Milestone Document MA-1
Requirements and their implications for EISCAT_3D data handling and processing at the operations centre.

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NeIC
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1 Purpose

The purpose of this document is to define the requirements on the EISCAT_3D operations centre. These requirements are those on the computing and data handling aspects within the operations centre. The requirements in this document try to follow the standard terminology as given in the NASA document [1].

2 Introduction

EISCAT_3D will establish a system of distributed phased array radars that will enable comprehensive three-dimensional vector observations of the atmosphere and ionosphere above Northern Fenno-Scandinavia. The use of new radar technology,
combined with the latest digital signal processing, will achieve ten times higher temporal and spatial resolution than obtained by present radars while simultaneously offering, for the first time, continuous measurement capabilities. The flexibility of the EISCAT_3D system will allow the study of atmospheric phenomena at both large and small scales unreachable by the present systems.

The EISCAT_3D system will, in its first stage, consist of three radar sites: one with both transmitting (TX) and receiving (RX) capabilities and two with only RX capabilities. The sites will be located in remote locations in three different countries (Finland, Norway and Sweden) and will be separated geographically by approximately 130 km. Two additional receive sites, at distances 200-250 km from the transmit site, are planned for the full EISCAT_3D system. In addition to the radar sites, EISCAT_3D will also have an operations centre and one or more data centres.

The EISCAT_3D operations centre will:

- Coordinate the radar operations and observation modes through a connection to the Control Center described in Section 9.3 of [2];
- Monitor the production of the standard data products from the different sites;
- Generate non standard products as well as the products that result from combining the measurements from the different sites (multi-static data products);
- Generate meta-data and transfer the data to the data centres for final storage.

It is calculated (See Appendix A) that computing capabilities of 500 TFLOPS and a storage capacity of 20 PB will be required at the operations centre.

In order to minimize the risk of disruption to the network data flow, the operations centre ideally should be both close (by network topology) to a site and located within one of the national infrastructures for computing. Location within one of the national infrastructures for computing would possibly be cost-efficient. It is anticipated that the operations centre for practical reasons will initially be run by EISCAT at least during the construction of the system, but that many of its tasks eventually will be performed at one of the e-infrastructure centres.

The EISCAT_3D data of levels 1a to 3a [3], see also Table 1, from the RX arrays will be sent over national networks to the operations centre. The position of the operations centre within the EISCAT_3D computing scheme can be seen in Figure 1. The data from the EISCAT_3D receiver (RX) sites will be processed at the operations centre and the results will be fed back to control the radar of the TX site and search directions of the RX sites (the TX site also has RX capability).

As the operations centre will produce results that are to be used to control the TX and RX sites, the computing at the operations centre will be essentially real-time high throughput computing. These results have to be available within less than 5 seconds in order to provide this level of latency in the control of the TX and RX sites.

The EISCAT_3D infrastructure will produce data on several levels from the raw voltages of the antennas to the three-dimensional views of atmospheric and near-space events. The data levels are summarized in Table 1.
In Table 1, it can be seen that the operations centre will receive data (levels 1a and 1b) from the RX sites to be kept (buffered) for 4 months. There will also be higher level data (levels 2 and 3a) from the RX sites that need to be processed for control of the transmit beam of the TX site and the look directions of the RX sites. The expected format of the data received by the operations centre from the RX sites is HDF5 \[4\]. These higher level data are also used for calculating the three-dimensional data products and sent for archiving at the EISCAT_3D data centre.

The data flow rate from the RX sites to the operations centre is not expected to be constant. The EISCAT_3D sites (TX and RX) are planned to be operational on a 24/7 year-round basis with the EISCAT_3D radar operating in the high power mode for 10% of the time and low power mode for 90%. In the low power mode, EISCAT_3D transmits at 0.5 MHz whereas the high power mode uses 5 MHz but with a factor of 10 greater duty cycle. Therefore, the high power mode transmits and receives 100 times the raw data of the low power case. The main reason for this anticipated mode of operation is that natural events are not scheduled and the experiment must be in a state of readiness at all possible times in order to be able to observe a rare event.

Table 2 summarizes the EISCAT_3D science cases that drive the construction of
Table 1: EISCAT_3D data levels. The operations centre will receive data from levels 1a to 3a and produce data level 3b. The 4 month data buffer is provisioned to be located at the operations centre. Data is archived at the data centre.

