LOFAR 2.0 Stage 1 Station PDR Design

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Station Architectural Design for LOFAR 2.0 Stage One

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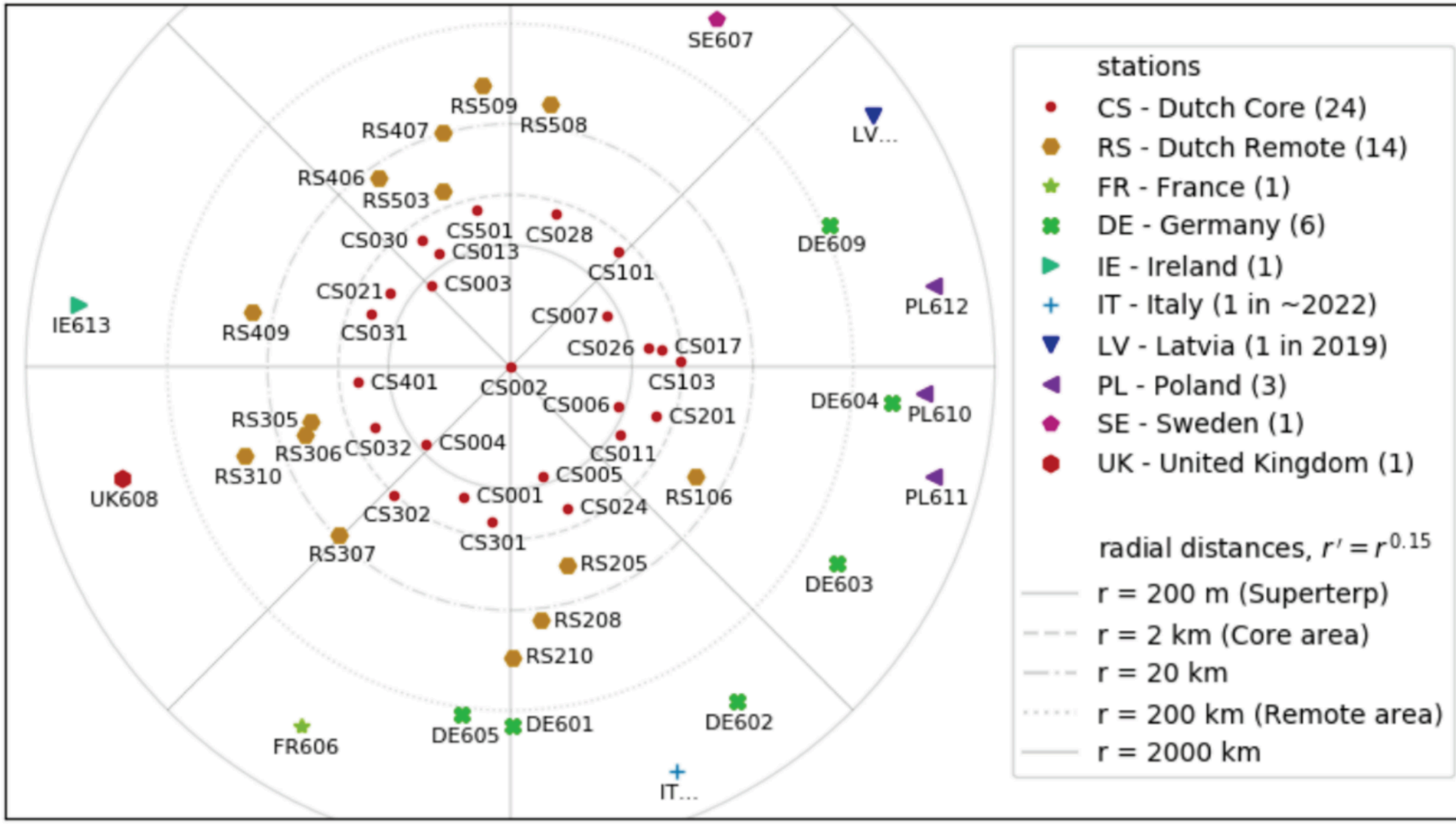
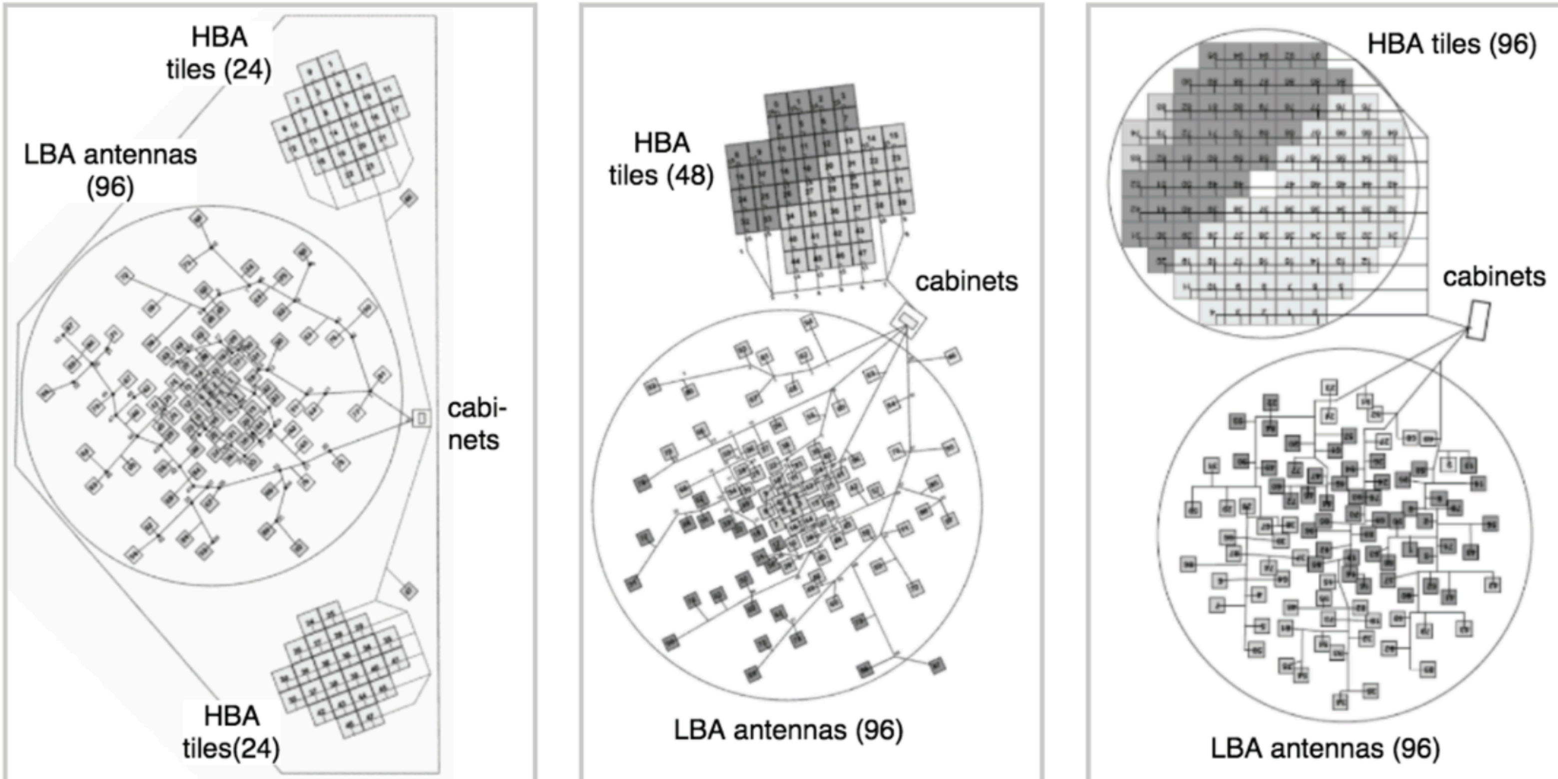
LOFAR2.0 Stage 1
Station Architectural
Design Document (ADD)

