Impact analysis of change request to use 1 MHz beamlets instead of 0.78125 MHz beamlets in APERTIF and ARTS

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**Terminology:**

Apertif APERture Tile In Focus

Arts Apertif Radio Transient System

Beam Group of beamlets that point in the same direction

Beamlet Beam formed subband, a small beam spanning one subband

BF BeamFormer

BN Back Node

bps Bits per second

BW BandWidth

FFT Fast Fourier Transform

FN Front Node

FPGA Field Programmable Gate Array

GbE Gigabit Ethernet

HDL Hardware Description Language

Im Imaginary

IO Input Output

MAC Multiply and Accumulate, Medium Access, Monitoring and Control

Nof Number of

PN Processing Node (BN or FN)

Re Real

RF Radio Frequency

sps Samples per second

Subband Frequency band, unit output of the filterbank

X Correlator

**Definitions:**

N 1024 FFT size of the FFT in the Apertif BF subband polyphase filterbank

K Average number of beams per subband

NCB 37 Number of compound beams, NCB = K

P 4 Wideband rate factor of sample clock rate divided by digital processing clock rate

RFBW 400M Radio frequency total input bandwidth

CBBW 300M Beam former total output bandwidth per compound beam

Bsub Subband bandwidth = beamlet bandwidth

fs 800M Digitizer sample frequency of the ADC at the Apertif BF frontend

fclk 200M Data processing clock rate in the FPGA

Nband 16 Number of bands in the Apertif BF to process the full CBBW

NFN 24 Number of subband per FN in the Apertif BF (= Nsel/Nband)

S 64 Number of ADC signal paths in the frontend of the Apertif BF

SBN 4 Number of ADC signal paths per BN in the frontend of the Apertif BF

nof\_uni 4 Number of UniBoards per polarization and dish in the Apertif BF

nof\_bn 4 Number of back node FPGAs (BN) per UniBoard

nof\_fn 4 Number of front node FPGAs (FN) per UniBoard

Wbeamlet 6 Number of bits per beamlet voltage sample at the output of the Apertif BF

Nchan 64 number of channels per beamlet in the Apertif X

nof\_adc\_bits 8 Number of bits per ADC sample at the input of the Apertif BF

nof\_pfb\_bits 16 Number of bits per subband sample

# Introduction

## Purpose

This document provides the information for the Arts change request to Apertif to have 1 MHz beamlets at the output of the Apertif beamformer (BF).

## Scope

This document investigates the impact of changing the current beamlet bandwidth of Bsub = 781250 Hz into Bsub = 1 MHz regarding both technical and development aspects. The conclusion regarding the technical aspects is that the change to Bsub = 1 MHz is quite feasible. Therefore section 2 first describes the impact regarding the development time and planning and then section 3 describes the technical details.

## Background

The Apertif beamformer uses a sample rate of fs = 800 MHz and the filterbank uses a 1024-point FFT. This results in subbands and beamlets of Bsub = 800M/1024 = 781250 Hz. The RF frequency band can be downconverted in steps of 10 MHz relative to 0 Hz. For a standalone radio telescope this 10 MHz frequency grid and 781250 Hz subband resolution are fine, but for a radio telescope that needs to measure together with other radio telescopes it is preferable to have a frequency grid of 1 MHz. Arts science cases SC1 Pulsar timing and SC2 VLBI require combining signals from different radio telescopes [1]. Therefore the Apertif BF beamlet bandwidth needs to be changed to preferrably Bsub = 1 MHz. The Apertif BF beamlet output is used by both the Apertif correlator (X) and by the Arts science cases (SC1, 2, 3 and 4).

