Digitizer Status Update & SDR System & Integration Options

https://edms.cern.ch/document/1823376

R. J. Steinhagen

with input from: R. Bär, C. Handel, J. Fitzek, D. Ondreka, V. Sanjari, A. Schwinn

Scope

- FAIR and notably the FAIR Control Centre will deploy a ‘fully-digitial’ control paradigm:
  - automatic monitoring
    - performance tracking & early fault detection
    - quantitative/semi-automatic feedback and setup applications
  - assisted isolation of HW faults (‘ref-actual’-monitoring)
  - remote expert diagnostics (as needed)
  - also: pre-requisite prior to major ‘alt-HKR’ upgrades and/or move of operations to FCC

- Primary goals
  - generic abstraction of the vendor-specific digitizer software interfaces ✓
    - explicitly open for new/future vendor/digitizer models extensions
  - limited range of generic user-definable data post-processing on the acquired data ✓
  - control system integration by providing standardised FESA interface ongoing..

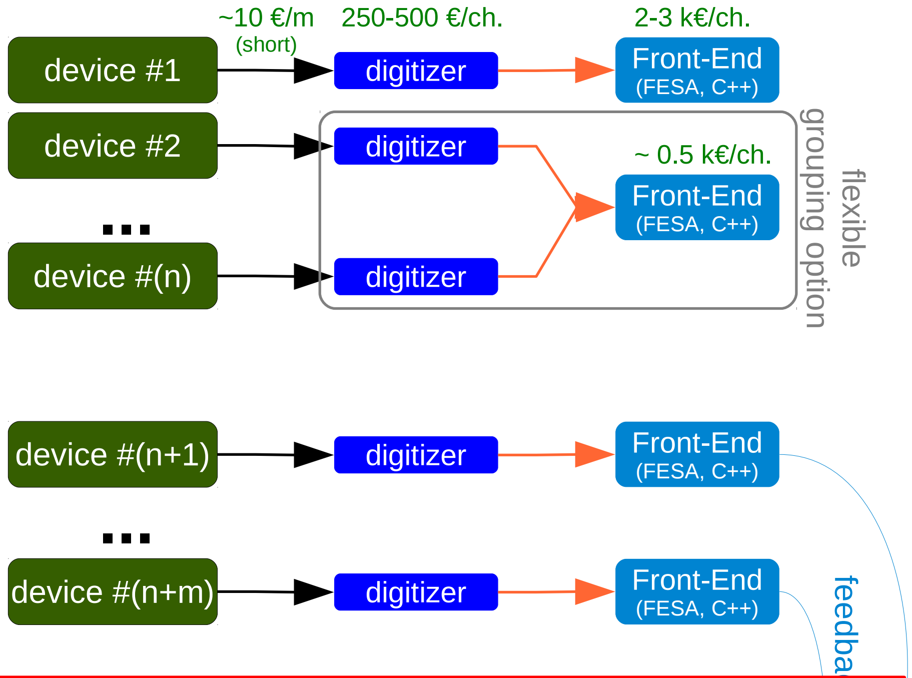
- Secondary goals
  - simplify further extensions, compactness, readability, re-usability, testability, and maintainability of the FESA implementation
  - Use of open-source signal processing and data fitting libraries
    - GNU-Radio – frame-work: https://www.gnuradio.org
    - ROOT – frame-work: https://root.cern.ch

- Not a new concept, existing specifications:
  - “Soft Oscilloscope System” https://edms.cern.ch/document/1176042/3
  - “Digitization of Analog Signals in the FAIR Accelerator Complex” https://edms.cern.ch/document/1823376/

Digitization of Analog Signals at FAIR I/II

https://edms.cern.ch/document/1823376/

- targeted concept
  (underlying assumption: scopes/digitizers are cheap, RF switches are expensive)



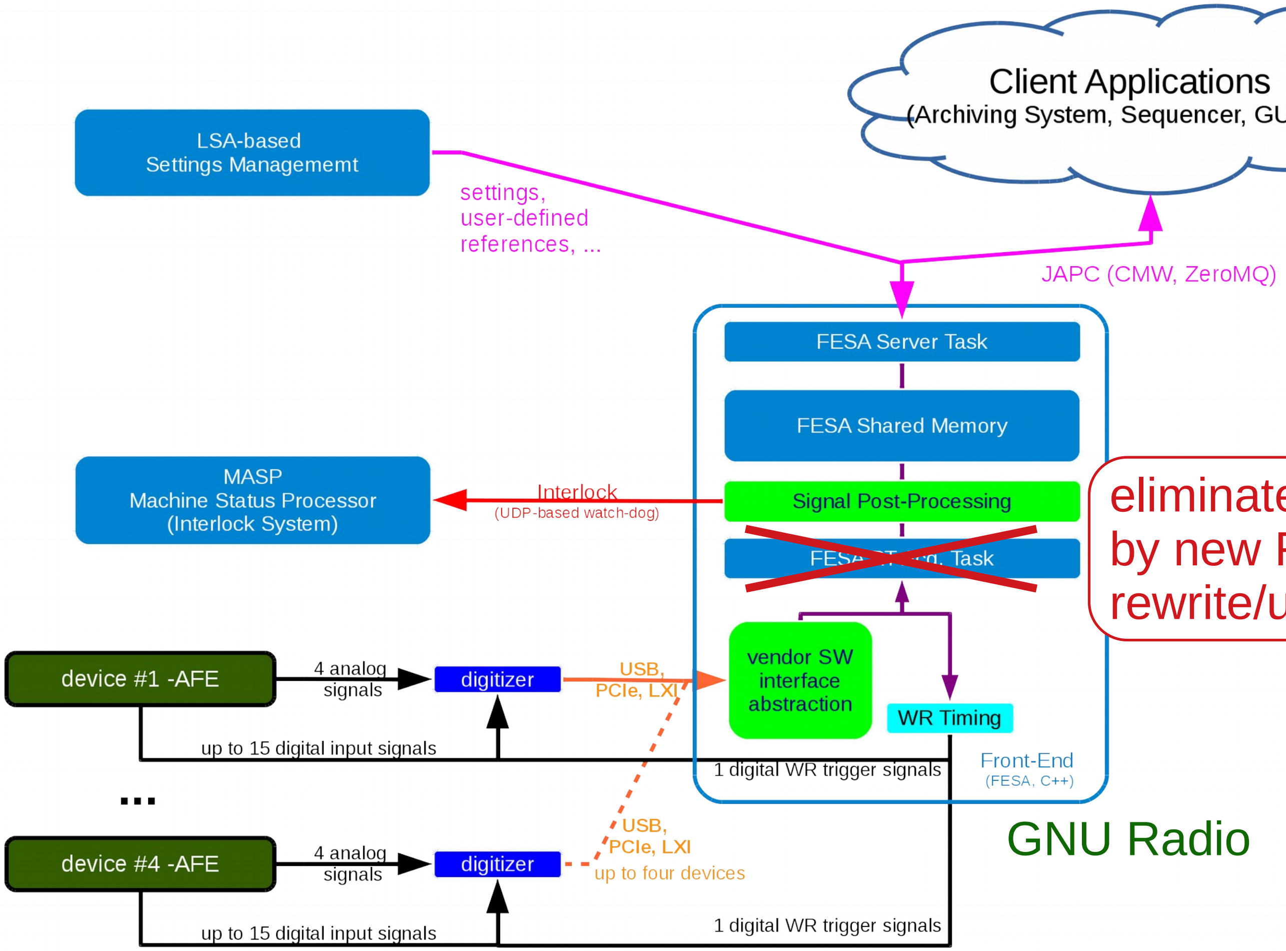
start deployment ≥2018 (SIS18), crucial for:

- migration to new FAIR Control Centre (FCC),
- optimisation of commissioning & operation
- tracking/isolation of faults (↔ post-mortem)
- less-biased performance indicator

link: more details

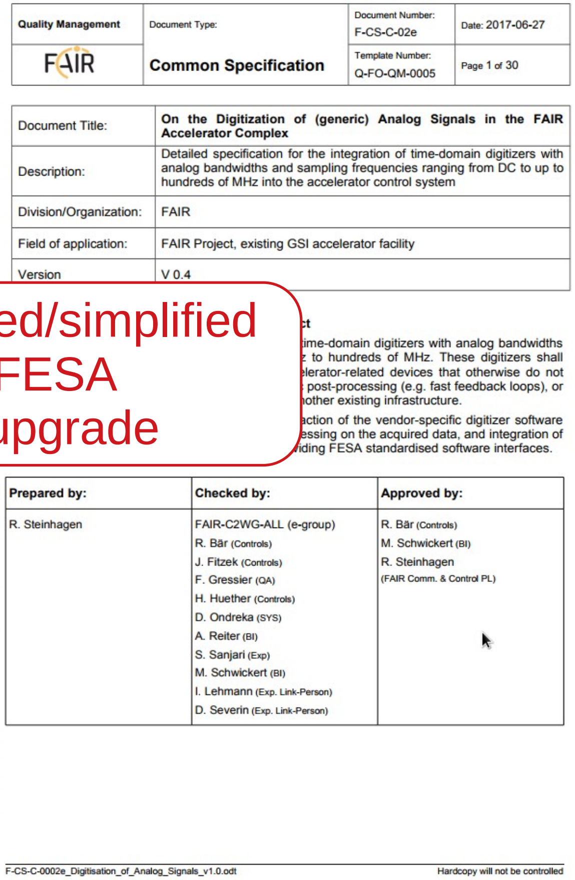
Digitization of Analog Signals at FAIR II/II

https://edms.cern.ch/document/1823376/



eliminated/simplified by new FESA rewrite/upgrade

GNU Radio



Quality Management	Document Type:	Document Number: F-CS-C-02e	Date: 2017-06-27
FAIR	Common Specification	Template Number: Q-FO-QM-0005	Page 1 of 30

Document Title:	**On the Digitization of (generic) Analog Signals in the FAIR Accelerator Complex**
Description:	Detailed specification for the integration of time-domain digitizers with analog bandwidths and sampling frequencies ranging from DC to up to hundreds of MHz into the accelerator control system
Division/Organization:	FAIR
Field of application:	FAIR Project, existing GSI accelerator facility
Version	V 0.4

ct

time-domain digitizers with analog bandwidths
z to hundreds of MHz. These digitizers shall
elerator-related devices that otherwise do not
post-processing (e.g. fast feedback loops), or
other existing infrastructure.

action of the vendor-specific digitizer software
essing on the acquired data, and integration of
viding FESA standardised software interfaces.

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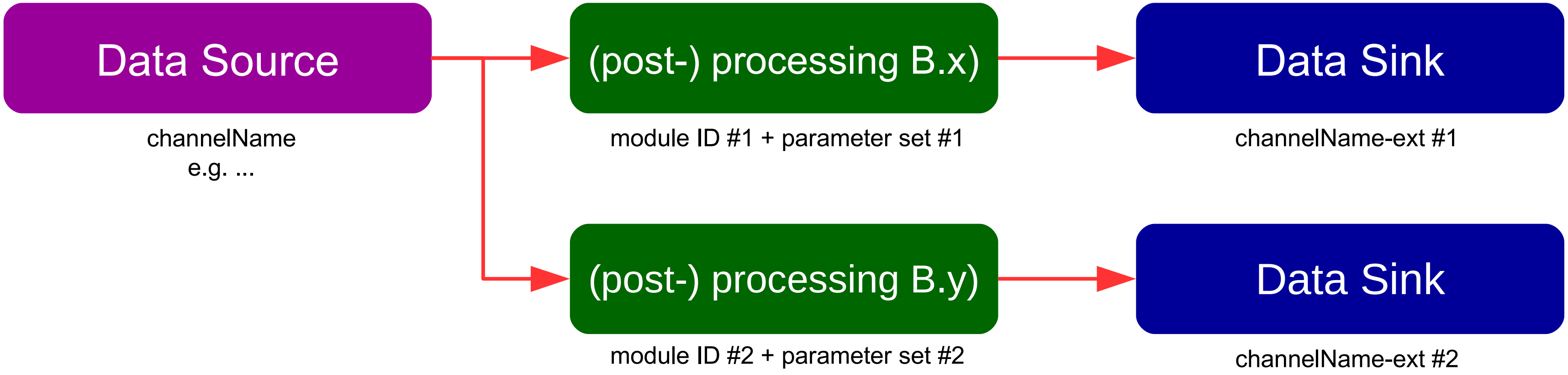
F-CS-C-0002e_Digitisation_of_Analog_Signals_v1.0.odt