LOFAR ILT Stations



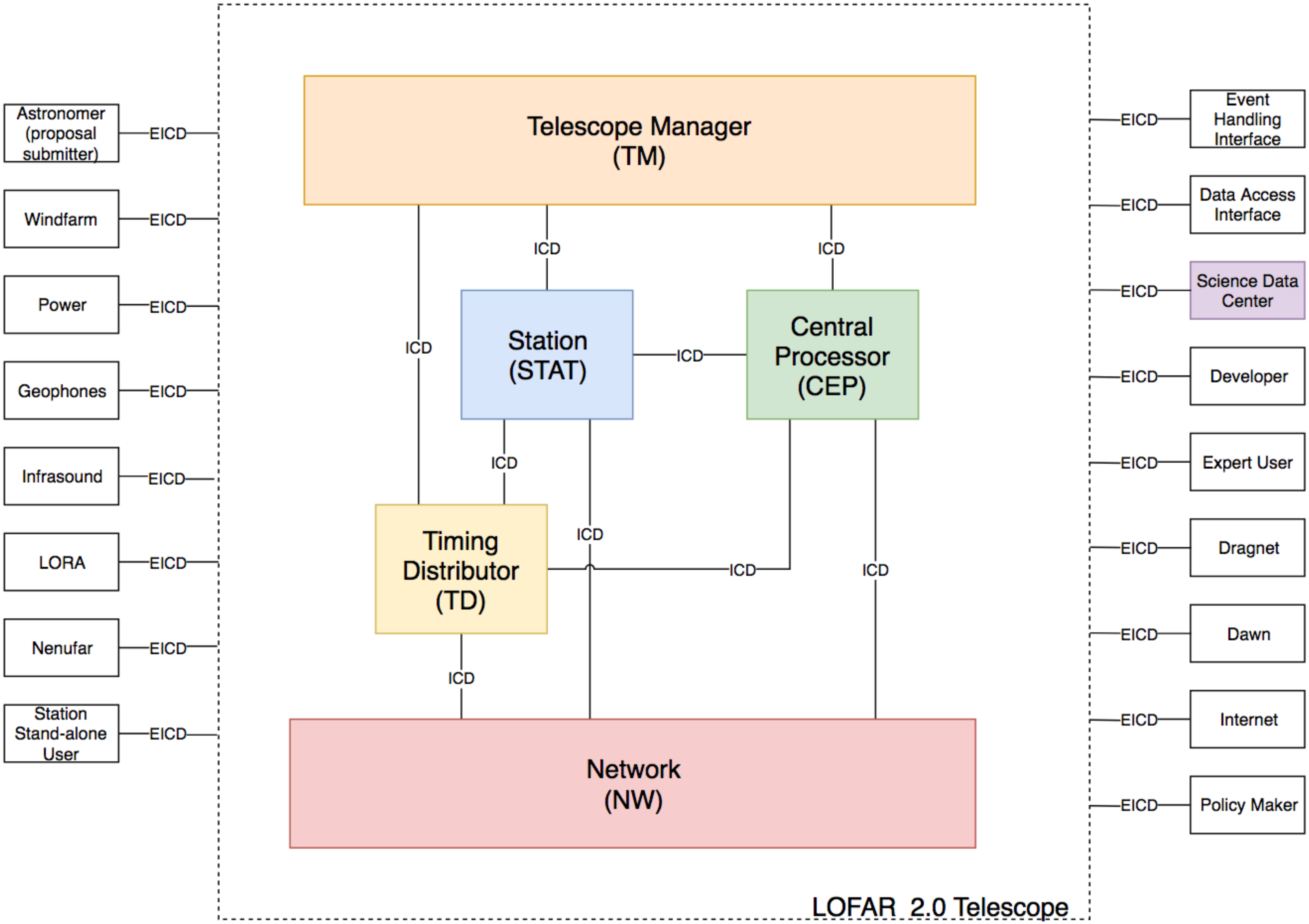
Distribution of LOFAR stations (total 52+1) in relative distances to the core centre plotted using an exponential scale

LOFAR Core, Remote, Int. Stations

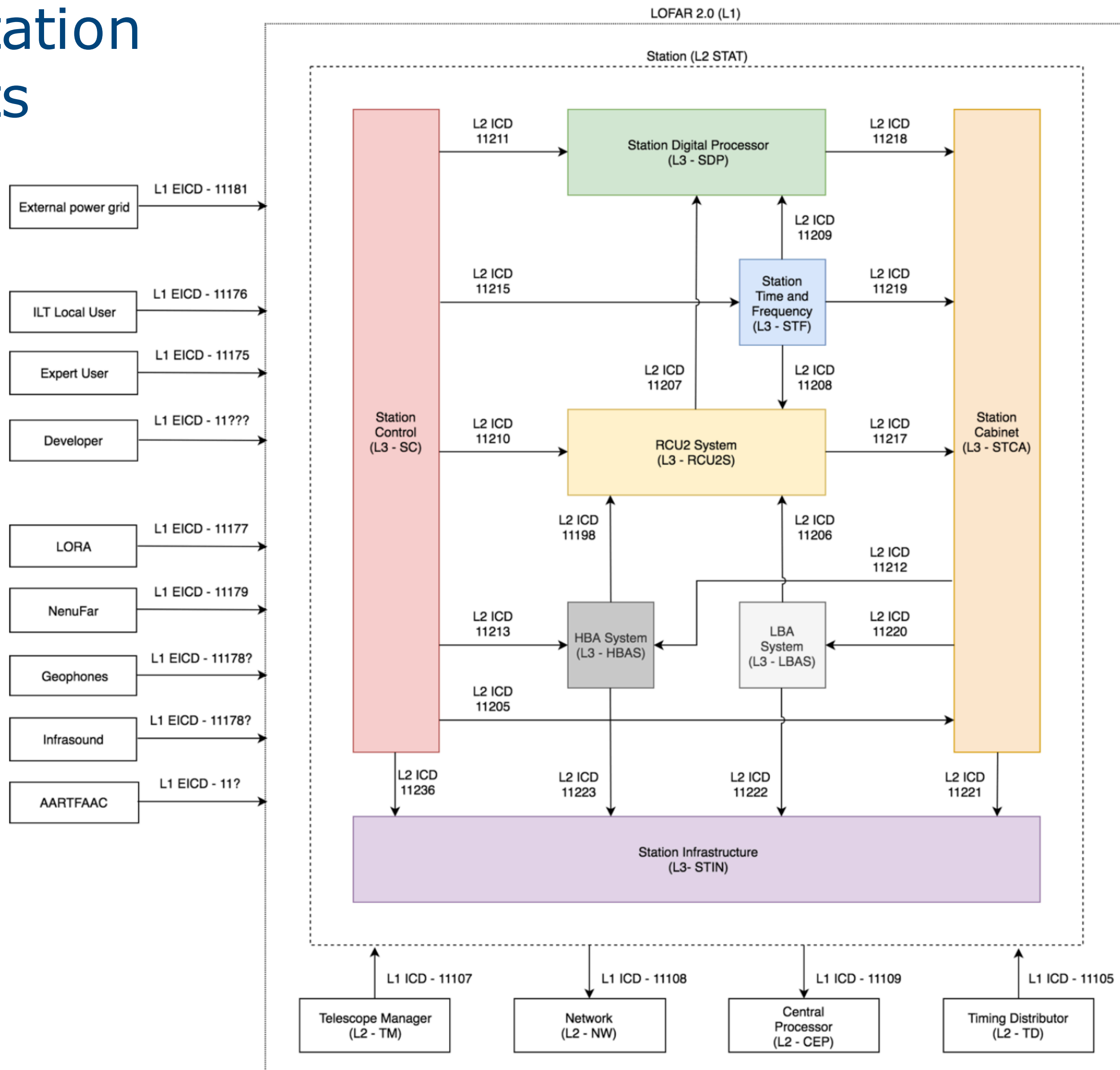


Core Station (24) | Remote Station (14) | International Station (14+1)

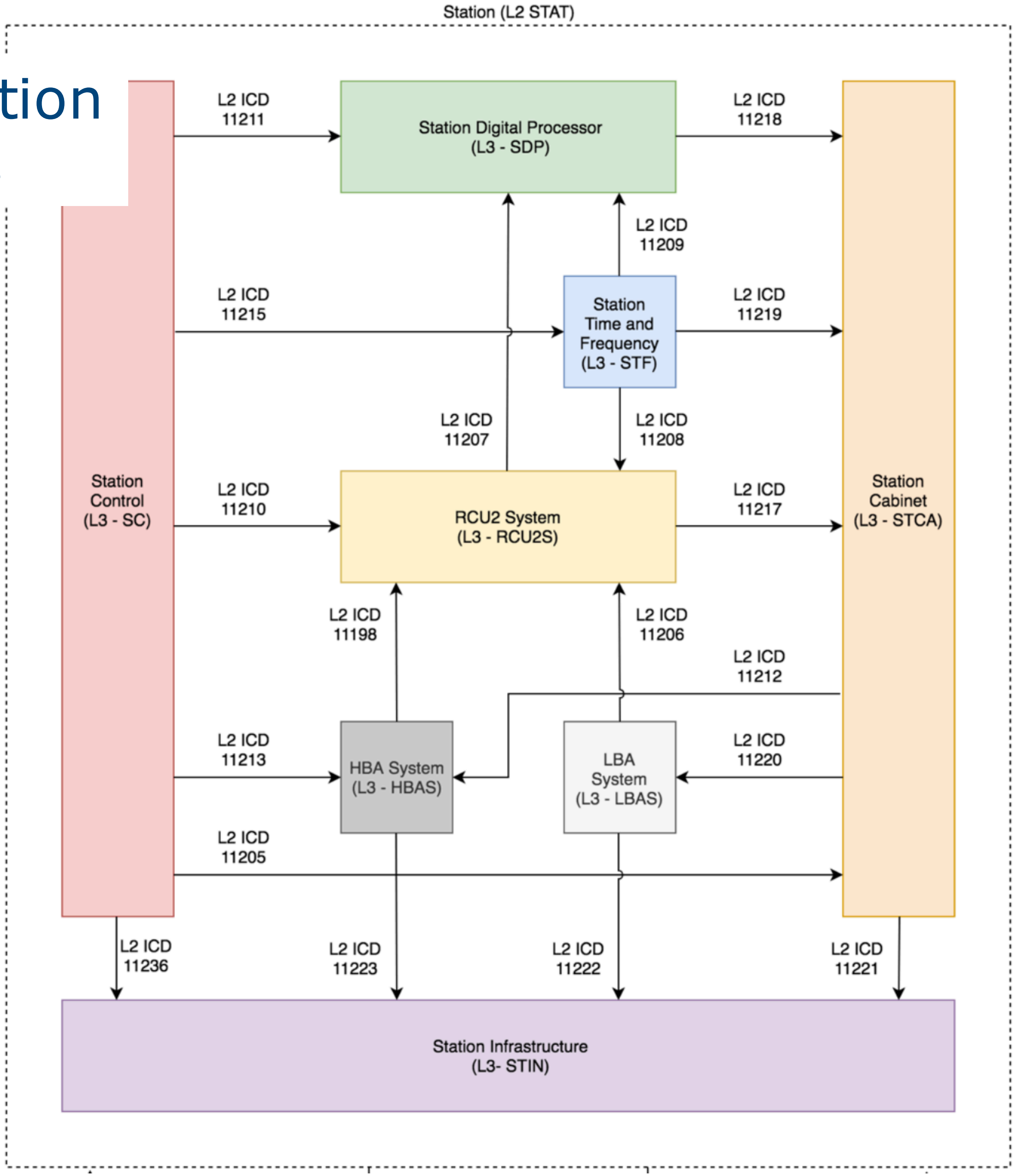
LOFAR L2 System Products



LOFAR L2 Station - L3 Products



LOFAR L2 Station – L3 Products



Prpoposed enhancements

Taking into account

- scientific requirements,
- component obsolescence, and
- telescope life time,

the LOFAR2.0 stage 1 station upgrade includes

- **Dual band**: enabling simultaneous observation capability for Low Band Antennas and High Band Antennas,
- **Receivers**: doubling the number of receiver channels for core and remote stations,
- **Clock**: improving clock and reference signal accuracies for core and remote stations,
- **Linearity**: improving receiver linearity, and
- **Hardware**: redesigning and replacing of