# Development impact

## Number of human weeks

Changing to Bsub = 1 MHz requires adding the mixed radix feature to the FFT in the filterbank and requires a parameter value change to designs and applications that use the Apertif BF. The parameter value change of Bsub and Nsel does not require new functionality in the firmware or software, but it does require verification in simulation and validation on hardware. Table 1 lists the development tasks and estimates the number of human weeks that they will need.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Nr.** | **Component** | **Task** | **Sub task** | **Effort [weeks]** |
| 1 | N=800-point FFT | * Specification of a mixed radix-2 and 5 FFT (Part 3 of [1]) * Implementation and verification of the mixed radix FFT in the filterbank | DSP/firmware engineer  Firmware engineer | 8  10 |
| 2 | Apertif BF | * Implementation and verification of parameter change for Bsub = 1MHz and Nsel=304 subbands to the VHDL firmware and Python test scripts | Firmware engineer   * for BN filterbank * for FN beamformer * for both together | 1  1  2 |
|  |  | * Adapt and verify the existing Apertif BF MAC software (weight calculation, weight control) | Software engineer | 2 |
|  |  | * Adapt and verify the existing Apertif BF Python scripts | Hardware engineer  Instrument engineer | 1  1 |
| 3 | Apertif X | * Adapt and verify the existing Apertif X VHDL firmware and Python software | Firmware engineer | 2 |
| 4 | Arts | * Adapt and verify the existing Arts VHDL firmware and Python software | Firmware engineer | 1 |
|  | **Total** |  |  | 31 |

Table 1: Development overview for changing to Bsub = 1 MHz

## Planning in time

Assumptions:

* The current development for Apertif BF, X and Arts can still continue with Bsub = 781250 Hz and Nsel = 384 subbands, but the engineers should even more than before keep in mind that these will change to Bsub = 1 MHz and Nsel = 304 subband. In this way the parameter change will have nearly no implication on the implementation and only require verification and validation.
* The Apertif BF firmware that runs on the UniBoards can only support either Bsub = 781250 Hz or Bsub = 1 MHz. It is awkward to maintain two sets of FPGA images because synthesizing these images takes ~3 hours and loading them into the FPGAs also takes ~1 min. Therefore it is best to change to FPGA images for Bsub = 1 MHz at some time in the planning and then freeze and no longer support the FPGA images for Bsub = 781250 Hz. The best time to do the change to Bsub = 1 MHz is when the mixed radix FFT is available and when the Apertif BF, Apertif X and Arts are running stable on Bsub = 781250 Hz, because then the change will least disturb the ongoing development.

Task 1 in Table 1 about the development of the mixed radix FFT will take about 4 months. This development needs to be done first but cannot start immediately due to limited resources.

Tasks 2, 3, and 4 in Table 1 concern the transition from Bsub = 781250 Hz to Bsub = 1 MHz for Aperitif BF, Apertif X and Arts will take about 3 man months to apply and verify.

In total the change takes about 7 man months. Some work can be done in parallel but most tasks need to be done in series.

Remarks:

* Changing Bsub takes development time but it will also have some beneficial side effects. First we will then have a mixed radix filterbank that can be reused in future projects, such as SKA [7]. Second changing such a fundamental parameter requires all developers to revisit and verify their code again (VHDL, Python, C etc.) which typically will enhance the overall quality.

# Technical impact

## N=800 point FFT

### FPGA resources

The polyphase filterbank (PFB) for Bsub = 781250 Hz uses a N=1024 point FFT [1]. In total the bn\_filterbank design in the Apertif beamformer has two PFB to be able to filter SBN=4 real ADC input signals per UniBoard back node (BN) FPGA. For Bsub = 1 MHz the FFT needs to be changed into a N=800 point FFT.

The Stratix IV FPGA that is used on UniBoard has 1288 multiplier DSP elements and 1235 M9K RAM blocks. Figure 1 shows that in total the bn\_filterbank design uses 872 multiplier DSP elements and 747 M9K RAM blocks, so there are still maximum 1288 – 872 = 416 multiplier DSP elements and 1235 – 747 = 488 M9K RAM blocks available. The bn\_filterbank contains two poly-phase filterbanks (PFB). The current N=1024 point FFT in the PFB takes 148 multiplier DSP elements and 39 M9K RAM blocks. Hence for the N=800 point FFT there are still 416 (free) / 2 (PFB) + 148 (current N=1024 FFT) = 356 multiplier DSP elements available and 488/2+39 = 283 M9K RAM blocks available. First impression is that this is more than sufficient.