Hardcopy will not be controlled

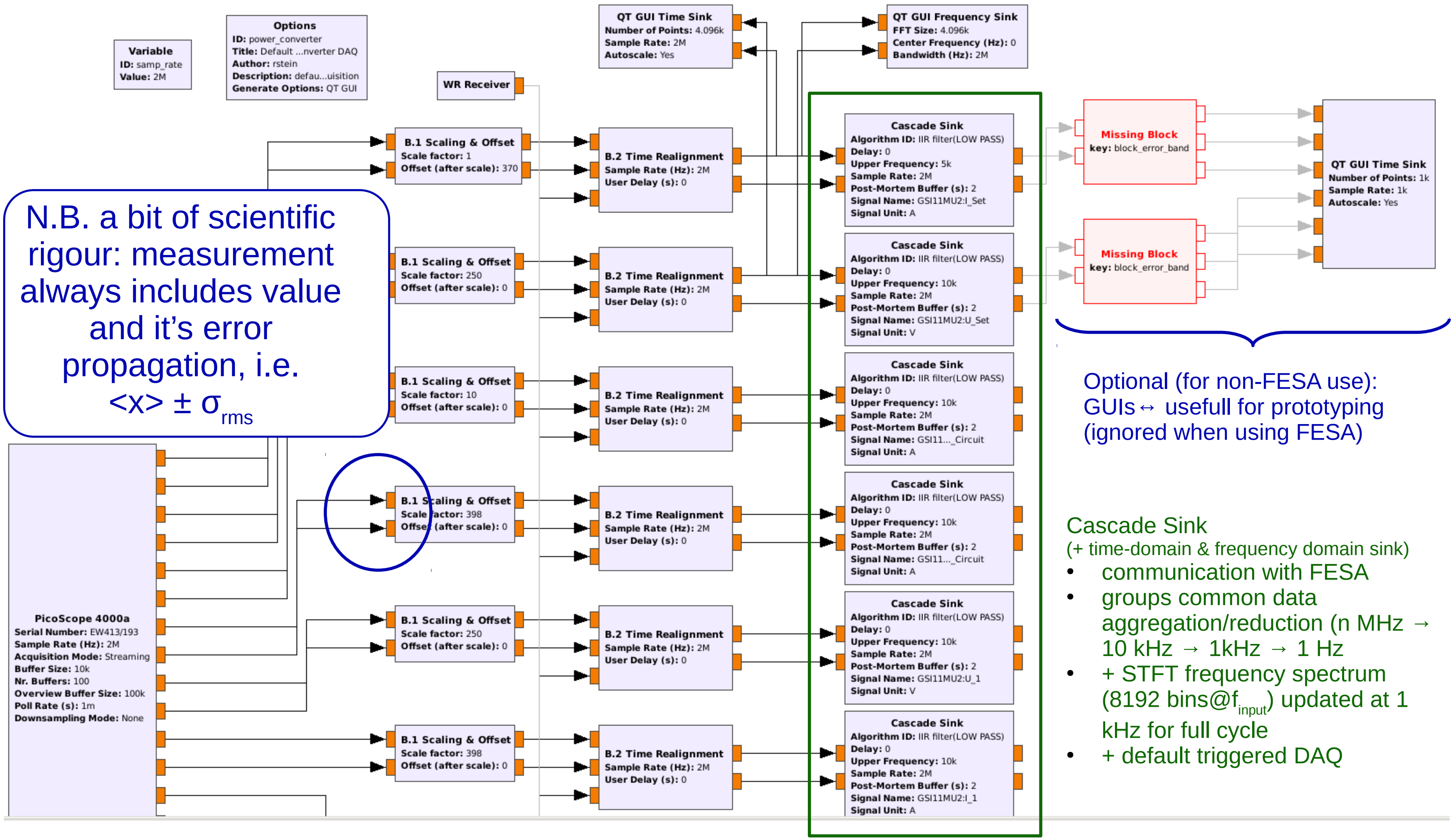
General Signal-Flow Scheme

N.B. GNU-Radio real-time streaming processing inspired



- Scheme can be further cascaded and combined with other modules
  - based on GNURadio‘s signal-flow concept https://www.gnuradio.org/
    - N.B. there are conceptually also other similar other projects: e.g. ADS, QUCS, Spice, LabVIEW … but with a different non-real-time (RF) signal processing

General Signal-Flow Scheme
Simple Example – AEG Dipole Acquisition



N.B. a bit of scientific rigour: measurement always includes value and it's error propagation, i.e.
$\langle x \rangle \pm \sigma_{rms}$

Variable
ID: samp_rate
Value: 2M

Options
ID: power_converter
Title: Default ...nverter DAQ
Author: rstein
Description: defau...uisition
Generate Options: QT GUI

WR Receiver

QT GUI Time Sink
Number of Points: 4.096k
Sample Rate: 2M
Autoscale: Yes

QT GUI Frequency Sink
FFT Size: 4.096k
Center Frequency (Hz): 0
Bandwidth (Hz): 2M

PicoScope 4000a
Serial Number: EW413/193
Sample Rate (Hz): 2M
Acquisition Mode: Streaming
Buffer Size: 10k
Nr. Buffers: 100
Overview Buffer Size: 100k
Poll Rate (s): 1m
Downsampling Mode: None

B.1 Scaling & Offset
Scale factor: 1
Offset (after scale): 370

B.1 Scaling & Offset
Scale factor: 250
Offset (after scale): 0

B.1 Scaling & Offset
Scale factor: 10
Offset (after scale): 0

B.1 Scaling & Offset
Scale factor: 398
Offset (after scale): 0

B.1 Scaling & Offset
Scale factor: 250
Offset (after scale): 0

B.1 Scaling & Offset
Scale factor: 398
Offset (after scale): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

B.2 Time Realignment
Sample Rate (Hz): 2M
User Delay (s): 0

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 5k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11MU2:I_Set
Signal Unit: A

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 10k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11MU2:U_Set
Signal Unit: V

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 10k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11..._Circuit
Signal Unit: A

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 10k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11..._Circuit
Signal Unit: A

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 10k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11MU2:U_1
Signal Unit: V

Cascade Sink
Algorithm ID: IIR filter(LOW PASS)
Delay: 0
Upper Frequency: 10k
Sample Rate: 2M
Post-Mortem Buffer (s): 2
Signal Name: GSI11MU2:I_1
Signal Unit: A

Missing Block
key: block_error_band

Missing Block
key: block_error_band

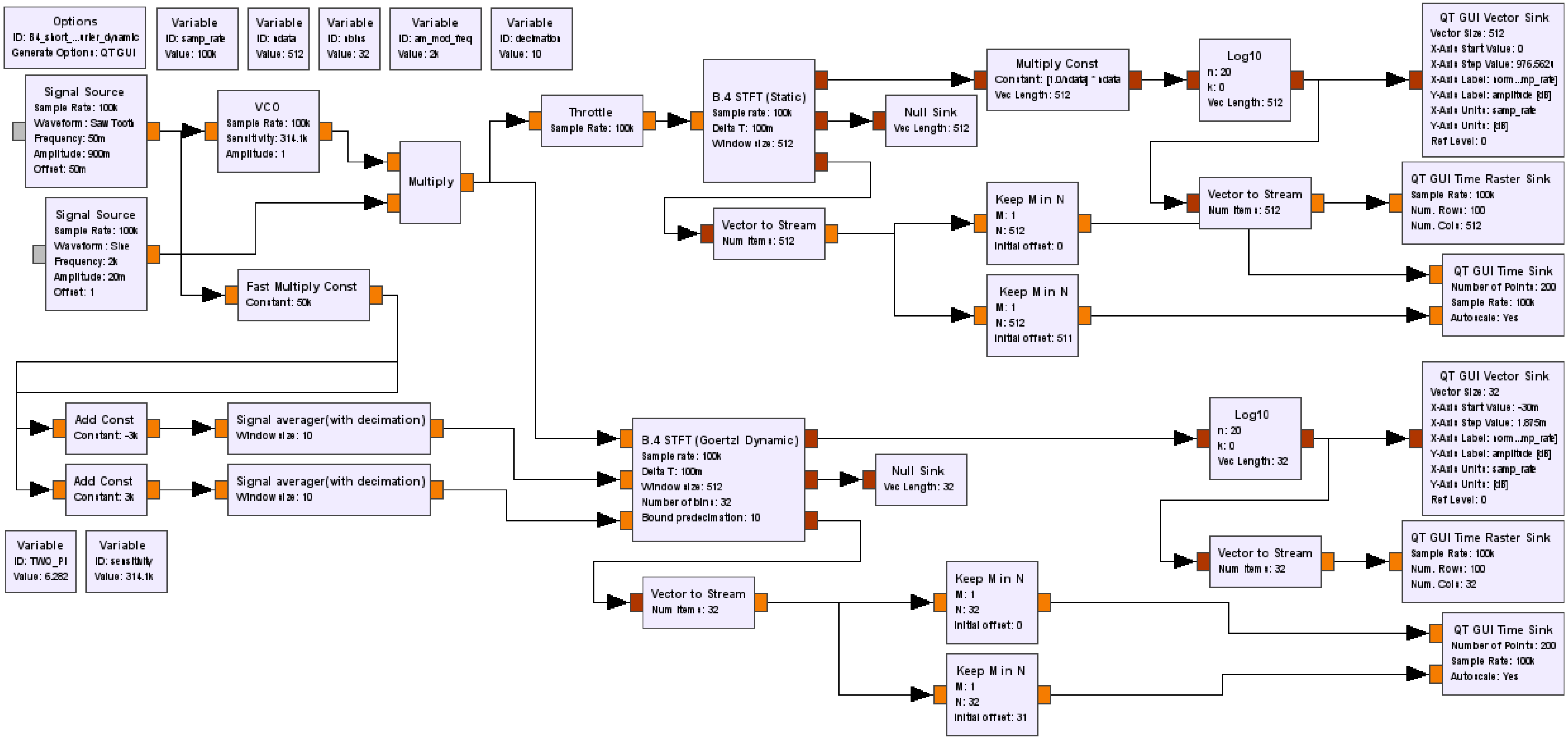
QT GUI Time Sink
Number of Points: 1k
Sample Rate: 1k
Autoscale: Yes

Optional (for non-FESA use):
GUIs ↔ usefull for prototyping
(ignored when using FESA)

Cascade Sink
(+ time-domain & frequency domain sink)

- communication with FESA
- groups common data aggregation/reduction (n MHz → 10 kHz → 1kHz → 1 Hz
- + STFT frequency spectrum (8192 bins@f_{input}) updated at 1 kHz for full cycle
- + default triggered DAQ

Short-Term-FFT, Goertzel-Transform etc. Example I/II



Options
ID: B4_short_...rier_dynamic
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 100k

Variable
ID: ndata
Value: 512

Variable
ID: nbins
Value: 32

Variable
ID: am_mod_freq
Value: 2k

Variable
ID: decimation
Value: 10

Signal Source
Sample Rate: 100k
Waveform: Saw Tooth
Frequency: 50m
Amplitude: 900m
Offset: 50m

VCO
Sample Rate: 100k
Sensitivity: 314.1k
Amplitude: 1

Multiply

Signal Source
Sample Rate: 100k
Waveform: Sine
Frequency: 2k
Amplitude: 20m
Offset: 1

Fast Multiply Const
Constant: 50k

Throttle
Sample Rate: 100k

B.4 STFT (Static)
Sample rate: 100k
Delta T: 100m
Window size: 512

Null Sink
Vec Length: 512

Multiply Const
Constant: [1.0/ndata] * ndata
Vec Length: 512

Log10
n: 20
k: 0
Vec Length: 512

QT GUI Vector Sink
Vector Size: 512
X-Axis Start Value: 0
X-Axis Step Value: 976.562u
X-Axis Label: norm...mp_rate]
Y-Axis Label: amplitude [dB]
X-Axis Units: samp_rate
Y-Axis Units: [dB]
Ref Level: 0

Vector to Stream
Num Items: 512

QT GUI Time Raster Sink
Sample Rate: 100k
Num. Rows: 100
Num. Cols: 512

Vector to Stream
Num Items: 512

Keep M in N
M: 1
N: 512
Initial offset: 0

Keep M in N
M: 1
N: 512
Initial offset: 511

QT GUI Time Sink
Number of Points: 200
Sample Rate: 100k
Autoscale: Yes

Add Const
Constant: -3k

Signal averager(with decimation)
Window size: 10

Add Const
Constant: 3k

Signal averager(with decimation)
Window size: 10

B.4 STFT (Goertzl Dynamic)
Sample rate: 100k
Delta T: 100m
Window size: 512
Number of bins: 32
Bound predecimation: 10

Null Sink
Vec Length: 32

Log10
n: 20
k: 0
Vec Length: 32

QT GUI Vector Sink
Vector Size: 32
X-Axis Start Value: -30m
X-Axis Step Value: 1.875m
X-Axis Label: norm...mp_rate]
Y-Axis Label: amplitude [dB]
X-Axis Units: samp_rate
Y-Axis Units: [dB]
Ref Level: 0

