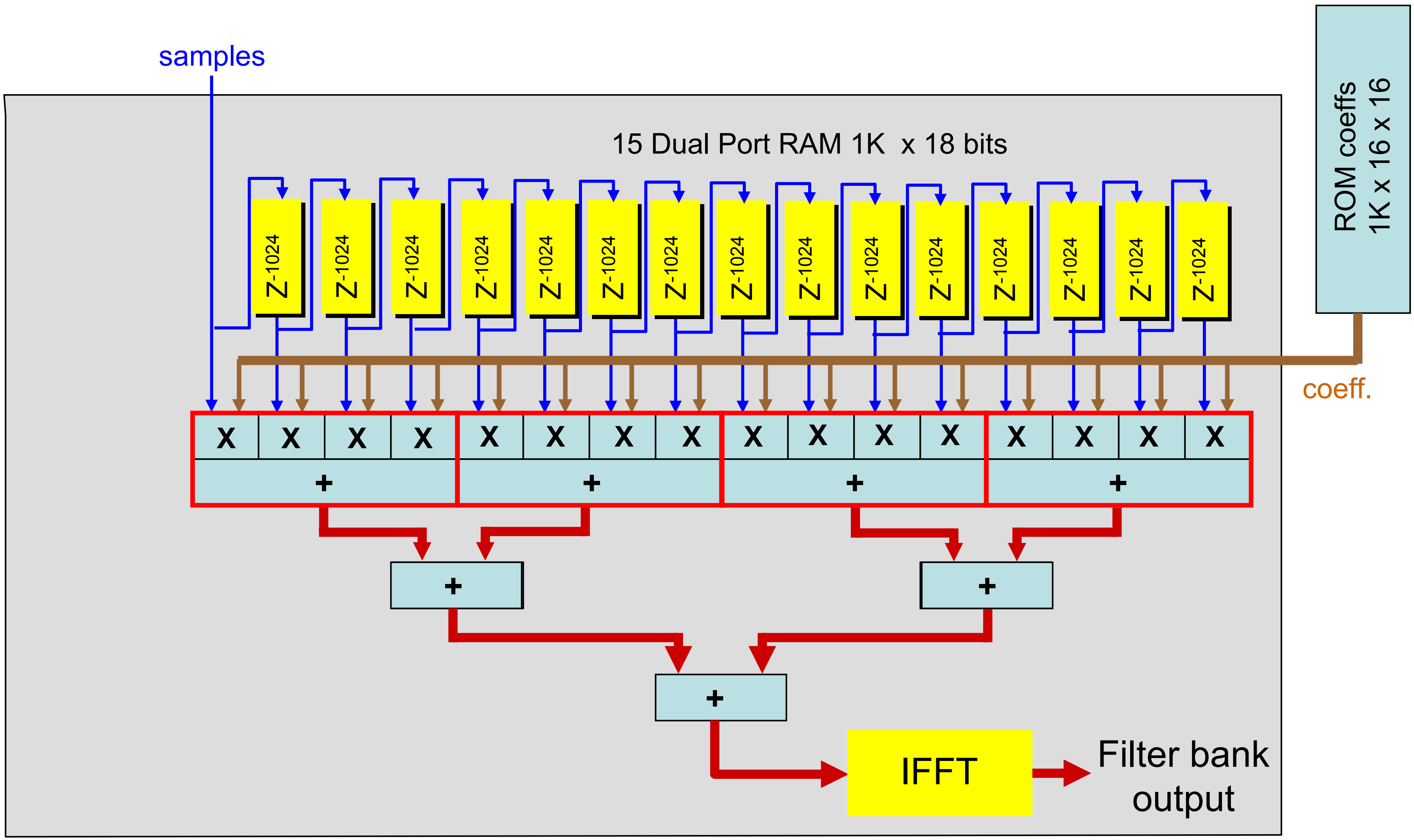
$$u_0(n) = \sum_{p=0}^{P-1} h_{pM}\, x(n - pM)$$