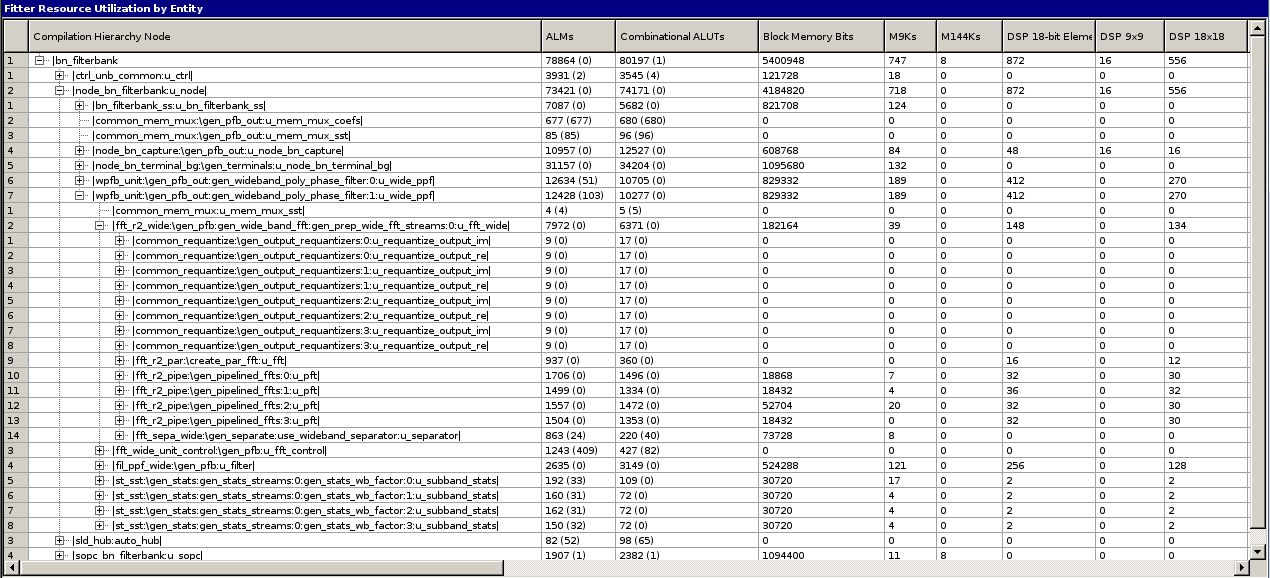


Figure 1 FPGA resource usage for the bn\_filterbank design in the Apertif BF

Note that the implementation runs at 200 MHz, whereas the samples arrive at 800 MHz. This factor P=4 is called a wideband factor and causes that the implementation requires about P=4 times more FPGA resources than it would if it could run on 800 MHz. However the FPGA cannot run much faster than 200 MHz, so the factor P=4 cannot be reduced.

### Radix-5 sections

For Bsub = 1 MHz the PFB will need an N=800 point FFT. An N=800 point FFT can be decomposed into 2 radix-5 stages and 5 radix-2 stages because 52\*25=800. Figure 2 shows the radix-2 section and radix-5 section [8]. The crossing lines and the dot indicate the butterfly operation. For the radix-2 the butterfly only requires an add and a subtract, but for the radix-5 the butterfly also involves some multiplies. The arrow indicates the twiddle factor, which involves the multiplication by the exponent term in the DFT. The twiddle factor is placed after the butterfly which indicates decimation-in-frequency (DIF).



Figure 2: Radix-2 (left) and Radix-5 (right) decimation-in-frequency FFT

Figure 3 shows that a N=10 point FFT can be constructed as a radix-5 and radix-2 stage or with a radix-2 stage and a radix-5 stage. The stage order does influence the output order. The twiddle factors in the last stage have exponent 0 so these multiplications reduce to multiply by 1 and do not need to be implemented. In a pipelined FFT the input samples arrive in series. This implies that each stage only requires the hardware resources for a single butterfly + twiddle factor operation. The stages operate in parallel so the stages all do need their own resources.



Figure 3: N=10 decimation-in-frequency point FFT using a radix-5 and a radix-2 stage

For example a N=1024 point FFT has log2(N)=10 stages, so it will need 10 complex multipliers in parallel to perform the twiddle factor multiplications. The multipliers operate at 50% efficiency because only 1 radix-2 butterfly output has a twiddle factor. Hence a radix-2 N-point FFT requires 0.5\*N\*log2(N) complex multiplies which agrees with the FFT theory [5]. An optimization is to avoid the multiply by 1 in the last stage. Another larger optimization is to try to use the multiplier at 100% instead of only 50% [7], but such optimization is not done in the current FFT implementation of the PFB in the Apertif BF [6]. Note that for a radix-r stage in general, the twiddle factor multiplier utilization is (r-1)/r, so for a radix-5 stage it is 4/5 = 80%, as indicated by the 4 arrows in the radix-5 butterfly in Figure 2. Hence trying to optimize the twiddle factor multiplier utilization in a mixed radix FFT becomes more difficult and less beneficial.

