ngVLA Final Design and Prototype of ngVLA 18m Antenna

DRD-22

Design Report

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1. Scope and introduction

The purpose of this document is to describe the selected design for the 18m ngVLA antenna. This document will serve as Design Report to be delivered to NRAO in accordance with the DDC. The basis for this report is the telescope design as presented in the technical proposal, the report will be updated during the individual project phases and for the defined milestones. NRAO intends to publish this report on their website.

Throughout all of the Design, Prototype Manufacturing, Installation and Testing phases, the Seven Objectives of the ngVLA Program will always be the guide for the mtex/KTF Team. They are:

I. Design
  - Design that meets the technical requirements
    - mtex/KTF is submitting a fully compliant technical solution
  - Design that is optimized for production of 244 units
    - mtex/KTF incorporated automated manufacturing techniques and high-density packaging
  - Design that has high reliability and low maintenance
    - mtex/KTF has designed long service life into all parts and selected components
  - Design that meets all building and safety codes and fit for operators
  - mtex/KTF design is designed for operator ease of use and meets all OSHA, local-state-national building codes, and National Electrical Codes.

II. Technology Testing
    - mtex/KTF proposes Technology Testing for Primary Reflector, Secondary Reflector, Carbon Fiber Structural components, and EMI components

III. Antenna Fabrication Tooling
    - mtex/KTF design only requires a limited production tooling because of automated manufacturing techniques

IV. Prototype Antenna Fabrication
    - mtex/KTF will fabricate the prototype antenna using production documentation
    - the design will be verified by in-process inspections, factory integration, factory proof assembly, and on-site assembly and test

V. Antenna Assembly and Alignment
    - mtex/KTF will assemble and align the antenna using a team with past experience on large precision antennas
    - the Primary Reflector will be trial assembled and aligned prior to transport to ngVLA site
    - mtex believes the ALMA foundation can be modified for prototype antenna testing

VI. Acceptance Testing
    - mtex/KTF will perform factory and on-site acceptance testing
    - mtex will perform and provide all test results and analysis as required

VII. Production Documentation
    - mtex/KTF will deliver the final production package to include all the experience gained from the prototype manufacturing and test

Notes and comments to changes adaptations since the preparation of the technical proposal

⚠ Some adaptations to the provided mtex design as per proposal are already incorporated, or incorporation has started, those are highlighted for easier reading (see left symbol).

2. References

2.1. Applicable documents

[AD1] none

2.2. Referenced documents

- Front End Volume, Mass, and Location Requirements,
  020.30.03.01.01-0002-DWG

- Environmental Control Equipment Volume, Mass, and Location Requirements
  020.30.03.10.00-0001-DWG

- Back End Volume, Mass, and Location Requirements
  020.30.03.05.00-0001-DWG

- DWVR Volume, Mass, and Location Requirements
  020.45.00.00.00-0004-DWG

- Software Best Practices, Rev. 1.1, 11.05.2020
  mtex-VA-25-000000-001_Software Best Practices

- Pointing and Focus Stability Error Budget, Rev. 1.0, 16.09.2020
  1019003-ANA-21-00000-002

- Optical Definition RFP (Oct2020)
  1021006-DWG-21-20100-001

- ngVLA Antenna Memo # 9, Practical Limits to Axis Offsets

- OPCUA NodeSet, the description for the MCL-ANT-01 interface,
  2020009 mtex Proposal for the ngVLA DDC Volume 3 Technical Proposal Annex O PCUA NodeSet.zip

- Performance Analysis Report
  1021006-ANA-22-00000-001

- Optical Definition RFP (Oct2020)
  1021006-DWG-21-20100-001

- ngVLA Antenna and Equipment HVAC Specification Rev1.0
  1021006-SPE-21-00000-001

3. Abbreviations

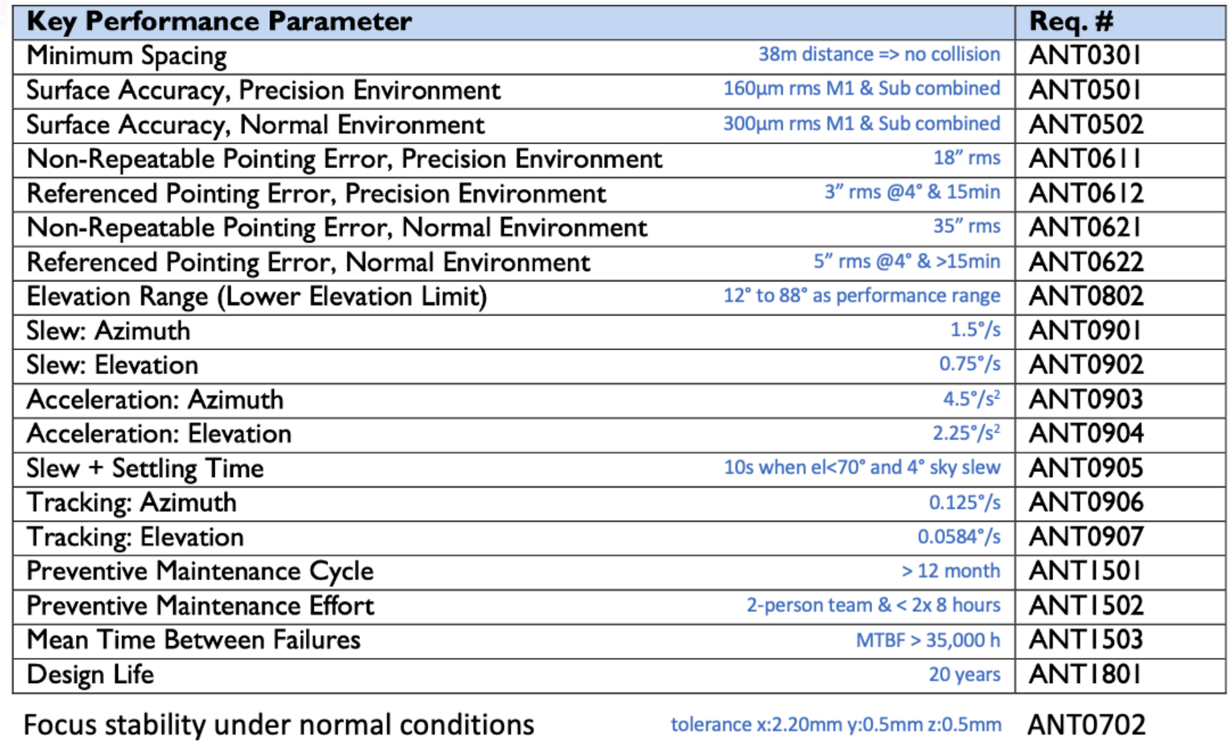
DDC	Design and Demonstration Contract
FAT	Factory Acceptance Testing
M&C	Monitoring and Control
RFP	Request for Proposal
TBD	To Be Defined

4. Main design drivers and requirements discussion

As specified the following main requirements have been considered as the most important for the design and selection of concepts and components.

The newly introduced Focus Stability is understood to be, of equal importance and one key performance parameters as well. The design and analyses were checked and adapted accordingly.