$$u_0(nM) = \sum_{p=0}^{P-1} h_{pM}\, x(nM - pM)$$

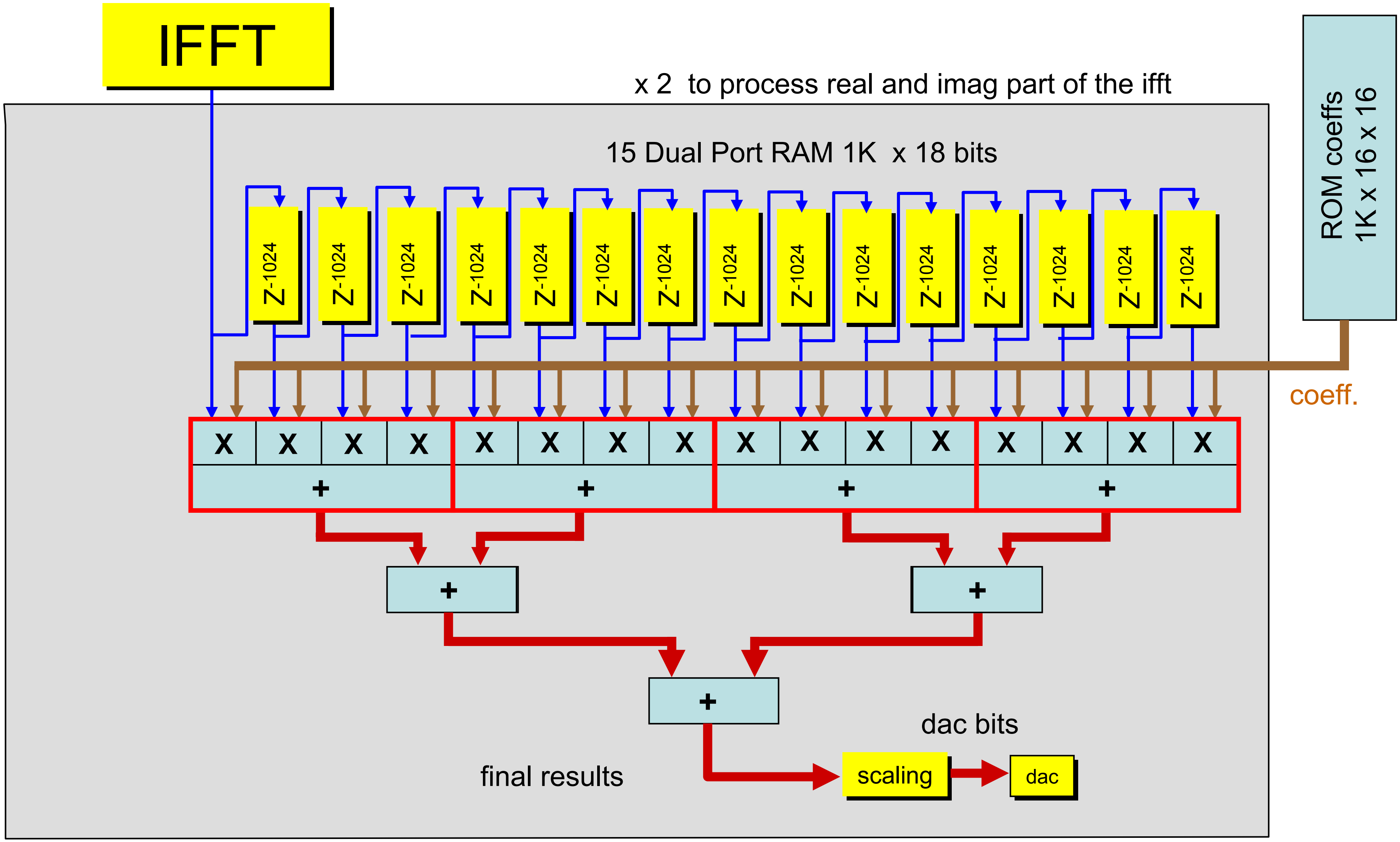
$$= \sum_{p=0}^{P-1} h_{pM}\, x((n-p)M)$$



LOFAR subbands filter bank



Synthesis filter bank for ECI



External Correlator Interface processing (do we need to oversample subbands?)

