EISCAT Scientific Association

Technical Specification

for

First Stage Receiver Unit

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1 Introduction

The EISCAT Scientific Association, also called "EISCAT" throughout this document, conducts research on the lower, middle and upper atmosphere, and ionosphere using the incoherent scatter radar technique. EISCAT is conducting a project called EISCAT_3D where the goal is a new system, the EISCAT_3D, which will be a next generation incoherent scatter radar capable of providing 3D monitoring of the atmosphere and ionosphere.

1.1 Purpose

The purpose of this document is to describe the technical requirements for the First Stage Receiver Unit, which consists of a Front End, an ADC, a First Stage Beamformer, a Subsystem Manager, and a WR Slave.

1.2 Application

The document is used as the technical specification for the procurement of the First Stage Receiver Unit. Note that this document describes logical interfaces and the actual system design is up to the vendor.

Both the text-based requirements *and* the activity diagrams shall be considered as requirements (with prefixes SS_BF_FE, SS_BF_BF, ...) that shall be fulfilled by the First Stage Receiver Unit.

1.3 Revision History

2016-04-18, issue 0.1, First version

2016-06-16, issue 0.2

2016-06-27, issue 0.3

2017-09-20, modifications after PfP project

2018-02-14, modifications for the draft version

2018-04-06, duplicate requirements removed

2018-04-26, modifications after negotiation phase including:

2 References

Reference	Title
[SOWFSRU]	Statement of Work for First Stage Receiver Unit

3 System Description

This chapter contains the system description for the First Stage Receiver Unit. The first section contains an overview of the whole system and the following sections contain the detailed description of the FSRU.

3.1 Typical EISCAT_3D operational set-up

The typical mode of operation for the EISCAT_3D system is to make three-dimensional observations of the parameters of the ionosphere within its field of view. The way that this is implemented is as follows:

A list of different directions (elevation and azimuth) with respect to the core site is pre-defined. The transmitter follows this list so that each beam pulse goes in a new direction. Each receiver site also has a corresponding pre-defined list identifying sets of viewing directions designed to observe the transmitter beam simultaneously at different altitudes. See the figure for a simplified example with a list of 4 transmitter directions and 4 corresponding sets of 5 simultaneous receiver viewing directions at one receiver site.

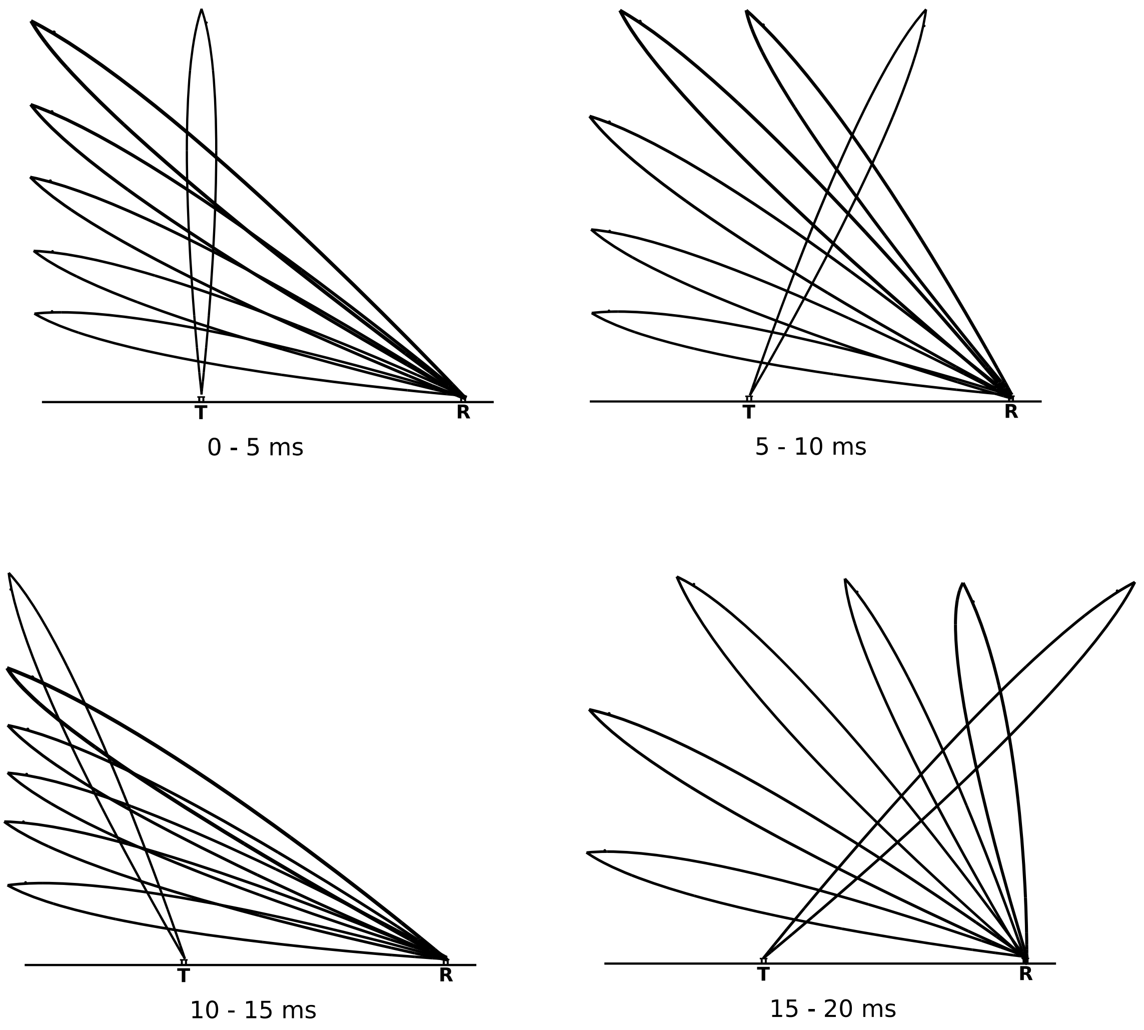

Figure 1. Simplified example of transmitter receiver beams.

