LOFAR remote station Back-End for LOFAR Super Station

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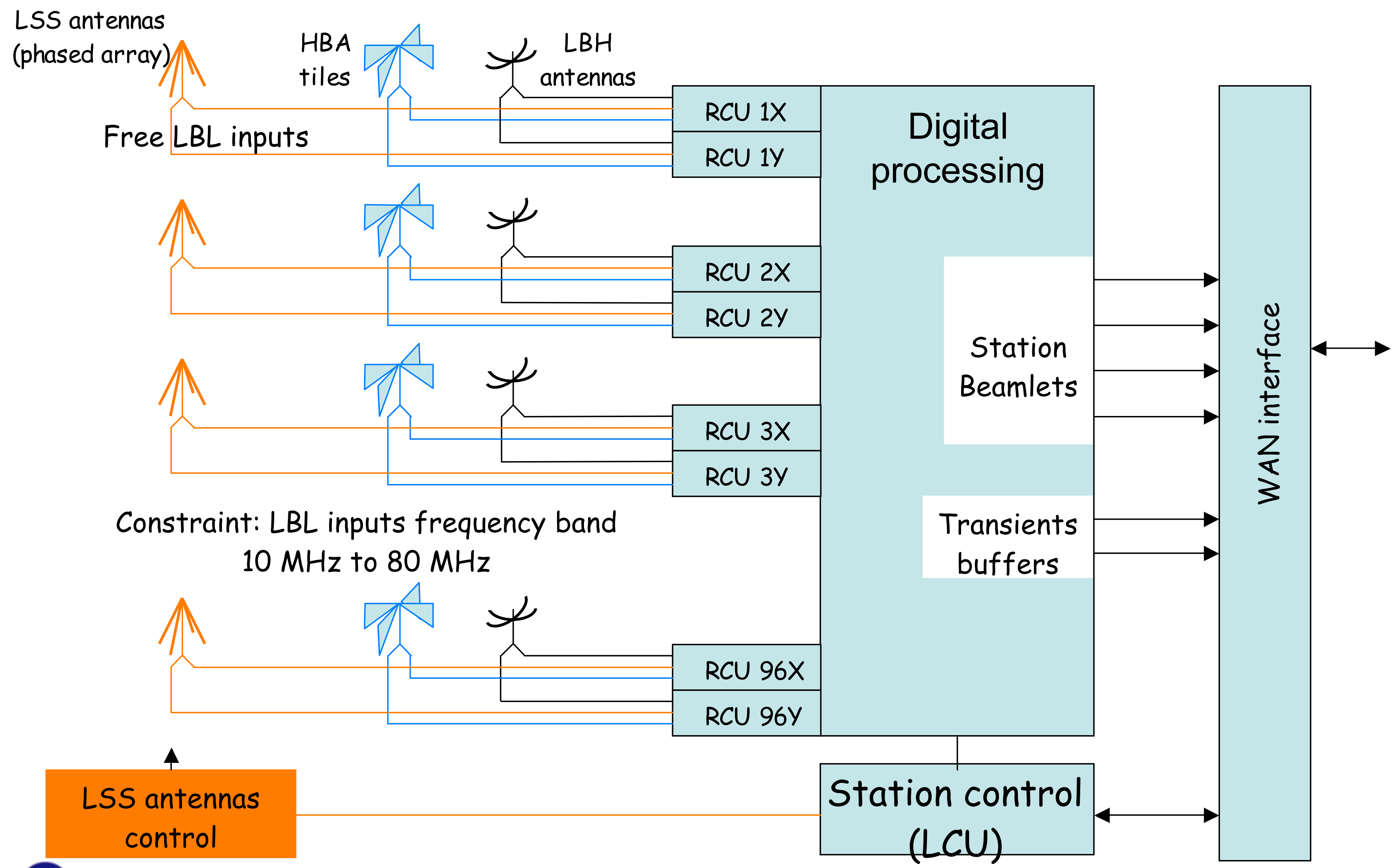