LOFAR 2.0 stage 1 system level modes

1. Imaging Mode
Correlation of station (subband) beams to produce visibilities(*), and derive sky maps

2a. Tied- Array Mode – Coherent Stokes
Adding station (subband) beam signals coherently, forming complex voltage time series

2b. Tied- Array Mode – Inoherent Stokes - Adding station (subband) beam signals incoherently, forming summed complex time series

3. Fly's Eye Mode
Multiple station (subband) beam time series signals are stored, not added

4. Direct Storage Mode
Triggered raw real antenna ADC signal time series dump. Triggers from

- LORA (cosmic rays, latency ~ 5s)
- station RMS triggers (cosmic rays, seldom used, latency < 1 s?)
- tied-array beam detectors (at CEP,latency ~ 5s)
- lightning website

5. Subband Storage Mode (a.k.a. spectral mode, dispersion based subband sel.)
Triggered complex sub-band antenna time series signal storage, triggers e.g. from ARTS.

6. Local Station Mode
All stations can be placed under local control, and local Station data are extracted

7. All-sky Imaging Mode, AARTFAAC (&AARDWOLF future extension)
Correlation of all LBA antenna subband signals, extracted before station beam-former

8. SSA / Space weather

Station Driving Requirements (1 of 4)

LOFAR2.0 - LOFAR 1.0 compatibility

- LOFAR2.0 stations shall be able to operate for nearly all observation types available to LOFAR 1
- Mixed simultaneous coherent observations should be possible between upgraded (LOFAR2.0) and LOFAR 1 stations

Dual band capability and spectral requirements

- LOFAR 2.0 should be able to operate in the same bands as LOAR 1.0 Stations, except for the 170-230 MHz (can be added later)
- LOFAR 2.0 is required to support processing (RF) bandwidth of about 96 MHz, but is specified in terms of number of subband beams
- Station shall be able to support at least 488 subbands per RF band for each polarization
- LOFAR 2.0 should also enable simultaneous observations for Low Band Antennas and High Band Antennas, one band in each antenna array.
- Simultaneously observing should be possible in any combination of LBA bands and HBA bands.

Receivers, doubling number of antenna inputs

- LOFAR2.0 shall observe simultaneously with the LBA outer and the LBA inner antennas, in dual polarization

Station Driving Requirements (2 of 4)

Antennas

- Station antenna upgrades are not part of stage 1

Cabin

- Stage 1 upgrade of the Station shall be installed and fit in the LOFAR 1.0 housings
- The Station outdoor (sub)system, assemblies and parts shall withstand 31 degrees ambient (outdoor) temperature without compromising any functional requirement

Station buffer

- Station supports capturing raw ADC voltages or subband voltages for all Station antennas in a storage buffer, but not LBA and HBA simultaneously (Direct Storage Mode or in Subband Storage Mode)
- Station in Direct Storage Mode shall buffer baseband electromagnetic signals for a buffer duration of >=2.5 seconds
- LOFAR2-2295, The Station in Subband Storage Mode, shall be able to increase the buffer duration up to 60 seconds.

Station correlator

- The Station, in Subband Correlate Mode, shall generate correlation data, being the array correlation matric (ACM) of the received EM signals.

Station Driving Requirements (3 of 4)

Latencies

- Stations shall be able to transit to another Production Mode within 20 seconds (7 seconds is nice to have)
- Station beam shall have scheduled repositioning latency of maximum 1 second, and a start-up time of maximum 10 seconds

Beamforming

- LOFAR2.0 should support the same beamforming functionality as for LOFAR 1.0 should be supported
- For Station subband beams, broadband reconstruction for combined subband contiguous frequencies should be alias-free, implying an oversampled filterbank must be used
- This has implications for joint LOFAR 1.0 – LOFAR 2.0 use as LOFAR 1.0 uses a critically sampled filterbank
- Each Core Station shall be able to form at least 2 HBA substations

Operational cost

- The L1 operational cost of LOFAR 2.0, should be lower or equal to the operational cost of LOFAR 1.0. Note: this is an L1 requirement not yet completely converted to Station requirement
- The Station, in Low-Power State, shall have a maximum power consumption of 250 W

Station Driving Requirements (4 of 4)

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Linearity requirements LBAS and HBAS

- The Station shall receive and process EM signals in the High Band such that the power of any spurious signal <=-56.5 dB relative to the power of the instantaneous thermal noise measured at the input of the ADC.
- The Station shall receive and process EM signals in the Low Band such that the power of any spurious signal <=-52 dB relative to the power of the instantaneous thermal noise measured at the input of the ADC.

Assumptions

This designs provided in this document assume the following:

- simultaneous LBA-HBA LOFAR 2.0 observations do not include LOFAR 1.0 stations
- commensal modes for LOFAR 1.0 and LOFAR 2.0 are the same
- subband fan out is considered in terms of scalability (AARTFAAC, AARDWOLF, SSA)
- 'tied-array' mentioned in L1 LOFAR-3060 means to include both coherent and incoherent beams,
- HBA reliability is out of scope for stage 1, as is pipelines, and
- Core Stations and Remote Stations will not be exported outside the Netherland, for environmental conditions (temperature) reasons, but will make separate Int. Station design

Stage 2 scalability considerations

LOFAR2.0 stage 2 envisioned upgrades (e.g. LOFAR4SW, AARDWOLF) are not included in the scope of this stage 1 station design. However, some aspects are looked into:

- redesigning and replacing the HBA tile electronics including the creation of a second tile (RF) beam (spurious signals during transit),
- redesigning and replacing the LBA antennas,
- doubling the number of LBA station beams,
- reducing responsive telescope latency (<10's of s for LOFAR as a whole), and
- improving reliability and efficiency of operations (more automatic).

LBA System (LBAS)

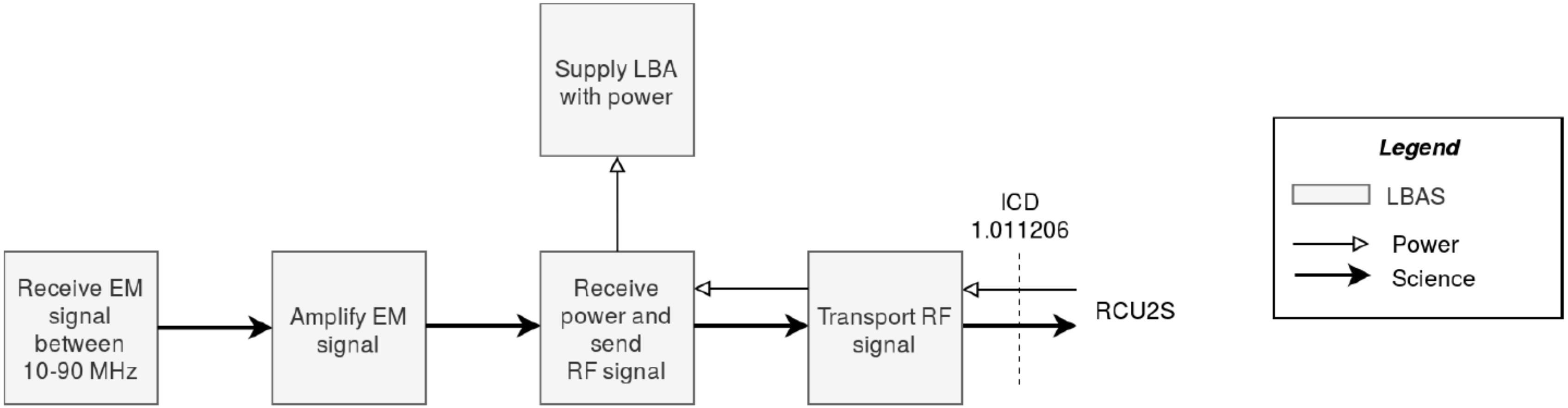

Figure 3.3.2-1 Overview of the functions and signal flow of the LBAS and its interface with the RCU2. The LBA System is reused from LOFAR 1.0.