Table 1 Key Performance Parameters



Key Performance Parameter		Req. #
Minimum Spacing	38m distance => no collision	ANT0301
Surface Accuracy, Precision Environment	160µm rms M1 & Sub combined	ANT0501
Surface Accuracy, Normal Environment	300µm rms M1 & Sub combined	ANT0502
Non-Repeatable Pointing Error, Precision Environment	18” rms	ANT0611
Referenced Pointing Error, Precision Environment	3” rms @4° & 15min	ANT0612
Non-Repeatable Pointing Error, Normal Environment	35” rms	ANT0621
Referenced Pointing Error, Normal Environment	5” rms @4° & >15min	ANT0622
Elevation Range (Lower Elevation Limit)	12° to 88° as performance range	ANT0802
Slew: Azimuth	1.5°/s	ANT0901
Slew: Elevation	0.75°/s	ANT0902
Acceleration: Azimuth	4.5°/s²	ANT0903
Acceleration: Elevation	2.25°/s²	ANT0904
Slew + Settling Time	10s when el<70° and 4° sky slew	ANT0905
Tracking: Azimuth	0.125°/s	ANT0906
Tracking: Elevation	0.0584°/s	ANT0907
Preventive Maintenance Cycle	> 12 month	ANT1501
Preventive Maintenance Effort	2-person team & < 2x 8 hours	ANT1502
Mean Time Between Failures	MTBF > 35,000 h	ANT1503
Design Life	20 years	ANT1801
Focus stability under normal conditions	tolerance x:2.20mm y:0.5mm z:0.5mm	ANT0702

4.1. Surface Accuracy, Pointing and Focus Stability

Surface Accuracy, Pointing and Focus Stability are three primary parameters that ultimately define the capability of a telescope or antenna. All three of these critical parameters are directly linked to overall design concepts, selection of key components and strategies for implementation and alignment. Those from the beginning concepts, considerations and definitions are of such fundamental influence to Surface Accuracy, Pointing and Focus Stability that they cannot be changed or improved at a later stage without enormous efforts. The exchange of a bad azimuth bearing type, or enlarging the tower diameter to increase stiffness, such things are economically not feasible.

From the very beginning mtex takes great care and understands the requirements and true needs involved behind provided requirements when designing precision antennas and telescopes.

“What and where” is the task of the antennas to measure strength of signals and their exact origin. The antennas are to direct the signals passing the defined 18m aperture plane to the receiver, namely the feed, combine and direct those signals in the way that they all amplify each other in the location of the feed. Additionally, the antenna shall precisely report the elevation and azimuth angles on the sky where those signals are measured. The pointing and

focus stability analyses are all performed with that understanding and described in for Pointing and for Focus Stability.
mtex provides all details and insights of the multiple performed analyses within this report or with associated files in their original file format. The important fact is that not only mtex understands what and how the analyses were performed, more important is that NRAO has the same understanding to judge the mtex design correctly, therefore mtex is always open and ready to investigate and provide the insights required.

4.2. Antenna Optics

The newly provided optics by NRAO

The antenna optics was delivered by NRAO at the beginning of the CCDC contract. It was delivered as two separate IGES files and with an appropriate assembly instruction. The optics shown below was confirmed by NRAO during several iterations in the bi-weekly meetings.

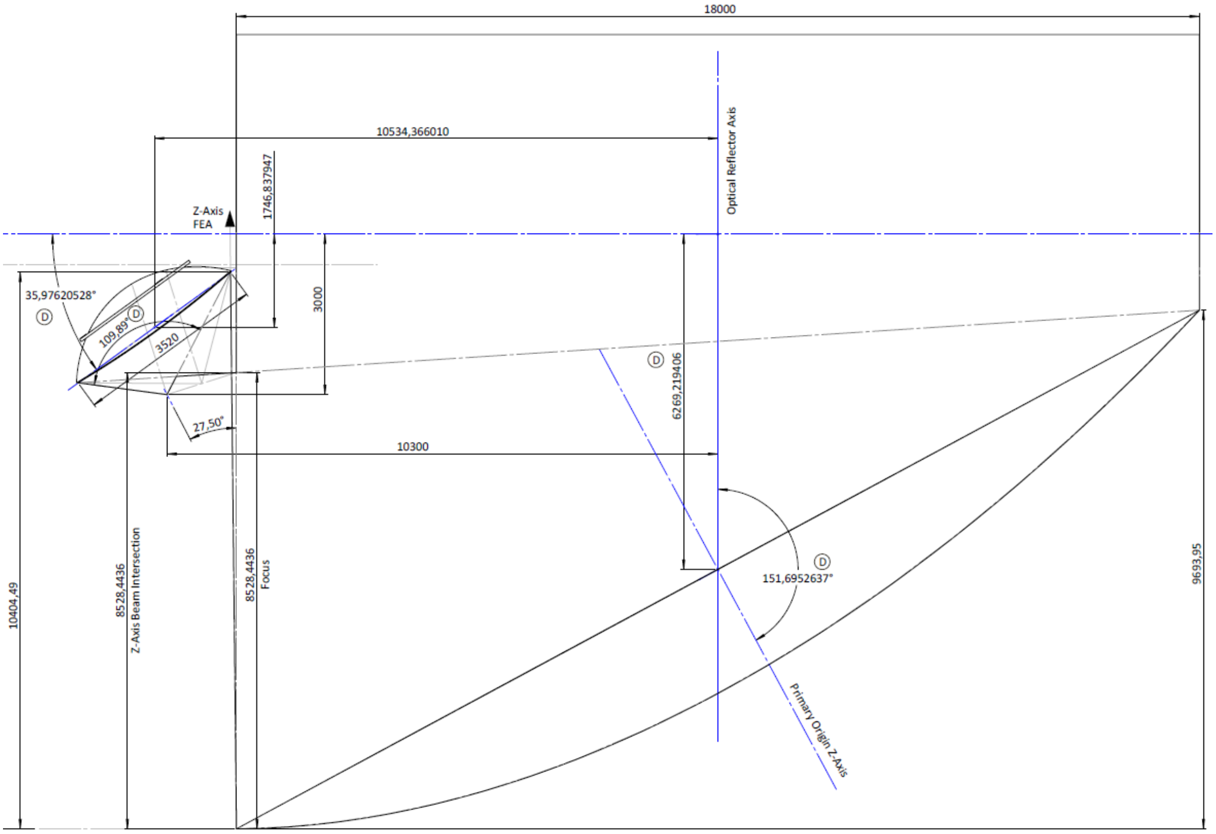


Figure 1 Antenna Optics

The axis offset between the optical reflector axis and a parallel axis through the elevation axis was requested by NRAO during the design process. The offset is shown in Figure 2 with a value of 363 mm.