In case the ionospheric conditions change or there is an interesting event (meteor, auroral arc) it should be possible within a one second to change the list of transmitter directions, and at the same time change the corresponding lists of sets of simultaneous viewing directions at all receive sites.

Thus, an EISCAT_3D experiment requires a number of lists. Each list identifies a number of transmitter beam directions, each with corresponding sets of simultaneous receiver viewing directions.

List				
	Transmitter	Receiver 1	Receiver 2	...
Pulse 1	(el1, az1)T	(el1,1, az1,1)R1 (el1,2, az1,2)R1 (el1,3, az1,3)R1	(el1,1, az1,1)R2 (el1,2, az1,2)R2 (el1,3, az1,3)R2	...

		...	...	
Pulse 2	$(el_2, az_2)_T$	$(el_{2,1}, az_{2,1})_{R1}$ $(el_{2,2}, az_{2,2})_{R1}$ $(el_{2,3}, az_{2,3})_{R1}$ ...	$(el_{2,1}, az_{2,1})_{R2}$ $(el_{2,2}, az_{2,2})_{R2}$ $(el_{2,3}, az_{2,3})_{R2}$ ...	...
Pulse 3	$(el_3, az_3)_T$	$(el_{3,1}, az_{3,1})_{R1}$ $(el_{3,2}, az_{3,2})_{R1}$ $(el_{3,3}, az_{3,3})_{R1}$ ...	$(el_{3,1}, az_{3,1})_{R2}$ $(el_{3,2}, az_{3,2})_{R2}$ $(el_{3,3}, az_{3,3})_{R2}$ ...	...
...	...	...	...	...

3.2 Technical description

Overall, the EISCAT_3D system includes 119 Sub-arrays at the Skibotn, Norway site and 109 Sub-arrays each at the Karesuvanto, Finland and Kaiseniemi, Sweden sites. This diagram displays the different subsystems within one Sub-array and also displays, where applicable, where the subsystems are located physically.

The instrument container houses:

- First Stage Receiver Unit (FSRU)
- Pulse & Steering Control Unit (PSCU)
- Time & Frequency Unit (TFU)
- Transmit Unit (TU)
- Sub Array Computer *(Sub Array Manager software)*
- Climate Monitoring Equipment

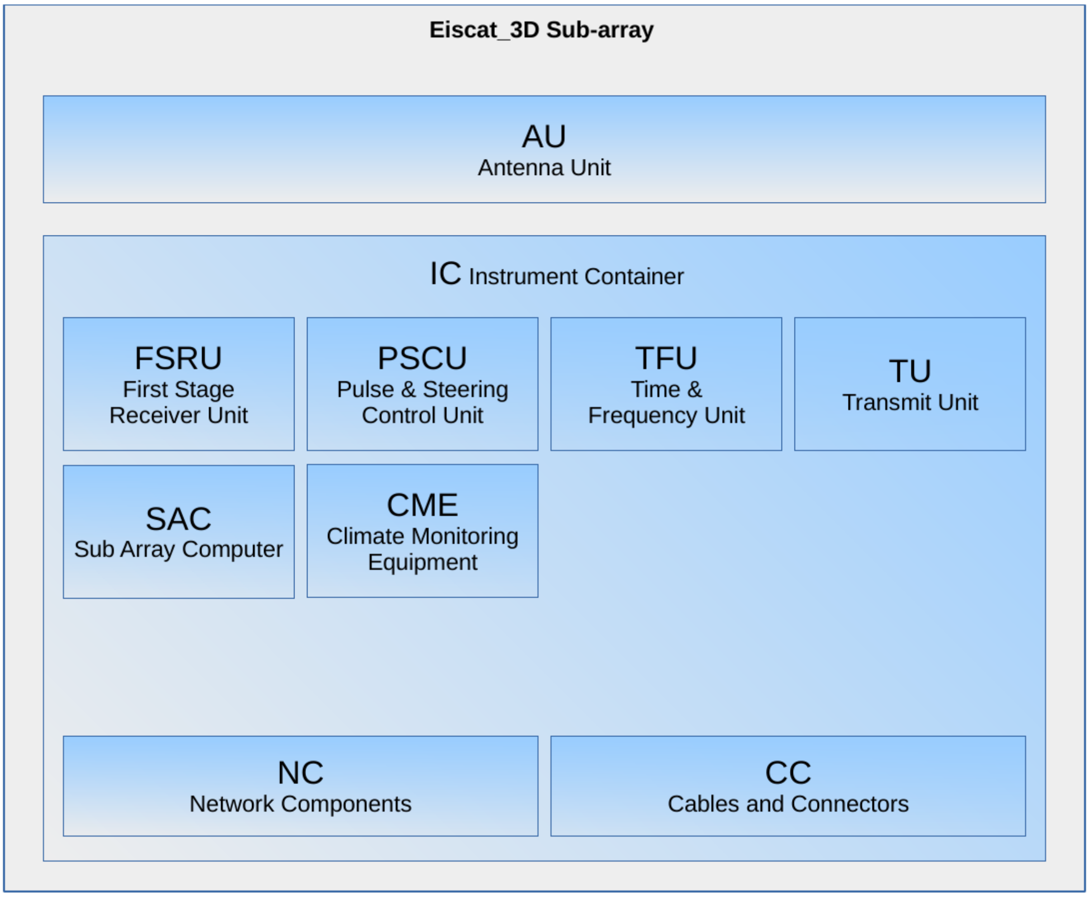

Diagram 1. The Sub-array system.

Also included in the Sub-array are Network Components plus Cables and Connectors to connect the different subsystems and components.

Note that the diagram only displays the Sub-array sub systems. External systems (e.g. Computing System which is located outside of the Instrument Container) are not displayed.

Antenna signals in the Sub-array are collected from a hexagonally shaped area and fed to the sub-array container placed underneath a steel structure ("Array Structure") which the Antenna Elements are also mounted on.