HBA System (HBAS)

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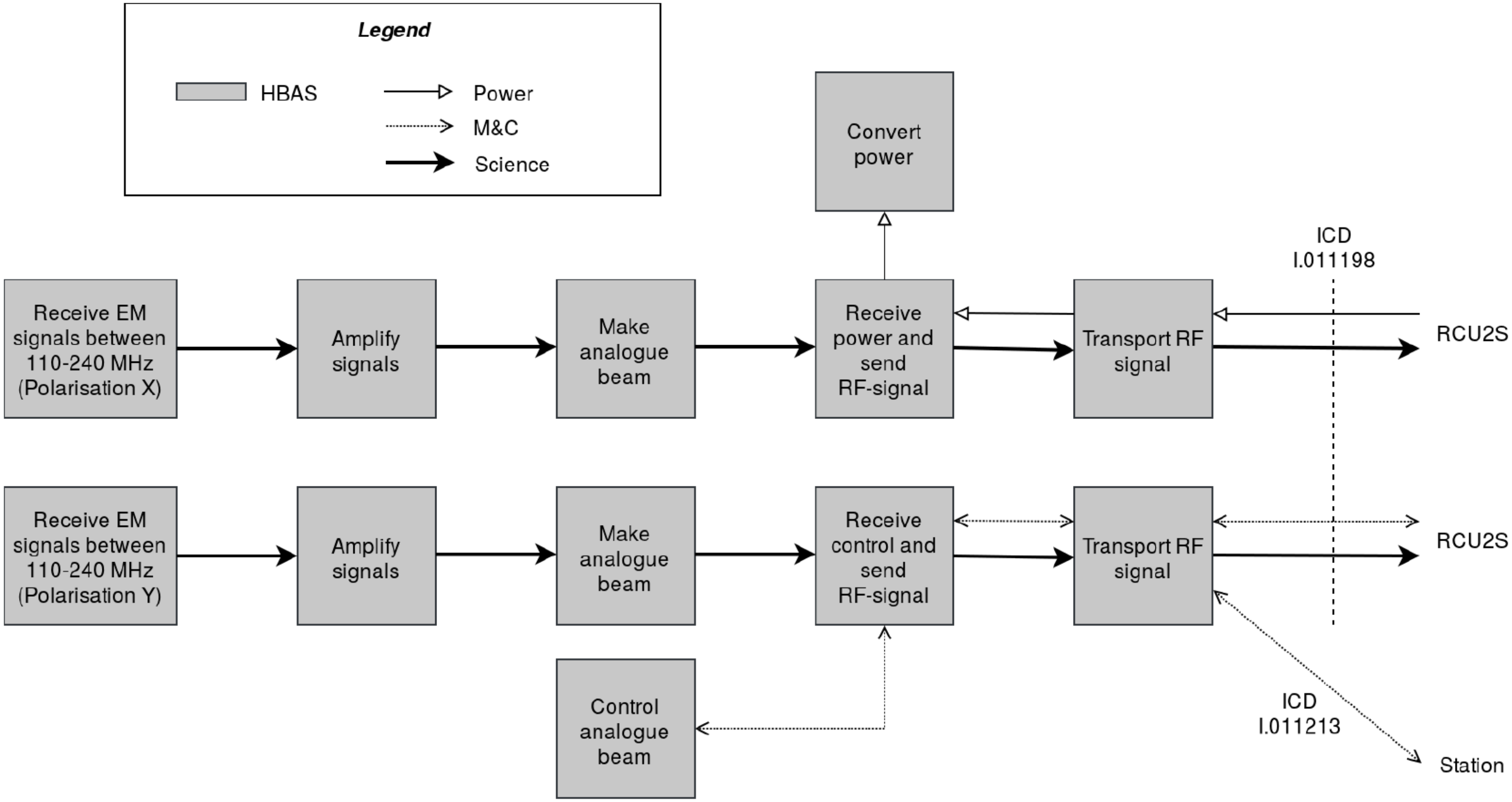

Figure 3.3.3-1 Overview of the functions and signal flow of the HBAS and its interface with the RCU2S. The HBA System is reused from LOFAR 1.0.

HBA System (HBAS) – design decision

Split between HBA and LBA receiver units

- More flexibility in the number of HBA antenna input versus the number of LBA inputs. To facilitate a second HBA beam for LOFAR4SW an extra HBA rack can be placed in the cabinet
- Functionality split between the high and the low band, relaxed data transport
- Upgrade-ability of only HBA or LBA possible
- Possible to run at two different clock frequencies

An RCU2 with 3 signal paths will be made (for LBAS and HBAS)

The drawback of this solution

- Two receiver designs could results in higher production cost due to start-up cost
- Cabling might be more difficult, it is not a simple board replacement
- The HBA receiver chain needs more board space compared to the LBA receiver chain, a mix could be helpful

Receiver Unit System (RCU2S)

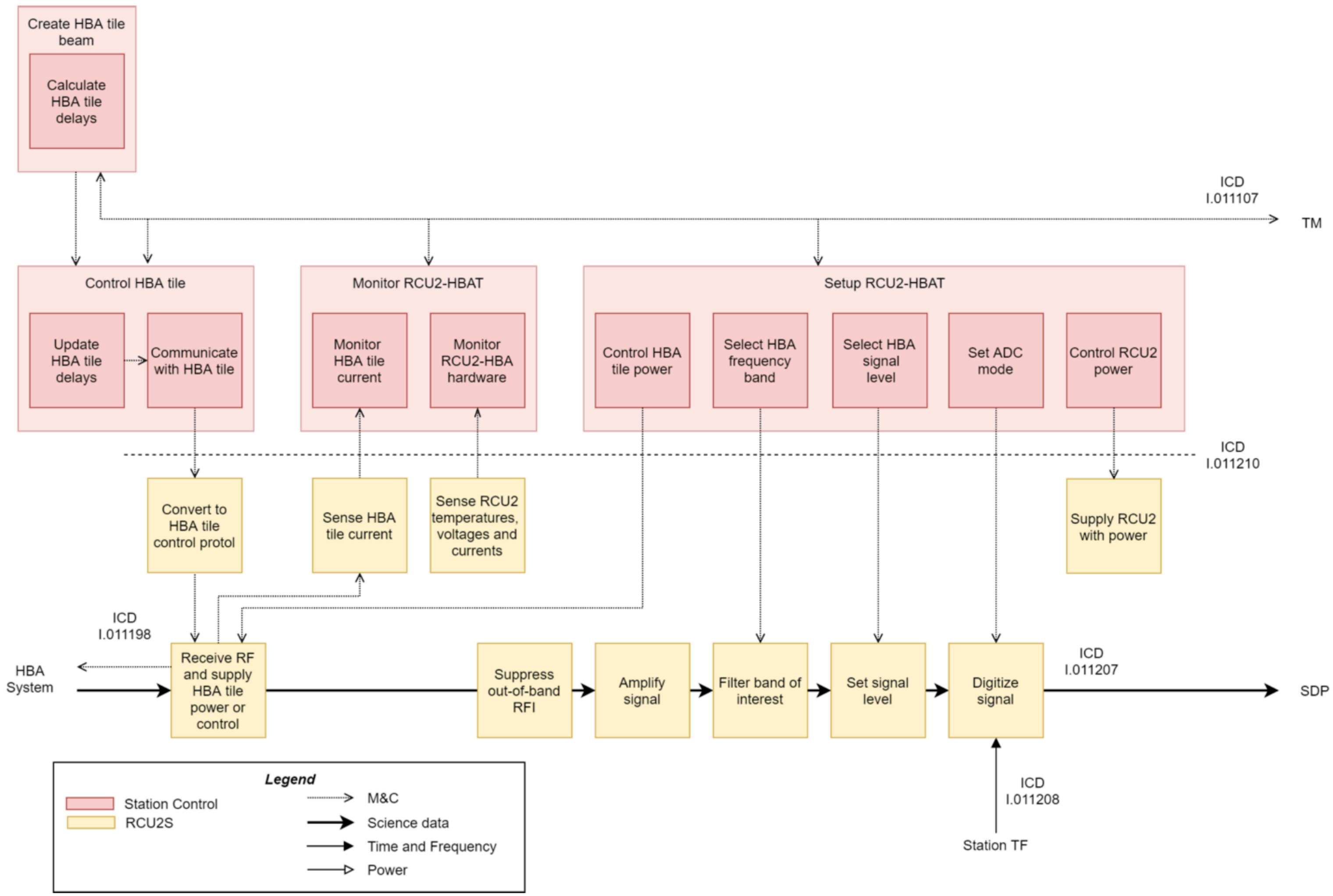

Figure 3.3.6-1 Overview of the functions and signal flow of RCU2S-HBAS and how these functions relate to functions in Station Control

Station Digital Processor (SDP)