Case of a strong RFI line at the edge of a subband:

What happens in the reconstruction process of the synthesis filter depends on the analyser filter bank:

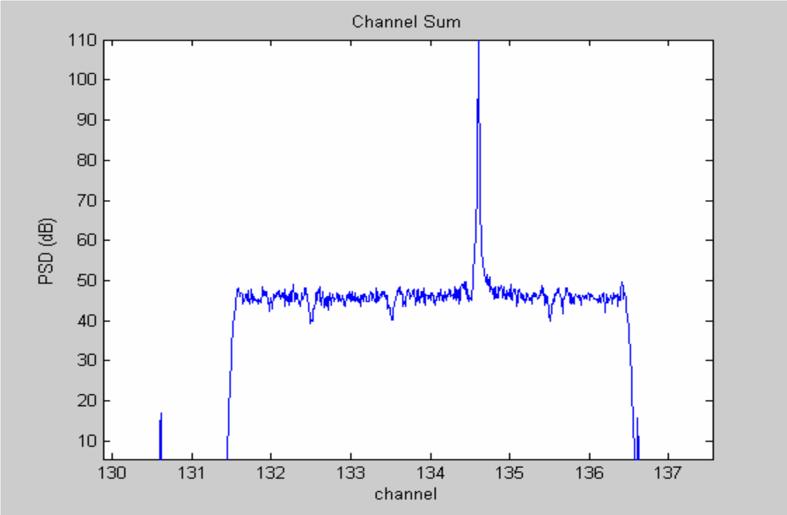
For an oversampled (factor 2) analysis filter bank, no alias in adjacent channels and « quasi perfect reconstruction »

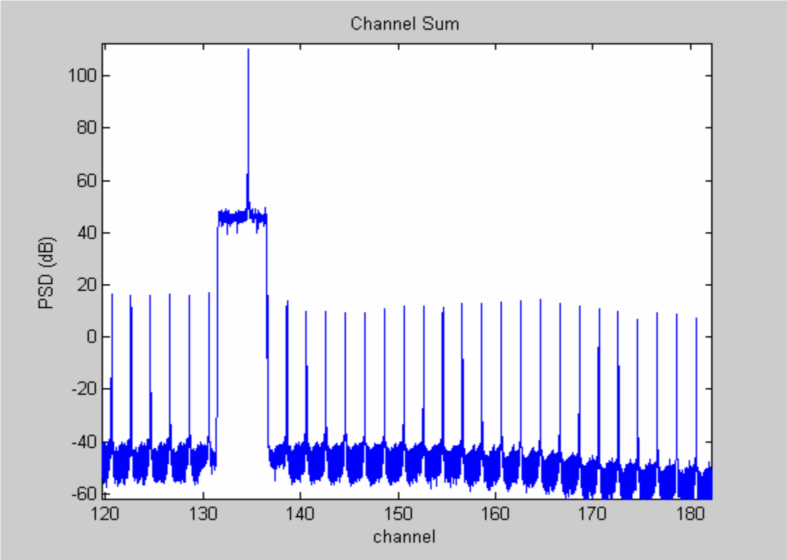
For a critically sampled analysis filter bank (LOFAR implementation), alias appears in the adjacent channels and in the reconstructed spectrum.

Oversampled subbands gives a better reconstructed spectrum for frequency lines at channels edges, but requires an increase (x2) of the digital bandwidth for all the processes after the filters, which is too high for the LOFAR processing boards.