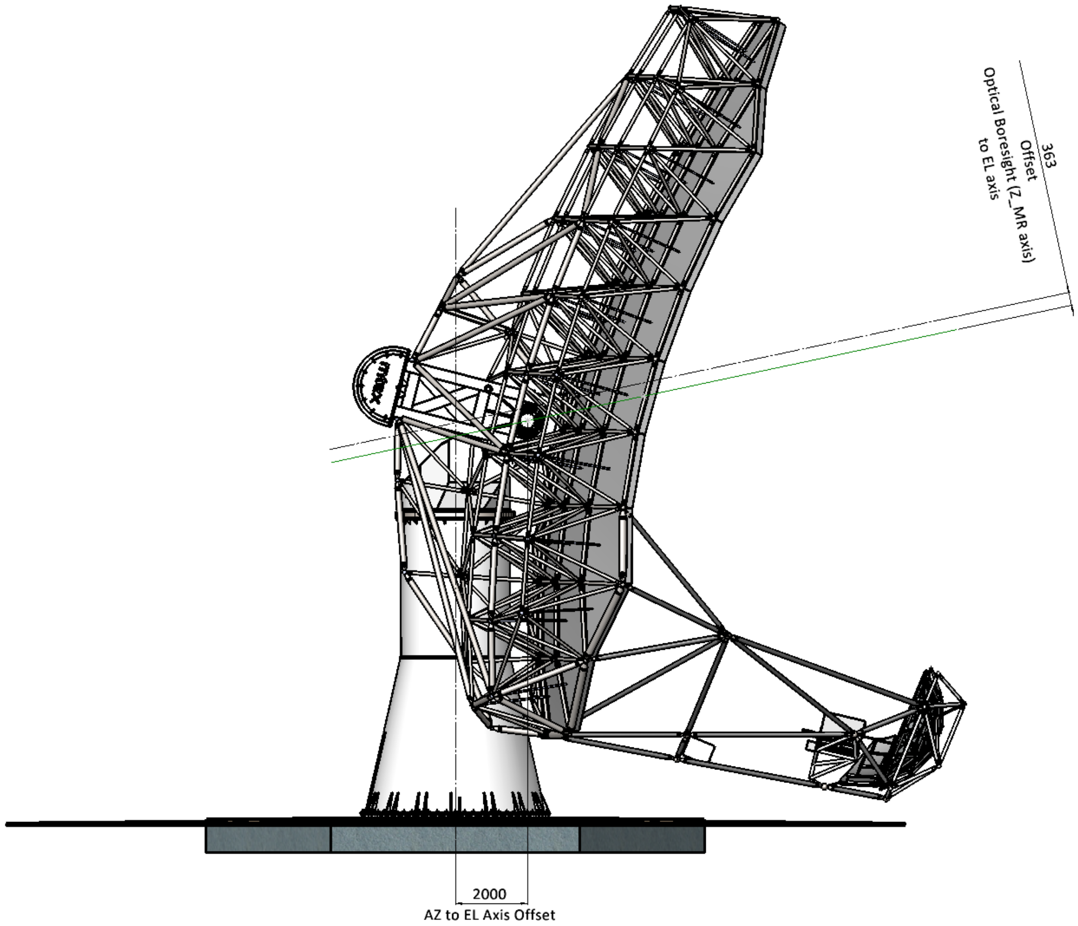


Figure 2 Offset Optical Reflector Axis to parallel EL-Axis

As a technical main requirement NRAO requested that there is no blockage in the optical beam. This is confirmed in the figures below. It is ensured that even the customer requested WVR is not interfering the beam at any time.

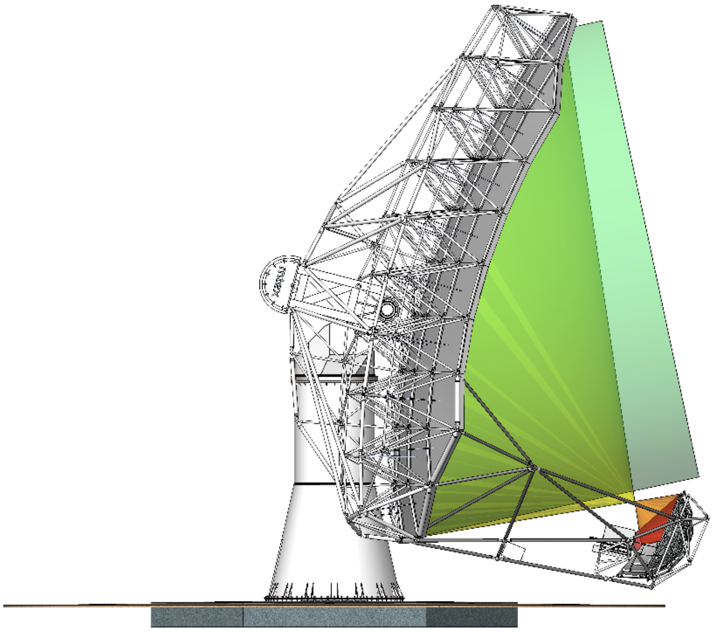


Figure 3 Antenna optics (side view)

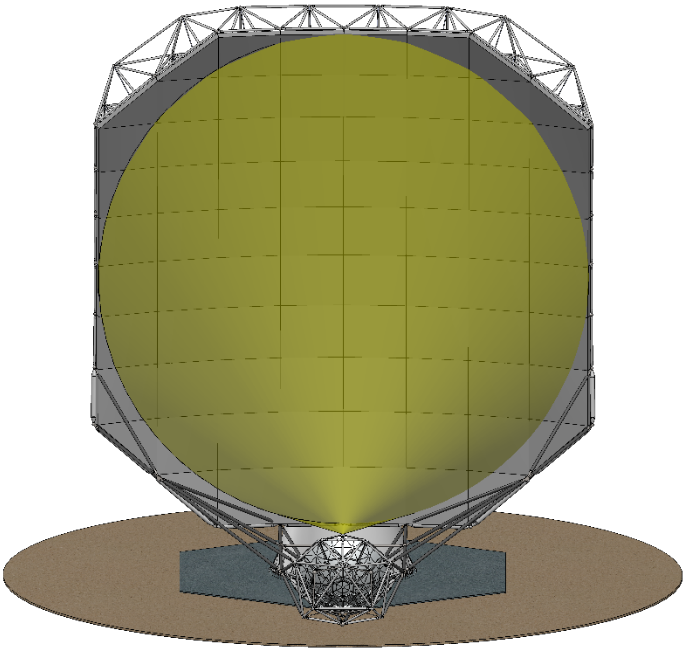


Figure 4 Antenna optics (view along optical axis into reflector)

mtex cross checked the files which have been provided by NRAO for the RFP. The new optic is different from the one mtex used for the CCDC. Nevertheless, mtex does not see any issue to adapt the ngVLA telescope design concept to the updated optics specification.

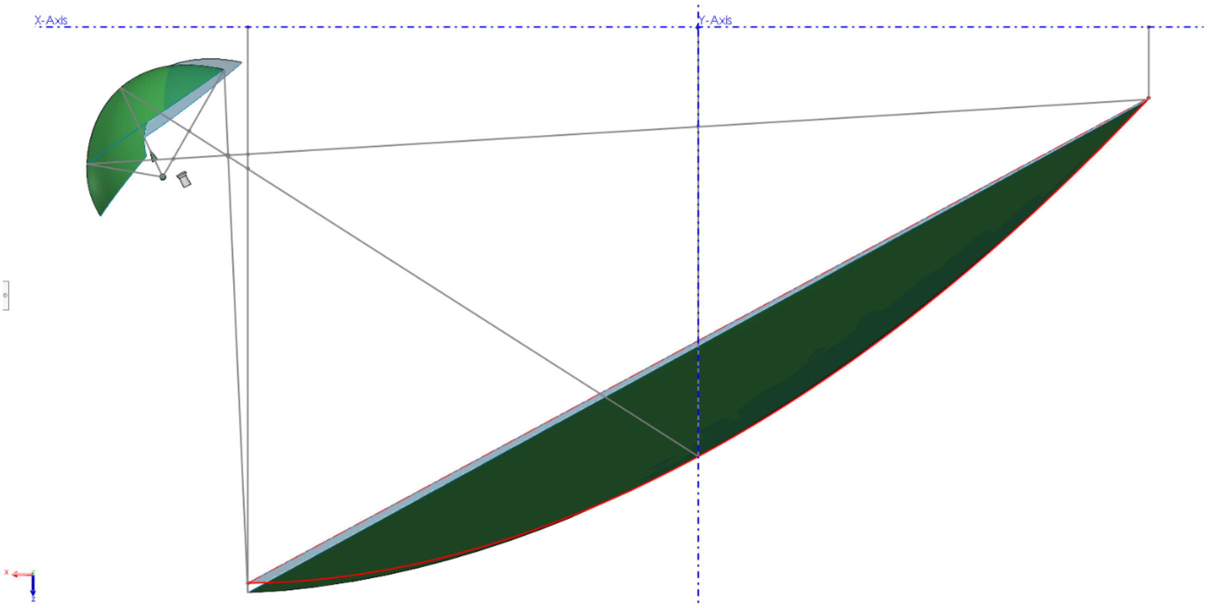


Figure 5 Comparison of Optics Definition (CCDC, blue to RFP, green)

A drawing has been created by mtex to show the differences of the two provided optics and as basis for clarification. mtex intent is to receive a formal confirmation to continue the design with the new optics as per drawing in .