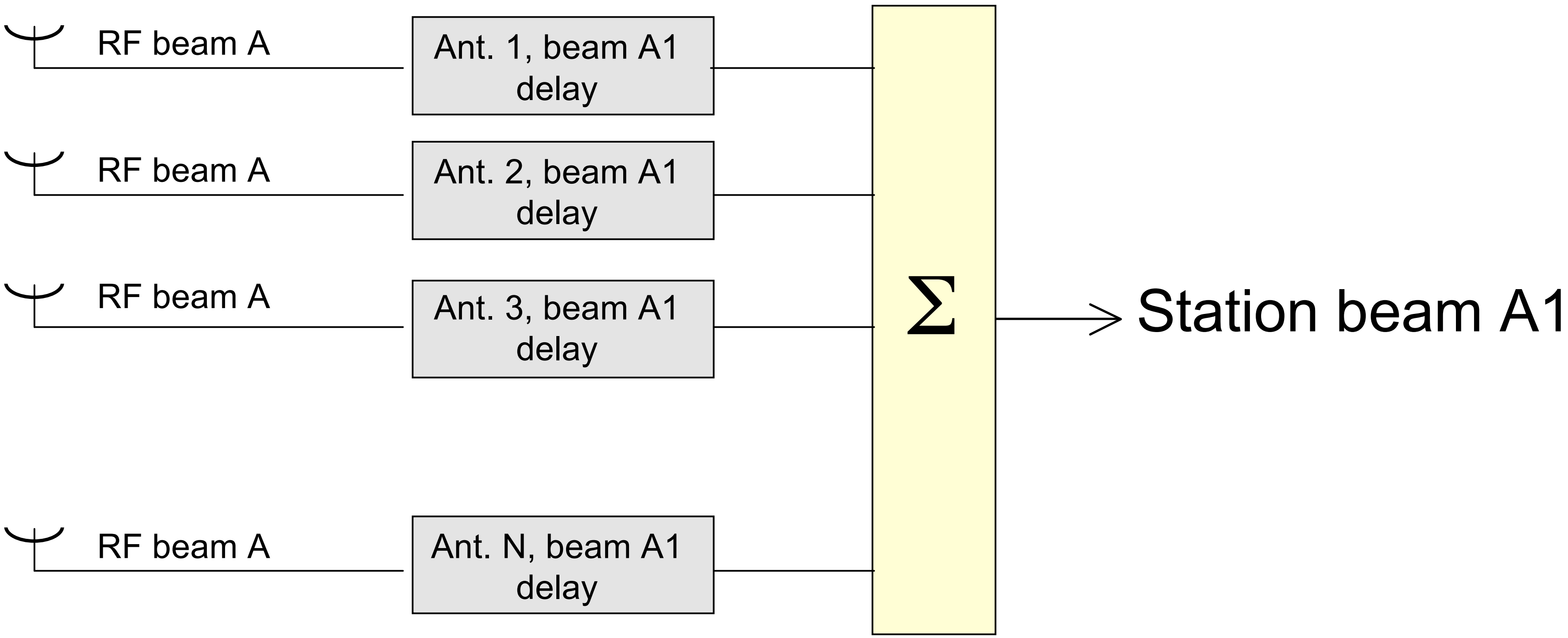
From LOFAR remote station to LOFAR Super Station
3 x 96 antennas, 2 polarizations