Vector to Stream
Num Items: 32

QT GUI Time Raster Sink
Sample Rate: 100k
Num. Rows: 100
Num. Cols: 32

Variable
ID: TWO_PI
Value: 6.282

Variable
ID: sensitivity
Value: 314.1k

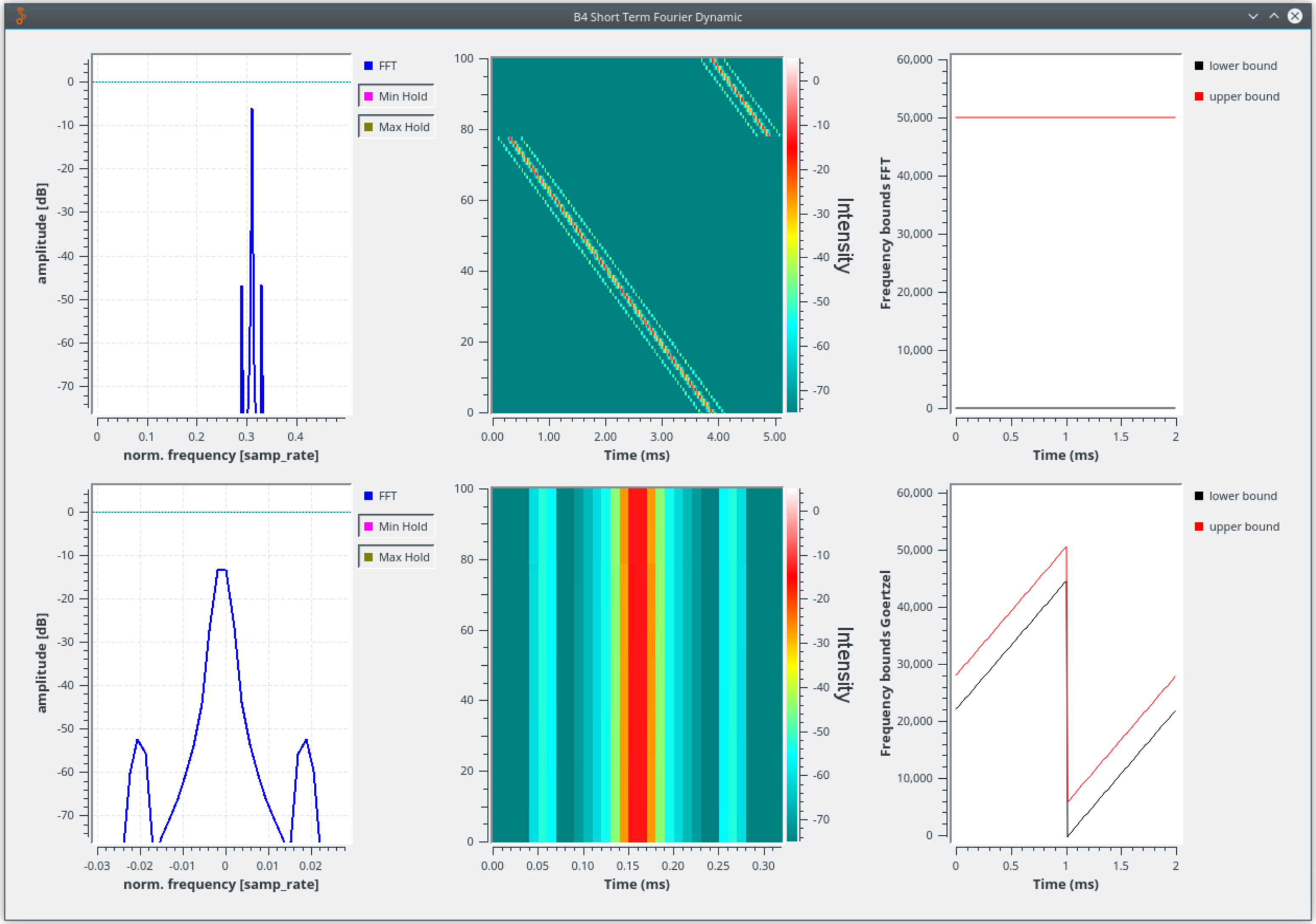
Vector to Stream
Num Items: 32

Keep M in N
M: 1
N: 32
Initial offset: 0

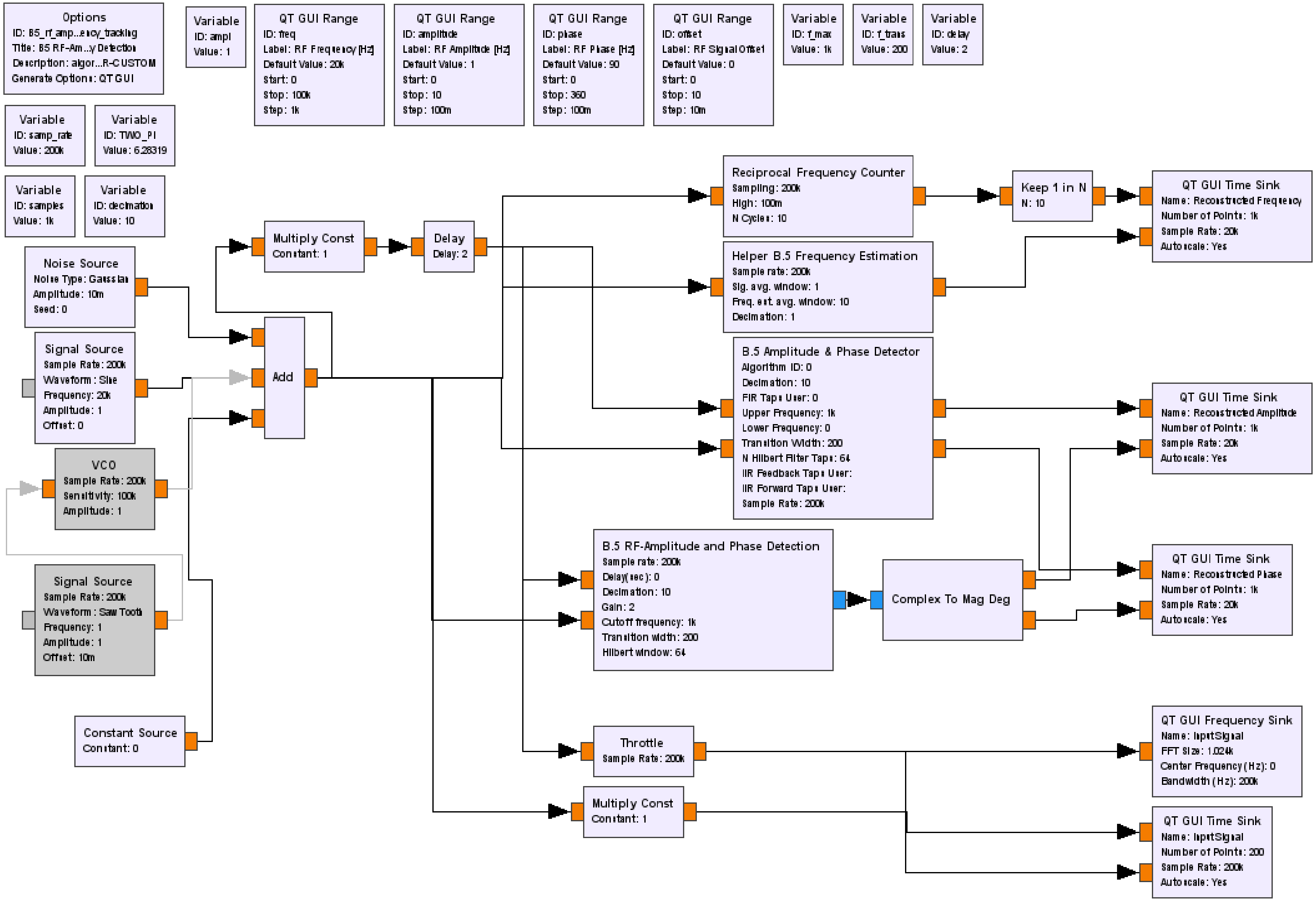
Keep M in N
M: 1
N: 32
Initial offset: 31

QT GUI Time Sink
Number of Points: 200
Sample Rate: 100k
Autoscale: Yes

Short-Term-FFT, Goertzel-Transform etc. Example II/II



RF-Amplitude, Phase, and Frequency Detection Example I/II



Options
ID: B5_rf_amp...ency_tracking
Title: B5 RF-Am...y Detection
Description: algor...R-CUSTOM
Generate Options: QT GUI

Variable
ID: ampl
Value: 1

QT GUI Range
ID: freq
Label: RF Frequency [Hz]
Default Value: 20k
Start: 0
Stop: 100k
Step: 1k

QT GUI Range
ID: amplitude
Label: RF Amplitude [Hz]
Default Value: 1
Start: 0
Stop: 10
Step: 100m

QT GUI Range
ID: phase
Label: RF Phase [Hz]
Default Value: 90
Start: 0
Stop: 360
Step: 100m

QT GUI Range
ID: offset
Label: RF Signal Offset
Default Value: 0
Start: 0
Stop: 10
Step: 10m

Variable
ID: f_max
Value: 1k

Variable
ID: f_trans
Value: 200

Variable
ID: delay
Value: 2

Variable
ID: samp_rate
Value: 200k

Variable
ID: TWO_PI
Value: 6.28319

Variable
ID: samples
Value: 1k

Variable
ID: decimation
Value: 10

Noise Source
Noise Type: Gaussian
Amplitude: 10m
Seed: 0

Signal Source
Sample Rate: 200k
Waveform: Sine
Frequency: 20k
Amplitude: 1
Offset: 0

VCO
Sample Rate: 200k
Sensitivity: 100k
Amplitude: 1

Signal Source
Sample Rate: 200k
Waveform: Saw Tooth
Frequency: 1
Amplitude: 1
Offset: 10m

Constant Source
Constant: 0

Add

Multiply Const
Constant: 1

Delay
Delay: 2

Reciprocal Frequency Counter
Sampling: 200k
High: 100m
N Cycles: 10

Keep 1 in N
N: 10

QT GUI Time Sink
Name: Reconstructed Frequency
Number of Points: 1k
Sample Rate: 20k
Autoscale: Yes

Helper B.5 Frequency Estimation
Sample rate: 200k
Sig. avg. window: 1
Freq. est. avg. window: 10
Decimation: 1

B.5 Amplitude & Phase Detector
Algorithm ID: 0
Decimation: 10
FIR Taps User: 0
Upper Frequency: 1k
Lower Frequency: 0
Transition Width: 200
N Hilbert Filter Taps: 64
IIR Feedback Taps User:
IIR Forward Taps User:
Sample Rate: 200k

QT GUI Time Sink
Name: Reconstructed Amplitude
Number of Points: 1k
Sample Rate: 20k
Autoscale: Yes

B.5 RF-Amplitude and Phase Detection
Sample rate: 200k
Delay(sec): 0
Decimation: 10
Gain: 2
Cutoff frequency: 1k
Transition width: 200
Hilbert window: 64

Complex To Mag Deg

QT GUI Time Sink
Name: Reconstructed Phase
Number of Points: 1k
Sample Rate: 20k
Autoscale: Yes

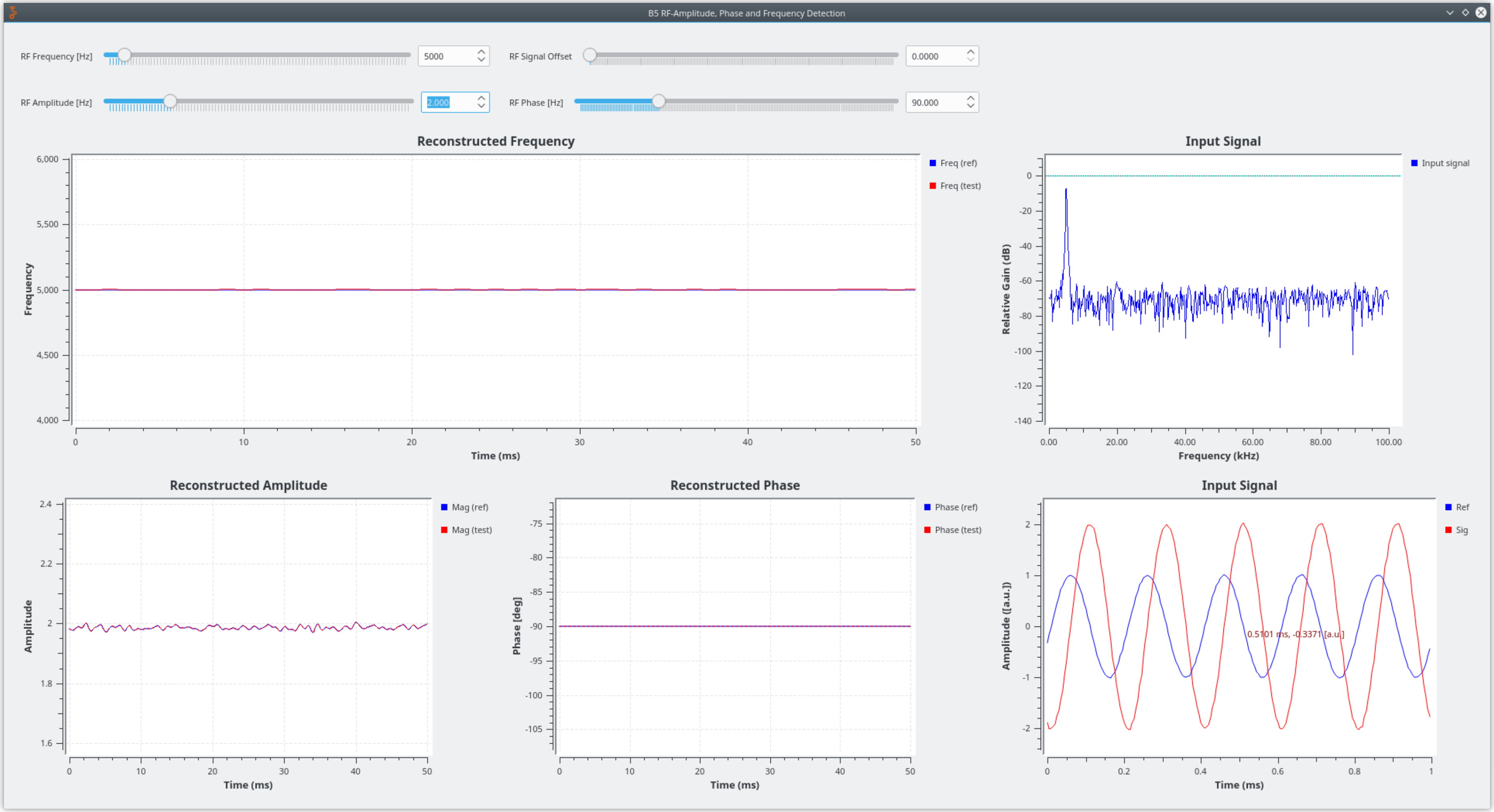
Throttle
Sample Rate: 200k

Multiply Const
Constant: 1

QT GUI Frequency Sink
Name: InputSignal
FFT Size: 1.024k
Center Frequency (Hz): 0
Bandwidth (Hz): 200k

QT GUI Time Sink
Name: InputSignal
Number of Points: 200
Sample Rate: 200k
Autoscale: Yes

RF-Amplitude, Phase, and Frequency Detection Example II/II



B5 RF-Amplitude, Phase and Frequency Detection

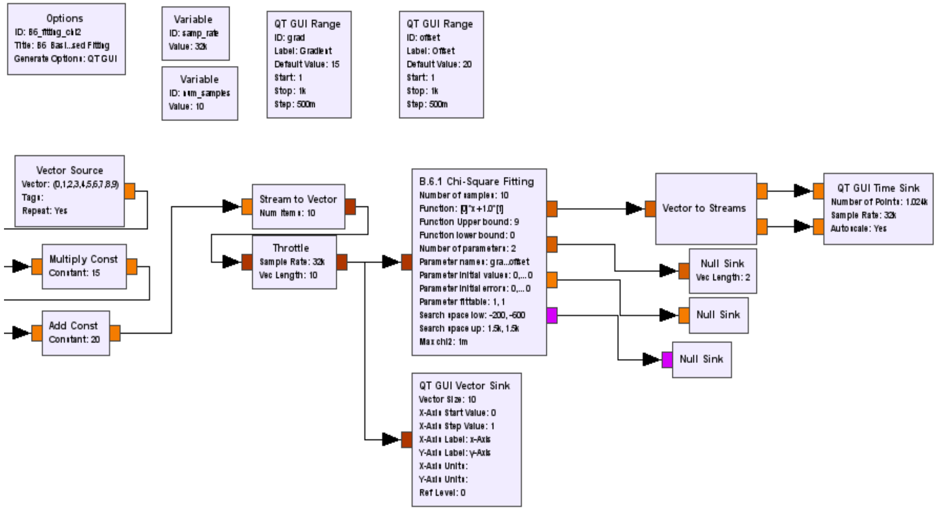
RF Frequency [Hz] 5000

RF Signal Offset 0.0000

RF Amplitude [Hz] 2.000

RF Phase [Hz] 90.000

Generic Chi-square based fitting Example



Options
ID: B6_fitting_chi2
Title: B6 Basi...sed Fitting
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 32k

