Detailed Design of the Arts FPGA Beamformer

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**Terminology:**

ADC Analogue to Digital Conversion  
AGC Automatic Gain Control   
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 FPGA on UniBoard

bps Bits per second

BSN Block Sequence Number (timestamp)  
BW BandWidth

CB Compound Beam, formed at dish level over the FPA  
channel Unit frequency band within a beam  
CPU Central Processing Unit  
CW Carrier Wave (single frequency signal)

DP Data Path (streaming interface)  
eop End of Packet (or frame, or block)  
ephemeris Pulsar data format file with the parameters used in the timing model  
FFT Fast Fourier Transform

FN Front Node FPGA on UniBoard

FoV Field of View  
FPA Focal Plane Array (= PAF)  
FPGA Field Programmable Gate Array

FR Functional Requirement  
FRB Fast Radio Burst  
GbE Gigabit Ethernet

GPU Graphics Processing Unit  
HDL Hardware Description Language

IAB Incoherent array beam, formed by incoherently combining dishes  
Im Imaginary

IO Input Output

LEAP Large European Array for Pulsars  
MAC Multiply and Accumulate, Medium Access, Monitoring and Control

MM Memory Mapped (control interface)

node Processing node (PN), typically 1 FPGA chip  
Nof Number of

OEB Optical-Electrical Board (provides UniBoard BN with same optical IO as the FN)

PFB Poly phase Filter Bank  
power beam Full Stokes power values: I, Q, U, V

PAF Phased Array Feed (= FPA, better use term FPA)  
PL Pipeline processing  
PN Processing Node (BN or FN)

PPS Pulse Per Second  
Re Real

RF Radio Frequency

SC Science Case  
SNR Signal to Noise Ratio

sop Start of Packet (or frame, or block)  
SP Signal Path, 1 CB consists of Npol = 2 SP, 1 SP per Apertif BF subrack

SR Science Requirement

ST Streaming, statistics  
sps Samples per second

subband Frequency band, unit output of the filterbank

TAB Tied array beam, formed by coherently combining dishes  
Tant Transpose to group data from all S = 64 (≥ Nant) antenna elements in the FPA  
Tdish Transpose to group data from all Ndish = 12 dishes  
Tpol Transpose to group data from both Npol = 2 polarizations  
Tsp Transpose to group data from all Nsp = Npol \* Ndish signal paths, so combines Tdish and Tpol   
Tband Transpose to group data from all Nband = 16 bands

Tintegration Transpose to group data from an integration interval  
TFoV Transpose to group data from all NCB = 37 beams for the full FoV

ToA Time of Arrival  
TT Terrestrial Time  
VDIF VLBI Data Interchange Format  
VLBI Very Large Baseline Interferometry  
voltage beam Dual polarization sample values with phase information: Xre, Xim, Yre, Yim

WSRT Westerbork Synthesis Radio Telescope  
X Correlator

**Definitions:**

Ncomplex 2 Two part of a complex number, the real and imaginary part   
Npol 2 Number of polarizations, X and Y  
NStokes 4 Number of power values in the Stokes vector [I, Q, U, V]  
Ndish 12 Number of WSRT dishes in Apertif  
Nsp 24 Number of signal paths = Ndish \* Npol  
N 1024 or 800 FFT size of the FFT in the Apertif BF subband polyphase filter

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

Nclk 256 or 200 = N/P, number of DP clock cycles per subband period  
Nsub 512 = N/2, number of subbands that covers RFBW=400MHz  
Nsel 384 Number of selected subbands to cover CBBW=300 MHz  
Nband 16 = nof\_fn\_bf, Number of bands in the Apertif BF to process the full CBBWNFN 24 Number of subband per FN in the Apertif BF (= Nsel/Nband)

NCB 37 Number of compound beams  
K 40 Average number of beamlets per subband (≥ NCB)

PBF 4 Number of parallel BF units per FN

Nblk  ≤ Nclk, number of valid DP clock cycles per subband period

Nbeamlet Number of compound beamlet slots per FN output, maximum PBF \* Nclk = 1024,

actual PBF \* Nblk = 960, required NCB \* NFN = 888

Ninterleave  2 = nof\_un/PBF, additional beamlet output interleave factor

Pinterleave  2 Number of interleaved streams that are regarded in parallel at rate 1/Pinterleave