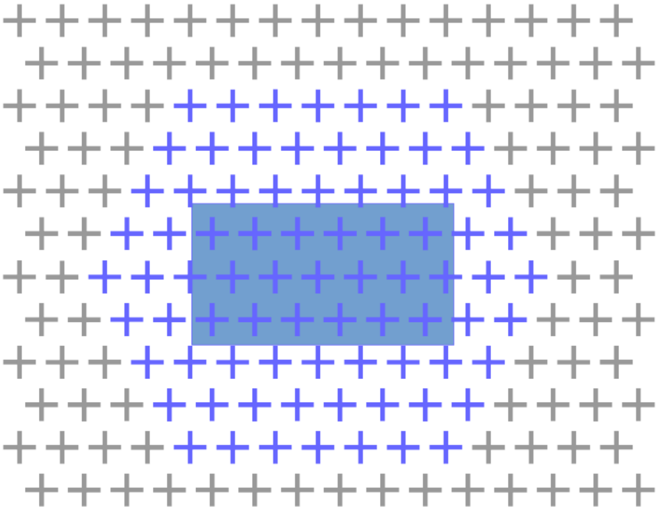

Diagram 2.EISCAT_3D Sub-array Layout

The image shows a sketch, from above, of how the containers physically can be placed in the Sub-array. *The sketch is not in scale and the measurements of the containers are approximate.*

3.3 EISCAT_3D Sub-array

The Sub-array consists of 91 crossed-dipole antenna elements, a beamformer, a receiver, a transmitter and other subsystems for control, time-keeping etcetera.

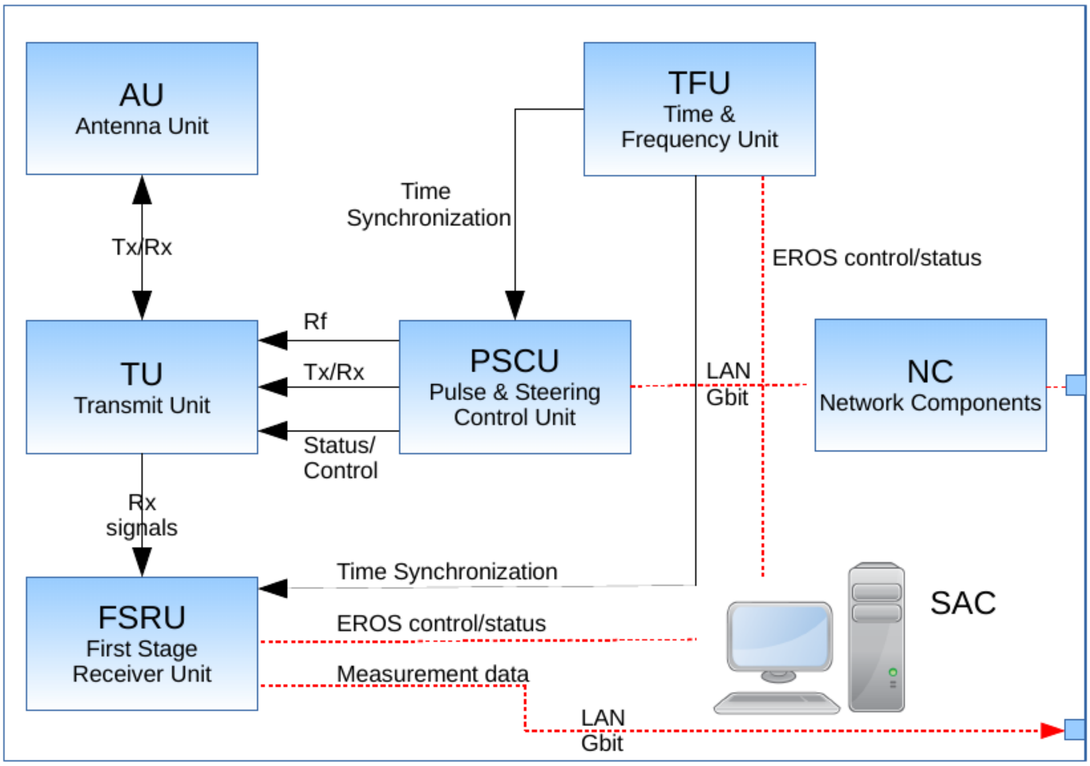

Diagram 3.Sub-array Technical systems High level Overview.

The diagram above displays a high-level overview of the technical subsystems of the Test Sub-array. It conveys not only which components interact with each other, but also the kind of information that is exchanged between the components.

3.4 First Stage Receiver Unit

The First Stage Receiver Unit is connected to other systems through control port, Data port and RF connectors. Diagram below shows connections.