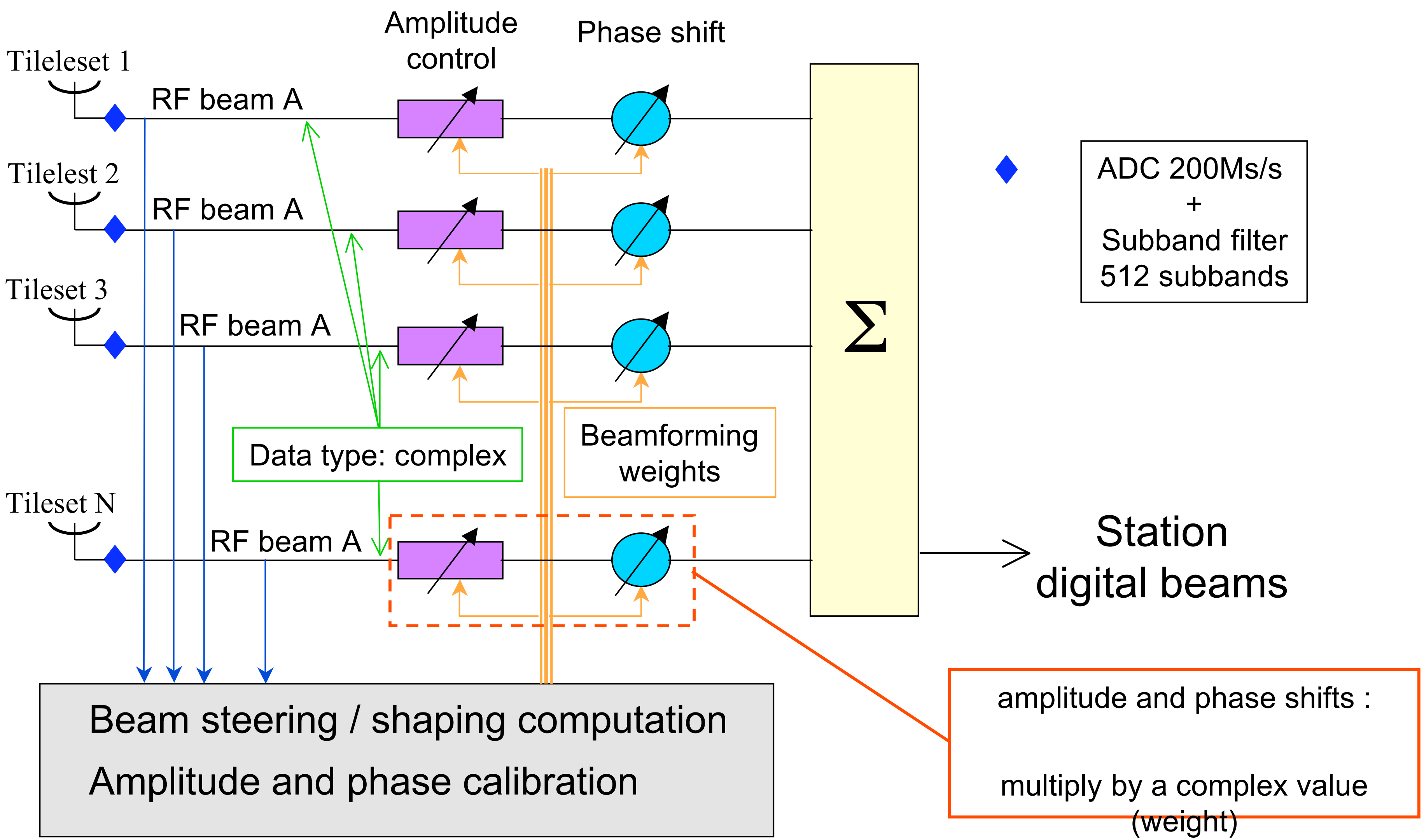
Sum of delays beamforming for wideband phased arrays