Ngr 12 Number of grating lobe patterns TABs to cover the full CB (SR-0.41)  
NVLBI 12 Number of TABs in the central CB for VLBI, choose = Ngr (SR-0.23)  
NIAB 37 = NCB, number of IABs   
NTAB 444 Number of TABs   
NPN 384 = Nsp \* Nband, total number of parallel processing nodes in the Apertif BF  
Nlink 384 = NPN, number of physical 10G output links of the Apertif BF, so 1 link per PN  
Nant 61 Number of antennas in the frontend FPA of the Apertif BF

S 64 Number of ADC signal paths in the frontend FPA of the Apertif BF (≥ Nant)

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

fclk 200M Data processing clock rate in the FPGA

fs 800 MHz Digitizer sample frequency of the ADC at the Apertif BF frontend  
Ts 1.25 ns = 1/ fs, digitizer sample period  
f0 Lower edge frequency of a subband, beamlet or channel  
RFBW 400 MHz = fs/2, sampled RF bandwidth   
CBBW 300 MHz Full bandwidth of the CB and also of the TAB and IAB (SR-0.2)  
Bsub 781250 Hz Subband bandwidth in Apertif BF, = beamlet bandwidth  
Nchan\_x 64 Number of channels per beamlet in the Apertif X

Nchan 4 Number of channels per beamlet, for SC3 and SC4  
Bchan = Bsub/Nchan, channel bandwidth within a beamlet, for SC3 and SC4

Nint\_x 800000 Number of channel power values that are integrated in the Apertif X  
Nint ≈ 10 Number of Stokes channel power values that are integrated in Arts  
TStokes ≈ 50 μs Minimum required sample period for the Stokes power values  
fStokes ≈ 20 kHz = 1/TStokes, minimum required sample frequency for the Stokes power values  
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

nof\_un 8 = nof\_fn + nof\_bn, number of processing node FPGAs per UniBoard

nof\_10g 3 Number of 10G links per FPGA node on UniBoard

nof\_pn Number of processing nodes (BN or FN)

nof\_bn\_fb 16 = nof\_uni\*nof\_bn, number of subband filterbank BN per SP in the Apertif BF

nof\_fn\_bf 16 = nof\_uni\*nof\_fn, number of beamformer FN per SP in the Apertif BF

byte\_w 8 Number of bits in a byte or an octet

word\_sz 4 Number of bytes per 32 bit long word  
longword\_sz 8 Number of bytes per 64 bit long word  
Wbeamlet 6 Word width in number of bits of a beamlet voltage sample  
Wchan Word width in number of bits of a channel voltage sample  
Wtab 4 Word width in number of bits of a TAB voltage sample  
Wpower 4 Word width in number of bits of a IAB or TAB power sample

# Introduction

## Scope

Arts [1] implements the tied array and VLBI functionality of Apertif [2]. Figure 1 shows the place of Arts within Apertif. Both the Apertif correlator (X) [5] and Arts use the beam data from the Apertif beamformer (BF) [3].



Figure 1: Top level overview of Apertif with Arts included

Within Arts the processing is consists of a FPGA beamformer and a GPU pipeline, as shown in Figure 2. Arts has four science cases (SC) and for all four SC the FPGA beamformer will be implemented on Uniboards.



Figure 2: Arts FPGA beamformer and GPU pipeline

This document specifies the detailed design for the Arts FPGA beamformer (BF) on UniBoard FPGAs. At the input interface the Arts BF receives NCB=37 compound beams from Ndish=12 dishes from the Apertif BF. At the output interface the Arts BF outputs compound beams (CB) for SC2, tied array beams (TAB) for SC1, 2 and 4 or incoherent array beams (IAB) for SC3 to a GPU cluster for further processing.

Note the difference between the Apertif BF and the Arts BF. The Apertif BF forms the compound beams over the focal plane array of each dish. These compound beams are input to Aperitif X and to Arts. The Arts BF uses the compound beams to form IAB or TAB over the array of dishes.

## Specification

This detailed design document is the L3 specification of the FPGA beamformer because it specifies how the FPGA beamformer should be implemented on Uniboards to fulfill all L0 science, L1 system and L2 subsystem requirements that are specified in [1]. This document only specifies the FPGA firmware design and the required FPGA interconnect and IO architecture. The UniBoard hardware and the subrack hardware are assumed to be available.