4.3. EMI

The electromagnetic emissions originating from the telescope's own equipment is an important factor to be considered when designing telescopes. In the case of a single antenna telescope, the receiver cabin provides shielding towards the receivers and the equipment, usually being behind the main reflector and installed in EMI shielded enclosures, is not critical when standard EMI/RFI design and workmanship is considered.

As the ngVLA will be an array-based telescope, combining the signals received from many antennas installed close to each other, the prevention of disturbance signals to be received by the antennas themselves or nearby antennas is even more critical.

mtex design provides already developed special measures and concepts relying on ordinary available components to ensure the compliancy of the mtex design with the provided RFI/EMI thresholds.

Section 6.8 describes the efforts and measures implemented in the mtex design for the ngVLA antenna.

4.4. Settling Time

Settling time is a crucial parameter for all observations as it defines the "left-over" time available for measurements with the receivers on the sky when performing a repositioning between two celestial objects.

Settling time is also a good parameter to judge the dynamical behavior of the complete antenna structure including any measures implemented within the control system to stabilize the optical and true pointing. mtex antenna design is optimized with respect to stiffness and weight/inertia which are the main parameters that define the settling time achievable considering simple and robust control loop structures. Here mtex objective to design for optimal "passive" performance supports the achievable settling time.

The analysis performed by mtex to calculate the worst-case settling time as specified is described in ⍰.

The worst-case sky slew can be reported to be in performance threshold after 6.7 s which meets the requirements of the antenna.

4.5. Manufacturability

A major design driver is also the optimization of manufacturability. The ngVLA requires a design that is optimized to support the deployment schedule of up to 3 antennas (or more) in a month. All antennas in an array must behave virtually identically. The mtex design took up on this challenge and has considered robust and proven technology together with a focus of automated manufacturing. The presented BUS and the main reflector surface panels are designed in this way, that state of the art machines can produce critical items in large quantity and with the highest accuracy. During the design development mtex and KTF have consulted various experts from material supply, manufacturing processes, milling machining suppliers, transportation and logistics experts to simplify the manufacturability. The drive system relies with a high percentage on industrial standardized components which guarantees a long availability. The software of the mtex servo system is using and following international software standards (OPC UA, Tango, Python) and follows a modular character that provides independency of specific hardware platform.

5. Antenna design overview

The 18 m ngVLA offset antenna (Figure 6 and Figure 7) in this design report is a new development by mtex antenna technology gmbh in Wiesbaden. When setting the goal of the design concept, we have specified an extremely compact arrangement of all main elements of the antenna in order to minimize the moment of inertia of the antenna.

For this reason, the elevation axis was arranged extremely close under the upper cord of the main reflector backup structure in such a way that it lies exactly in the center of gravity of the entire elevation structure with minimal ballast. At the same time, the sub-reflector with feed and electronics box can be moved to the lowest elevation position up to 0.6 m from the ground, so that work on the rf components can be carried out safely near the ground.

Furthermore, we want to make the structure of the antenna in steel, the panels in aluminum and the feed arm in CFRP. With this choice of materials, we achieve the best possible rigidity, stiffness and sufficient thermal stability at low cost.

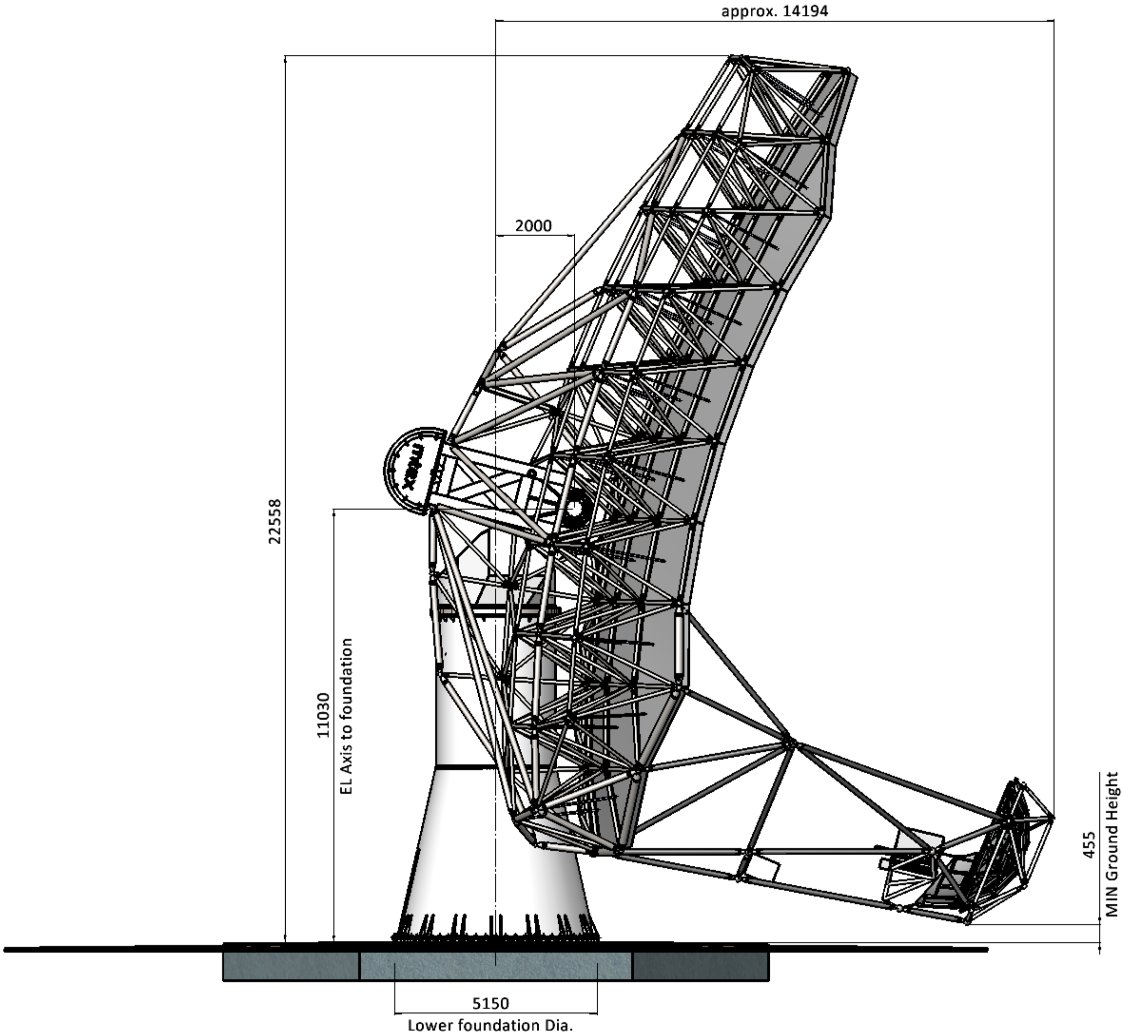


Figure 6 Antenna Main Dimensions (EL 12deg)

The main reflector is a space framework consisting of steel knots and steel struts according to Figure 12, Figure 13 and Figure 14. These two elements are connected with an M12 (partly with

an M16) screw and a pre-tensioning force of 54 kN (102 kN). For the steel knot, we assume that it is manufactured on a CNC machine starting from a solid steel ball or round.
The data for production is not transferred via technical drawings, but directly electronically from the 3D-CAD to the CNC machine. This enables fully automatic production for this precision component in order to be able to manufacture the knot in large quantities at low cost. At the same time, construction work is saved, errors are avoided, and a manufacturing precision is achieved.
The connecting elements or struts, between the knots, are welded from a standard steel tube with a connecting cone and enables galvanization inside and outside, see Figure 13. Finally, the strut is shortened to the exact length by machining. Such a space framework requires only a small transport volume when dismantled, is easy to assemble and all system lines of the struts lead exactly to the center of the knot, so that no framework rigidity is lost due to imprecise strut connection at the knots.