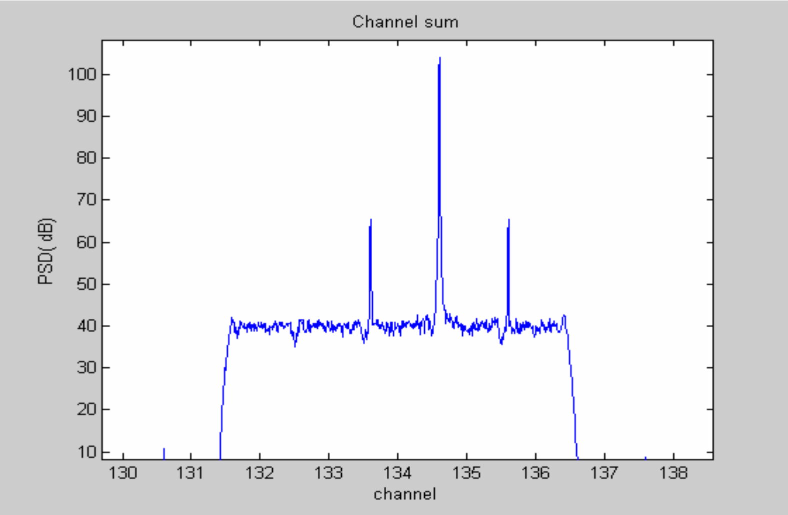
Synthesis Filter bank output : RFI @ 134.6/1024

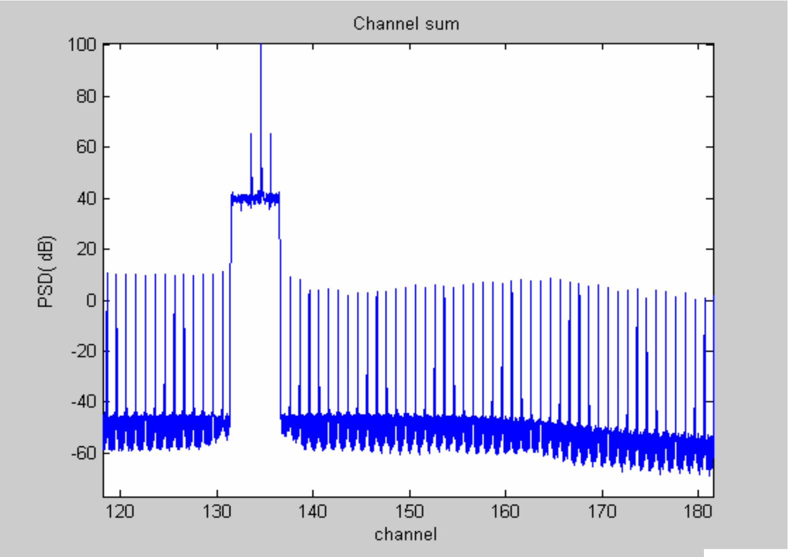
Channel Spectra when oversampled by 2





Channel Spectra when critically (maximally) decimated





At this point answer to question 2 is:

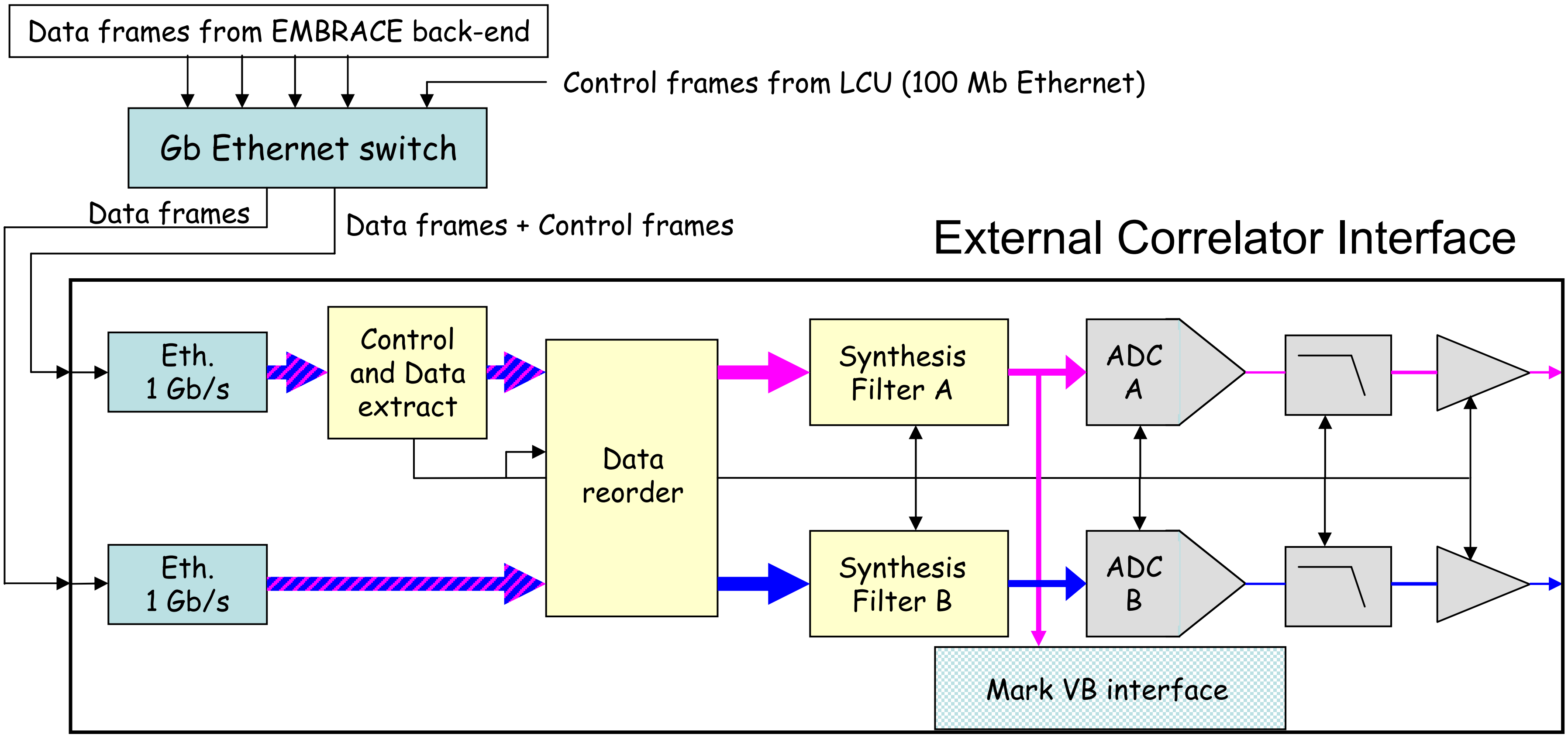
We can define for the ECI a synthesis filter for agregation of narrow subbands (195 KHz) in wider bandwidth (20 MHz).