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

LOFAR: digital beamforming using digital phase shifts



Beamforming process for N antennas, in one subband sb:

$$S = (a_1 e^{j\varphi_1})\,(g_1 e^{j\Psi_1}) + (a_2 e^{j\varphi_2})\,(g_2 e^{j\Psi_2}) + .. + (a_n e^{j\varphi_n})\,(g_2 e^{j\Psi_n}) + (a_N e^{j\varphi_N})\,(g_2 e^{j\Psi_N})$$

a_n amplitude of antenna n output
φ_n phase of antenna n output

One data sample, antenna n in subband sb, beam (θ,Φ) value: $a_n \cos(\varphi_n) + j a_n \sin(\varphi_n)$

g_n gain to apply to antenna n
Ψ_n phase shift to apply to antenna n
beam θ,Φ

Beamformer weight for antenna 1, subband sb and beam (θ,Φ)

From $ge^{j\Psi}$ weight to matrix weights:

$ge^{j\Psi} = g\cos(\Psi) + jg\sin(\Psi)$ beamforming weight for a given subband and antenna

$ae^{j\varphi} = a\cos(\varphi) + ja\sin(\varphi)$ output of subbands filter for these subband and antenna

$$(ae^{j\varphi})(ge^{j\Psi}) = \underbrace{g\cos(\Psi).a\cos(\varphi) - g\sin(\Psi).a\sin(\varphi)}_{X'_{re}} + j\,[\underbrace{g\sin(\Psi).a\cos(\varphi) + g\cos(\Psi).a\sin(\varphi)}_{X'_{im}}]$$

$$\begin{vmatrix} X'_{re} \\ X'_{im} \end{vmatrix} = \begin{vmatrix} g\cos(\Psi) & -g\sin(\Psi) \\ g\sin(\Psi) & g\cos(\Psi) \end{vmatrix} * \begin{vmatrix} a\cos(\varphi) \\ a\sin(\varphi) \end{vmatrix}$$

for one antenna

LOFAR beamformer process for one antenna and two polarizations:

$$\begin{vmatrix} X'_{re} \\ X'_{im} \\ Y'_{re} \\ Y'_{im} \end{vmatrix} = \begin{vmatrix} g_{xn}\cos(\Psi_{xn}) & -g_{xn}\sin(\Psi_{xn}) & g_{xyn}\cos(\Psi_{xyn}) & -g_{xyn}\sin(\Psi_{xyn}) \\ g_{xn}\sin(\Psi_{xn}) & g_{xn}\cos(\Psi_{xn}) & g_{xyn}\sin(\Psi_{xyn}) & g_{xyn}\cos(\Psi_{xyn}) \\ g_{yxn}\cos(\psi_{yxn}) & -g_{yxn}\sin(\psi_{yxn}) & g_{yn}\cos(\psi_{yn}) & -g_{yn}\sin(\psi_{yn}) \\ g_{yxn}\sin(\psi_{yxn}) & g_{yxn}\cos(\psi_{yxn}) & g_{yn}\sin(\psi_{yn}) & g_{yn}\cos(\psi_{yn}) \end{vmatrix} * \begin{vmatrix} a_{xn}\cos(\varphi_{xn}) \\ a_{xn}\cos(\varphi_{xn}) \\ a_{yn}\cos(\varphi_{yn}) \\ a_{yn}\sin(\varphi_{yn}) \end{vmatrix}$$

usefull for orthogonality correction

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'(b)re + jX'(b)im, Y'(b)re + jY'(b)im
- Subband for beamlet b: from Subband Select map
- Beamformer weights for beamlet b : from weights matrix (4x4) => (θ, Φ) for subb. s, ant. a