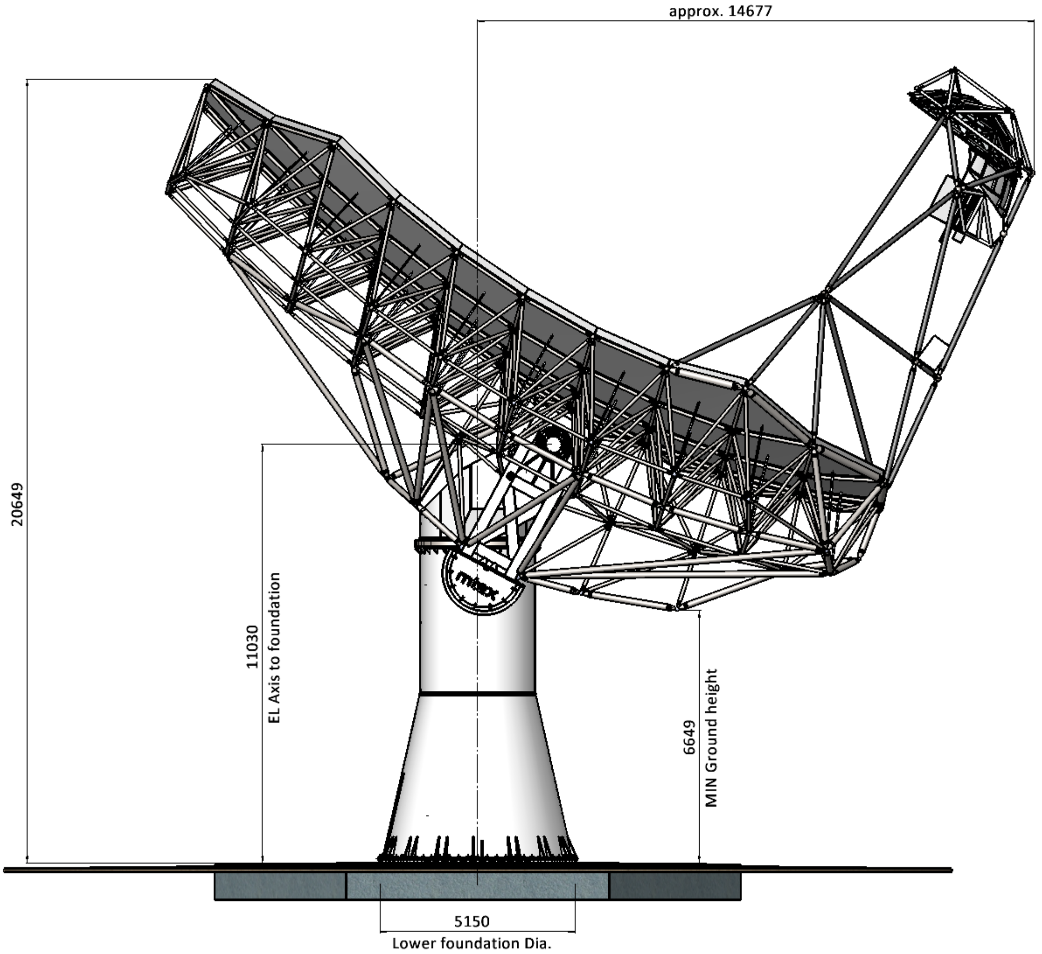


Figure 7 Antenna Main Dimensions (EL 88deg)

The same construction is provided for the feed arm, however, instead of steel struts, CFRP struts are used to improve thermal stability and reduce weight. Great care must be taken when connecting CFRP and steel components to ensure compatibility under all thermal load cases.

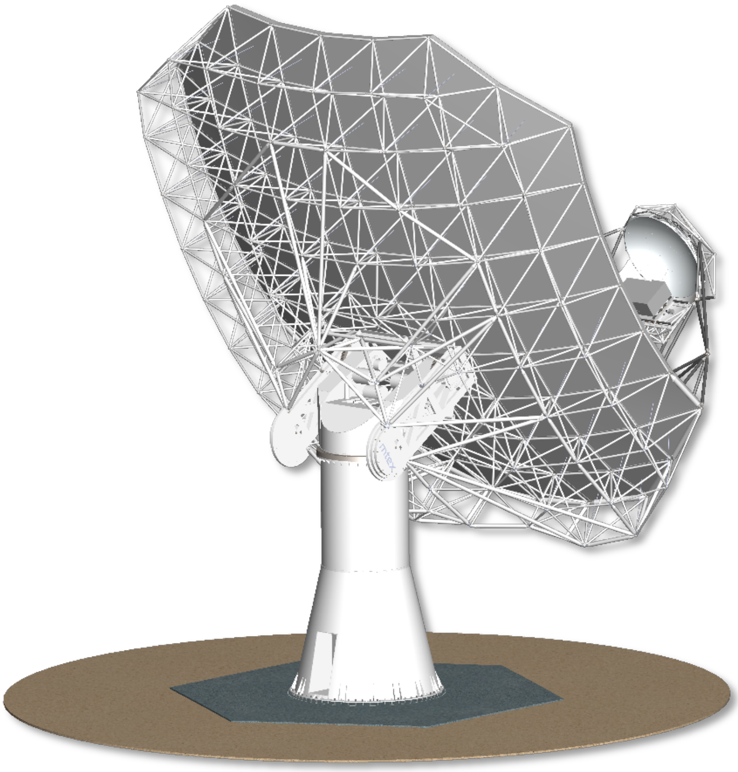
The central part of the elevation structure is a machined welded construction to which the machined components, the space framework and the ballast counterweights are attached as bolted connections.

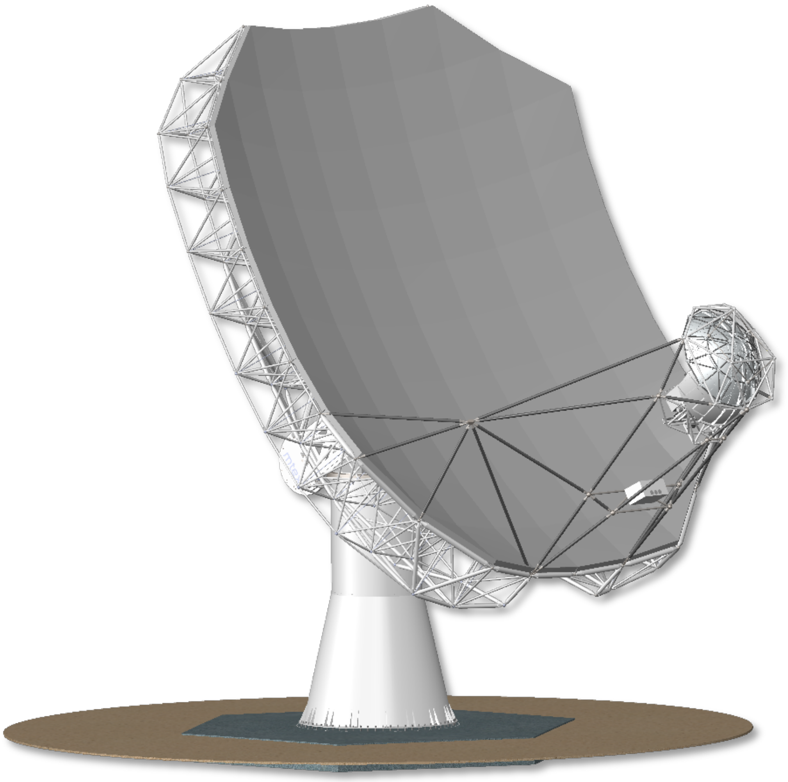
The main reflector backup structure framework made of steel, carries 68 aluminum panels with a panel area of 4.6 m^2 each and 8 panels with 2.3 m^2 each, Figure 26. Larger panels are more economical but lose the desired accuracy disproportionately as the panel area increases over 4 m^2. Our main reflector was reduced in weight to only 30.7 tons using mathematical vector optimization still considering its desired performance. As the baseline we have considered to use our new developed high-performance (<50 µm RMS) low-cost panels developed by mtex. Optionally, aluminum panels in sheet metal construction with a custom manufacturing accuracy of approx. 90 µm could also be used, however, each panel requires an expensive mold due to the different panel contours. Hence the lower quality and costs are no longer in a reasonable relationship.