Variable
ID: num_samples
Value: 10

QT GUI Range
ID: grad
Label: Gradient
Default Value: 15
Start: 1
Stop: 1k
Step: 500m

QT GUI Range
ID: offset
Label: Offset
Default Value: 20
Start: 1
Stop: 1k
Step: 500m

Vector Source
Vector: (0,1,2,3,4,5,6,7,8,9)
Tags:
Repeat: Yes

Multiply Const
Constant: 15

Add Const
Constant: 20

Stream to Vector
Num Items: 10

Throttle
Sample Rate: 32k
Vec Length: 10

B.6.1 Chi-Square Fitting
Number of samples: 10
Function: [0]*x+1.0*[1]
Function Upper bound: 9
Function lower bound: 0
Number of parameters: 2
Parameter names: gra...offset
Parameter initial values: 0,...0
Parameter initial errors: 0,...0
Parameter fittable: 1, 1
Search space low: -200, -600
Search space up: 1.5k, 1.5k
Max chi2: 1m

Vector to Streams

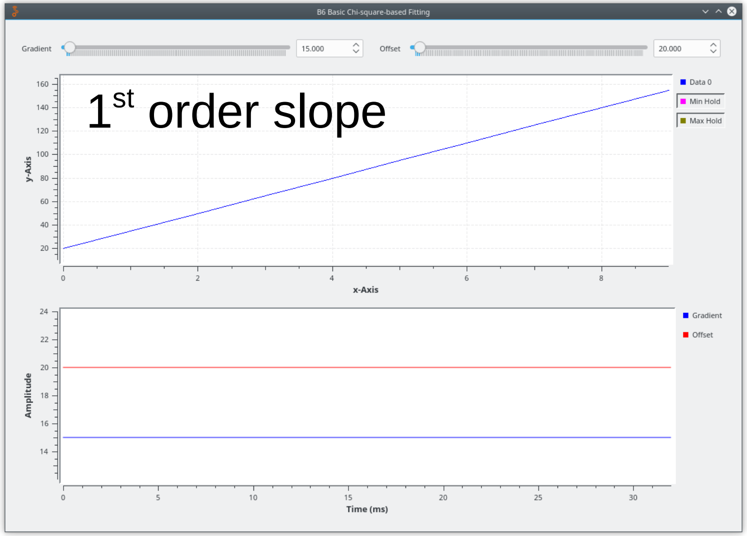
QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 32k
Autoscale: Yes

Null Sink
Vec Length: 2

Null Sink

Null Sink

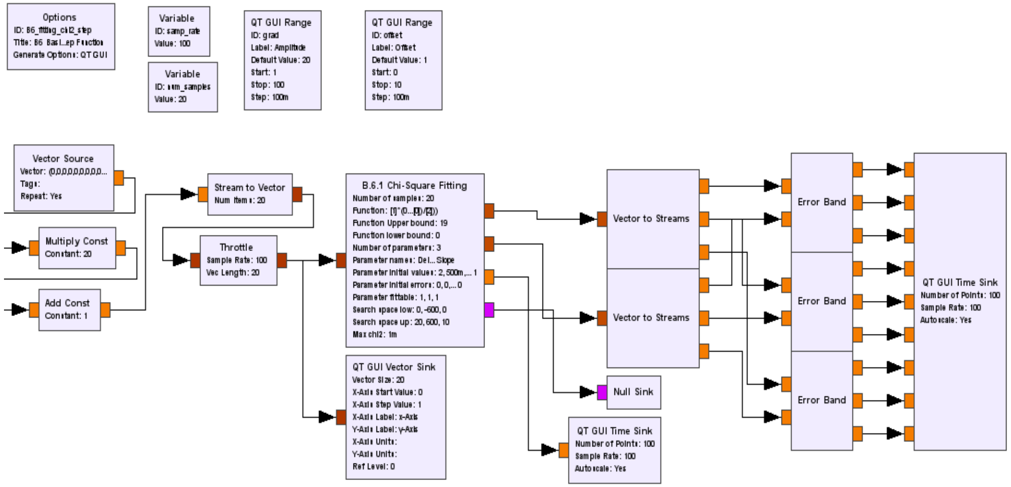
QT GUI Vector Sink
Vector Size: 10
X-Axis Start Value: 0
X-Axis Step Value: 1
X-Axis Label: x-Axis
Y-Axis Label: y-Axis
X-Axis Units:
Y-Axis Units:
Ref Level: 0



B6 Basic Chi-square-based Fitting

Gradient 15.000 Offset 20.000

1^{st} order slope



Options
ID: B6_fitting_chi2_step
Title: B6 Basi...ep Function
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 100

Variable
ID: num_samples
Value: 20

QT GUI Range
ID: grad
Label: Amplitude
Default Value: 20
Start: 1
Stop: 100
Step: 100m

QT GUI Range
ID: offset
Label: Offset
Default Value: 1
Start: 0
Stop: 10
Step: 100m

Vector Source
Vector: (0,0,0,0,0,0,0,0,0,0...
Tags:
Repeat: Yes

Multiply Const
Constant: 20

Add Const
Constant: 1

Stream to Vector
Num Items: 20

Throttle
Sample Rate: 100
Vec Length: 20

B.6.1 Chi-Square Fitting
Number of samples: 20
Function: [1]*(0...[0])/[2]))
Function Upper bound: 19
Function lower bound: 0
Number of parameters: 3
Parameter names: Del...Slope
Parameter initial values: 2, 500m,... 1
Parameter initial errors: 0, 0,... 0
Parameter fittable: 1, 1, 1
Search space low: 0, -600, 0
Search space up: 20, 600, 10
Max chi2: 1m

Vector to Streams

Vector to Streams

Error Band

Error Band

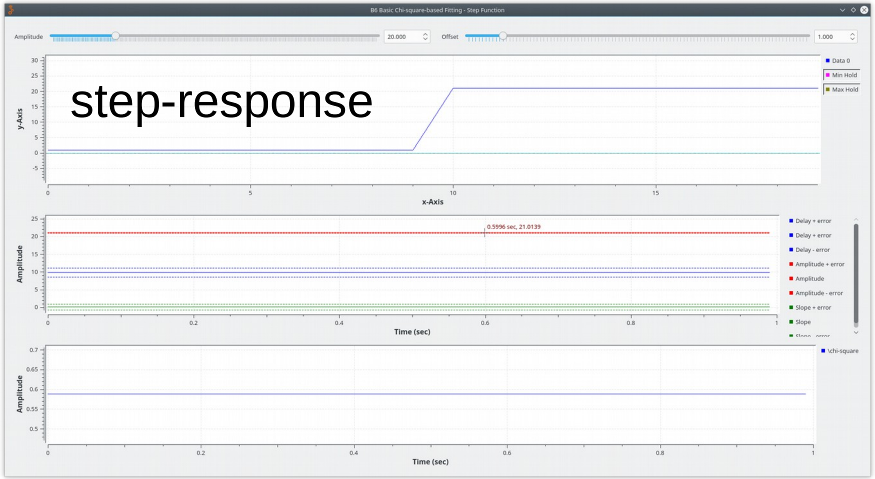
Error Band

QT GUI Time Sink
Number of Points: 100
Sample Rate: 100
Autoscale: Yes

Null Sink

QT GUI Time Sink
Number of Points: 100
Sample Rate: 100
Autoscale: Yes

QT GUI Vector Sink
Vector Size: 20
X-Axis Start Value: 0
X-Axis Step Value: 1
X-Axis Label: x-Axis
Y-Axis Label: y-Axis
X-Axis Units:
Y-Axis Units:
Ref Level: 0



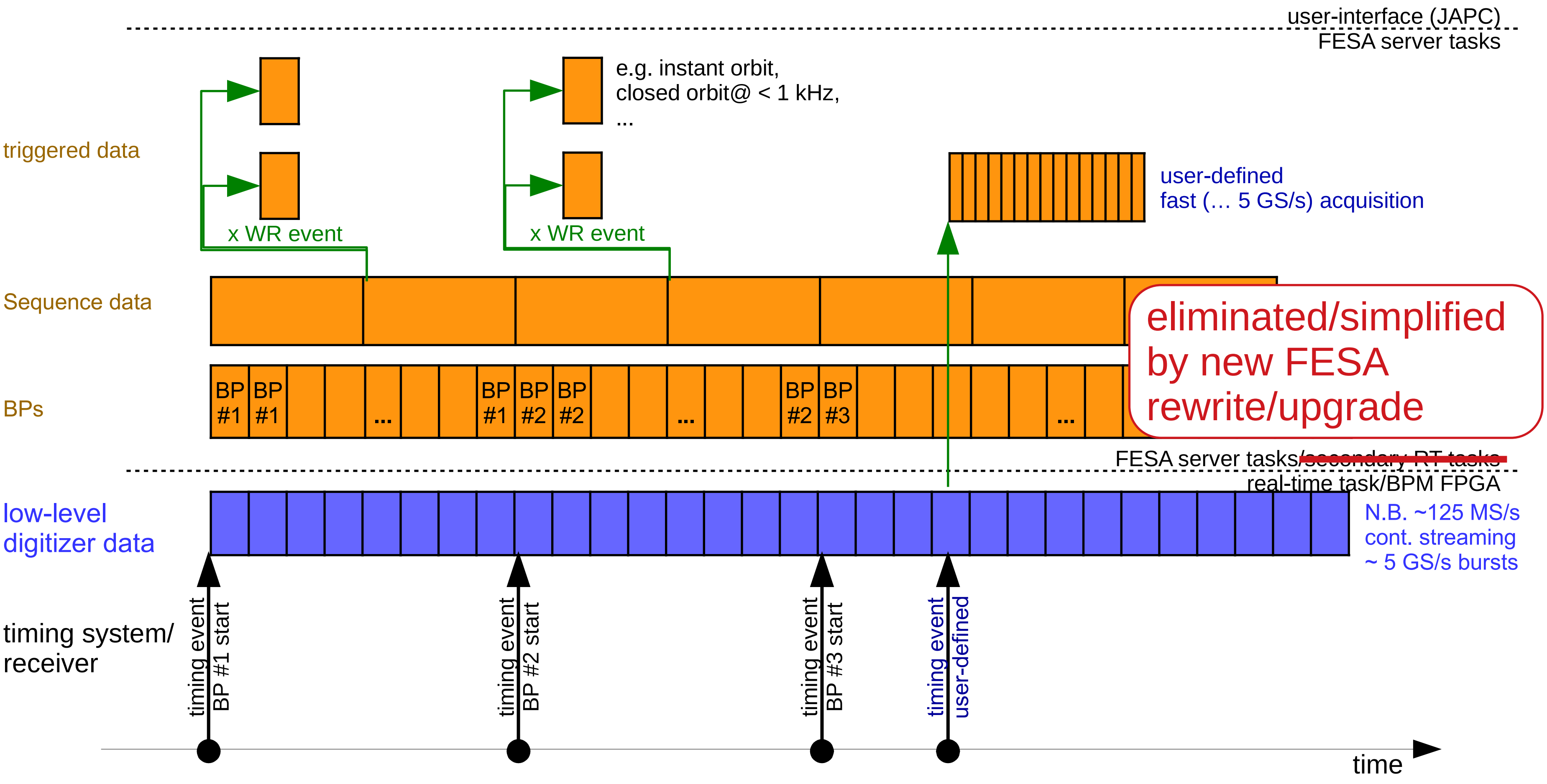
B6 Basic Chi-square-based Fitting - Step Function

Amplitude 20.000 Offset 1.000

step-response

Low-Level Acquisition Modes
A.1) Streaming-mode acquisition I/II

acquisition schematic:



user-interface (JAPC)

FESA server tasks

triggered data

e.g. instant orbit, closed orbit@ < 1 kHz, ...

x WR event

x WR event

user-defined fast (… 5 GS/s) acquisition

Sequence data

BPs

BP #1 | BP #1 | ... | BP #1 | BP #2 | BP #2 | ... | BP #2 | BP #3 | ...

eliminated/simplified by new FESA rewrite/upgrade

FESA server tasks/~~secondary RT tasks~~

real-time task/BPM FPGA

low-level digitizer data

N.B. ~125 MS/s cont. streaming ~ 5 GS/s bursts

timing system/ receiver

timing event BP #1 start

timing event BP #2 start

timing event BP #3 start

timing event user-defined

time

Generic Acquisitions I/II
Specified FESA Data Streams

Following modes of acquisition would be expected to be served simultaneously (though some of them could be implemented as down-sampled copies of the higher bandwidth acquisition):

A. Slow-acquisition (FESA property: ‘Acquisition’) – sub-choices (selected via CMW-filter):

1) **'Sequence'** acquisition between ‘beam injection’ and ‘beam extraction’: the specific signal averaged and decimated to the rate needed for the given client (e.g. 1 kHz).
   → *property notifies complete trace as a function of time at the end of the sequence (up to 30-60 s)*
2) **‘Continuous’** real-time data publication during the cycle (↔N.B long SIS100 cycles and/or storage rings):
   → *property notifies single measurement at typical update rate around 10-25 Hz*
   - use-case: user-level applications (inj./extr. steering), software-based real-time feedbacks, ...
3) **‘Instant’** signal acquisition: → *property notifies single measurement at pre-defined time delays (ms-scale)*
   - software interlock on injection/extraction orbit deviations (via MASP)