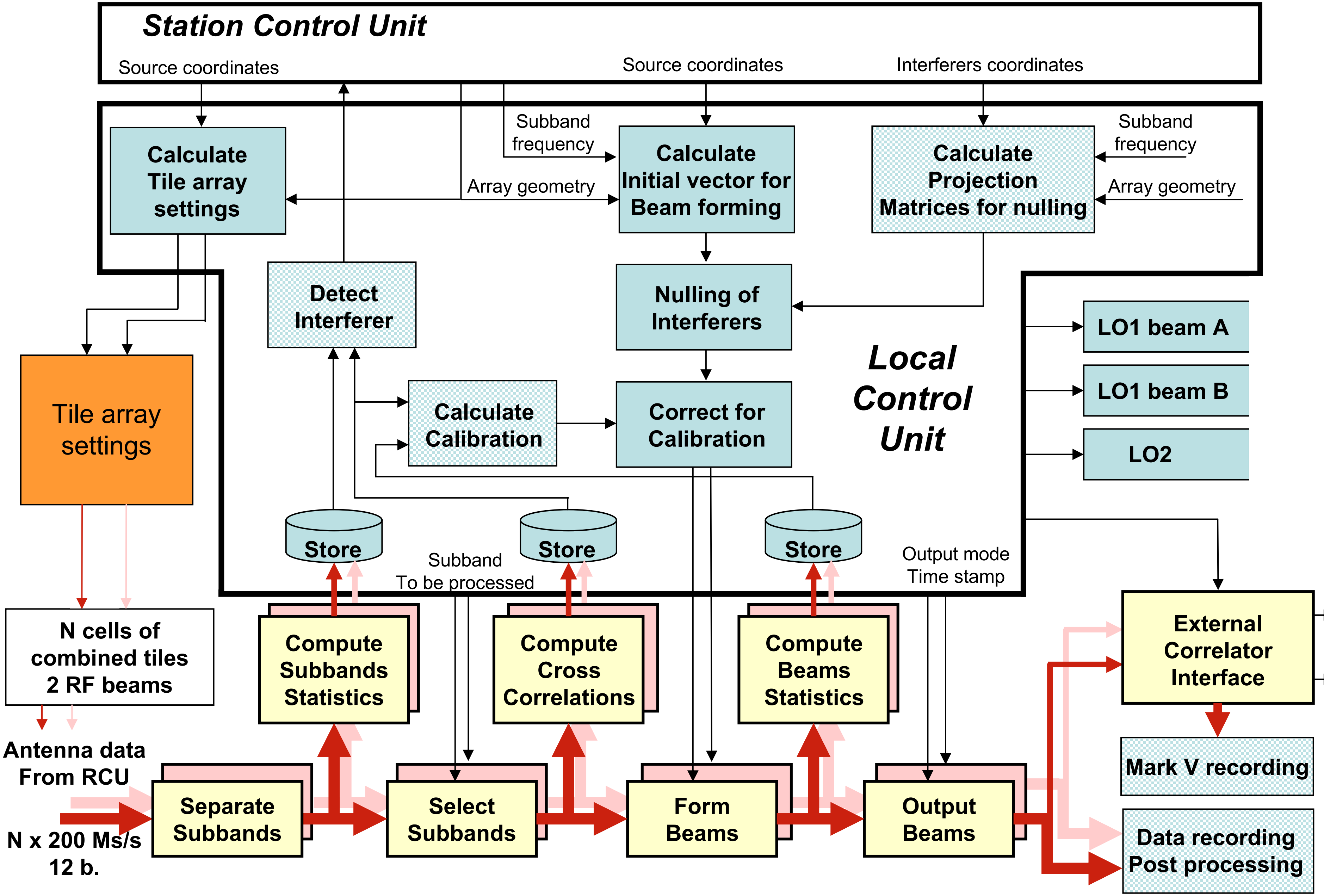
Given the existing LOFAR subbands filter bank, frequency lines at the edge of subbands (RFI) may create alias in the reconstructed spectrum.

Embrace station outputs are 4 Ethernet Gb links, each one delivering 54 beamlets

To deliver 2 x 20MHz digital beams we need at least 103 beamlets

=> ECI input needs 2 Ethernet Gb links (2 lanes)




Station Control Unit
Source coordinates
Source coordinates
Interferers coordinates
Calculate Tile array settings
Subband frequency
Array geometry
Calculate Initial vector for Beam forming
Calculate Projection Matrices for nulling
Subband frequency
Array geometry
Detect Interferer
Nulling of Interferers
Local Control Unit
LO1 beam A
LO1 beam B
LO2
Tile array settings
Calculate Calibration
Correct for Calibration
Store
Store
Store
Subband
To be processed
Output mode
Time stamp
N cells of combined tiles
2 RF beams
Compute Subbands Statistics
Compute Cross Correlations
Compute Beams Statistics
External Correlator Interface
Antenna data
From RCU
Mark V recording
N x 200 Ms/s
12 b.
Separate Subbands
Select Subbands
Form Beams
Output Beams
Data recording
Post processing

Conclusion:

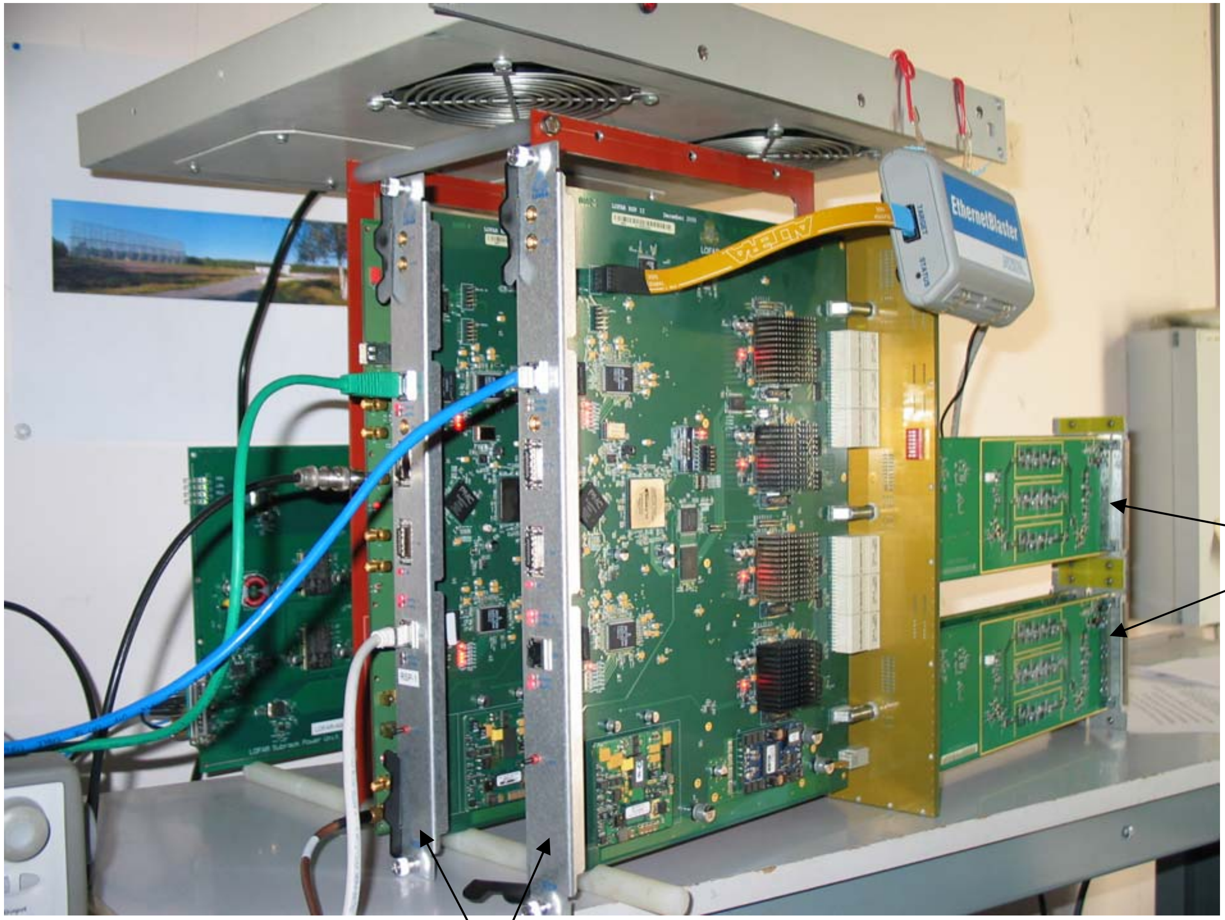
For EMBRACE station processing we can use LOFAR back-end as is, with specific settings of subband select maps and weights matrix.

Subbands are critically sampled, RFI on channel edges may pollute adjacent channels.

We can design a synthesis filter in the ECI to output 2 analog 20 MHz BW beams for external analysers with sensitivity to RFI on channel edges.