# System overview

## Apertif BF subsystem

The Apertif BF separates the digitized data from the FPA into subbands by means of a filterbank and then it forms beamlets for these subbands. The beamforming (BF) for one single polarization of the FPA cannot be done on a single node for the full bandwidth, so therefore the subband load has to be distributed across Nband = nof\_fn\_bf = 16 processing nodes. The beamlet for one subband requires the input from all FPA elements, so therefore there needs to be a transpose Tant that groups the subbands from all S = 64 antennes. A CB is formed by a group of Nsel= 384 beamlets all with the same direction that span the CBBW = 300 MHz. Figure 3 shows the filterbank Fsub, the transpose Tant and the beamformer (BF) that is distributed over Nband nodes. The Tintegration transpose is used for the Apertif X, for Arts it needs to be bypassed. The MAC takes care of the proper operation, the subband selection and the BF weights.



Figure 3: The Apertif BF subsystem

## Apertif X subsystem and Arts subsystem

In [1] various options for the Arts subsystem were investigated. Figure 4 shows the selected option for the Arts subsystem and how it relates to the Apertif X subsystem. The same Tdish and Tpol transpose that are needed for Apertif X can also be used for Arts.



Figure 4: The Apertif X subsystem and the Arts subsystem

# Hardware architecture

## Apertif BF using Uniboard

The Apertif BF outputs NCB=37 compound beams with CBBW=300 MHz. The Apertif BF beam forms the FPA input per polarization and per dish. The single dish, single polarization output of the Apertif BF is called a signal path (SP) and to beam form 1 signal path requires a subrack with nof\_uni=4 UniBoards. To be able to distribute the processing over nof\_fn\_bf=16 front nodes (FN) on nof\_uni=4 UniBoards the Apertif BF is separated into Nband= nof\_fn\_bf =16 frequency bands. Figure 5 shows the Apertif BF subrack with 4 UniBoards. Each FN in the subrack uses one 10GbE port to output its frequency part of the signal path.



Figure 5: One Apertif BF subrack per signal path with nof\_uni=4 UniBoards and Nband=16 FN

## Signal path transpose to Arts

In total the Apertif BF has Nsp = Npol \* Ndish = 24 signal paths so also 24 subracks, 96 UniBoards and NPN=Nsp\*Nband = 384 processing (front) nodes. Hence the total Apertif BF output is carried via Nlink=NPN=384 10GbE links as shown in Figure 6. For both the Apertif X and for Arts the Nsp=24 signal paths from the Apertif BF need to be transposed to gather them together. This transpose Tsp can be implemented by interconnecting the Apertif BF to Nband=16 Uniboards as shown in Figure 6. Each of the Nband=16 UniBoards in Figure 6 processes 1/Nband part of the CBBW band for all Nsp=24 signal paths.



Figure 6: Apertif BF transpose interconnect to Apertif X and Arts

## Arts using UniBoard

Figure 7 shows the UniBoard with the Optical-Electrical Board (OEB). The OEB is needed to be able to use fiber optics IO for the BN. For the Arts application (and also for the Apertif X application) the distinction between FN and BN is not needed, because all nof\_un = nof\_fn + nof\_bn = 8 FPGA have the same function. Therefore the FPGAs on UniBoard are also referred to as processing nodes (PN). Each PN has nof\_10G = 3 10G links so in total the UniBoard has nof\_un \* nof\_10G = 24 10G links. This is just enough IO to accept the input from Nsp=24 links.



Figure 7: One UniBoard to process 1/Nband part of the CBBW for Nsp=24 signal paths

On UniBoard the Nsp=24 inputs need to be distributed further via the on board mesh interconnect to gather them together at each PN. Therefore the input needs to be divided into 1/nof\_un parts to evenly distribute the processing load over the PN.

# Interfaces

## Streaming data

The array notation for streaming data is explained in [6].

### CB signal path input

#### Entire system

The compound beam data output interface of the Apertif BF is defined by [7]:

Equation 1:

The wiring of the Nlink=384 10GbE links in Figure 6 implements the first part of the Tdish and Tpol transpose to group the SP data from all Nsp=24 signal paths per band at a single UniBoard. The Tdish and Tpol transposed beam data input for Arts BF (and also for Apertif X) is defined by (note the swapped band and dish indices):

Equation 2:

The subscript indices indicate parallel links and the array index contains serial data on the link. The subscript *band* has range 0:Nband-1, subscript *pol* has range 0:Npol-1, subscript *dish* has range 0:Ndish-1. In total there are Nband \* Npol \* Ndish = 16 \* 2 \* 12 = Nlink = 384 parallel links. The array index *t* increments at the rate of Bsub. The array index *b* has range 0:Nbeamlet-1 where Nbeamlet  is the number of compound beamlet slots per FN output of the Apertif BF. Required Nbeamlet ≥ NCB\*NFN = 37 \* 24 = 888, note that NFN = Nsel / Nband. The actual Nbeamlet = K\*NFN = 40 \* 24 = 960. The order of beamlet directions and beamlet frequencies can be mapped to the beamlet slots in almost any order by the reorder function in the Apertif BF.