B. Fast block-mode acquisition (also ‘Acquisition’):

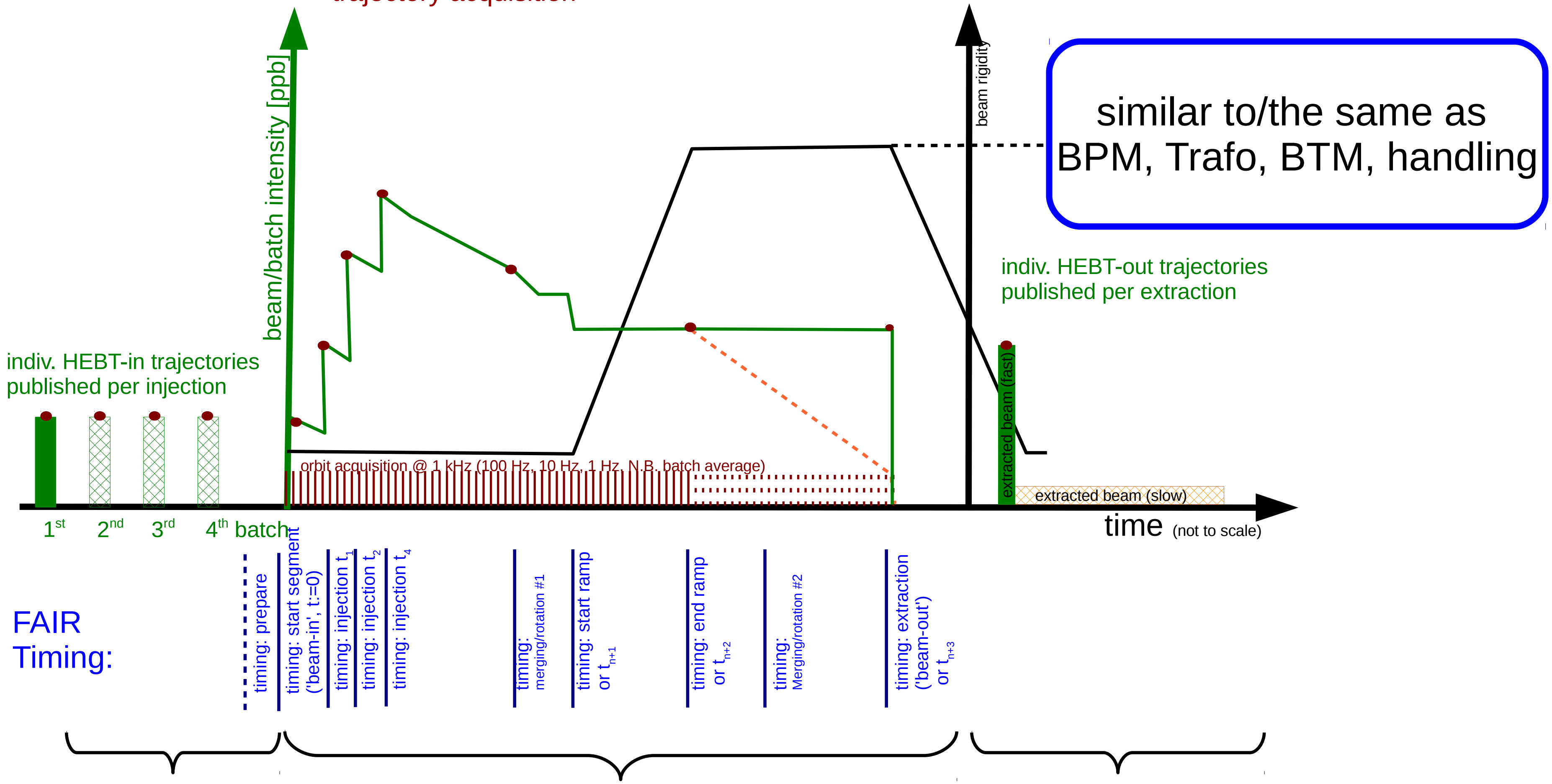
- up to 10 external user-defined timing triggers per sequence (ie. each injection, extraction etc.)
  - corresponding CMW property subscription: e.g. ‘TRIGGERED’ or name of specific timing event
- horizontal channel settings are assumed to be fixed per digitizer

C. Post-Mortem (FESA property 'PostMortem'): not finalized but provisionally:

1) first circular buffer storing each signals @ 1 kHz for the last second of beam or full cycle
2) second circular buffer storing the last 1k (10k?) turns at maximum sampling rate

Data Acquisition, Client Interfaces & Synchronisation

- trajectory acquisition



similar to/the same as BPM, Trafo, BTM, handling
beam/batch intensity [ppb]

indiv. HEBT-out trajectories published per extraction
indiv. HEBT-in trajectories published per injection
orbit acquisition @ 1 kHz (100 Hz, 10 Hz, 1 Hz, N.B. batch average)

timing: start segment ('beam-in', t:=0)

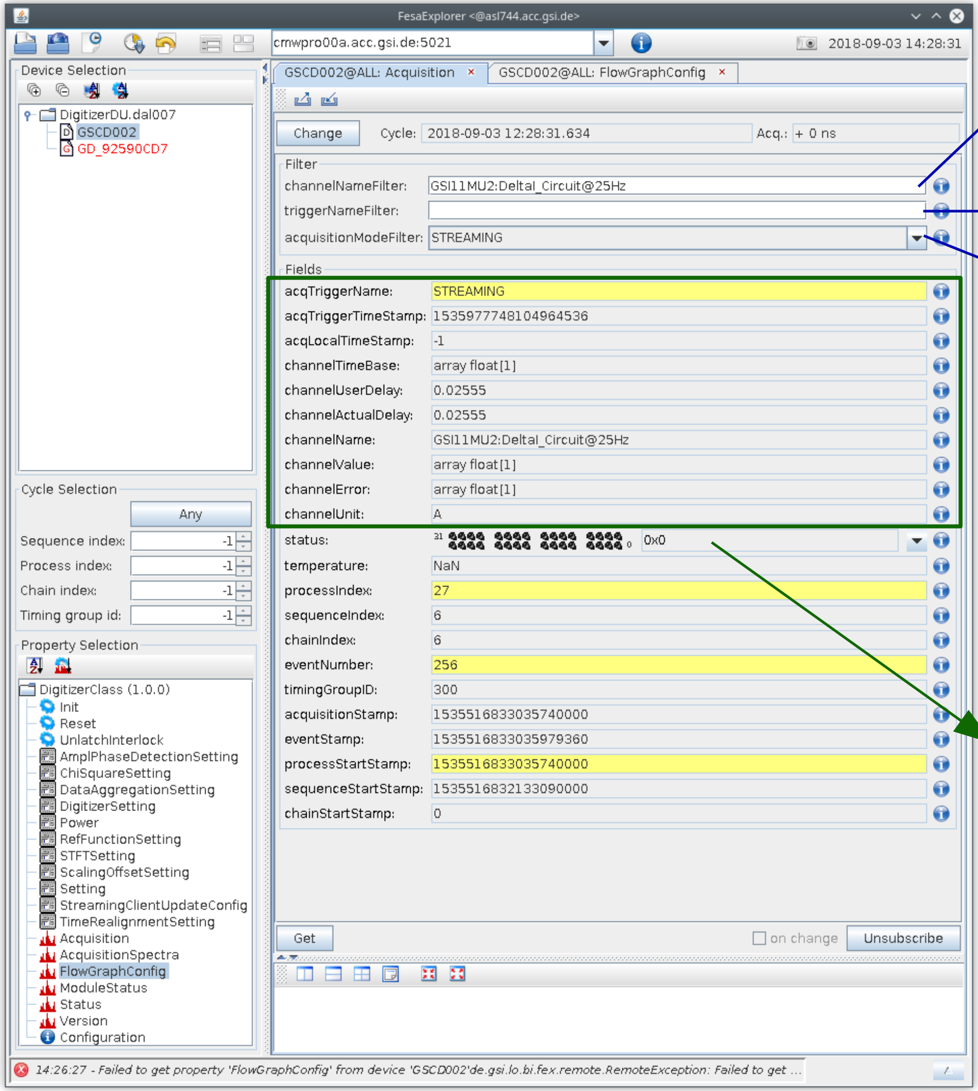
timing: merging/rotation #1
timing: start ramp or t_{n+1}
timing: end ramp or t_{n+2}
timing: Merging/rotation #2
timing: extraction ('beam-out') or t_{n+3}

transfer line 1
e.g. SIS18 → HEBT → SIS100
or: SIS18 → HEBT → ESR
or: ESR → HEBT → CRYRING

Circular Machine Cycle
e.g. SIS100, CR, HESR, CRYRING, SIS18, ESR

transfer line 2
e.g. SIS100 → HEBT → $\bar{p}$-target/CR
or. SIS100 → HEBT → CBM

FESA Acquisition(Sepctra) Property Layout



FesaExplorer <@asl744.acc.gsi.de>

cmwpro00a.acc.gsi.de:5021 — 2018-09-03 14:28:31

Device Selection
- DigitizerDU.dal007
  - GSCD002
  - GD_92590CD7

Cycle Selection: Any
Sequence index: -1
Process index: -1
Chain index: -1
Timing group id: -1

Property Selection
- DigitizerClass (1.0.0)
  - Init
  - Reset
  - UnlatchInterlock
  - AmplPhaseDetectionSetting
  - ChiSquareSetting
  - DataAggregationSetting
  - DigitizerSetting
  - Power
  - RefFunctionSetting
  - STFTSetting
  - ScalingOffsetSetting
  - Setting
  - StreamingClientUpdateConfig
  - TimeRealignmentSetting
  - Acquisition
  - AcquisitionSpectra
  - FlowGraphConfig
  - ModuleStatus
  - Status
  - Version
  - Configuration

GSCD002@ALL: Acquisition × | GSCD002@ALL: FlowGraphConfig ×

Change — Cycle: 2018-09-03 12:28:31.634 — Acq.: + 0 ns

Filter
- channelNameFilter: GSI11MU2:Deltal_Circuit@25Hz
- triggerNameFilter:
- acquisitionModeFilter: STREAMING

Fields
- acqTriggerName: STREAMING
- acqTriggerTimeStamp: 1535977748104964536
- acqLocalTimeStamp: -1
- channelTimeBase: array float[1]
- channelUserDelay: 0.02555
- channelActualDelay: 0.02555
- channelName: GSI11MU2:Deltal_Circuit@25Hz
- channelValue: array float[1]
- channelError: array float[1]
- channelUnit: A
- status: 0x0
- temperature: NaN
- processIndex: 27
- sequenceIndex: 6
- chainIndex: 6
- eventNumber: 256
- timingGroupID: 300
- acquisitionStamp: 1535516833035740000
- eventStamp: 1535516833035979360
- processStartStamp: 1535516833035740000
- sequenceStartStamp: 1535516832133090000
- chainStartStamp: 0

Get — □ on change — Unsubscribe

14:26:27 - Failed to get property 'FlowGraphConfig' from device 'GSCD002'de.gsi.lo.bi.fex.remote.RemoteException: Failed to get ...

signal name, e.g. '*GSI11MU2:I_Circuit@1kHz*'

WR event (optional), e.g. 'CMD_BEAM_INJECTION', '*CMD_BEAM_EXTRACTION*', '*CMD_START_ENERGY_RAMP*', '*CMD_CUSTOM_DIAG_[1,3]*'

acquisition mode:
- STREAMING
- FULL SEQUENCE
- SNAPSHOT
- POST_MORTEM
- TRIGGERED

user data:
- acqTriggerStamp (UTC-seconds of trigger/start)
- channelTimeBase (N.B. time stamps relative w.r.t. 1st injection)
- channel[Actual/User]Delay (↔ bunch-to-bucket-inj./group delay)
- channelName
- channelValue (N.B. array)
- channelError (N.B. array)
- channelUnit
- [..]

GUI in preparation

Digitisation of Analog Signals Next Steps

- Sub-categories:
  - a) time-domain: functional actual-vs-reference monitoring (DC – up to 2GHz) ✓
  - b) frequency-domain: SA- & VNA-type funct. Δf_{bw}≈20 MHz@fLO≈DC…6 GHz
  - c) video-signal (IPM, screens, etc.) → not covered ✓
    - existing BI technology/integration, main issue: budget/MC commitment
    - need interim solution for ‘alt-HKR’ retrofitting → personell resources needed
  - d) generic signals < 1 MHz bandwidth → also not covered (e.g. QPS, BI)
    - different strategy: local low-cost high-ADC-density controller, ...

< 30 MHz ↔ time-domain digitizer
> 30 MHz → proper SDR

- Frequency-domain covering Software-Defined-Radio (SDR)-like functionalities:
  - e.g. RF vector signal analyzer, RF network analyzer, RF signal generator, ...
    - DAQ of Rx-path is very similar to existing time-domain digitizers
      - N.B. often already existing GNU Radio integration + (tbd.) integration of White-Rabbit-Trigger/Synchronisation integration
    - Open-question:

      A)SDR hardware choice (next slide)

      B)Integration of Tx-path: signal/function types, triggering schemes

      C)Low-level RF feedback functionalities
      - probably requires (custom) FPGA modifications (functionality needed)

Software Defined Radio

Wikipedia: “[..] components that have been traditionally implemented in hardware (e.g. mixers, filters, amplifiers, modulators/demodulators, detectors, etc.) are instead implemented by means of software on a personal computer or embedded system. [..]”