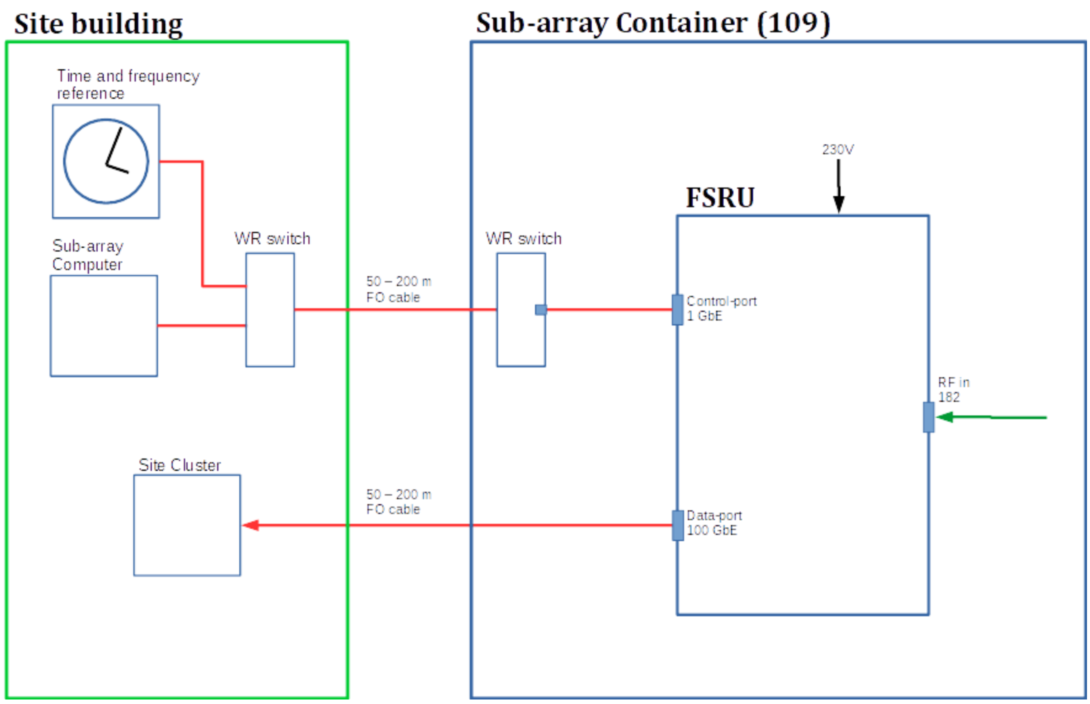

Diagram 4. FSRU connections.

The First Stage Receiver Unit consists of the following main parts: the receiver Front End, the Analogue-to-Digital conversion, and the First Stage Beamforming. The receiver Front End receives the wide-band, weak signals from each of the individual antenna elements and conditions them so that they are suitable for sampling and further digital processing. The conditioning includes frequency-band limitation by an Anti-aliasing Filter and amplification with a Low Noise Amplifier.

The conditioned signals are then sampled with analogue-to-digital converters (ADC) and fed to the Beamformer. The Beamformer performs the first few stages of the digital signal processing that ultimately gives the antenna array its characteristic directional sensitivity ("forms the antenna beams"). Broadly described, the Beamformer will take the 91x2 data streams (91 antennas times two polarizations) and combine them into 10x2 beamformed data streams (10 different simultaneous beams times two polarizations).

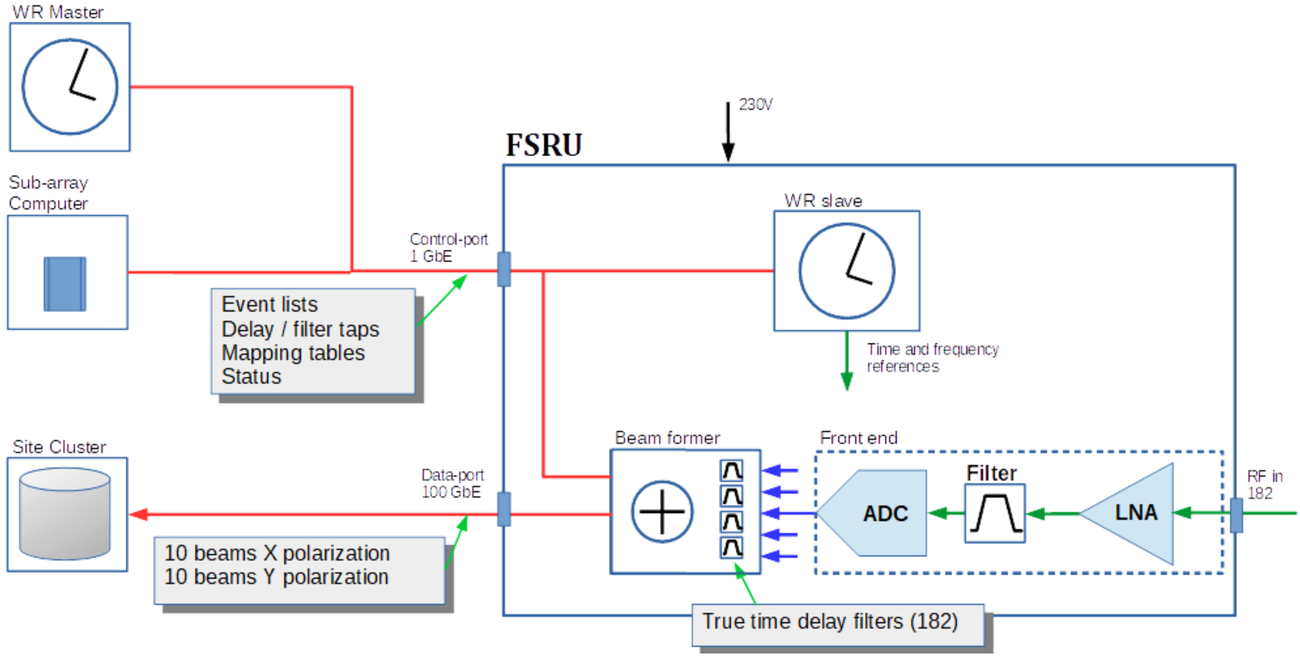

Diagram 5.First Stage Receiver Unit.

As shown on the diagram, the First Stage Receiver Unit consists of a Front End (containing LNA, filters and ADC), a Beamformer and a WR Slave.

First Stage Receiver Unit can be made of many units internally, but for Sub-array control it should be seen as one logical system.

3.5 Interfaces

Interfaces of the system are descripted the table

Name	*Type*	*Information*
RF in	Analog coaxial	Interface for analog signals from antennas, 182 connectors. 91 from polarization X and 91 from polarization Y.
Control	1 GbE	Interface for receiving control signals and time information.
Data	100 GbE	Interface for data streams.
Mains	230V standard socket	Interface with the Mains Power.

3.6 Front End

The Front End Unit consists of Low Noise Amplification (LNA) filters, and Anti-aliasing filters. The band-pass filtering done in the **Front End** has two main functions. First, it ensures that the signal bandwidth in front of the ADC is compatible with the sampling frequency in terms of the Nyquist criterion for bandpass sampling. The criterion states that the periodic spectral replicas of the analog band, by the sampling frequency, must not overlap. The other task is to prevent unwanted, often very strong, neighboring electromagnetic signals, the out-of-band interference, of entering the digital processing chain. This protection task of the filter can only succeed if the low noise amplifier in front of the filter can tolerate all the extra load caused by the out-of-band interference without losing its linearity, so that no spurious signals are generated directly into the measurement band.