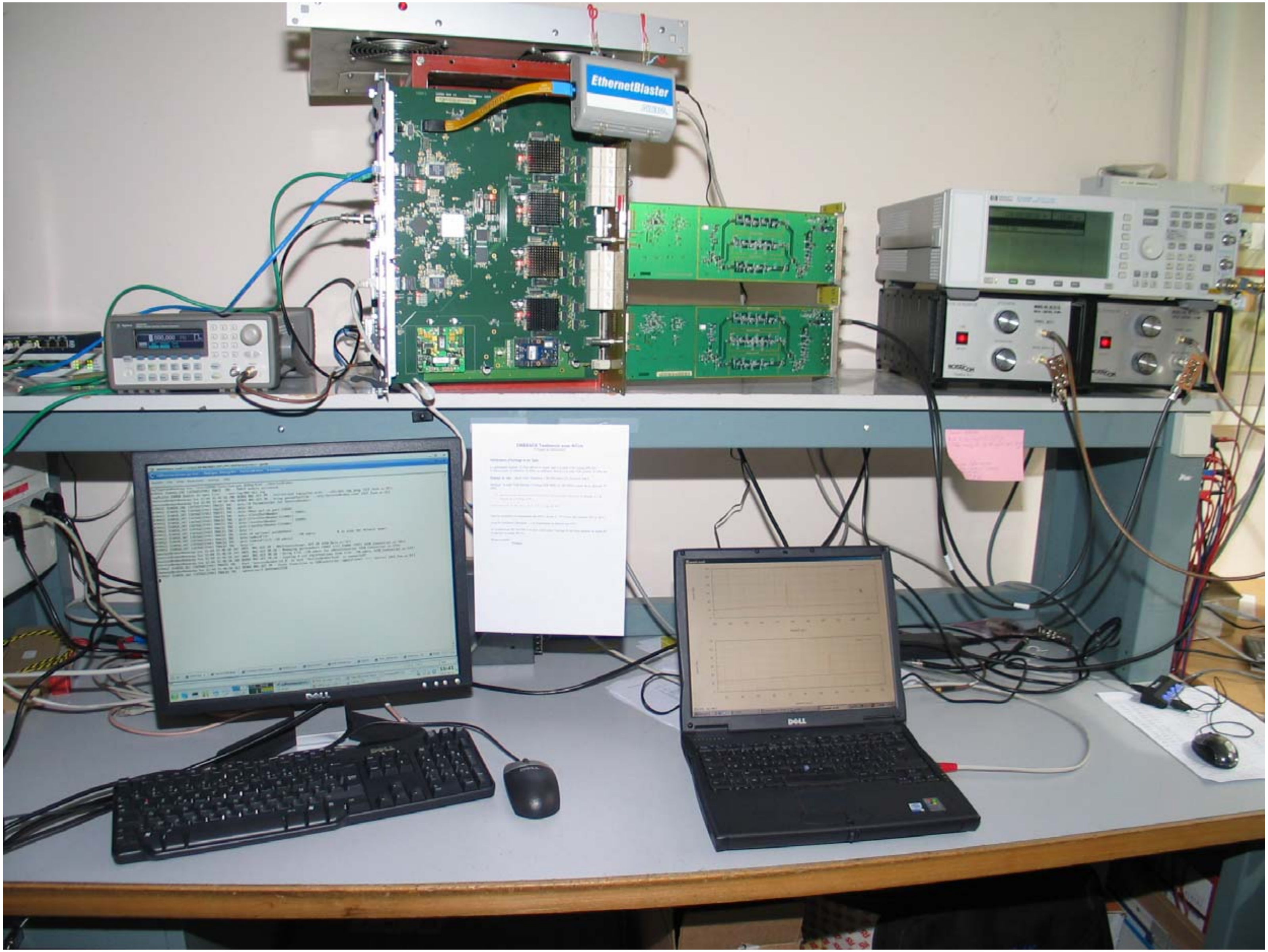
The remaining key point is the Monitoring And Control software (ongoing).

EMBRACE testbench



ADC boards

Processing boards


EthernetBlaster
DELL