EISCAT_3D, the operational parameters and expected data rates at the sub-array level.

Table 2 shows that the data rates expected in the EISCAT_3D project vary widely. The value of “R” in Table 2 gives a measure of the expected frequency that a particular science case is studied. A lower “R” value implies a science case will be studied more often.

One of the key areas of study is Anthropogenic Global Warming (AGW) and the AGW science cases are given in Table 2 with “R” value of zero. The operating mode of EISCAT_3D for these science cases implies a low to moderate data rate. In contrast the operational mode for the highest data rate, expected from Naturally Enhanced Ion Acoustic Lines (NEIALs), is expected to be needed far less frequently.

In summary, the rate of data sent from the RX sites to the operations centre is expected to vary widely. In general the projected data rate is low to moderate (tens to hundreds of Mbit/s) for the majority of the operation time with rare spikes of high data rates (hundreds of Gbit/s).

### 3 Requirements

The requirements for the computing and data handling at the operations centre are now given.
### REQUIREMENTS

<table>
<thead>
<tr>
<th>R</th>
<th>Science case</th>
<th>Height</th>
<th>Bandwidth</th>
<th>Beams</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Atmosphere-ionosphere coupling (Global warming, winds)</td>
<td>0-400 km</td>
<td>100 kHz</td>
<td>30</td>
<td>192 Mb/s</td>
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<tr>
<td>1</td>
<td>D-region phenomena</td>
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<td>1 MHz</td>
<td>10</td>
<td>640 Mb/s</td>
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<tr>
<td>1</td>
<td>Small scale (auroral) dynamics</td>
<td>70-500 km</td>
<td>30 MHz</td>
<td>30</td>
<td>58 Gb/s</td>
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<td>Fine scale auroral structures</td>
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<tr>
<td>1</td>
<td>Topside composition</td>
<td>300-1500 km</td>
<td>10 kHz</td>
<td>100</td>
<td>64 Mb/s</td>
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<tr>
<td>1</td>
<td>Transition region composition</td>
<td>100-300 km</td>
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<td>Meso-scale electrodynamics and flows (incl.BBFs)</td>
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<td>2</td>
<td>Heating experiments</td>
<td>100-2000 km</td>
<td>$10^5 \times 3$</td>
<td>100</td>
<td>1.92 Gb/s</td>
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<td>2</td>
<td>Heating experiments - aperture synthesis imaging</td>
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<td>4</td>
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Table 2: The science cases and operational parameters for EISCAT_3D. The “R” value represents an estimation of the amount of time EISCAT_3D will operate for a particular science case. Higher “R” value is less likely.
3.1 Computing capacity requirements

The computing capacity required for the operations centre may be calculated from the parameters of the overall apparatus and some assumptions. This calculation is well-known from [5] and is included in Appendix A of this document. It is assumed that to process the lag profiles from the 3 RX sites of the first stage of the EISCAT 3D implementation will require $10^4$ cores each with a processing power of 5 GFLOPS/core. Another assumption is made that the ratio of lag profile processing to other analysis tasks is 10.

\[ N_{\text{sites}}^2 \times 5 \text{ GFLOPS/core} \times 10^4 \text{cores} \times 1.1 = 495 \text{ TFLOPS} \]

Therefore the installed computing capacity at the operations centre must be a minimum of 500 TFLOPS.

The computing capacity at the operations centre is increased if the array process computers (block 8 in Figure 1) were integrated to the operations centre computing. This modification would require a network capacity of $\approx 400$ Gbit/s from each of the RX sites. Moving computing from the remote array locations to a constantly staffed and controlled environment would benefit the operations aspect. Currently, this option is not under serious consideration as the array process computing is planned to be used for on-site calculations that require very low latency.

This calculation scales with the square of the number of RX sites. Therefore if more RX sites are added to the experiment then the computing capacity at the operations centre will have to be approximately doubled for 4 sites and tripled for 5 sites.

The RX site servers decode the data into time-integrated lag profiles, i.e. transforms the second stage beam formed data to the auto-correlation function domain (thus representing the power spectrum). One of the main tasks of the operations centre computing is to combine such data products from the RX sites into 3-dimensional products.