A N=800 point FFT has 2 radix-5 stages and 5 radix-2 stages. From a memory resource usage point of view it is better to use 2\*2\*2\*2\*2\*5\*5 than to use 5\*5\*2\*2\*2\*2\*2. However the parallel wideband factor P=4 implies that the last two stages need to b radix-2, so eg. 2\*2\*2\*5\*5\*2\*2. The FFT also need to reorder the output to normal order because the normal output order is necessary to be able to implement two real FFTs using one complex FFT. For an FFT with radix-5 stages the reorder is no longer a simple bit reversal.

Gianni Comoretto from INAF in Arcetri Italie has implemented a radix-5 FFT [7]. A synthesis trial for a N=3125 point FFT with 5 radix-5 stages reveals that stages 2, 3, 4, 5 each use 6 real DSP 18x18 multipliers that get mapped onto 8 DSP 18x18 elements. The memory usages increases for each stage and stage 4 uses 22 RAM M9K blocks.

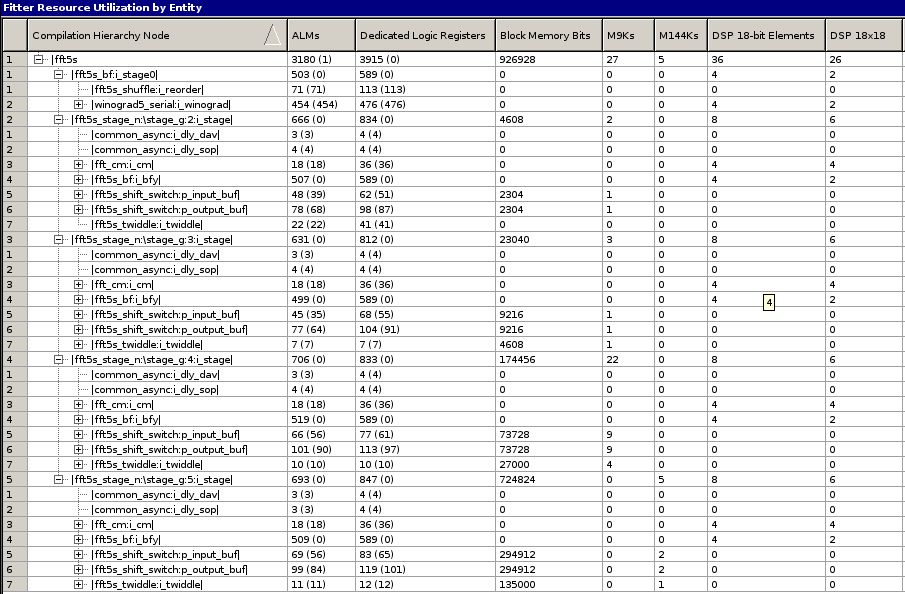


Figure 4: Fitter resource usage report per stage for a N=3125 point radix-5 FFT

Assume that the resource usage of radix-5 stage 4 in the N=3125 point FFT is representative for the resource usage of the two radix-5 stages in the N=800 point FFT. Given the wideband factor P=4 this then implies that these two radix-5 stages will then require about 88 M9K RAM blocks and 32 multiplier DSP elements. This will easily fit given the resources that are still available in bn\_filterbank design (see section 3.1.1).

## Parameter change from N=1024 🡪 N=800

The Apertif BF VHDL design is fully parameterized, so to changing N from 1024 🡪 800 can be done by simply changing the value. Still there will be impact at several locations, because there is no single central location where N is defined. The VHDL does use a central location, but the Python scripts and MAC software have their own central parameter locations. Therefore changing N will require rerunning several regression tests and fixing some unforeseen dependencies.

## Processing and transporting Nsel = 304 subbands when Bsub = 1 MHz

The Apertif BF subband bandwidth is Bsub = fs/N = 800 MHz/1024 = 781250 Hz. The subband bandwidth can be increased to 1 MHz by using an N=800 point FFT in the subband filterbank. In total the Apertif must be able to process CBBW = 300 MHz. Hence the number of subbands that need to be selected for the beamformer is Nsel= 384 for Bsub = 781250 Hz and Nsel = 304 for Bsub = 1 MHz, because Nsel needs to be dividable by Nband=16 to be able to distribute the Aperif BF load over Nband=16 front node (FN) FPGAs in the Apertif BF subrack. The Apertif BF processing and data IO has sufficient spare capacity to handle CBBW = 304 MHz, so it is not necessary to fall back to Nsel=288 which would fail the requirement of having CBBW ≥ 300 MHz.