The order of the subscript indices indicates that band 0 maps on UniBoard 0 and band 15 maps on UniBoard 15. The pol index before the dish index implies that the X-pol inputs are connected via stream [0:11] to FN0:3 and the Y-pol inputs are connected via stream [12:23] to BN0:3 as shown in Figure 7. Based on this the *pol* and *dish* indices can be mapped to *port* and *pn* indices and to index *sp* = 0:Nsp-1 = 0:23 according to:

Equation 3:

Equation 4:

Equation 5:

With Equation 3 the Equation 2 can be rewritten as:

Equation 6:

#### Per UniBoard

One UniBoard processes one band of all Nsp=24 SP. Call this signal CB\_band, so CB\_band = CBband where *band* is mapped to this UniBoard. For one UniBoard equation Equation 6 then reduces to:

Equation 7:

Internally the Apertif FN beamformer contains PBF=4 parallel BF units that each process Nclk=256 beamlets to achieve Nbeamlet= PBF \* Nclk=1024 in total. From these Nclk beamlets only Nblk=240 are actually output [7]. With subscript *u* = 0:PBF-1 = 0:3 to indicate the parallel BF units and index *bu* = 0:Nblk-1 = 0:239 to count the number of valid beamlet slots per BF unit, then the relation with the absolute beamlet index *b* is given by:

Equation 8:

With Equation 8 the Equation 7 can be rewritten as:

Equation 9:

#### Distribution on the UniBoard mesh

Next part to complete the Tdish and Tpol transpose is to bring all SP to one processing node (PN) on UniBoard. Therefore the beamlets that are received at each PN need to be split into nof\_un=8 parts, whereby one part is kept at this PN and the other nof\_un-1 = 7 parts are passed on via the UniBoard mesh to the other 7 PN on the UniBoard. Choose to distribute the beamlets over the nof\_un=8 in the order in which they arrive at the PN. The index *u* already provides range PBF=4 beamlets, therefore define an additional interleave subblock size of Ninterleave = nof\_un/PBF = 2 beamlets to be able to distribute the beamlets in order over the nof\_un=8 PN. Equation 9 can then be rewritten as:

Equation 10:

Whereby the relation between index *bu* and index *bi* = 0:Ninterleave-1 =0:1 and *bu\_i* = 0:Nblk/Ninterleave-1 = 0:119 is given by:

Equation 11:

Define index *dest* = 0:nof\_un-1 = 0:7 for the destination PN as:

Equation 12:

With Equation 12 the Equation 10 can be rewritten as:

Equation 13:

Whereby the Ninterleave = 2 beamlets in series are regarded as Pinterleave = Ninterleave = 2 parallel streams that run at 1/Pinterleave rate of fclk.

Equation 14:

Together the indices *port* and *dest* cover the entire range of SP, because Nsp=Nlink\*nof\_un=3\*8=24. The order of the indices *port* and *dest* can be swapped at no cost, because all streams are available in parallel within the PN FPGA. It is convenient to swap *port* and *dest*, because then the Nsp=24 streams are again in incrementing order. Therefore rewrite Equation 13 as:

Equation 15:

The beamlets stream for which index *pn* = *dest* remains on this PN and the beamlet streams for which *pn* != *dest* are received from the corresponding other PN via the UniBoard mesh. This transport operation across the UniBoard mesh implements the last part of the Tdish and Tpol transpose. Starting with Equation 10 this swaps the *dest* and *pn* indices and results in:

Equation 16:

With Equation 3 the Equation 16 can be expressed in terms of the SP index *sp* = 0:Nsp-1:

Equation 17:

#### Per PN

One processing node (PN) on UniBoard processes 1/nof\_un = 1/8 part of the beamlets of one band of all Nsp=24 SP. Call this signal cb\_band, so cb\_band = CB\_banddest where *dest* is this PN. For one PN Equation 17 then reduces to:

Equation 18:

### BF component input and output

The BF component that is used in the FN of the Apertif BF is a voltage beamformer and can therefore also be reused to beamform TABs.

### SC1 TAB1 output

### SC2 CB12 output

### SC2 TAB12 output

### SC3 IAB37 output

### SC4 TAB444 output

## Memory-mapped control

# Processing

# Storage