The premise that the main job of the operations centre computing is to combine the beam-formed results into 3-dimensional vector products affects the processing architecture. This is not envisioned to be an easily-parallelized process. A tightly-coupled high performance computing infrastructure is required. The computing infrastructure installed in the operations centre must be a tightly-coupled high performance processing cluster.

Since, as outlined above, the EISCAT 3D experiment will not produce full data rates for a significant portion of the operating time the full operations centre computing capacity will not be required all of the time. If the computing resources are able to be shared with other communities of users then costs can be reduced through cost-sharing on procurement and operations. This EISCAT 3D computing infrastructure should be usable by other users on the overall e-infrastructure in which the operations centre is located.
3.2 Data capacity requirements

The data storage capacity at the operations centre can be split into three general categories: the short-term data buffer, fast storage for real-time processing and RAM.

3.2.1 Short term data buffer

The storage required at the operations centre is approximately 20 PB. This number is calculated from the expected data rate from each site, using the ion line case and the ring buffer rate. This 20 PB storage is required in order to retain a buffer of approximately 4 months of primary data types 1a and 1b (from Table 1) from the RX sites.

As the data in this 20 PB buffer will possibly be reprocessed more than once, a data management system will be needed. Therefore, the data management system installed at the operations centre must be able to scale to 20 PB of storage. Also, some limited access to EISCAT_3D users should be available through the data management interface(s). In general, the EISCAT_3D users are expected to access data through the data centre. The data management system used in this buffer space will be used by EISCAT_3D for data re-processing and is not needed to share data to external experiments.

3.2.2 Storage for real-time processing

The processing model, mentioned above in Section 2, is real-time data processing for control of the TX and RX sites. Therefore, it is expected that the HDF5 data files received by the operations centre are not to be stored in a long term storage system but buffered to a fast storage media for real time processing. For the real-time processing there needs to be a mix of fast disk and RAM in order to process the incoming HDF5 files and protect against data loss due to power failures or similar. Entering these files into a data management system would slow down the processing, possibly to a level that would increase the latency to the RX/TX sites to an unacceptable level. The fast storage for real-time processing should be accessible directly and not only through the data management system.

3.2.3 RAM

The computing capacity is projected to be spread over $10^4$ cores. Each core must be equipped with sufficient RAM to process the HDF5 files with an acceptable latency to the TX/RX sites. Currently, servers can be equipped with up to 2 TB of RAM as an extreme configuration option [6]. The all-RAM storage option would be ideal for speed of real-time calculations but is not practical due to the risk of data loss through faulty RAM or server reboot.
3.3 Network capacity requirements

The network requirements for the operations centre can be split into three sections: the incoming network from the RX sites; the operations centre internal network; and the network out to the data centre.

3.3.1 Incoming network

The incoming network for the operations centre **must** provide a standard TCP/UDP service with a capacity of 18 Gbit/s from each of the TX/RX sites. This is the calculated data rate from the process computer at each site, using the full 30 MHz bandwidth case. The HDF5 files to be transferred from the RX sites are time stamped and do have a time-order. Simply transferring by copying over TCP/IP will not guarantee this timing property. Data transfers into the data centre **should** be managed by data transfer software.

The networking equipment **should** be off-the-shelf commodity hardware. As the operations centre is expected to be co-hosted in an existing computing e-infrastructure centre, the networking equipment can be managed by local services. In order to be protected against router and/or switch firmware attacks, the networking hardware **must** conform to the security requirements of the e-infrastructure centre.

3.3.2 Internal network

The internal network of the operations centre is primarily concerned with the connections between the buffer and real-time storage and the computing resources. Since the real-time processing is generating three-dimensional results combining information from different RX sites, this points toward tightly-coupled high-performance computing servers. The connections between the buffer storage and the computing resources will pass the HDF5 files to the tightly-coupled computing servers.

The speed of this network **must** be able to handle the data transfer rate of 18 Gbit/s per RX site. Since this data is being effectively fanned out to the $10^4$ processing cores (multiple cores housed per server), an estimate of the network speed may be made. Assuming 3 RX sites sending 18 Gbit/s and 10 cores per server, the network speed from the buffer storage to each of the computing servers **must** be at least 60 Mbit/s. It is safe to state that Gigabit ethernet connections **should** be sufficient.