Both panel variants are supported on the four corner points and additionally provided with a fifth adjustment point in the centroid of each panel. This improves the panel deformations under all load cases. In particular, the load case for direct solar radiation with 1,200 W/m^2 on the reflector surface is improved from 159 µm RMS to 49 µm RMS, see Section 8.1.6.

The stiffness of an antenna is not insignificantly determined by the size of the azimuth bearing, which is why we decided on a 3 m azimuth bearing. In addition, the tower is provided with a cone towards the ground, which is supported on the foundation with a diameter of 5m.

The drive trains for elevation are equipped with four drives and for azimuth with two drives and are controlled by our mtex servo, see Sections 6.9 and 6.10.





6. Design details

The following sections will describe the mtex antenna design in detail. The description will be divided into the main components (Reflector System, Pedestal and Turnhead), as well as an additional section for Mechanical Equipment.

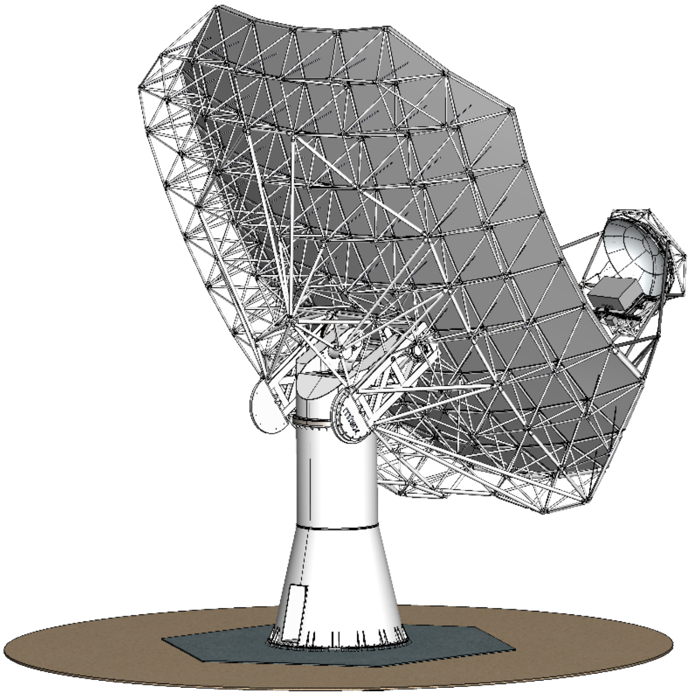


Figure 8 Antenna Overview

The antenna rear view shows the stiff Pedestal on its six-sided foundation with the Turnhead on top. The bolted Main Reflector Backup Structure (BUS) is connected to the Turnhead with a very stiff welded steel structure. CFRP tubes are used to hold the sub-reflector and the front-end equipment in place.

6.1. Weight budget

The antenna weight after FEA optimization is shown in the table below. The weight includes all of customer supplied items.

Table 2 Antenna weight budget

NRAO WP	Description	Weight in kg
1.4.3	**Elevation Assembly**	**48.215**
1.4.3.1	**Main reflector**	**26.500**
	Al Panels + Adjuster	5.250
	Steel BUS	21.250
1.4.3.4	**Feedarm**	**2.445**
	CFRP Structure	745
	Hexapod + Al Sub-reflector + Extension	260
	Feed Positioner	380
	RF Customer Equipment	1.060
	Counterweight Structure	**19.270**
	Steel Structure	8.750
	Gear Segments	520
	El Bearing Components	1.040
	Counterweight	8.960
	Pedestal Assembly	**57.250**
1.4.2	**Turnhead**	**19.550**
	Steel Structure	12.000
	El. Drive components	3.100
	El. Bearing components	1.600
	Az. Bearing Components	1.650
	Customer Equipment & Compressor	1.200
1.4.1	**Pedestal Tower**	**37.700**
	Steel Structure	29.600
	Az. Drive Components	2.500
	Az. Bearing Components	4.100
	Servo and other equipment	1.500
Total weight mtex ngVLA Design		**105.465**

6.2. Reflector System

The main reflector system of the antenna is a very stiff, light-weight structure that was optimized to fulfill the performance specification of NRAO. It carries the main reflector panels, sub-reflector, feed indexer actuator, as well as the customers Front-End equipment. This system is balanced with counterweights to ensure that the center of gravity is always in the middle of the elevation bearing axis.

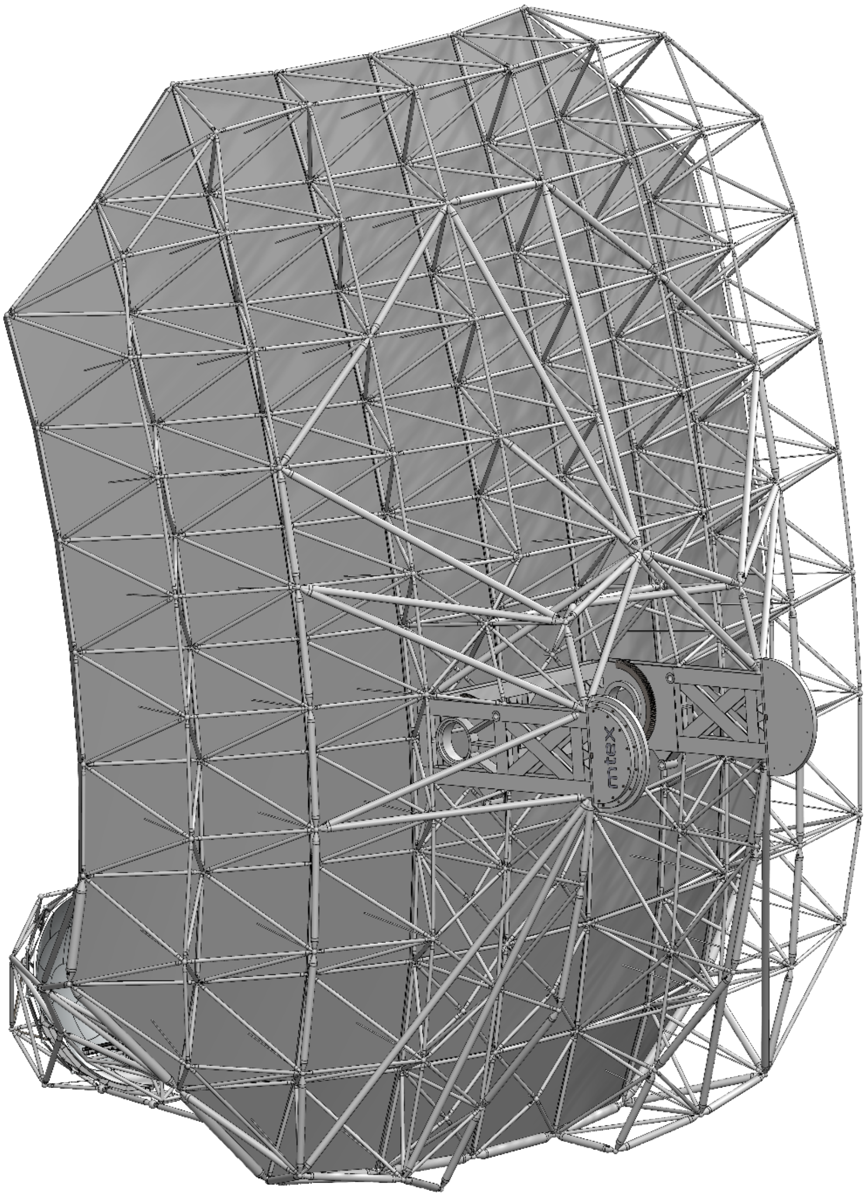


Figure 9 Reflector System (rear-iso view)

The cables are routed on both sides of the reflector to provide the opportunity of divided customer and mtex cabling. The route is close to the main reflector center and is routed along the bottom of the feed arm structure straight to the rear of the sub-reflector.