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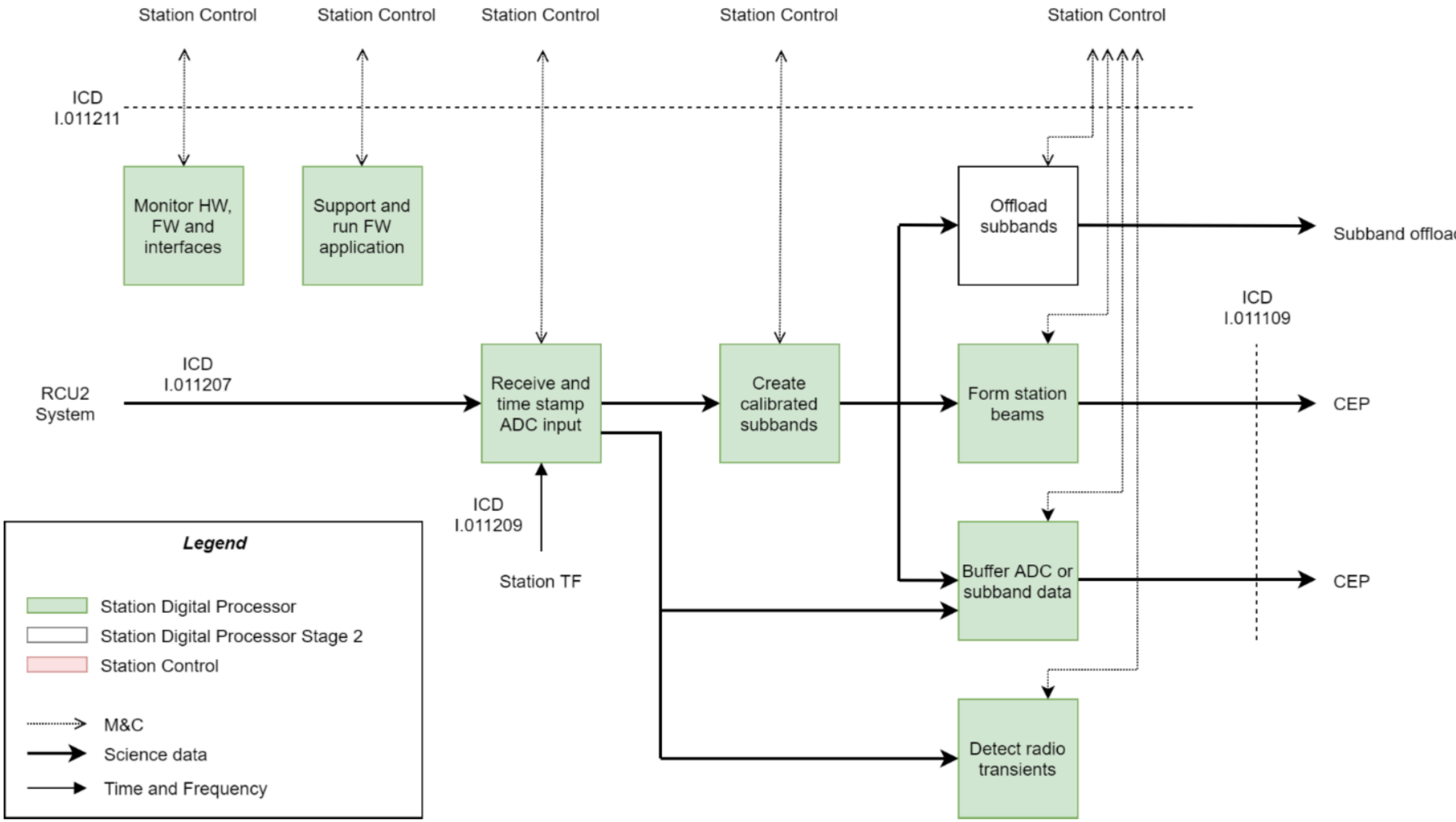
overview of the functions and signal flow of SDP



Station Digital Processor (SDP)

The driving properties of the UniBoard2 are:

- TBB storage of ≥ 2.5 seconds per signal input possible
- Existing solution resulting in relative high TRL, level 8
- Reduced development time, only relative small changes are needed
- Solution fits the current LOFAR 1.0 cabinets, 3 subracks with electronics
- Spare processing capacity for future updates, expected that 50% is used for the LOFAR 2.0 stage 1 application

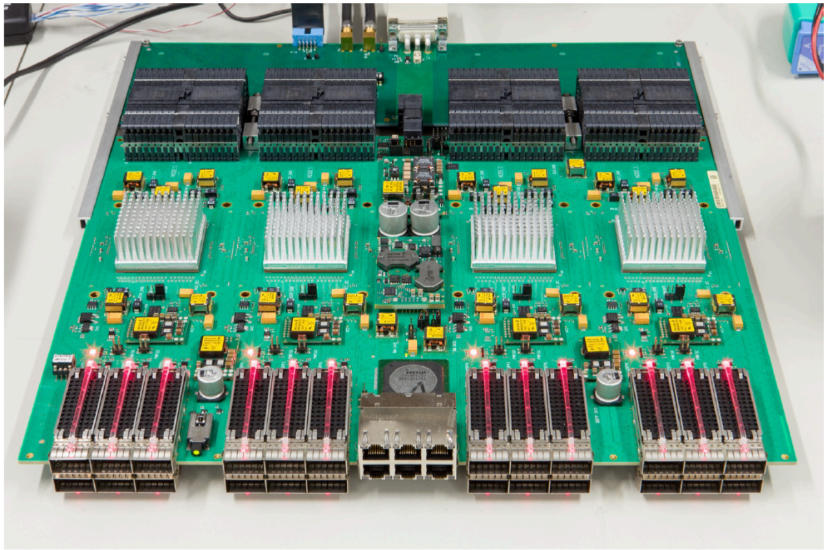


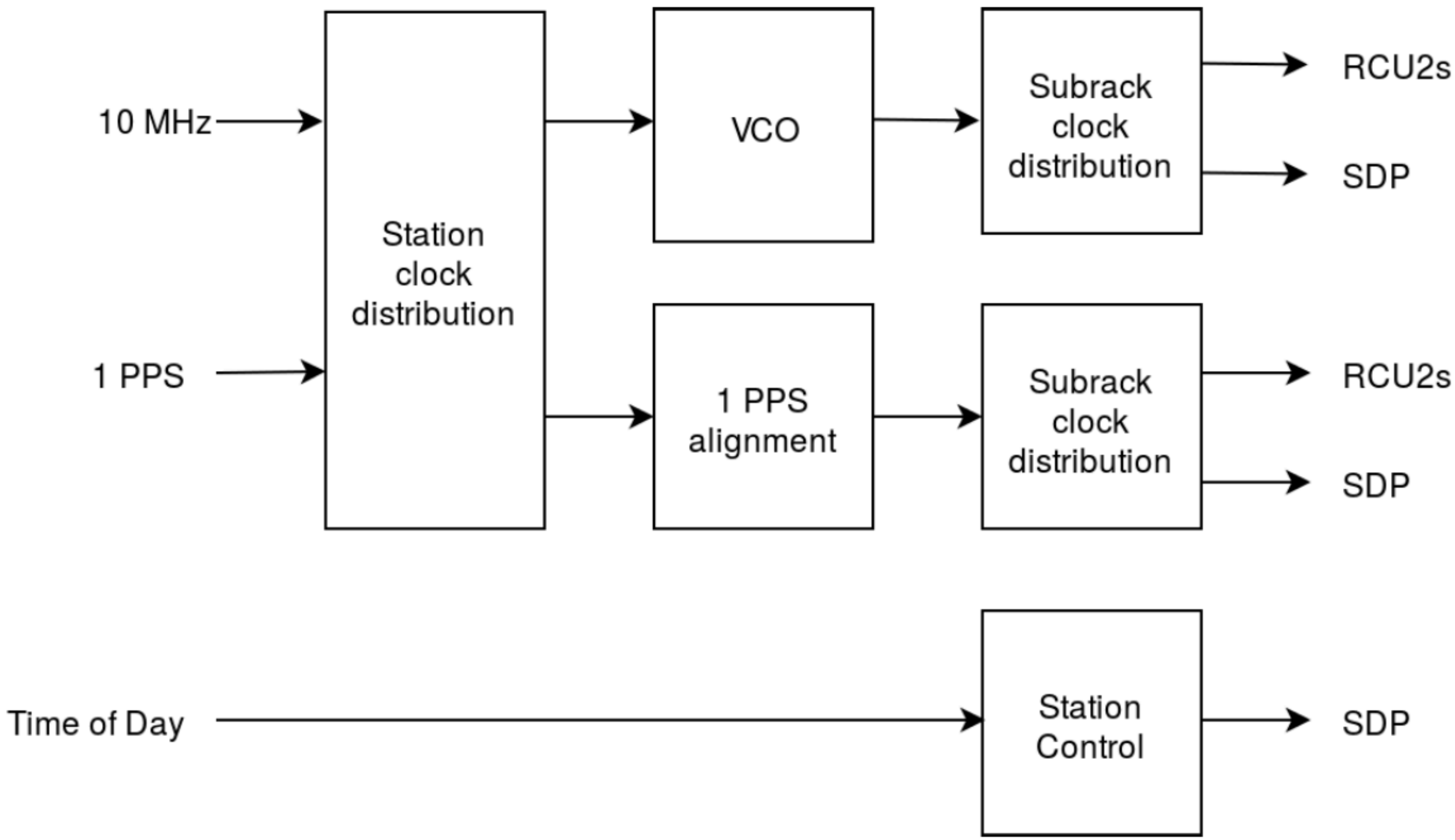
Figure 4.5.1.1-1 Picture of UniBoard²

SDP – design decision

SOme of the SDP design decisions:

- Using same **subband bandwidth** of 195312.5 kHz at 200 Msps (or 156250 Hz at 160 Msps) as in LOFAR 1.0
- For compatibility with LOFAR 1 a critically sampled (i.e. R_os = 1) subband filterbank will be used. For LOFAR 2.0 only observations an **oversampled subband filterbank** will be used with R_os ~ 1.25
- **BF weights update rate** of 1 Hz based on the PPS, similar as in LOFAR 1.0
- **Apply BF weights immediately** when they are set by M&C, instead of at the next PPS (lower implementation cost)
- The Station does **not do orthogonalization** per station beam output, any orthognalization per station beam will be done at CEP
- The station digital beamformer will support **8 bit beamlet** mode. The 16 bit and 4 bit beamlet mode from LOFAR 1.0 are not supported
- Current baseline: A **ring architecture** of option 1 will used to implement the beamformer, the correlator and the data output. As fall back we can use a ring + 10GbE switch
- The **subband correlator** will be implemented on the FPGA (GPU is more expensive) as a dedicated function that can run online, similar as in LOFAR 1.0