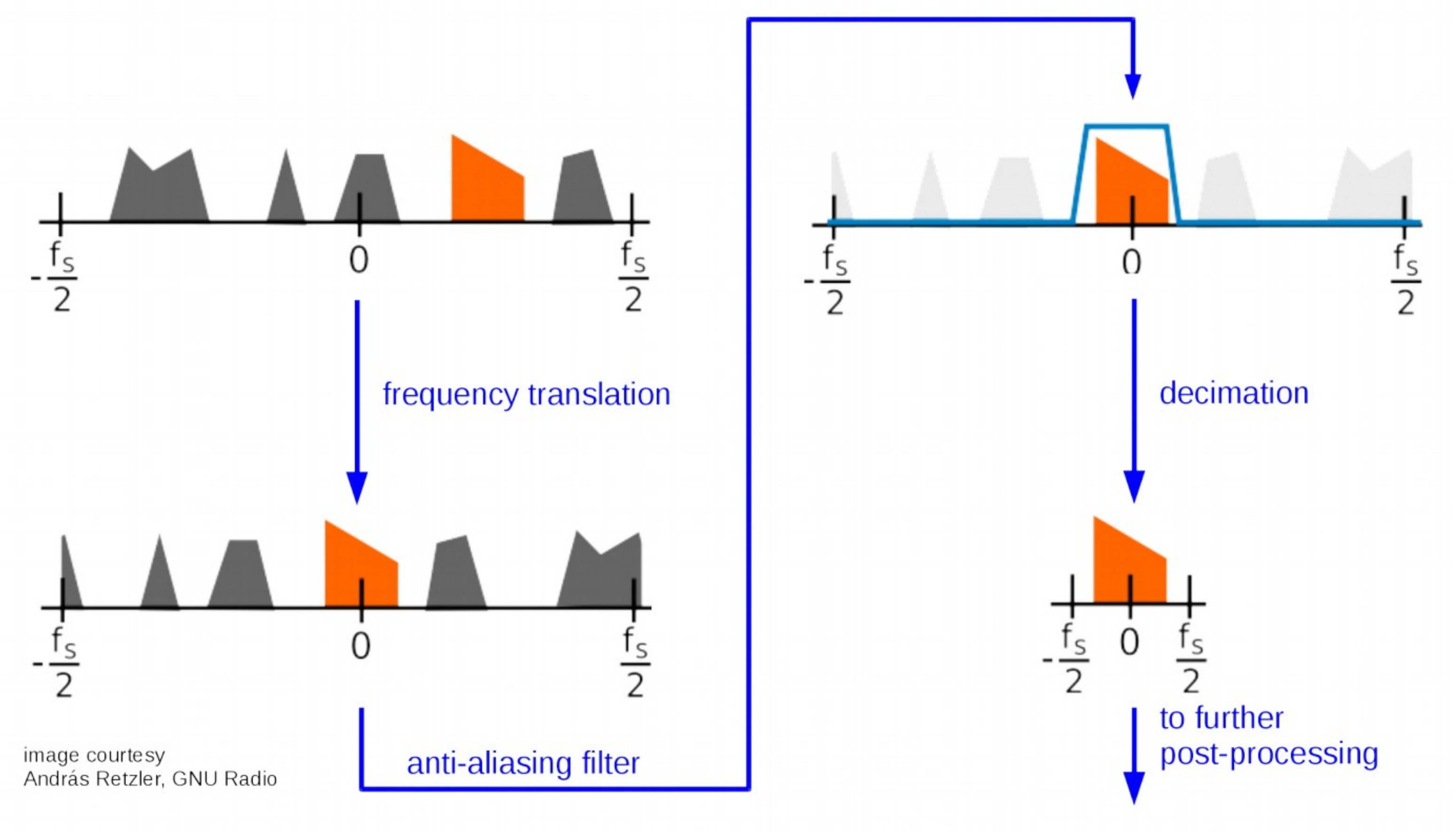
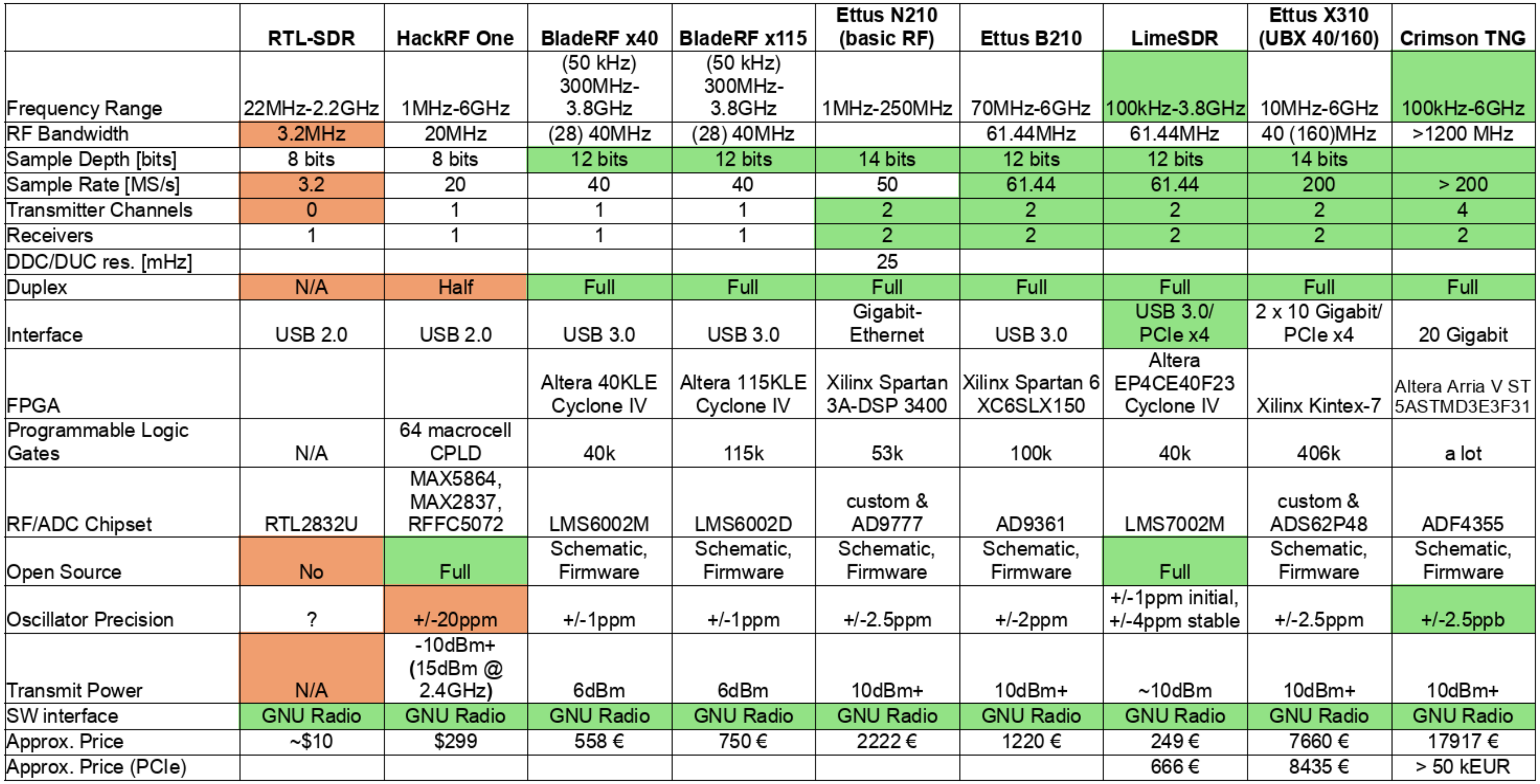


image courtesy
András Retzler, GNU Radio

Software-defined Radio
Hardware choices – Impressions

- wide range of academic, commercial, and military applications:
  - cellular radios (3G, 4G, 5G), (passive) radar systems, SIGINT, …
  - market at its infancy and will likely continue to grow significantly
- focused on commercial/open-source systems → easier integration (GNU Radio, less NDAs, …)

Software-defined Radio
Market Survey & Pre-Selection



	RTL-SDR	HackRF One	BladeRF x40	BladeRF x115	Ettus N210 (basic RF)	Ettus B210	LimeSDR	Ettus X310 (UBX 40/160)	Crimson TNG
Frequency Range	22MHz-2.2GHz	1MHz-6GHz	(50 kHz) 300MHz-3.8GHz	(50 kHz) 300MHz-3.8GHz	1MHz-250MHz	70MHz-6GHz	100kHz-3.8GHz	10MHz-6GHz	100kHz-6GHz
RF Bandwidth	3.2MHz	20MHz	(28) 40MHz	(28) 40MHz		61.44MHz	61.44MHz	40 (160)MHz	>1200 MHz
Sample Depth [bits]	8 bits	8 bits	12 bits	12 bits	14 bits	12 bits	12 bits	14 bits	
Sample Rate [MS/s]	3.2	20	40	40	50	61.44	61.44	200	> 200
Transmitter Channels	0	1	1	1	2	2	2	2	4
Receivers	1	1	1	1	2	2	2	2	2
DDC/DUC res. [mHz]					25				
Duplex	N/A	Half	Full	Full	Full	Full	Full	Full	Full
Interface	USB 2.0	USB 2.0	USB 3.0	USB 3.0	Gigabit-Ethernet	USB 3.0	USB 3.0/ PCIe x4	2 x 10 Gigabit/ PCIe x4	20 Gigabit
FPGA			Altera 40KLE Cyclone IV	Altera 115KLE Cyclone IV	Xilinx Spartan 3A-DSP 3400	Xilinx Spartan 6 XC6SLX150	Altera EP4CE40F23 Cyclone IV	Xilinx Kintex-7	Altera Arria V ST 5ASTMD3E3F31
Programmable Logic Gates	N/A	64 macrocell CPLD	40k	115k	53k	100k	40k	406k	a lot
RF/ADC Chipset	RTL2832U	MAX5864, MAX2837, RFFC5072	LMS6002M	LMS6002D	custom & AD9777	AD9361	LMS7002M	custom & ADS62P48	ADF4355
Open Source	No	Full	Schematic, Firmware	Schematic, Firmware	Schematic, Firmware	Schematic, Firmware	Full	Schematic, Firmware	Schematic, Firmware
Oscillator Precision	?	+/-20ppm	+/-1ppm	+/-1ppm	+/-2.5ppm	+/-2ppm	+/-1ppm initial, +/-4ppm stable	+/-2.5ppm	+/-2.5ppb
Transmit Power	N/A	-10dBm+ (15dBm @ 2.4GHz)	6dBm	6dBm	10dBm+	10dBm+	~10dBm	10dBm+	10dBm+
SW interface	GNU Radio	GNU Radio	GNU Radio	GNU Radio	GNU Radio	GNU Radio	GNU Radio	GNU Radio	GNU Radio
Approx. Price	~$10	$299	558 €	750 €	2222 €	1220 €	249 €	7660 €	17917 €
Approx. Price (PCIe)							666 €	8435 €	> 50 kEUR

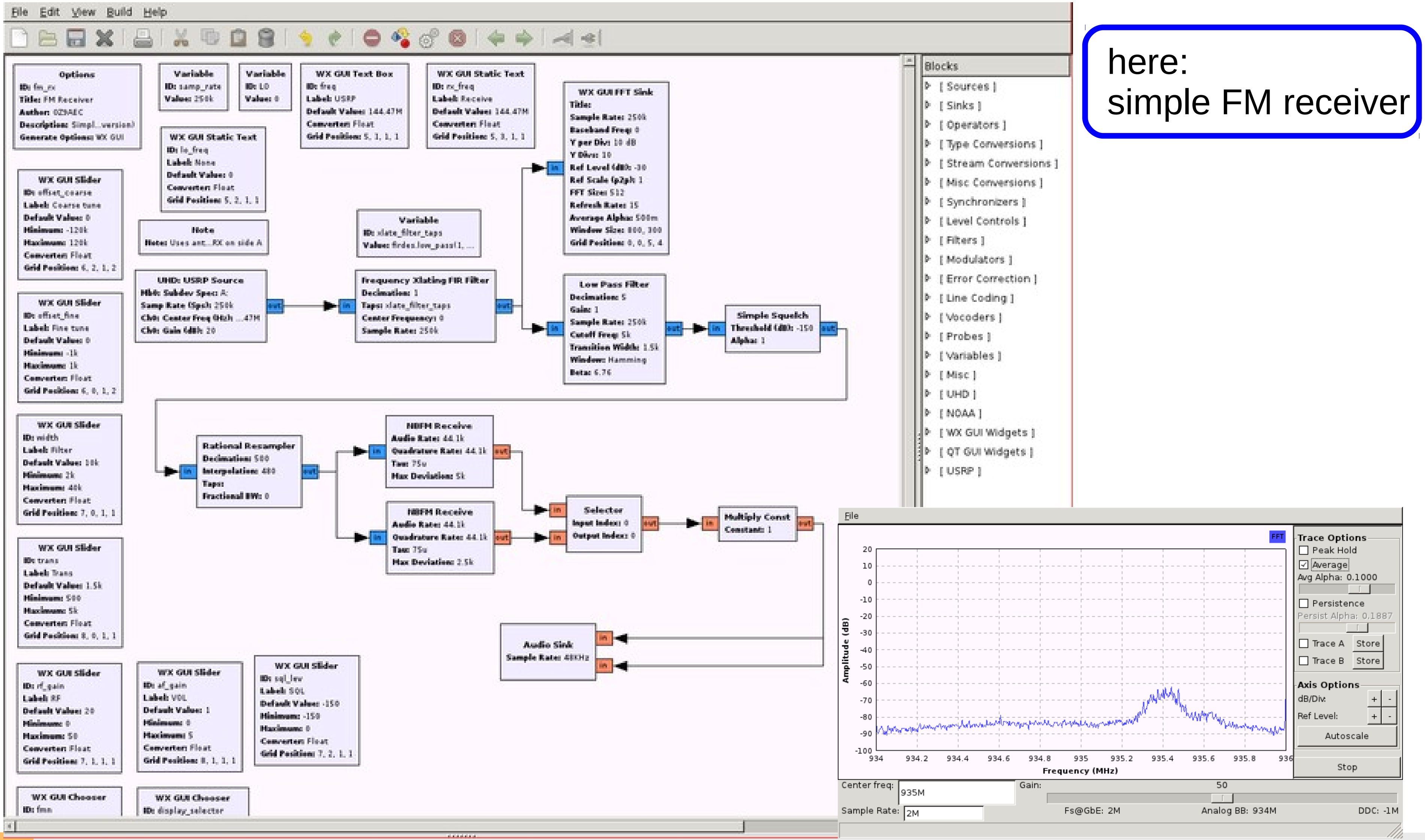
N.B. 61.44 MS/s
↔ USB 3.0 limit
50 MS/S ↔
1 Gigabit link

low-end

high-end

Most SDRs already integrated in GNU-Radio (via UHD)

N.B. still requires WR event/synchronisation (via GPIO? Rx?)



here:
simple FM receiver

Options
ID: fm_rx
Title: FM Receiver
Author: 0Z9AEC
Description: Simpl...version)
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 250k

Variable
ID: LO
Value: 0

WX GUI Text Box
ID: freq
Label: USRP
Default Value: 144.47M
Converter: Float
Grid Position: 5, 1, 1, 1

WX GUI Static Text
ID: rx_freq
Label: Receive
Default Value: 144.47M
Converter: Float
Grid Position: 5, 3, 1, 1

WX GUI Static Text
ID: lo_freq
Label: None
Default Value: 0
Converter: Float
Grid Position: 5, 2, 1, 1

WX GUI FFT Sink
Title:
Sample Rate: 250k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): -30
Ref Scale (p2p): 1
FFT Size: 512
Refresh Rate: 15
Average Alpha: 500m
Window Size: 800, 300
Grid Position: 0, 0, 5, 4

WX GUI Slider
ID: offset_coarse
Label: Coarse tune
Default Value: 0
Minimum: -120k
Maximum: 120k
Converter: Float
Grid Position: 6, 2, 1, 2

Note
Note: Uses ant...RX on side A

Variable
ID: xlate_filter_taps
Value: firdes.low_pass(1, ...