The reflector system is designed with 76 main reflector panels. There are 68 rectangular panels with almost the same edge length. Each corner of the reflector is designed with 2 triangular panels which makes 8 special panels in total.

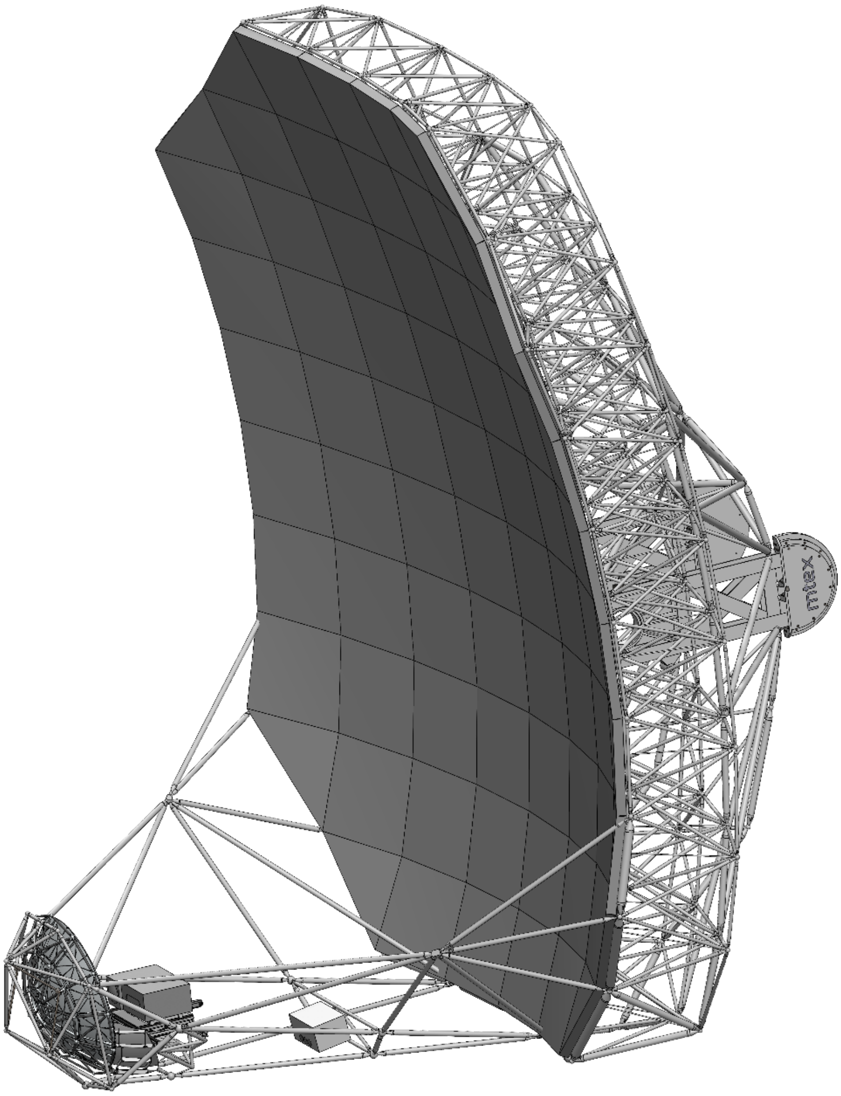


Figure 10 Reflector System (front-iso view)

The WVR is located outside the structure in the lower corner. This ensures easy access and avoid any beam interference. More details of the reflector system are about to follow in the next sections.

6.2.1. Backup structure (BUS)

The Main Reflector BUS is a bolted system with a stiff welded center structure. The bolted connections are made with spherical knots and tubes with conical ends.

Basically, the BUS consists of octahedron segments that are designed to a dimension of 2.3 x 2.0 x 2.2 m. Each segment consists of 5 knots and 8 tubes.

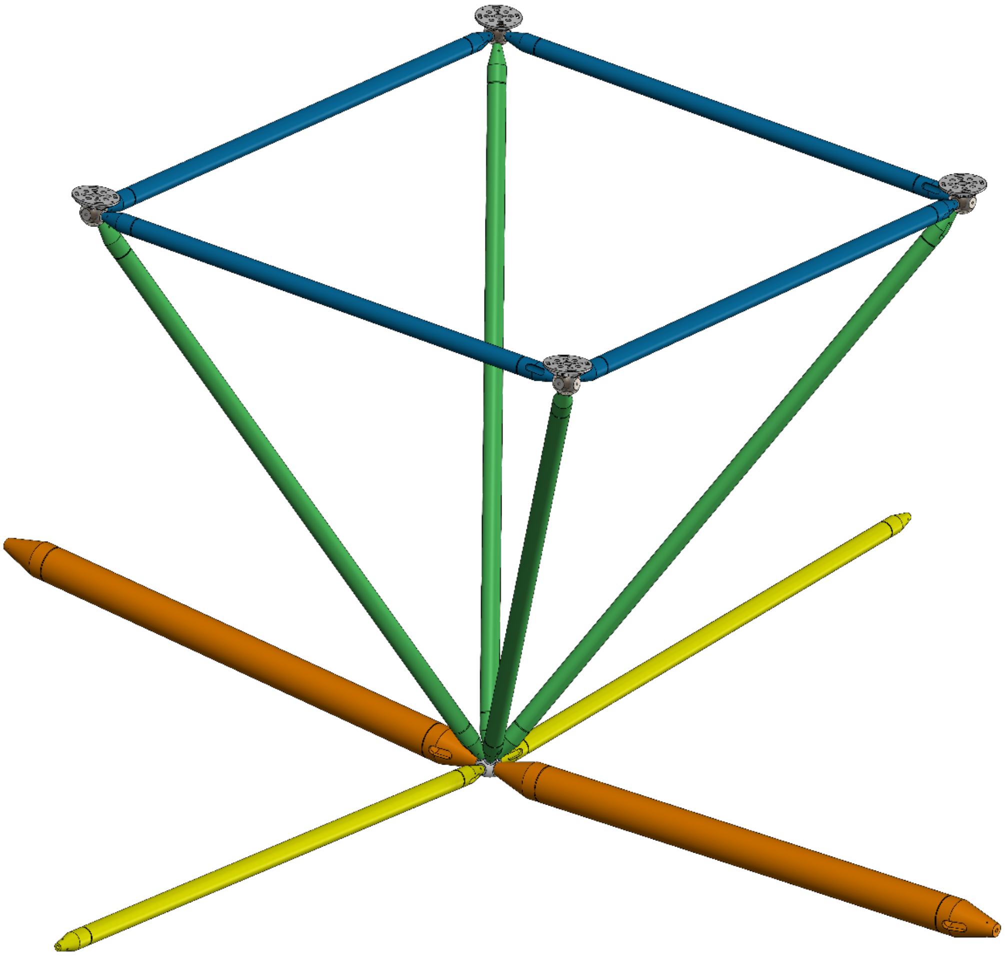


Figure 11 Sample of Octahedron Main Reflector Segment

This design concept was proven in the past in several projects and is optimized for automated, serial production.