Station Time and Frequency distribution(STC)



Station T. and F. distribution (STC)

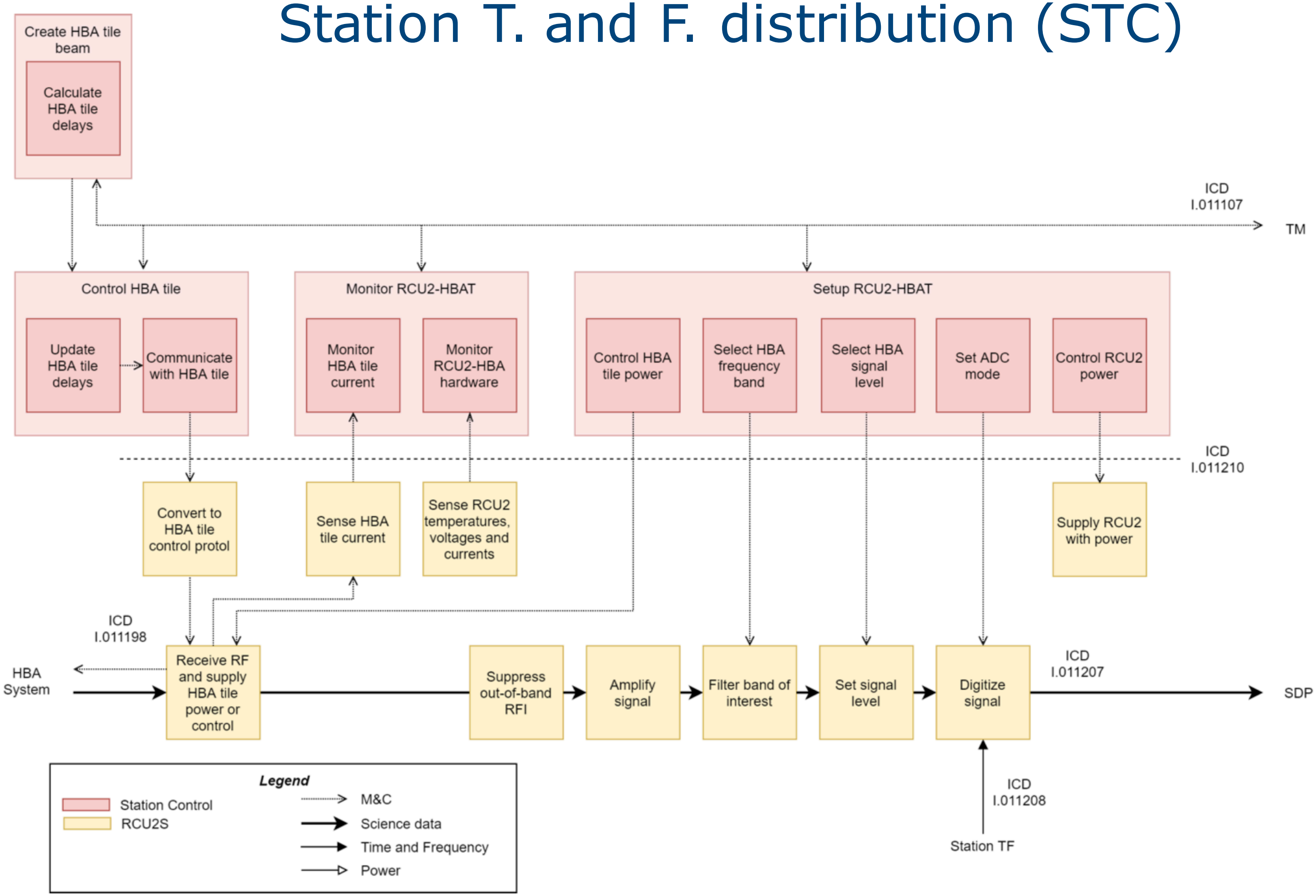
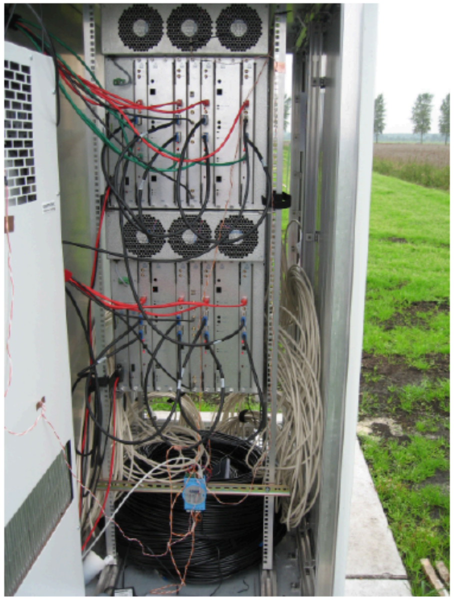


Figure 3.3.6-1 Overview of the functions and signal flow of RCU2S-HBAS and how these functions relate to functions in Station Control

Station Cabinet (STCA)

The driving aspects for the LOFAR 2.0 Station Cabinets are:

- Limit cross talk between signal processing paths
- Limit self-generated EMI.
- High reliability over a life time of 10 years.
- Station electronics designed for LOFAR 2.0 should fit in the LOFAR 1.0 cabin
- Minimal installation time
- Minimal time to repair (MTTR)



Station Cabinet (STCA)

Design decisions Dutch cabinet cooling
for the Remote and Core Stations.

- It is preferred to use an air to air heat exchanger since overall it seems to be the better option especially in relation to operational related items

Design decisions cooling for the International stations.

- International stations use a 20ft container for housing the electronics. Since at this moment there seem to be no problem with cooling capacity the proposal is to keep the current cooling system in place

Station Cabinet (STCA)

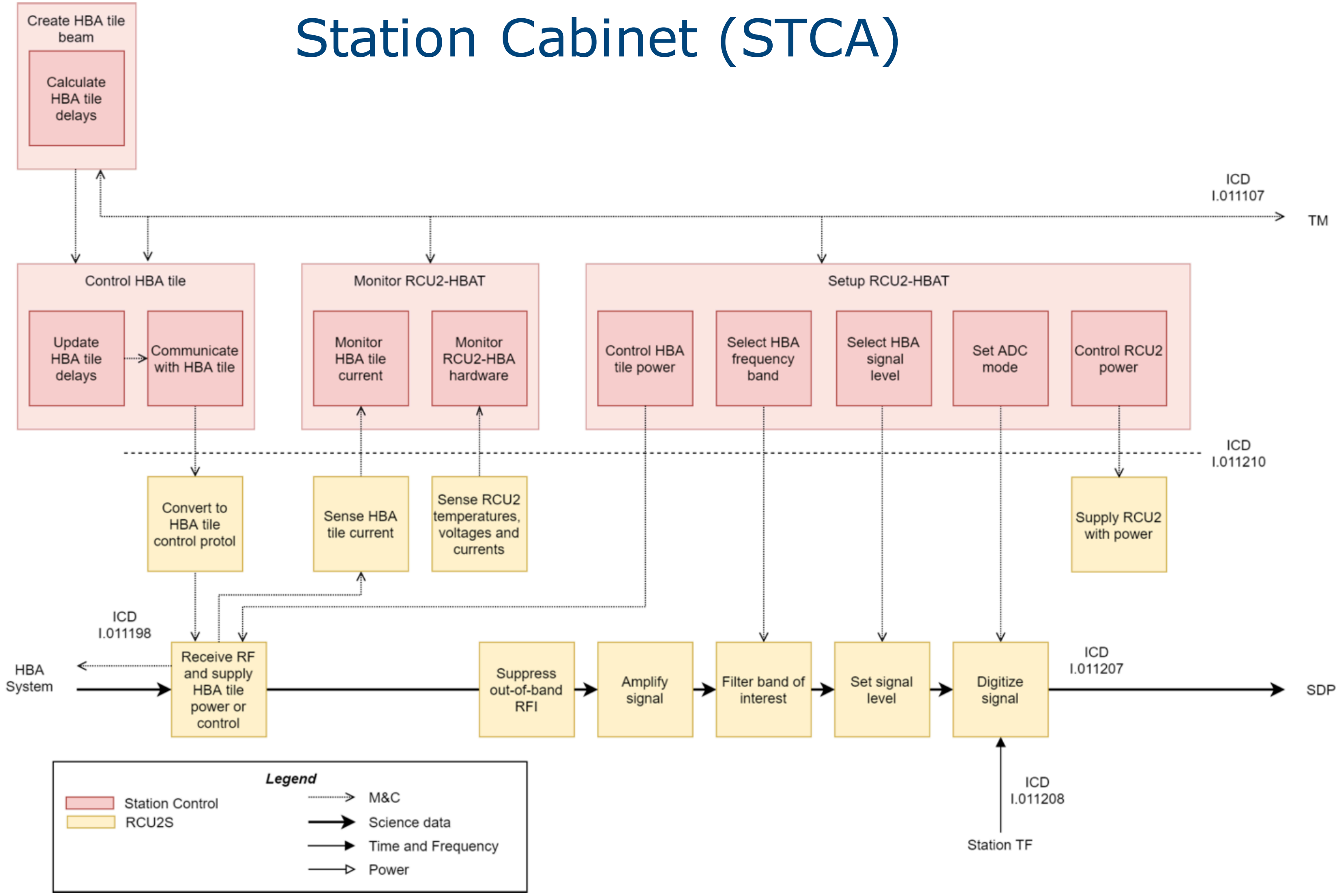


Figure 3.3.6-1 Overview of the functions and signal flow of RCU2S-HBAS and how these functions relate to functions in Station Control