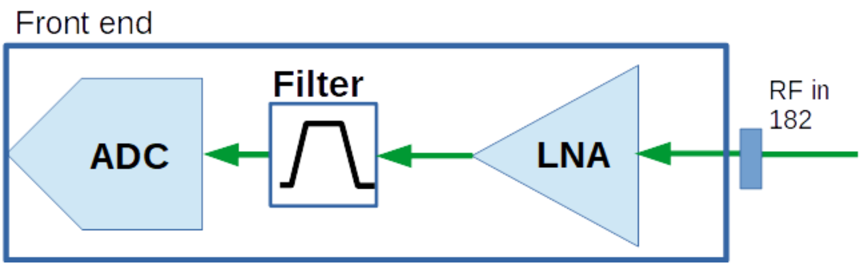

Diagram 6. Front End.

3.7 Beamformer

The Beamformer provides discrete spatial filtering across the aperture of the 91 antennas of the sub array. The system is responsible for filtering signals from Antenna Unit and forming multiple receive beams. Beamforming can, as previously mentioned, reduce the interference signals (external electromagnetic interference) *but* only if the receiver chain associated with each antenna element remains fairly linear.

The First Stage Beamformer introduces carefully calculated, antenna element specific time delays to each of the digitized signals coming from the elements; sums the signals coherently, that is, adds them in the voltage domain rather than in the power domain; and performs the so-called IQ-detection which converts a real-valued signal into a complex-valued signal that represents only one side of the original two-sided spectrum. In IQ-detection, the data flow rate, typically expressed in units of a million samples per second (MS/s), is converted from type “NN MS/s real” to “NN/2 MS/s complex”. Depending on the used IQ-detection method, the First Stage Beamformer also shifts the signal to near the zero frequency. In addition, the First Stage Beamformer will reduce the bandwidth of the signal and the data flow rate in a process called decimation.

The Beamformer produces complex-valued sample streams, each representing a signal coming from a particular direction in the sky. Thus, each stream corresponds to a particular radar receiver beam, and so we call also these data streams “beams”. It is required that up to 20 beams (10 from both polarizations), in different pointing directions, are produced simultaneously. The Beamformer accomplishes this by using the same data samples from the Front End as above, but by using up to nine other sets of the element-specific time delays and repeating the calculations (possibly in parallel). Taking into account the available two antenna polarizations, a data stream corresponding to up to 20 full bandwidth beams (in 10 directions) will be produced out of the First Stage Beamformer.

The Beamformer also makes available optional decimation filters to reduce required data rate in the output streams. For an example see Diagram 1.

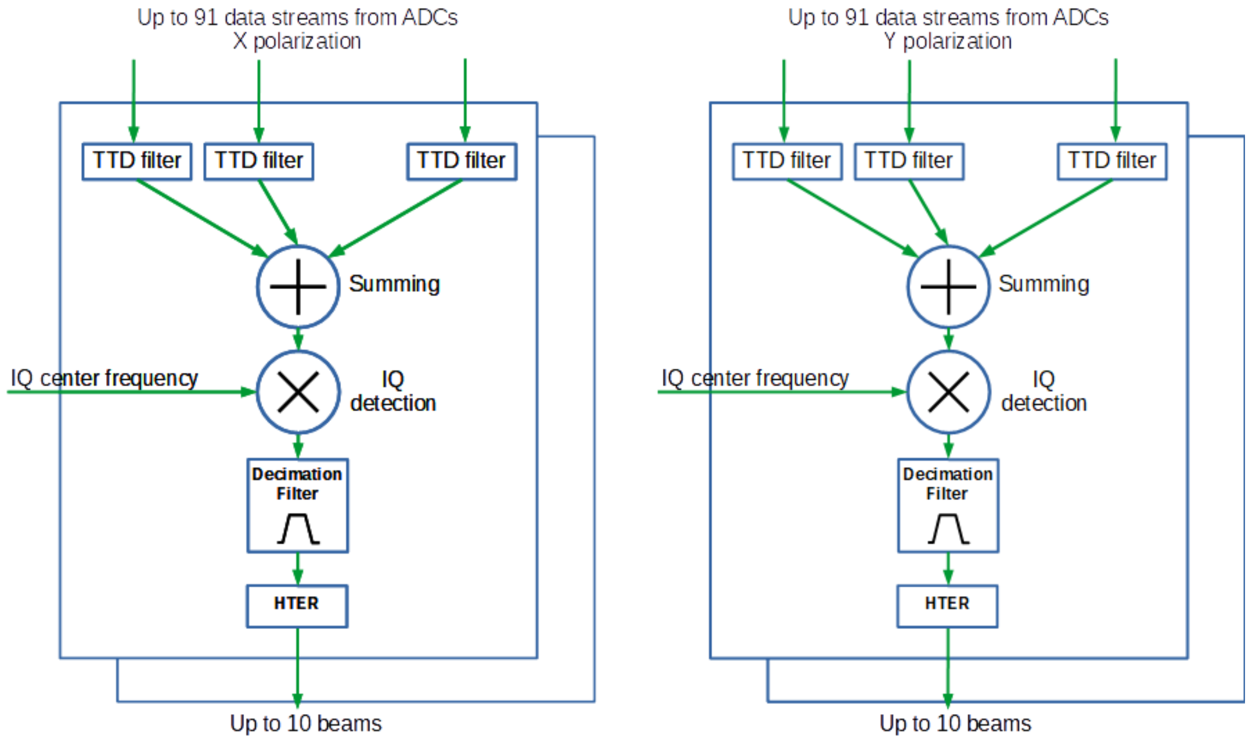

Diagram 7. Beamformer functions.

3.8 SW control and Application Programming Interface (API)

The Subsystem Controller in the FSRU is a logical part of the system which takes commands from the control network and performs operations according to those commands. This is enabled by the FSRU providing a TCP socket listener at a fixed (but configurable) network address.

The Controller also issues *Notifications* to the Sub-Array Computer, without being explicitly prompted by EROS, if it detects an anomaly, e.g. if the temperature exceeding a set maximum value.