UHD: USRP Source
Mb0: Subdev Spec: A:
Samp Rate (Sps): 250k
Ch0: Center Freq (Hz): ...47M
Ch0: Gain (dB): 20

Frequency Xlating FIR Filter
Decimation: 1
Taps: xlate_filter_taps
Center Frequency: 0
Sample Rate: 250k

Low Pass Filter
Decimation: 5
Gain: 1
Sample Rate: 250k
Cutoff Freq: 5k
Transition Width: 1.5k
Window: Hamming
Beta: 6.76

Simple Squelch
Threshold (dB): -150
Alpha: 1

WX GUI Slider
ID: offset_fine
Label: Fine tune
Default Value: 0
Minimum: -1k
Maximum: 1k
Converter: Float
Grid Position: 6, 0, 1, 2

WX GUI Slider
ID: width
Label: Filter
Default Value: 10k
Minimum: 2k
Maximum: 40k
Converter: Float
Grid Position: 7, 0, 1, 1

Rational Resampler
Decimation: 500
Interpolation: 480
Taps:
Fractional BW: 0

NBFM Receive
Audio Rate: 44.1k
Quadrature Rate: 44.1k
Tau: 75u
Max Deviation: 5k

NBFM Receive
Audio Rate: 44.1k
Quadrature Rate: 44.1k
Tau: 75u
Max Deviation: 2.5k

Selector
Input Index: 0
Output Index: 0

Multiply Const
Constant: 1

WX GUI Slider
ID: trans
Label: Trans
Default Value: 1.5k
Minimum: 500
Maximum: 5k
Converter: Float
Grid Position: 8, 0, 1, 1

Audio Sink
Sample Rate: 48KHz

WX GUI Slider
ID: rf_gain
Label: RF
Default Value: 20
Minimum: 0
Maximum: 50
Converter: Float
Grid Position: 7, 1, 1, 1

WX GUI Slider
ID: af_gain
Label: VOL
Default Value: 1
Minimum: 0
Maximum: 5
Converter: Float
Grid Position: 8, 1, 1, 1

WX GUI Slider
ID: sql_lev
Label: SQL
Default Value: -150
Minimum: -150
Maximum: 0
Converter: Float
Grid Position: 7, 2, 1, 1

WX GUI Chooser
ID: fmn

WX GUI Chooser
ID: display_selector

Trace Options
☐ Peak Hold
☑ Average
Avg Alpha: 0.1000
☐ Persistence
Persist Alpha: 0.1887
☐ Trace A Store
☐ Trace B Store

Axis Options
dB/Div: + -
Ref Level: + -
Autoscale

Stop

Center freq: 935M
Sample Rate: 2M
Gain: 50
Fs@GbE: 2M
Analog BB: 934M
DDC: -1M

Known/possible SDR Applications@FAIR

- SIS18/SIS100 K.O. exciter monitoring/signal generation:
  - broad-band signal surveillance (+ time-domain digitizer)
  - flexible spectrum & time dependencies for excitation
  - option: fast(er) spill-extraction FB?

- Generic accelerator-related diagnostics
  - Long. Schottky: momentum width, energy mismatch, intensity, ...
  - trans. Schottky: Q/Q’, emittances, … ??
  - experiments: use-cases see V. Sanjari’s presentation

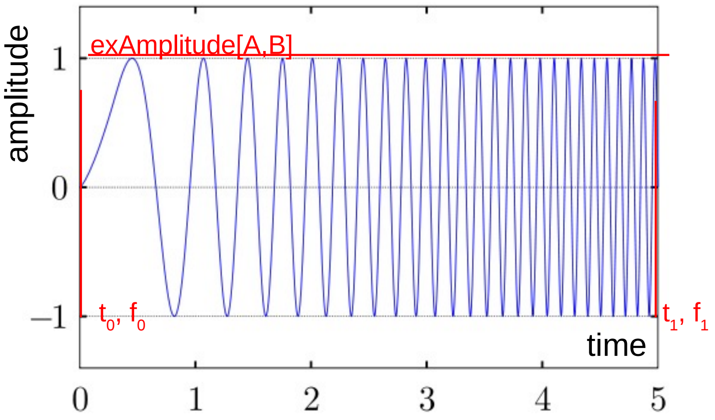
- RF leakage monitoring/EMC compliance for UNILAC RF driver (pLinac?) ??
  - N.B. 36.136 MHz ↔ (civ/mil: BOS, micros, ...)
  - N.B. 108.408 MHz ↔(civ/mil: aviation, navigation, ...)

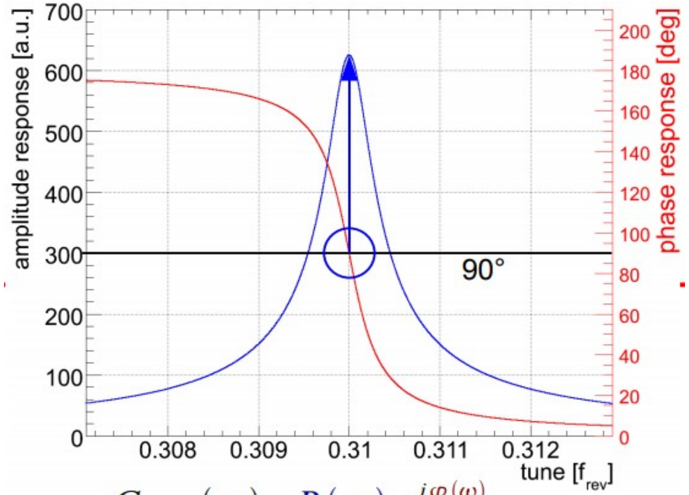
- Low-Level RF (reuse same HW/SW platform)?
  - second-/third-order harmonic measurements

- <you application here> – it’s a generic CO platform that can be further expanded:
  - under the responsibility of CO:
    - Digitizer (SDR) HW integration
    - HW abstraction/driver-integration (GNU Radio)
    - basic signal post-processing & FESA export
  - Under the user responsibility
    - RF analog input adaptation & cabling (ie. AFE, analog front-end)
    - non-standard signal post-processing, i.e. custom FPGA processing/modifications

Integration of Tx-path I/II
– excitation types (+ WR triggered → needs proof-of-concept)

- No excitation/white or remnant noise
- Kick/frequency sweep aka. ‘chirp’
  - enableExcitationTx-[A,B]
  - exAmplitude[A,B]
  - chirpStartDelay t_0, chirpStopDelay t_1
  - chirpStartFreq[A,B] f_0, chirpStopFreq[A,B] f_1
  - + all the above as function of time in cycle/BPC sequence
- Phase-Locked-Loop (PLL) System
  - Similar to chirp but on slower time-scales
  - Beam-Transfer-Function (BTF)
- Bandwidth-limited/shaped white-noise
  - Uniform, Gaussian,Laplacian, Impulse, inverted-Gaussian, ...
  - + all the above as function of time in cycle/BPC sequence





$$G_{Beam}(\omega)=R(\omega)\cdot e^{i\varphi(\omega)}$$

Integration of Tx-path II/II
– excitation types (+ WR triggered → needs proof-of-concept)

- Deterministic signal source
  - sine, square, triangle, saw-tooth, sin(x)/x, gaussian, half-sine

- Arbitrary Waveform Generator (SDR can operate as DDS generator)
  - options are limitless but ressources to implement these are finite → need to prioritise

- External Rx-driven output relation (ie. FB-loop, required FPGA mod)
  - simple PID +simple Smith-Predictor for 1st/2nd-order latency compensation

- Misc:
  - ADC/DAC clockSource = external vs. internal oscillator
  - FirDecimationValue, ...
  - external gating???

Digitizer Status Summary & SDR Open Questions

- FAIR Control Centre (FCC): ‘fully-digitial’ control paradigm
  - pre-requisite prior to ‘alt-HKR’ to FCC move
  - automatic monitoring, performance tracking & early fault detection
  - assisted isolation of HW faults (‘ref-actual’-monitoring) & remote expert diagnostics (as needed)

- Primary goals of digitizer integration:
  1. generic abstraction of the vendor-specific digitizer software interfaces (via GNU Radio) ✓
  2. limited range of generic user-configurable data post-processing on the acquired data ✓
  3. control system integration by providing standardised FESA interfaces ongoing..

- Sub-categories:
  a) time-domain: functional actual-vs-reference monitoring (DC – up to 2GHz) ✓
  b) frequency-domain: SA- & VNA-type funct. $\Delta f_{bw}\approx$20 MHz@$f_{LO}\approx$DC…6 GHz
     < 30 MHz ↔ time-domain digitizer
     > 30 MHz → proper SDR
  c) video-signal (IPM, screens, etc.) → not covered (existing BI technology/integration) ✓

- Open-question regarding frequency-domain digitization via Software-Defined-Radios (SDRs):
  1. SDR hardware choice → cross-check favoured candiates
  2. Integration of Tx-path: signal/function types, triggering schemes
     - to be demonstrated: integration of White-Rabbit-Trigger/Synchronisation integration (via GPIO?)
  3. Low-level RF feedback functionalities → … an option to be followed-up?

Appendix

Final Vendor/Model Selection PicoScopes from Pico Technology

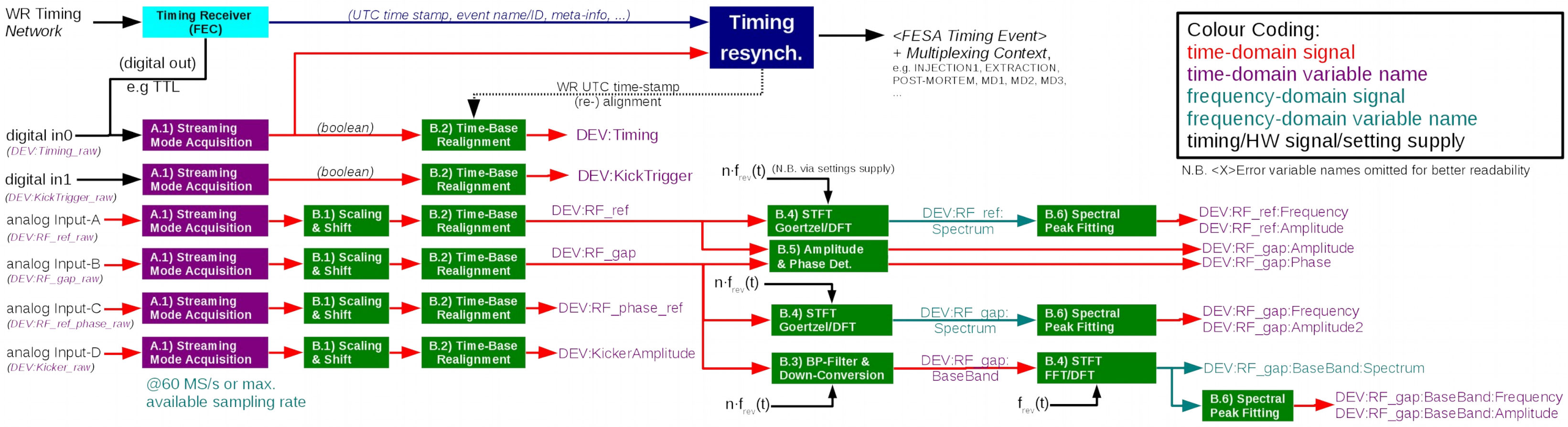
- Low-Bandwidths (< 20 MHz)
  - PicoScope 4824, 7 (8) channels, 11.3 ENOB @ 20 MHz)
    - N.B. ~ 16 ENOB @ 10 kHz ($\Delta I/I_{max} \sim 10^{-5}$)
  - 2018: primarily used for EPC-related systems (→ 2018: “AEG”)
    - planned to digitize: I_{ref}, U_{ref}, I_{actual}, U_{actual}, ΔI, U_{int}, + 1 spare
    - 8th channel for WR timing synchronisation

- Medium-range Bandwidths (< 200 MHz)
  - PicoScope 3403D MSO ↔ 3406D MSO), 4 ch, 6.9 ENOB @ 200 MHz
    - N.B. ~ 7.9 (15) ENOB @ 10 MHz (10 kHz) ($\Delta U/U_{max} \sim 10^{-3}$ ($3 \cdot 10^{-5}$))
  - 15 (16) digital channels → triggering e.g. on fast RF loops states, etc.
  - 2018: primarily for Ring-RF (→ “Gap Voltage”) and HV-extraction kicker trigger acquisition

- High-Bandwidth (< 500 MHz, (1 GHz))
  - PicoScope 6402C↔ 6404C, 4 channel, 7.3 (7.9) ENOB @ 500 (200) MHz
  - 2018: primarily used for HV extraction and tune kicker waveform
- Open: specification for further digitizer devices
  - tentatively: Ettus Research SDR for spectra-related applications

N.B. Ordered/deploy 150+ digitizer for 2018/19 for SIS1/ESR/Cryring

Signal Flow-Graph → SAT I/II



WR Timing Network

Timing Receiver (FEC)

(UTC time stamp, event name/ID, meta-info, ...)