Station Cabinet (STCA)

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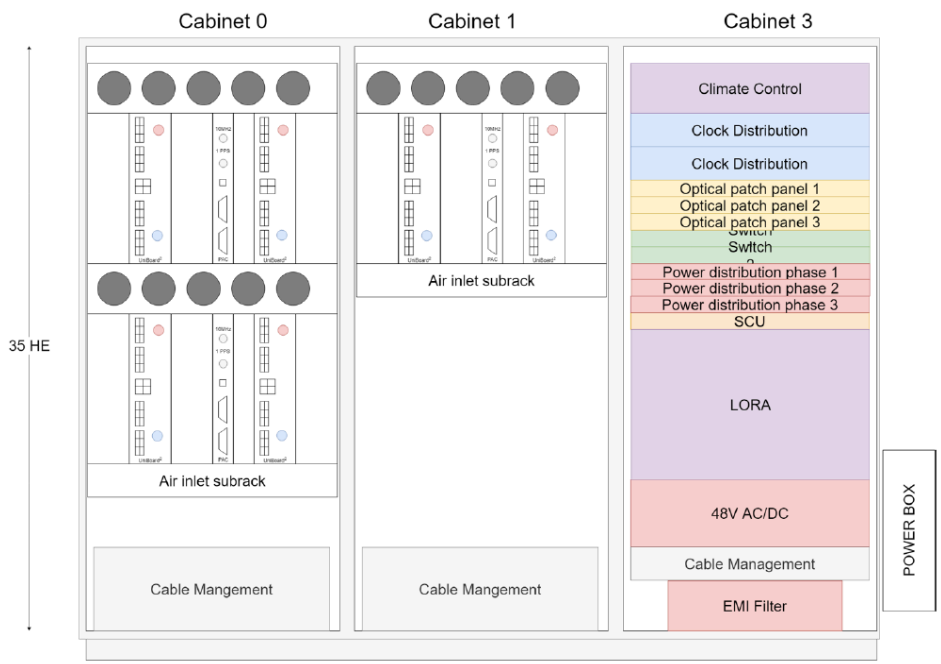


Figure 4.7.1-2 Station cabinets for a Dutch station seen from the UniBoard[2] side with on the left the control cabinet, the middle the HBA cabinet and at the right the LBA cabinet.

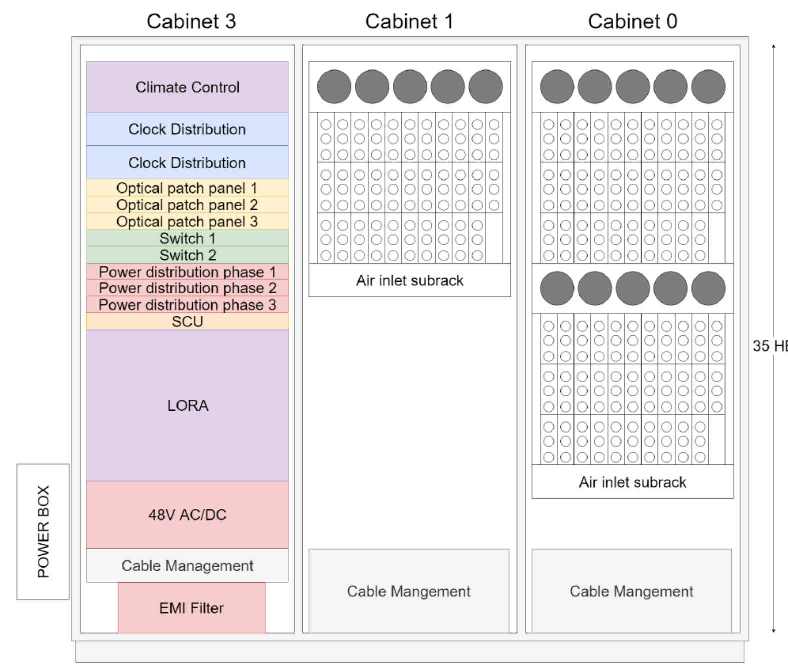


Figure 4.7.1-1 Station cabinets for a Dutch station seen from the RCU2 side with on the left the control cabinet, the middle the HBA cabinet and at the right the LBA cabinet.

Station Cabinet (STCA)

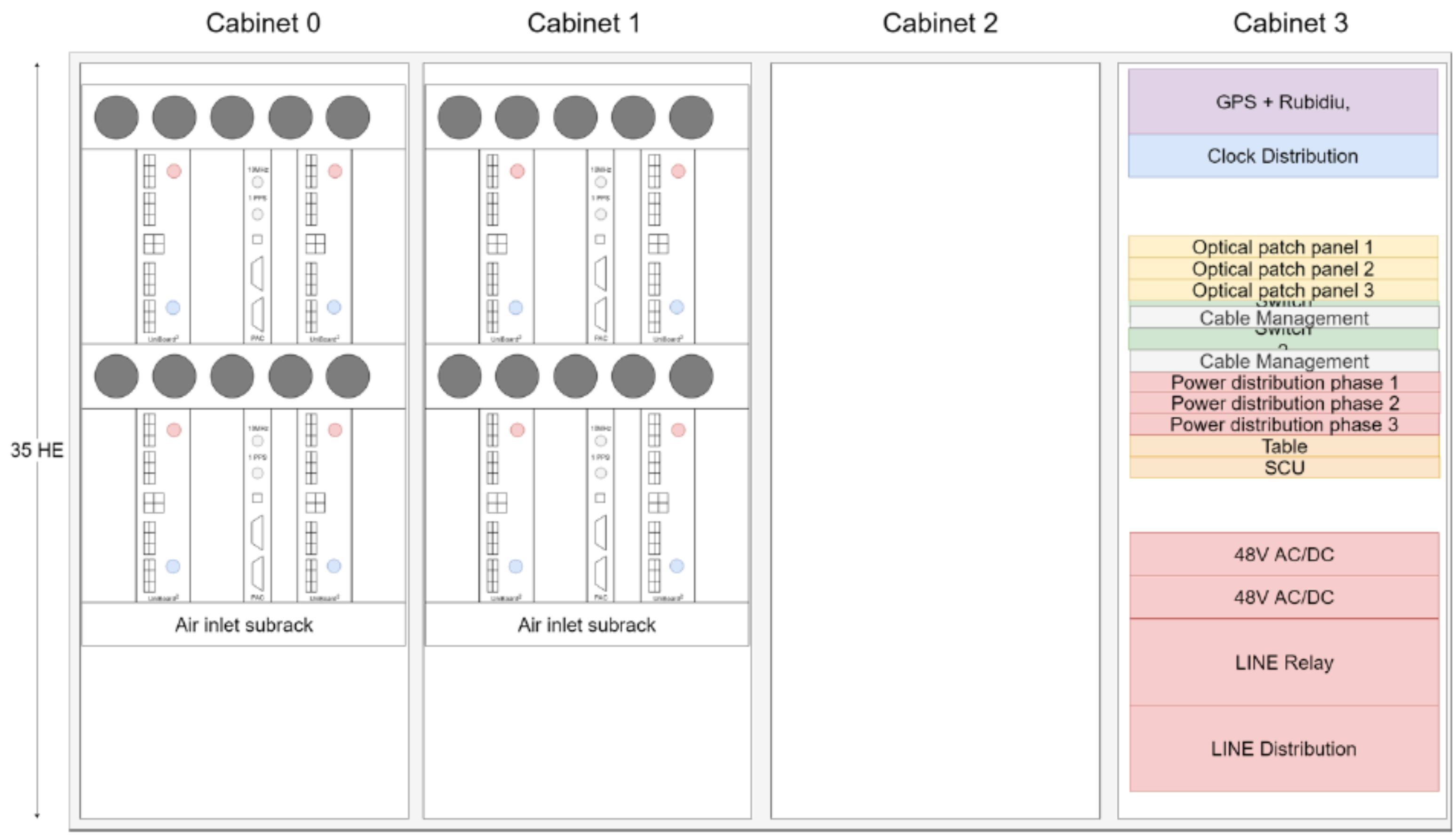
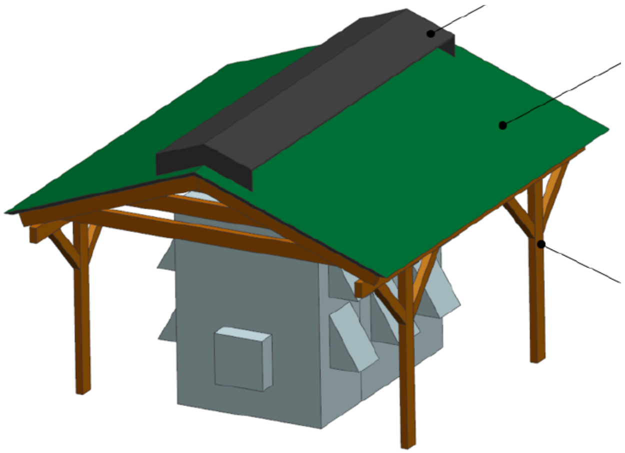


Figure 4.7.1-3 Cabinet layout of an International station seen from the UniBoard² side.