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

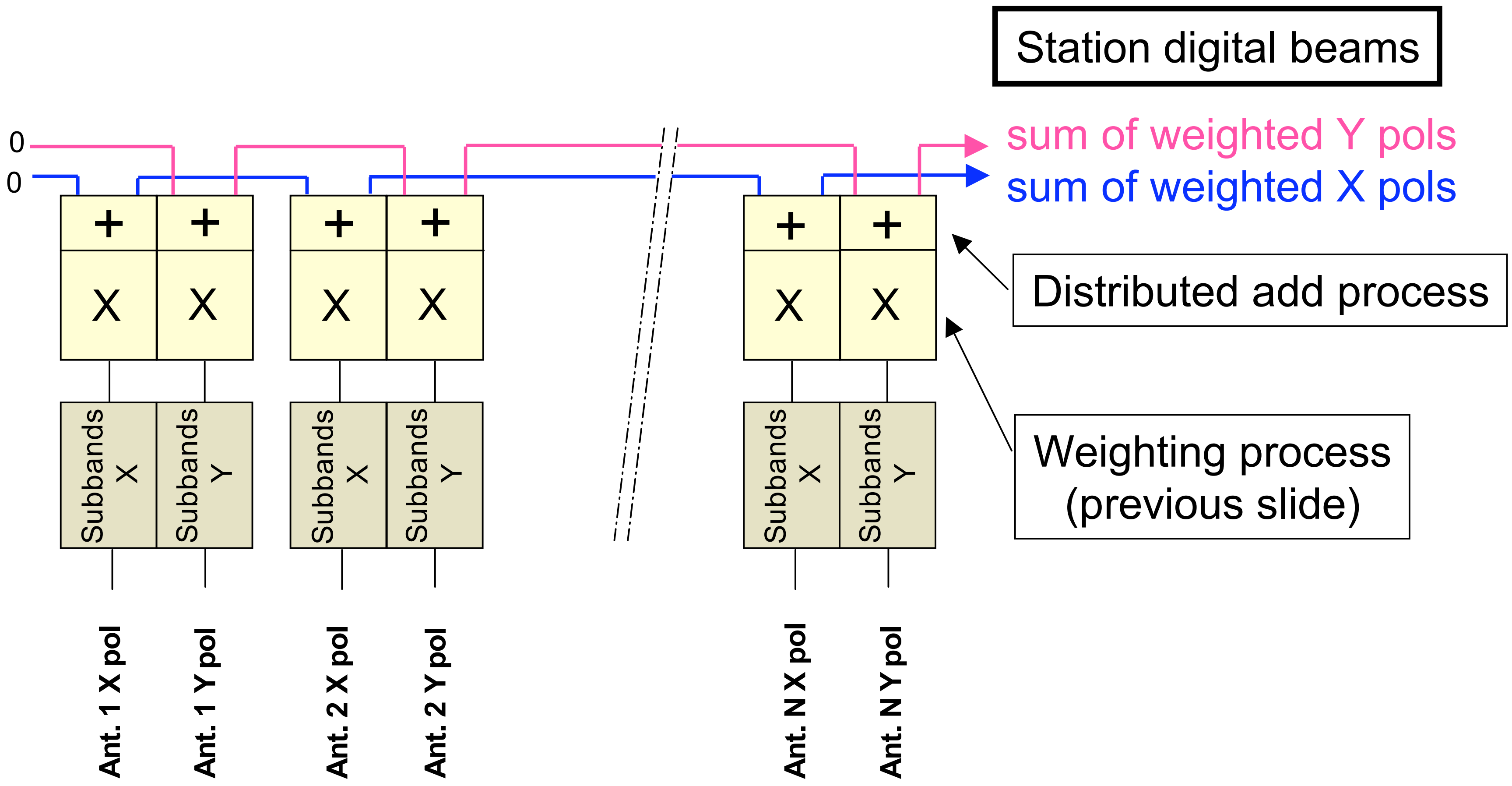
black weights = 0 if no orthogonalization process (or beam rotate)