The computing resources will be calculating the 3-D products and therefore will require a very high speed network to build the tightly-coupled cluster. These MPI-type calculations will require high-speed and low-latency connections and in this case usually a specialized network other than standard ethernet is used. The network connections between the computing servers in the cluster (the $\approx 10^4$ cores) **must** be a specialized networking infrastructure and integrated with the cluster.

3.3.3 Network to data centre

The network connection between the operations centre and the data centre(s) does not have such stringent demands placed upon it compared to those of the incoming
network. The calculated annual total rate that EISCAT_3D will write data to the
data centre is 3.5 PB. This gives an average rate over a year of 890 Mbit/s.

As EISCAT_3D will operate in many modes, as shown in Table 2, the data rate
will vary widely. In Table 2 it can be seen that the ratio of the highest data rate
of data those of the most-expected data rates is 300. The network connection to
the data centres must be of sufficient capacity to transmit the levels 2 and 3 to the
data centre. It is expected that by the time EISCAT_3D is operational 100 Gbit/s
network will be widely available in the relevant countries.

3.4 Operations requirements

Unlike the on-site computing for EISCAT_3D, the operations centre computing will
not be located in remote rural locations. The EISCAT_3D operations centre computing
should be co-located in an existing e-infrastructure location to benefit from
24/7 monitoring and local services. The location of the EISCAT_3D operations centre
must be the most cost-efficient method of obtaining this amount of computing
power and storage. The operations centre computing should be utilisable by other
scientific communities while capacity is unneeded (low power or standby modes).
Cost-sharing agreements may be made with other communities.

3.4.1 Monitoring

The computing and storage of the operations centre can be located in an e-infrastructure
centre whereas the actual operation of the equipment will be performed by EIS-
CAT_3D. In control centre(s) in, for example Kiruna or Ramfjordmoen, EISCAT_3D
staff would control the TX and RX through the operations centre. Therefore the
operations centre must provide all the monitoring data, such as quick-look graphs
and status of processing machines, to the EISCAT_3D control sites.

3.5 Hardware requirements

The hardware that will be installed for the operations centre not only has to fulfill
the capacities and operational requirements described above but also a set of physical
requirements.

3.5.1 Computing

The real-time processing in the operations centre may be implemented on any com-
puting architecture: “traditional” x86 servers, ARM servers, field-programmable
gate array (FPGA), GPU or state of the art parallel co-processors e.g. Intel Xeon
Phi.

The operations centre computing selected must be specialized to the task of
performing the real-time operations. As the EISCAT_3D project is planned to run
for 30 years or more, the hardware selected should be “future-proof” in that it
should be a technology that will not become obsolete or unsupported in the medium
term. A technology that has widespread use in industry and other scientific areas
would fulfill this requirement as commercial and open-source support can be more easily obtained. Therefore, the computing technology should be used in other fields in industry and research.

Given the long duration of the EISCAT_3D project and the academic nature of the project, it can be expected that the software programming is managed and performed by non-professionals in computing on a transitory basis. Therefore, the real-time computing hardware in the operations centre must be “easy to program” and the support for the programming (APIs, libraries) must be planned. The hardware must be extensible, scalable and flexible: if more RX sites are added then the computing power required will increase rapidly, as mentioned above.

The requirement on cost includes not only the purchase cost but energy consumption and heat efficiency and must fit within the EISCAT_3D budget. In order to mitigate unforeseen circumstances beyond the medium term, the computing hardware should be compatible with a standard hardware rack system.

4 Conclusions and recommendations

The requirements in this document are summarized below. The summary tries to follow the standard terminology as given in the NASA document [1].

- **Computing**
  - Must be at least $\approx 500$ TFLOPS.
  - Must be a tightly-coupled cluster.
  - Should be able to be used by other users in the e-infrastructure.

- **Data capacity**
  - Must have a buffer capacity of 20 PB.
  - Should provide some access to EISCAT_3D users through a data management system.
  - Fast storage for real-time processing should be accessible directly.
  - Each core must have enough RAM storage to process the HDF5 files.

- **Network capacity**
  - Must provide standard TCP/UDP connectivity.
  - Must have a capacity of at least 18Gbit/s from each of the RX sites.
  - Data transfers should be managed by specialized data transfer software.
  - Networking equipment should be standard off-the-shelf hardware.
  - Must conform to e-infrastructure site security requirements.
  - Network between the buffer storage and computing resources must be at least Gigabit ethernet.
4 CONCLUSIONS AND RECOMMENDATIONS

– The network between computing resources must be specialized for tightly-coupled high performance computing.