The descriptions below explain that processing CBBW = 304 MHz is feasible. The description uses the load parameters for the Apertif BF that are defined in [3]. Figure 5 shows where the load parameters apply in the data path.



Figure 5 Load overview for the Apertif Beamformer

### Processing load

The beamformer units in the FN can beamform NFN=24 subbands (Bsub\*NFN= CBCW/Nband= 300M/16 = 18.75 MHz) into P\*Nclk = 4 \* 256 = N = 1024 beamlets at the rate Bsub=781250 Hz. Hence the maximum number of beamlets per subband Kmax = N / NFN = 1024 / 24 = 42.6.

For the Bsub=1 MHz the same beamformer units will beamform NFN=19 subbands (=Bsub\*NFN= 19 MHz) into P\*Nclk = 4 \* 200 = N=800 beamlets at rate Bsub=1MHz. Hence the maximum number of beamlets per subband Kmax = N / NFN = 800/ 19 = 42.1.

The processing load does not change, only the parameter settings of the beamformer units change and the balance between bandwidth CBBW and number of beams K changes slightly. For Bsub=1 MHz the CBBW increases from 300 to 304 MHz bandwidth and the maximum number of compound beams K decreases from 42.6 to 42.1, but is still more than the required K=NCB=37.

### Subband transport

Regarding the subband transport within the Apertif BF subrack the following points lead to the conclusion below.

1. In total the FPA of the Apertif BF has S=64 (actually 61, but the processing can handle 64) inputs per polarization that each get sampled by an ADC. The time series load per ADC signal path is LTsp = 2 (Nyquist) \* nof\_adc\_bits \* RFBW = 2 \* 8 \* 400M = 6.4 Gbps. There are SBN=4 ADC signal paths per BN so the time series input load per BN is LTBN = SBN \* LTsp = 25.6 Gbps.
2. The subband filterbank outputs subbands with a data width of nof\_pfb\_bits = 16 bit (14b is sufficient, but assume 16b for easier transport using 32b words). The load per subband is Lsubband = 2 (complex) \* nof\_pfb\_bits \* Bsub = 2 \* 16b \* 781250 Hz = 25 MHz and will become Lsubband = 2 \* 16b \* 1 MHz = 32 MHz. The subband load per ADC signal path is Lsp = Nsel \* Lsubband = 384 \* 25M = 9.6 Gbps and will become Lsp = 304 \* 32M = 9.728 Gbps. The subband load per BN is LBN = SBN \* Lsp = 4 \* 9.6G = 38.4 Gbps and will become LBN = 4 \* 9.728G = 38.912 Gbps.
3. The Apertif BF subrack has nof\_uni=4 UniBoards. The load on the backplane in the Apertif BF subrack BN-BN links is LBN\_BN\_link = LBN / nof\_uni = 9.6 Gbps and will become LBN\_BN\_link = 9.728 Gbps. Each UniBoard has nof\_fn=4 FN. Therefore the load on the UniBoard mesh BN-FN links is LBN\_FN\_link = LBN / nof\_fn = 9.6 Gbps and will become LBN\_FN\_link = 9.728 Gbps.
4. The capacity of the backplane links is 4 transceivers each operating at 5 Gbps including 8b/10b encoding, so an effective user data rate of 16 Gbps. The capacity of the mesh is 3 transceivers each operating at 5 Gbps including 8b/10b encoding, so an effective user data rate of 12 Gbps.
5. The subbands are transported in so called f-frames [3]. The frame rate is Bsub and the frame payload size SBN \* NFN where the number of subbands per FN is NFN = Nsel /Nband = 384 / 16 = 24 and will become NFN = 304 / 16 = 19 (note that Nband = nof\_uni \* nof\_fn = 4 \* 4 =16). Hence the f-payload size is SBN\* NFN = 4 \* 24 = 96 subbands and will become 4 \* 19 = 76 subbands. The f-frame data width is 32b so given nof\_pfb\_bits=16b there fits 1 complex subband sample per frame data word. The f-frame overhead consists of 4 words for the Uthernet header [9] and tail and 4 words for the data path (DP) header and tail [10]. Hence the f-frame length is 8 + 96 = 104 words and will become 8 + 76 = 84 words. With a f-frame overhead factor of 84 / 76 the data rate for both the back plane BN-BN links and the mesh BN-FN links is (104 / 96) \* 9.6 Gbps = 10.4 Gbps and will become (84 / 76) \* 9.728 Gbps = 10.752 Gbps.