Station Infrastructure (STIN)
Station Cabinet cooling (STCA)



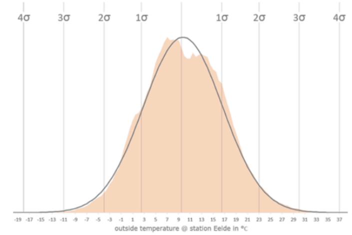
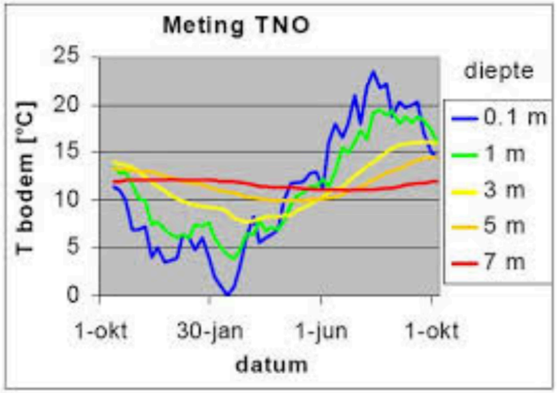
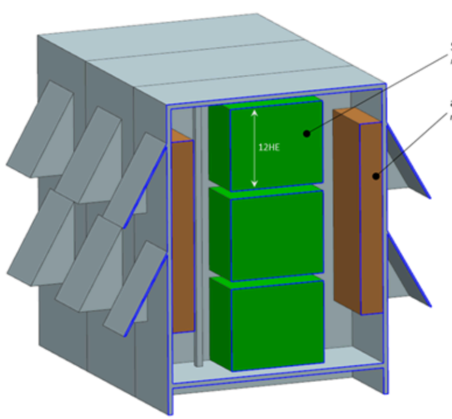


Figure 4.8.1.4-1 Normal distribution of hourly temperatures of station Eelde over a period of 30 years





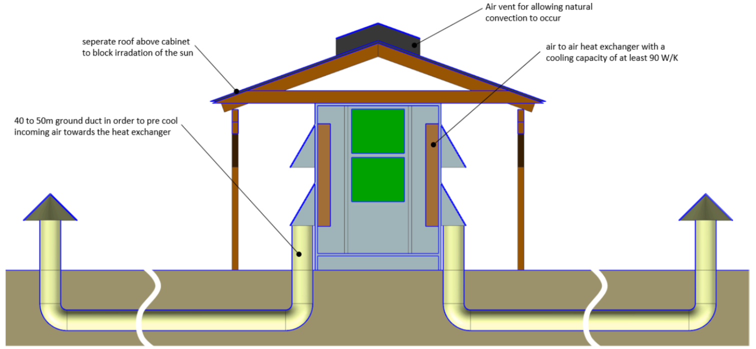


Figure 4.8.1.6-4 Potential construction when all concepts applied.

Assumptions

- Maximum allowed downtime <1.5 % per y
- Heat load per Dutch cabinet: 8 kW

LRUs

Table 4.7.1-1 The number of line replaceable units in the subrack and station.

LRUs	1 Antenna Processing Subrack	1 Core or remote station	38 Dutch Stations	1 International station	14 International Stations	All (incl. 5% spare)
UniBoard[2]	2	6	228	8	84	328
RCU2_L RCU2_H	32 or 32	64 32	2432 1216	64 64	896 896	3495 2218
PCC	1	3	114	4	56	179
Midplane	1	3	114	4	56	179
Station Time Distributor		1	38	1	14	55
SCU		1	38	1	14	55
48V power supply		1	38	1	14	55
Power Line Filter		1	38	1	14	55
Power Distribution		1	38	1	14	55
10 GbE Switch		1	38	1	14	55

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LOFAR1-LOFAR2.0 compatibility

Value	LOFAR 1.0	LOFAR 2.0
Antenna Set		
Max fraction of antennas	33%	100%
LBA_INNER	✓	✓
LBA_OUTER	✓	✓
LBA_SPARSE_EVEN	✓	✓
LBA_SPARSE_ODD	✓	✓
LBA_X	-	✓
LBA_Y	-	✓
LBA_ALL (TBD)	-	✓
HBA_ZERO	✓	✓
HBA_ONE	✓	✓
HBA_DUAL	✓	✓
HBA_JOINED	✓	-
HBA_ZERO_INNER	✓	✓
HBA_ONE_INNER	✓	✓
HBA_DUAL_INNER	✓	✓
HBA_JOINED_INNER	✓	✓
Clock Mode		

Setting	Value	LOFAR 1.0	LOFAR 2.0
Local scripts	It is possible to add user scripts or programs that are not parts of the station control.	✓	-

Value	LOFAR 1.0	LOFAR 2.0
160 MHz	✓	-
200 MHz	✓	✓
Bits/sample		
2 bit	-	-
4-bit	-	-
8-bit	✓	✓
16-bit	✓	-
Band Filter		
LBA_10_70	✓	✓
LBA_10_90	✓	✓
LBA_30_70	✓	✓
LBA_30_90	✓	✓
HBA_110_190	✓	✓
HBA_170_230	✓	-
HBA_210_250	✓	✓
Data Stream		
Count (Core Stations)	2	3
Count (Remote Stations)	1	2
Count (International Stations)	1	2
Beamlets (@8-bit, 200 MHz)	488	488
Pointings		
Digital beams (SAPs)	~400	
Analog beams (HBA)	1	1

Table 10.2-1 Overview of the main (science driven) non-compliant requirements.

#Requirement	Requirement	ADD Chapter	ADD result	Action
LOFAR2-2278	Alias-free subbands	4.5.2.2		See section 8.4.1
LOFAR2-1013 (L1) LOFAR2-4504 (L2) LOFAR2-2207	Operational cost LOFAR 2.0 < LOFAR 1.0 Low power mode < 5%	4.7.3 6.5		Although LOFAR 1.0 is designed 10 years ago, and the processing increase for LOFAR 2.0 is only a factor 3, keeping the power equal is not trivial as Moore's law is flattening and the power consumption of the analog processing, which is not included in Moore's law is dominating. To keep the operation budget at the station equal, a more advanced maintenance schema will be made.
LOFAR2-3179	Linearity requirement: Spurious signal HB <= -56.5 dB w.r.t. thermal noise.	6.1.3		Non-compliant at stations with high levels of RFI when using LOFAR 1.0 HBA. RCU2 designed so that it will be compliant when using a more linear HBA. Compliant using L4SW HBA.
LOFAR2-3180	Linearity requirement: Spurious signal LB <= -52 dB w.r.t. thermal noise.	6.1.3		Non-complaint at stations with high levels of RFI when using LOFAR 1.0 LBA. RCU2 designed so that it will be compliant when using a more linear LBA.
LOFAR2-3630	minimum boresight sensitivity	6.1.1		Non-complaint above 180 MHz and below 55 MHz. RCU2 is designed so that it will be compliant when using a lower noise HBA and LBA.

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Requirement non-compliance

Potential cost reduction

Options include

- Limiting the number of stations available for upgrading, while keeping nonupgraded (LOFAR 1.0) stations functional and active
- Limiting the number of stations with double HBA receiver inputs, for example in the Core (Superterp) area HBA tiles from one station could be used to calibrate the LBA antennas on the same station and on a nearby station
- Reusing designs (HW, SW FW)
- Limiting options and flexibility,
    - not implementing the 160 MHz ACD clock option FW
    - using a fixed sample width at the Station output (8b complex)
- Using CEP as station correlator
- Using external weather monitoring services instead of installing local weather stations at each LOFAR 2.0 station.

Table 10.1-1 Overview driving requirements of with the design is expected to be in compliance with.

Requirement compliance

#Requirement	Requirement	ADD Chapter	Summary
LOFAR2-3203	LOFAR 2.0 and LOFAR 1.0 compatibility mode	4.4.3	The same sampling rate and digital filterbank will be used for LOFAR 2.0 resulting the same subband width.
LOFAR2-2165 LOFAR2-3098 LOFAR2-3578 LOFAR2-3109	Dual band capability Frequency range Beamlets	4.4.1 4.4.2 4.7	It will be possible to simultaneously observe with LBA and HBA (96 dual polarized antennas at frequencies between 10 and 90 MHz or 30 and 90 MHz simultaneously with 48 dual polarized high band tiles at Dutch stations or 96 tiles at international stations observing at frequencies between 110 and 190 MHz or 210 and 270 MHz)
LOFAR2-3630	Doubling no of LBA antenna receiver inputs	4.7	It will be possible to measure with 96 dual pol. LBA's simultaneously with 48 dual polarization (Core, Remote) tiles
LOFA2-4388	New Station should fit in LOFAR 1.0 Cabin	4.7	It will be made possible
LOFAR2-2305 LOFAR2-2295 LOFAR2-3420	Station buffer length >= 2.5 seconds Trade bandwidth with storage time.	4.5.1 4.5.2.5	LOFAR2.0 will be able to store 3.3 seconds of data. Update could be performed to increase this storage length up to 6.6 seconds.
LOFAR2-4053	Correlate ACM of received EM signals	4.5.2.4	LOFAR 2.0 will be able to correlate >=1 subband per second.
LOFAR2-3176 LOFAR2-4232 LOFAR2-3125	Latencies, see chapter two	6.4.1	We expect to be compliant
LOFAR2-3096	2 HBA substations for Core Stations	4.7.2	We expect to be compliant

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Questions?