Timing resynch.

<FESA Timing Event>
+ Multiplexing Context,
e.g. INJECTION1, EXTRACTION, POST-MORTEM, MD1, MD2, MD3, ...

(digital out)
e.g TTL

WR UTC time-stamp (re-) alignment

Colour Coding:
time-domain signal
time-domain variable name
frequency-domain signal
frequency-domain variable name
timing/HW signal/setting supply

N.B. <X>Error variable names omitted for better readability

digital in0 (DEV:Timing_raw) → A.1) Streaming Mode Acquisition → (boolean) → B.2) Time-Base Realignment → DEV:Timing

digital in1 (DEV:KickTrigger_raw) → A.1) Streaming Mode Acquisition → (boolean) → B.2) Time-Base Realignment → DEV:KickTrigger

analog Input-A (DEV:RF_ref_raw) → A.1) Streaming Mode Acquisition → B.1) Scaling & Shift → B.2) Time-Base Realignment → DEV:RF_ref

analog Input-B (DEV:RF_gap_raw) → A.1) Streaming Mode Acquisition → B.1) Scaling & Shift → B.2) Time-Base Realignment → DEV:RF_gap

analog Input-C (DEV:RF_ref_phase_raw) → A.1) Streaming Mode Acquisition → B.1) Scaling & Shift → B.2) Time-Base Realignment → DEV:RF_phase_ref

analog Input-D (DEV:Kicker_raw) → A.1) Streaming Mode Acquisition → B.1) Scaling & Shift → B.2) Time-Base Realignment → DEV:KickerAmplitude

@60 MS/s or max.
available sampling rate

n·f_rev(t) (N.B. via settings supply)

B.4) STFT Goertzel/DFT → DEV:RF_ref: Spectrum → B.6) Spectral Peak Fitting → DEV:RF_ref:Frequency, DEV:RF_ref:Amplitude

B.5) Amplitude & Phase Det. → DEV:RF_gap:Amplitude, DEV:RF_gap:Phase

n·f_rev(t)

B.4) STFT Goertzel/DFT → DEV:RF_gap: Spectrum → B.6) Spectral Peak Fitting → DEV:RF_gap:Frequency, DEV:RF_gap:Amplitude2

B.3) BP-Filter & Down-Conversion → DEV:RF_gap: BaseBand → B.4) STFT FFT/DFT → DEV:RF_gap:BaseBand:Spectrum

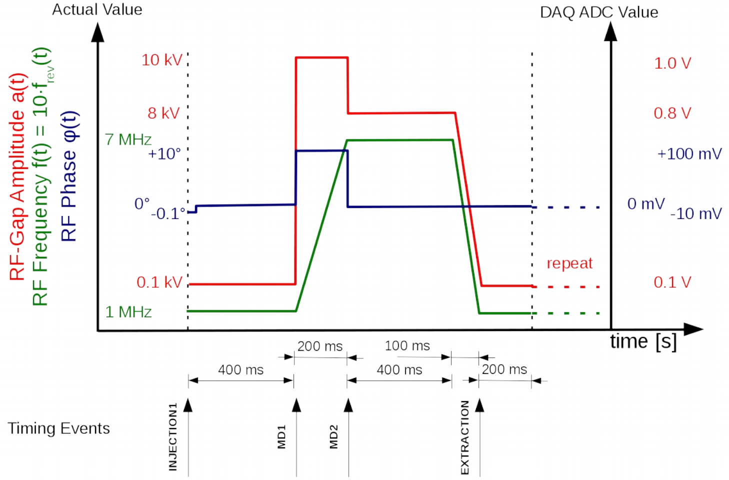
n·f_rev(t)

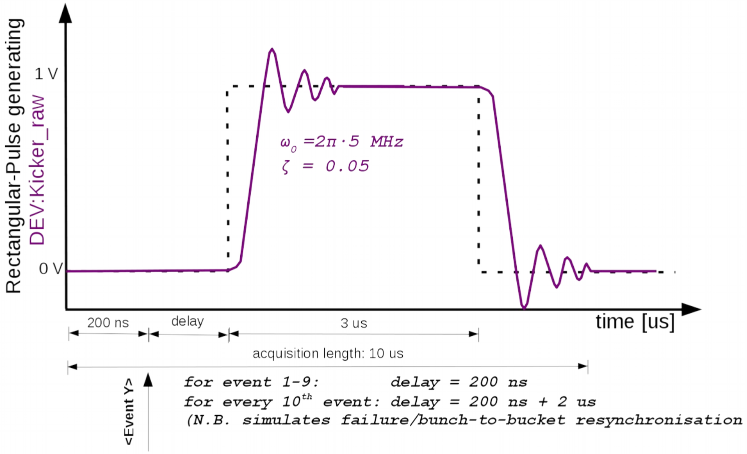
f_rev(t)

B.6) Spectral Peak Fitting → DEV:RF_gap:BaseBand:Frequency, DEV:RF_gap:BaseBand:Amplitude

Test Signal Definition:

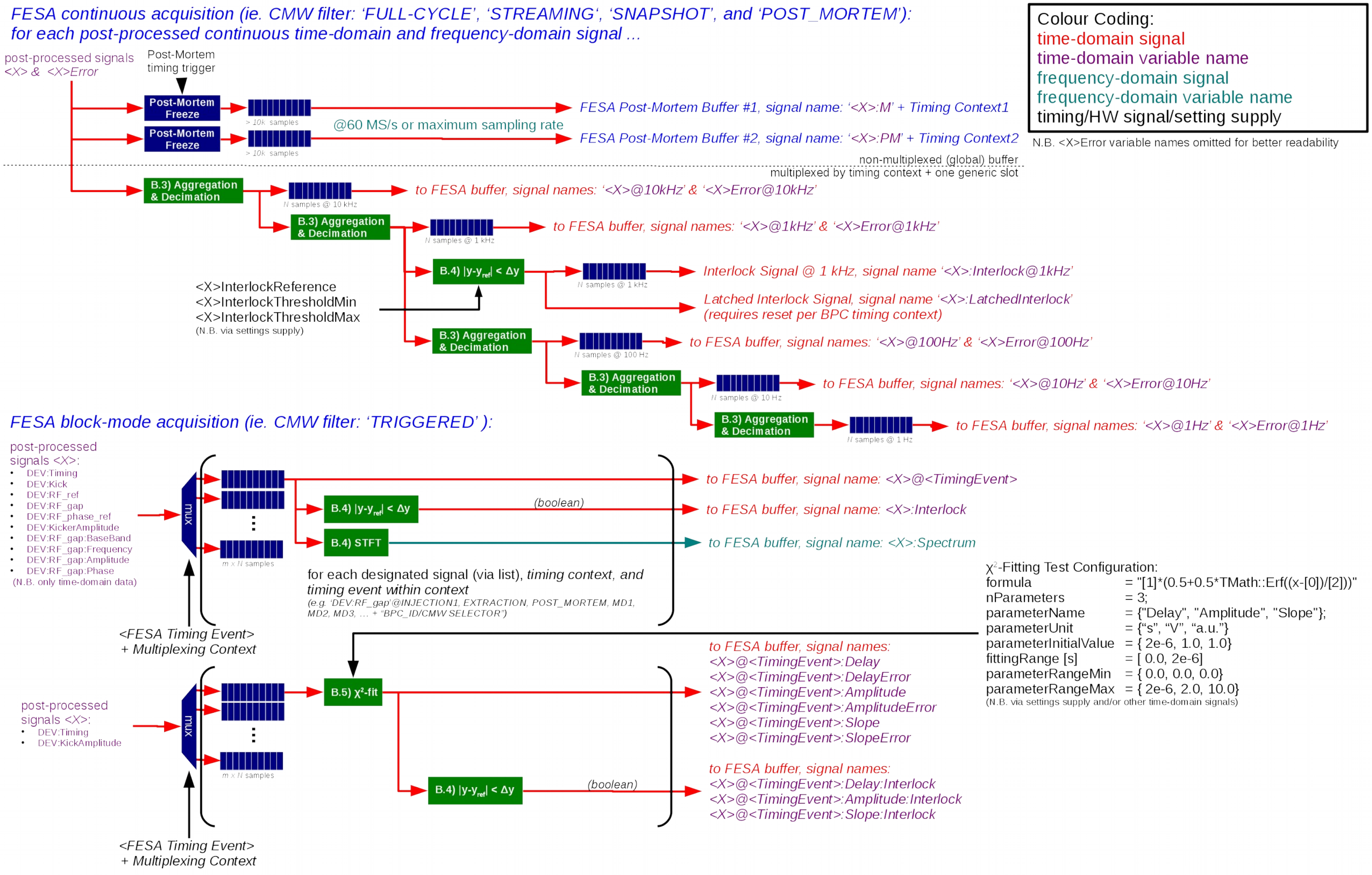
```
Analog Input-A: DEV:RF_ref_raw (t)       =  '1 V'·sin(2π·[f(t) + φ(t)]) + '1% noise'
Analog Input-B: DEV:RF_gap_raw (t)       =  a(t)·sin(2π·[f(t) + φ(t)]) + '1% noise'
Analog Input-C: DEV:RF_ref_phase (t)     =  φ(t) + '1% noise'
Analog Input-D: DEV:Kicker_raw (t)       =  2nd-orderIIR(Rectangular-Pulse(t-t_event, <parameter see below>), ω_0=2π·5 MHz, ζ= 0.05)+ '2% noise'
```





```
for event 1-9:         delay = 200 ns
for every 10th event:  delay = 200 ns + 2 us
(N.B. simulates failure/bunch-to-bucket resynchronisation
```

Signal Flow-Graph → SAT II/II



FESA continuous acquisition (ie. CMW filter: ‘FULL-CYCLE’, ‘STREAMING‘, ‘SNAPSHOT’, and ‘POST_MORTEM’):
for each post-processed continuous time-domain and frequency-domain signal …

Colour Coding:
time-domain signal
time-domain variable name
frequency-domain signal
frequency-domain variable name
timing/HW signal/setting supply

N.B. <X>Error variable names omitted for better readability

post-processed signals
<X> & <X>Error
Post-Mortem
timing trigger
Post-Mortem Freeze
> 10k samples
FESA Post-Mortem Buffer #1, signal name: ‘<X>:M’ + Timing Context1
@60 MS/s or maximum sampling rate
Post-Mortem Freeze
> 10k samples
FESA Post-Mortem Buffer #2, signal name: ‘<X>:PM’ + Timing Context2
non-multiplexed (global) buffer
multiplexed by timing context + one generic slot
B.3) Aggregation & Decimation
N samples @ 10 kHz
to FESA buffer, signal names: ‘<X>@10kHz’ & ‘<X>Error@10kHz’
B.3) Aggregation & Decimation
N samples @ 1 kHz
to FESA buffer, signal names: ‘<X>@1kHz’ & ‘<X>Error@1kHz’
B.4) |y-y_ref| < Δy
N samples @ 1 kHz
Interlock Signal @ 1 kHz, signal name ‘<X>:Interlock@1kHz’
Latched Interlock Signal, signal name ‘<X>:LatchedInterlock’
(requires reset per BPC timing context)
<X>InterlockReference
<X>InterlockThresholdMin
<X>InterlockThresholdMax
(N.B. via settings supply)
B.3) Aggregation & Decimation
N samples @ 100 Hz
to FESA buffer, signal names: ‘<X>@100Hz’ & ‘<X>Error@100Hz’
B.3) Aggregation & Decimation
N samples @ 10 Hz
to FESA buffer, signal names: ‘<X>@10Hz’ & ‘<X>Error@10Hz’
B.3) Aggregation & Decimation
N samples @ 1 Hz
to FESA buffer, signal names: ‘<X>@1Hz’ & ‘<X>Error@1Hz’

FESA block-mode acquisition (ie. CMW filter: ‘TRIGGERED’):

for each designated signal (via list), *timing context, and timing event within context*
(e.g. ‘DEV:RF_gap’@INJECTION1, EXTRACTION, POST_MORTEM, MD1, MD2, MD3, … + “BPC_ID/CMW SELECTOR”)

χ²-Fitting Test Configuration:

formula	= "[1]*(0.5+0.5*TMath::Erf((x-[0])/[2]))"
nParameters	= 3;
parameterName	= {"Delay", "Amplitude", "Slope"};
parameterUnit	= {“s”, “V”, “a.u.”}
parameterInitialValue	= { 2e-6, 1.0, 1.0}
fittingRange [s]	= [0.0, 2e-6]
parameterRangeMin	= { 0.0, 0.0, 0.0}
parameterRangeMax	= { 2e-6, 2.0, 10.0}

(N.B. via settings supply and/or other time-domain signals)

post-processed
signals <X>:
- DEV:Timing
- DEV:KickAmplitude
mux
m x N samples
B.5) χ²-fit
to FESA buffer, signal names:
<X>@<TimingEvent>:Delay
<X>@<TimingEvent>:DelayError
<X>@<TimingEvent>:Amplitude
<X>@<TimingEvent>:AmplitudeError
<X>@<TimingEvent>:Slope
<X>@<TimingEvent>:SlopeError
B.4) |y-y_ref| < Δy
(boolean)
to FESA buffer, signal names:
<X>@<TimingEvent>:Delay:Interlock
<X>@<TimingEvent>:Amplitude:Interlock
<X>@<TimingEvent>:Slope:Interlock
<FESA Timing Event>
+ Multiplexing Context