Conclusion:

The f-frame load for Bsub = 781250 Hz is 10.4 Gbps and for Bsub= 1 MHz it becomes 10.752 Gbps, but this still easily fits on the BN-BN backplane links (that can carry 16 Gbps) and on the BN-FN mesh links (that can carry 12 Gbps).

### Beamlet output

Regarding the beamlet output of the Apertif BF subrack the following points lead to the conclusion below.

1. The subband beamformer in the FN can beamform N iblets. An iblet is a container that at the input of the beamformer carries a subband and at the output carries a beamlet. A beamlet can be regarded as a subband with direction. The Apertif BF must be able to produce K=37 beams, so on average NCB=K=37 beamlets per subband. Each FN can maximum produce Kmax = N/NFN = 1024 / 24 = 42.6 beams for Bsub= 781250 Hz and Kmax = N/NFN = 800 / 19 = 42.1 beams for Bsub= 1 MHz.
2. The Apertif BF outputs beamlets that are Wbeamlet = 6 bits. The load for 1 beamlet is LBbeamlet = 2 (complex) \* Wbeamlet \* Bsub = 9.375 Mbps and will become LBbeamlet = 2 \* 6b \* 1 MHz = 12 Mbps. The beamlet output load per FN is LBFN\_link = N \* LBbeamlet = 1024 \* 9.375M = 9.6 Gbps and will be the same for Bsub= 1 MHz because then LBFN\_link = 800 \* 12M = 9.6 Gbps.
3. The beamlet output load per FN is carried via a single 10GbE link. This link has a frame overhead of 12 (interpacket gap) + 14 (Ethernet) + 20 (IP) + 8 (UDP) + 14 (Data Path) = 68 octets. A block of N=1024 beamlets is packed into 64b words and then takes 2 \* 6b \* 1024 / 8b (octet) = 1536 octets for Bsub = 781250 Hz and 2 \* 6b \* 800 / 8b (octet) = 1200 octets for Bsub = 1 MHz. With 1 block per packet the Ethernet packet rate is Bsub.
4. With 1 block of N=1024 beamlets per Ethernet packet the required data rate is ((1536 + 68)/1536) \* 9.6 Gbps = 10.025 Gbps and will become ((1200 + 68)/1200) \* 9.6 Gbps = 10.144 Gbps. This just does not fit, so therefore the number of blocks per Ethernet packet needs to be set > 1. The 10GbE link can use jumbo frames up to about 8192 octets, hence it is possible to transport > 1 blocks of N=1024 beamlets per single Ethernet packet. Choosing Nblock = 2 yields ((1536\*Nblock + 68)/(1536\*Nblock)) \* 9.6 Gbps = 9.8125 Gbps for Bsub=782150 Hz and ((1200\*Nblock + 68)/(1200\*Nblock)) \* 9.6 Gbps = 9.872 Gbps for Bsub=1 MHz, which fit 10GbE in both cases.
5. The frequency tolerance of 10GbE is 100ppm, so worst case the link can carry 9.999 Gbps instead of 10 Gbps.

Conclusion:

The Apertif BF output rate does not change when Bsub is increased to 1 MHz, because the number of beamlets decreases as much. The fact that the produced CBBW increases from 300 MHz to 304 MHz does mean that slightly less than the original Kmax=42.6 beams can be formed, but the number of beams that can be produced is Kmax=42.1 which is still more than the required NCB = K = 37. The number of beamlet blocks per Ethernet frame does not change either and needs to be at least Nblock=2 for both Bsub=781250 and Bsub=1 MHz.

## Channel bandwidth in the Apertif X

The channel filterbank in the Apertif X separates the beamlets into Nchan = 64 channels. For Bsub=781250 the Bchan = 12.207 kHz and for Bsub = 1 MHz this becomes Bchan=15.625 kHz. Having Bchan=15.625 kHz still fits the Apertif X requirement SYS-09-04 that the spectral resolution should be at least 20 kHz [2].