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

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

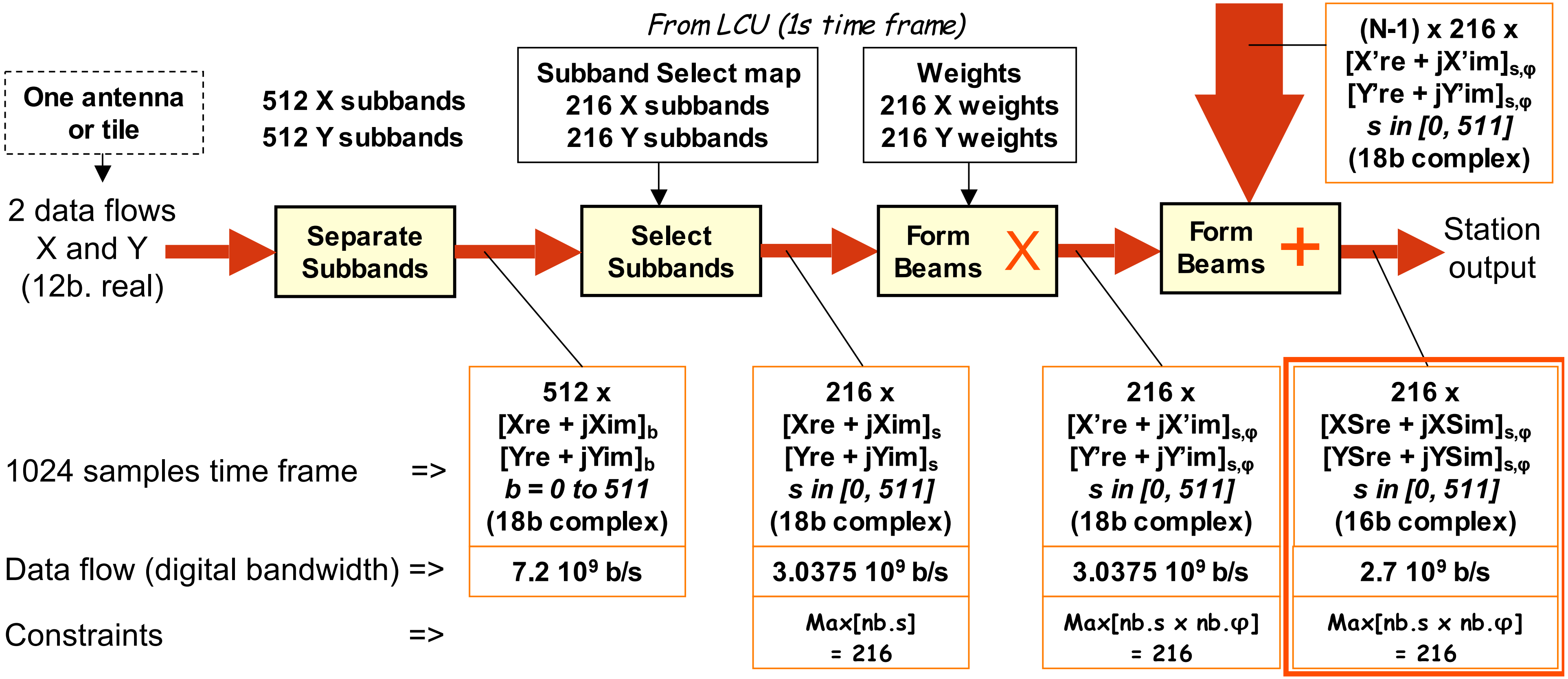
A LOFAR back-end delivers 216 beamlets each one for one subband, (θ,Φ), pol. X, Y