– The network connection to the data centre must be able to transmit the level 2 and 3 data to the data centre at the highest expected data rate.

• Operations

– The operations centre should be close to the RX/TX sites.

– The operations centre should be co-located in an existing e-infrastructure centre.

– The deployment must be the most cost-efficient method to obtain the capacities.

– The operations centre computing and storage should be usable by other scientific communities.

– The operations centre must provide monitoring data to the EISCAT 3D control site(s).

• Hardware

– The operations centre computing must be specialized to the task of real-time computing.

– The computing hardware should be “future-proof”.

– Should have widespread use in industry and other scientific areas.

– Must be easy to program and the support for the programming (APIs, libraries) must be planned.

– Must be extensible, scalable and flexible.

– Energy consumption and heat efficiency and must fit within the EISCAT 3D budget.

– Should be compatible with a standard hardware rack system of the e-infrastructure centre.
A MATLAB script for EISCAT_3D rates

n_pol=2; % # polarisations
n_ant_sub=91; % # antennas/subarray
n_beam_sub=10; % # beams/subarray
calc_beam=1.5e9*2; % MAC*2 = flop delay calculations/beam
bw=30e6; % bandwidth
bw_i=5e6; % ionline bandwidth = tx bw
bit_sub=32; % # bits/sample after 1 stage beamforming
n_sub=109; % # subarrays
calc_beam_i=1.5e9*2*bw_i/bw; % MAC*2 = flop calculations/beam ionline
n_beam=100; % # beams/array
bit_site=16; % # bits in the final beam
iq=2; % iq factor
lag_prof=1e4*5e9; % lagprofiling 1e4 cores 5Gflop/core
t_buffer=1000; % 1000s ringbuffer
bit_byte=8; % # bits/byte
calc_anal=0.1; % calcs for analysis relative lp

calc_sub=n_ant_sub*n_pol*n_beam_sub*calc_beam % calculations at subarray
rate_sub=bw*iq*bit_sub*n_beam_sub*n_pol % output rate from subarray
rate_sub_i=bw_i*iq*bit_sub*n_beam_sub*n_pol % output rate from subarray, only ion line
calc_beam=n_pol*n_beam*n_pol*n_sub*calc_beam_i % calculations at 2nd stage beamformer
rate_site=bw_i*iq*n_beam*n_pol*bit_site % output rate from 2nd beamformer
calc_lp_anal=lag_prof*(1+calc_anal) % processing at site, lag profiling + analysis
ringbuffer=t_buffer*rate_sub_i*n_sub/bit_byte % ringbuffer size

low_duty=0.1; % low duty cycle factor
low_rate=0.9; % time on low duty
high_rate=0.1; % time on full duty
low_bw_i=5e6; % bandwidth on low duty
lp_red=0.1; % lagprofile data reduction
depol=1/n_pol; % depolarisation factor
rb_rate=7*86400; % save 1 full ringbuffer/week
rb_site=ringbuffer/rb_rate*bit_byte; % output rate from site, ringbuffer
volt_site=rate_site*(high_rate+low_rate*low_duty*low_bw_i/bw_i);
% output rate voltage data from site

tot_site_i=volt_site*(1+lp_red*depol)+rb_site
% output rate from site, ion line case
tot_site=volt_site+bw/bw_i*rate_site*lp_red*depol*(high_rate+low_rate*low_duty)+rb_site*bw/bw_i

12
%output rate from site, ion+plasma lines

n_site=3; %#sites

t_buffer=120*86400; %buffer time @ op centre

et_volt=0.01; %voltage data to eternal storage

et_lp_i=1; %lp data integration to eternal storage, ion line

et_lp_p=0.10; %lp data integration to eternal storage

op_storage=tot_site_i*n_site*t_buffer/bit_byte %storage at op/data centre

op_calc=n_site^2*calc_lp_anal %processing at op/data centre

et_storage_i=n_site*(volt_site*(et_volt+lp_red*depol*et_lp_i))...
*365*86400/bit_byte %to archive per year, ion line case

et_storage=n_site*(volt_site*...
(et_volt+lp_red*depol*(et_lp_i+(bw/bw_i-1)*et_lp_p)))...
*365*86400/bit_byte %to archive per year, i+p lines

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