See Diagram 8 for expected beam direction mapping functions. The beam direction is given as an index value to the Beam Direction Mapping (BDM) array. BDM has calibrated delay values for each channel to perform optimum beam forming to all beam directions inside the field of view. BDM delay values are calculated by EROS during the array calibration procedures. Delay value shall be a 1-byte value to the index of array of filter taps. Receiver shall have an array for delay to filter taps representing 256 delay values from 0 to 25ns. It’s up to supplier to design needed filters to perform required true-time-delay filtering function.

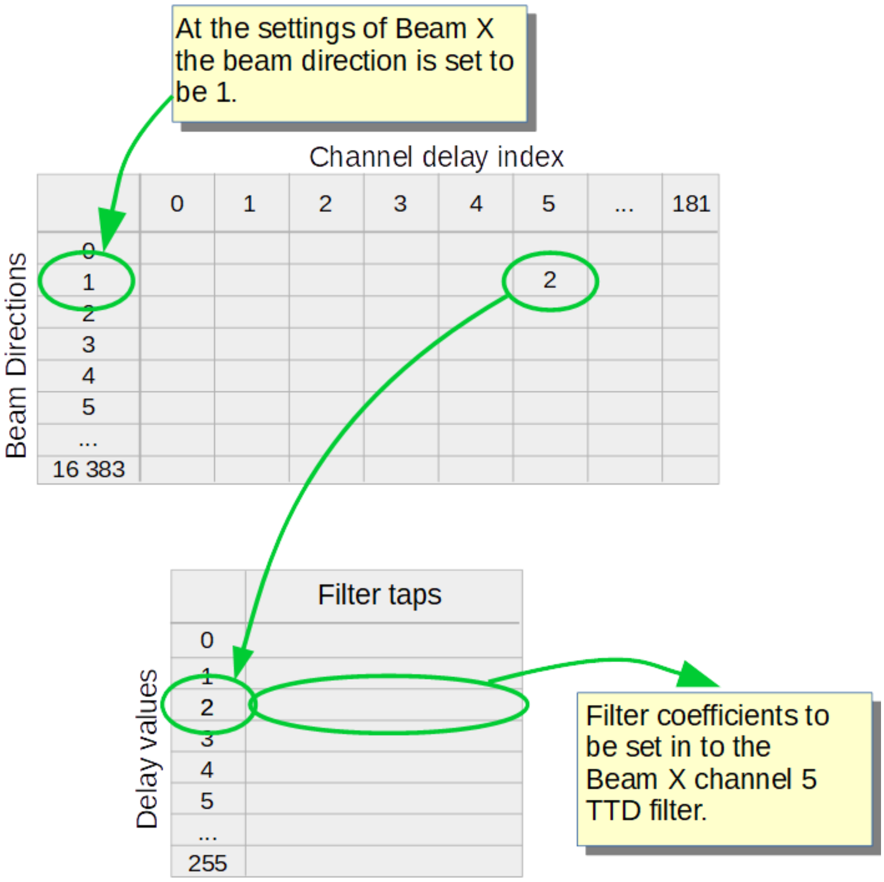

Diagram 8. Beam directions mapping..

Beam parameters are send before and FSRU is expected to change beam configuration at the time marked in the parameters table. See Diagram 9 for detailed timing chart.

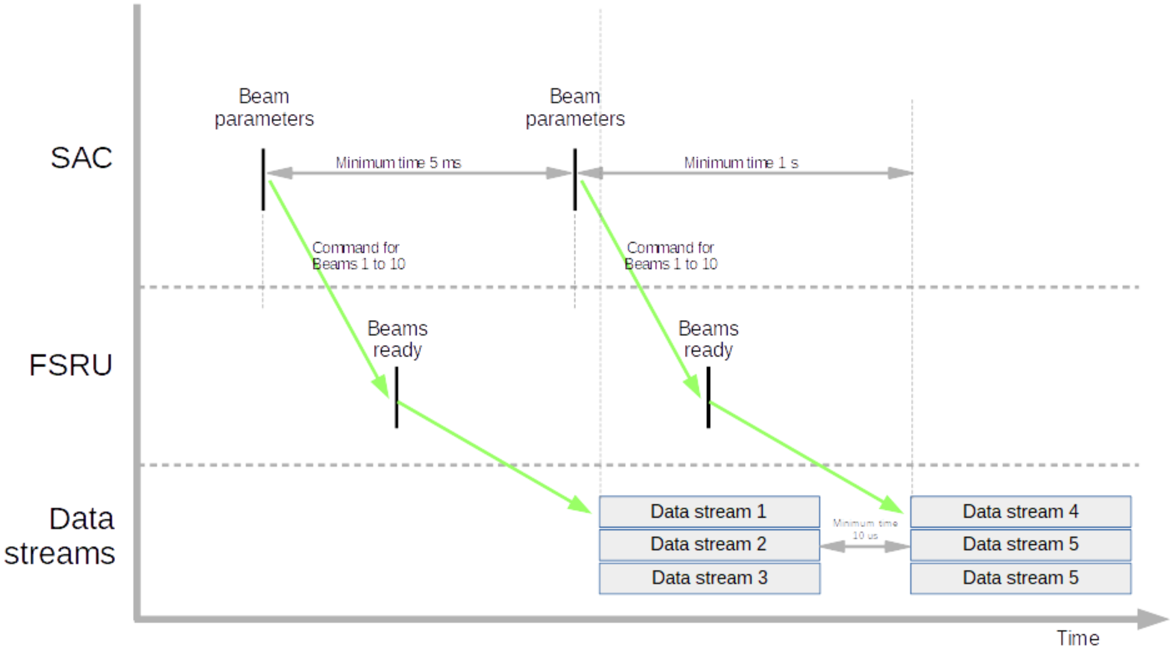

Diagram 9. Timing chart for beam parameter -command and data streams.