LOFAR beamformer topology: parallel / serial processing



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

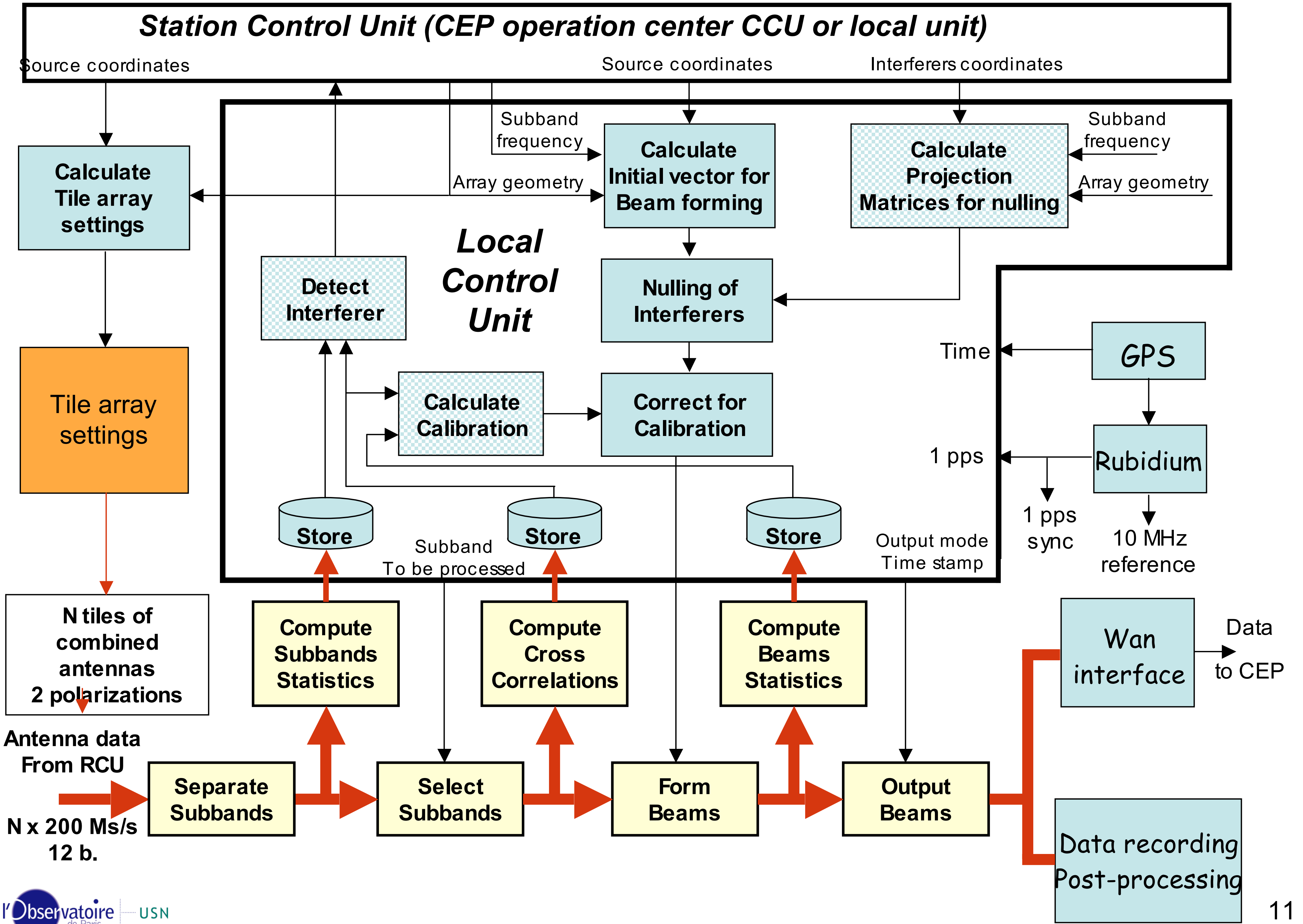
Subband width: 195.3125 Khz at 200 Ms/s and 156.25 KHz at 160 Ms/s



Station digital beam = collection of $[XSre + jXSim]_{s,(\theta,\Phi)}$, $[YSre + jYSim]_{s,(\theta,\Phi)}$ for the required number of subbands, with the same direction (θΦ)

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

Separate beams	Separate spectral windows	Window width (MHz)
1	1	33.75
2	2	16.87
1 4	1 2	16.87 8.4375
4	4	8.4375
.	.	.
24	24	1.4
.	.	.
1 36	1 36	
.	.	.
216	216	0.15625



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Output data:

Low temporal resolution (recorded in the LCU)

- Subbands statistics (1s accumulated power) for all antennas (whole FOV)
- Beamlets statistics (1s accumulated power) throughout the beamforming chain
- Cross correlation (1s accumulated) of all antennas by all antennas

High temporal resolution data (no data record in LCU) to CEP

4 x 1Gb/s Ethernet lines, each one with data frames of 16 blocks of 54 beamlets
Transport bandwidth load: > 65%

Time resolution:	5.12 μs	or	6.4 μs
Frequency resolution:	195.3125 KHz	or	156.25 KHz

Data recording (beamlets): > 300 MB/s