3.9 Hard target echo removal

Hard target echo removal (HTER) function is used to block unwanted echoes from satellites and other hard targets. In the beam parameters there is values for rms voltage threshold, integration time and time window for detection to be calculated. During the detection window, the square sum over given integration time is calculated. If calculated value exceeds given threshold value a hard target is detected.

Samples having HTER detection active shall be made to 0 and corresponding data packets shall be flagged. This is done independently on both polarizations.

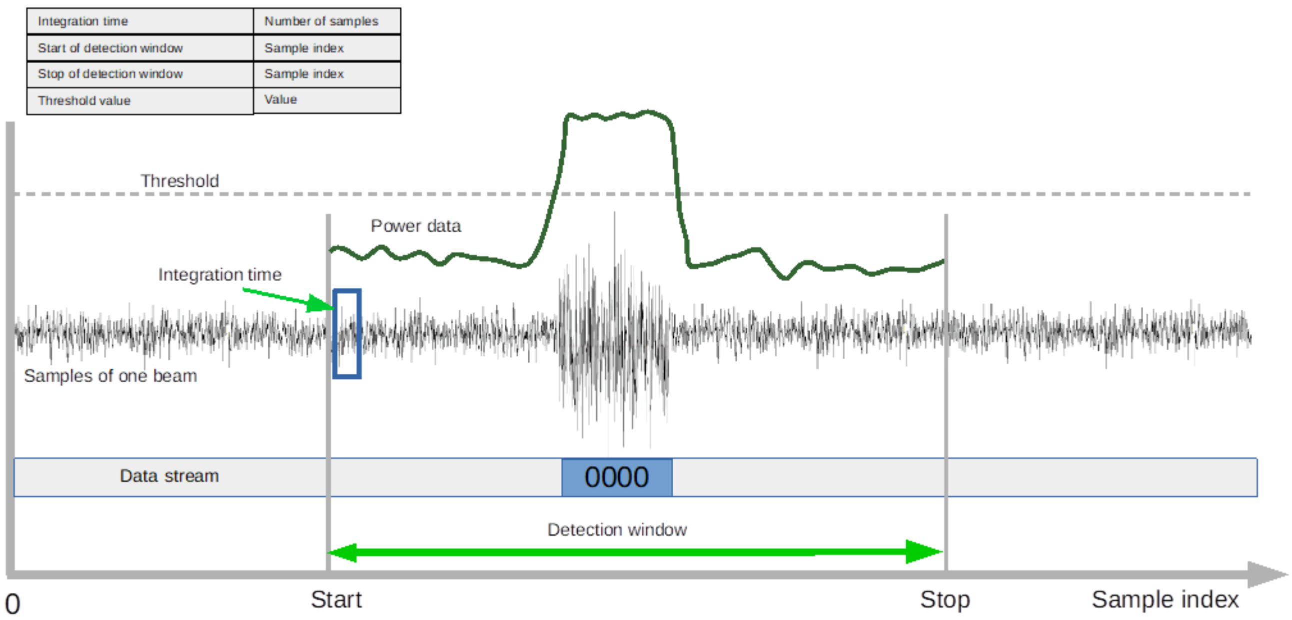

Diagram 10. HTER sequence.

3.10 WR Slave

The White Rabbit (WR) Slave extracts the time and synchronization from the 1 Gb Ethernet network and provides it to the subsystem. Sampling and timestamps used in the data stream and control commands shall base on timing from WR system.

4 Requirements

The following chapter and subchapters contain requirements on the First Stage Receiver Unit and its subsystems. Each chapter contains general requirements and interface requirements.

4.1 General requirements

Requirement	
SS_BF_01_01	The Front End shall have 182 interfaces for receiving radio frequency signals.
SS_BF_01_02	The FSRU shall be able to perform digital beamforming.
SS_BF_01_03	The FSRU shall have a low noise amplifier.
SS_BF_01_04	The FSRU shall have an anti-aliasing filter.
SS_BF_01_05	The FSRU shall have an analog-to-digital converting (ADC) function.
SS_BF_01_06	Following a power off command, the FSRU hardware shall be shut down gracefully.
SS_BF_01_07	The FSRU shall include an API for high level controls system.
SS_BF_01_08	The FSRU shall have a technical life time of at least 15 years.
SS_BF_01_09	The FSRU shall be able to operate in an ambient temperature from 15 to 40 degrees Celsius.
SS_BF_01_10	The FSRU shall be rack mountable.
SS_BF_01_11	The space allocated for the FSRU shall not exceed 21 unit vertical rack space.
SS_BF_01_12	Power supply shall be standard 230V connection.
SS_BF_01_13	FSRU power consumption shall be less than 1 kW.
SS_BF_01_14	FSRU shall have remote firmware update possibility including FPGA image if applicable.
SS_BF_01_15	Access to custom source code and rights to modifications for own use shall be given to EISCAT.

4.2 Requirements for analog signal conditions

Requirement	
SS_BF_02_01	Input impedance of the Front End LNA function shall be 50 ohms.
SS_BF_02_02	Return loss over the entire passband shall be better than -15 dB.
SS_BF_02_03	The FSRU shall have 3 dB receiving band of 233.28 +- 15 MHz.
SS_BF_02_04	Stop band attenuation shall be better than 80 dB (can be done partly in digital domain, see SS_BF_03_09). Analog attenuation shall be better than 30 dB outside of 25 MHz from center frequency.
SS_BF_02_05	The Front End LNA function shall have a maximum gain variation of 1 dB
SS_BF_02_06	The goal for the noise figure of the LNA design shall be 0.5 dB and in any case better than 1.0 dB over the receive band.
SS_BF_02_07	The maximum allowed input power into the Front End shall be 10 dBm (no damage).
SS_BF_02_08	Group delay stability over the operation temperature range shall be less than 100 ps
SS_BF_02_09	The spurious free dynamic range (SFDR) of the First Stage Receiver Unit shall be better than 70 dB for a -40 dBm single tone input signal.
SS_BF_02_10	Analog to digital conversion can be done using the so called super-nyquist or under-sampling method at 104 MSPS or a multiple of this sampling frequency but is up to supplier to choose correct sampling frequency.
SS_BF_02_11	LNA gain from shall be at least 40 dB including possible transformer.
SS_BF_02_12	Output TOI measurement shall be better than 30 dBm.
SS_BF_02_13	Isolation between channels shall be better than 30 dB.
SS_BF_02_14	Recovery time from 0 dBm input signal shall be less than 10 us.

4.3 Beamformer

Requirement	
SS_BF_03_01	The total number of beams of the First Stage Beamformer shall be 20, 10 for each polarization formed from 91 channels
SS_BF_03_02	Beamformer shall perform IQ detection having settable center frequency within receiving bandwidth and at least 1 KHz resolution..
SS_BF_03_03	Output 3 dB bandwidth after IQ detection shall be at least 25 MHz.
SS_BF_03_04	Maximum delay variation over the receiving bandwidth shall be less than, or equal to 50 ps
SS_BF_03_05	The First Stage Beamformer shall have an Ethernet interface to output the data streams.
SS_BF_03_06	TTD Filter should perform a true time delay filtering over receiving bandwidth.
SS_BF_03_07	Maximum delays for the TTD filters shall be greater than, or equal to, 25 ns
SS_BF_03_08	Resolution for TTD filter shall be less, or equal to, 100 ps.
SS_BF_03_09	Out of band attenuation of decimation filter shall be more than 80 dB measured 2 MHz out of decimation 3 dB point.
SS_BF_03_10	Additional decimation factors shall be at least 2, 3, 4, 13, 26, 52

4.4 Operational requirements

Requirement	
SS_BF_04_01	The FSRU shall be able to receive control commands.
SS_BF_04_02	The FSRU shall be able to receive Status inquiry commands.
SS_BF_04_03	The FSRU shall be able to send error messages without specific inquiries.
SS_BF_04_04	The FSRU shall boot up automatically to an operational state and without requiring access to higher level control system (e.g. SAC).
SS_BF_04_05	It shall be possible to reboot the system by cycling power.
SS_BF_04_06	Commands shall include at least following tasks: • Reset FSRU • Stop current streaming • Down load filter bank values • Down load Beam Direction Mapping array • Set beam parameters • Power off
SS_BF_04_07	Following a power off command, FSRU shall perform the necessary shutdown procedures on the subsystem hardware.
SS_BF_04_08	Status messages from the FSRU shall be time stamped.
SS_BF_04_10	The Subsystem Manager shall be able to respond with the following status messages as a result of Status Inquiry Commands: • Operation state • Clock state • Configuration loaded • Ready for operation • Errors • Internal temperature
SS_BF_04_11	Beam parameters shall include following items:

	• Beam number to be written to data stream • Beam direction number • IQ detection center frequency • Decimation value • HTER threshold value • HTER integration time • HTER window start and end sample numbers • Start time for beam streaming (UTC in 1 ns resolution) • Set number of samples to acquire • Bypass mode (Raw samples form one ADC for diagnostics)
SS_BF_04_12	Start time is expressed as UTC with resolution of at least 1 ns.
SS_BF_04_13	Filter bank shall have place for at least 256 pre-calculated filter values representing delays from 0 to 25 ns.
SS_BF_04_14	Filter bank shall have pre-calculated filter values.
SS_BF_04_15	Beam parameters shall be possible to down load in advance during the normal data streaming.
SS_BF_04_16	Minimum delay between new beam parameters - command and data streaming shall be 1 second.
SS_BF_04_17	Maximum cap between data streams with different beam configurations shall not be greater than 10 us.
SS_BF_04_18	Beam direction for a beam is given as an index value in the beam direction mapping array.
SS_BF_04_19	Direction mapping array shall have at least 16K directions.
SS_BF_04_20	Direction Mapping Array has direction index as an input and 182 delay values as output.

4.5 Hard target echo removal (HTER)

Requirement	
SS_BF_05_01	FSRU shall perform a simple hard target removal algorithm.
SS_BF_05_02	HTER detection is calculated as rolling square sum of voltage values during given measurement window.
SS_BF_05_03	Measurement window is expressed as index number of start and stop samples in the data stream.
SS_BF_05_04	If measured square sum level is greater than the threshold value given in the beam configuration then unwanted object is detected.
SS_BF_05_04	Data samples having hard targets are replaced with 0 and data packet shall be flagged.

4.6 Software Application Programming Interface (API)

Requirement	
SS_BF_06_01	The FSRU must provide a socket remote command (RPC) server, which can be accessed by EISCAT client programs using data serialization and data transfer protocols that have library-level support in both standard C, and either in python or Tcl.
SS_BF_06_02	The network address where the TCP socket listener is provided shall be configurable by EISCAT.
SS_BF_06_03	Data port shall be 100 GbE QSFP or another standard plugin.
SS_BF_06_04	Header of the data packet shall have at least Beam index, data packet index and time stamp of the first sample.

4.7 Time and frequency reference

Requirement	
SS_BF_07_01	The First Stage Receiver Unit shall be compatible with White Rabbit time and Frequency distribution protocol.
SS_BF_07_02	ADC sampling frequency and operation time shall be based to White Rabbit timing system.
SS_BF_07_03	Timing uncertainty between White Rabbit reference and sampling shall not exceed 100 ps.

5 Definitions

Definition	Description
AAF	Anti-Aliasing Filter
ADC	Analog to Digital Converter
API	Application Programming Interface
CPU	Central Processing Unit
dBm	**dBm** (sometimes **dB$_{mW}$** or decibel-milliwatts) is an abbreviation for the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW). (wikipedia)
EROS	EISCAT Realtime Operating System
HTER	Hard Target Echo Removal
LNA	Low Noise Amplifier
M&C	Monitoring and Control
ns	Nano second
PfP	Preparation for Production
ps	picoseconds
RC	Radar Controller
RF	Radio Frequency
SFDR	Spurious Free Dynamic Range
SNR	Signal to Noise Ratio
SSDD	System and Subsystem Design Description
SSPA	Solid State Power Amplifier
TTD	True Time Delay
VSWR	Voltage Standing Wave Ratio
WR	White Rabbit