During optimization, the inner and outer diameters were reduced to a required minimum of 10 different tube types.

All the tubes are hot-dip galvanized from the in- and outside for proper 9.15.3 protection, as well as painted RAL9010.
The tubes are laser welded with the cones and precision machined to the correct length and marked with their specific number.

Table 3 Main Reflector BUS Tube diameters and locations

#	*Outer Diameter [mm]*	*Wall Thickness [mm]*	*Location Description*
1	70	3	Space trusses
2	70	5	Upper chord
3	70	7	Middle chord
4	70	10	Upper chord
5	70	20	Planar center trusses
6	90	5	Lower bent tubes in reflector center
7	90	7	Bent tubes in reflector center
8	90	15	Cross connection reflector rear
9	140	5	Lower chord and support to feed arm interfaces

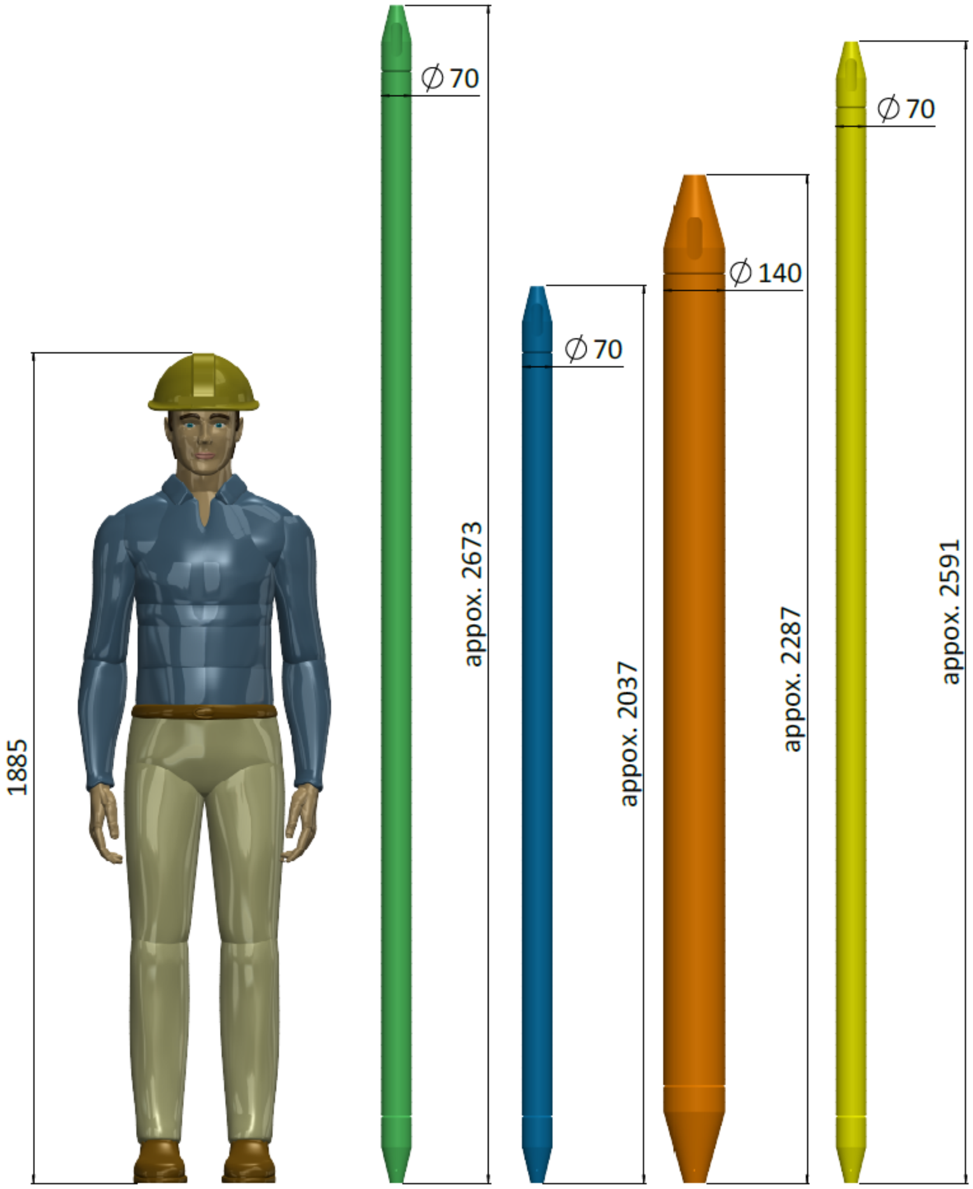


Figure 12 Typical Tube Length

The typical pipe lengths are shown in Figure 12 and are located at the following points in the BUS:

- space truss green
- upper chord blue
- lower chord orange
- middle chord yellow

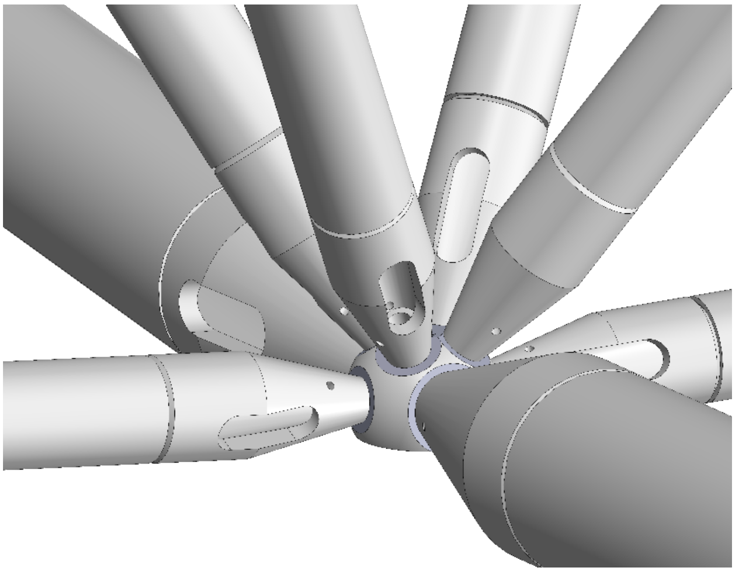


Figure 13 Tube/Sphere Connection sample

Within the main reflector system there is a total number of 662 tubes.

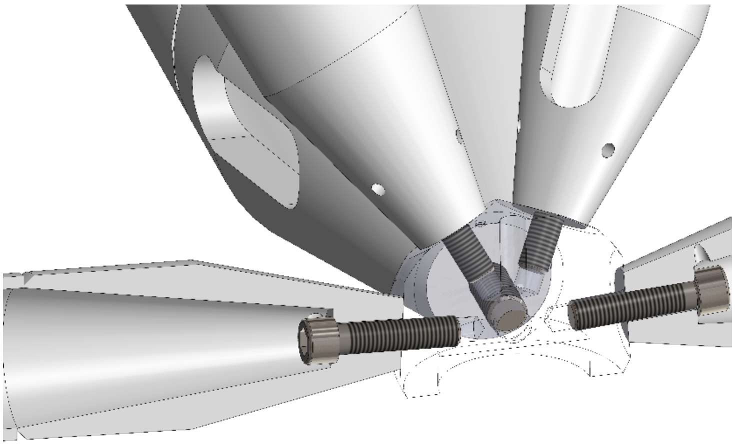


Figure 14 Tube/Sphere Connection Sample (Cross-Section)

The bolted connection is designed with M16 threaded bolts and a preload force of approx. 100kN.

Each steel sphere has an outer diameter of 100mm and a weight of 2.4kg with a manufacturing tolerance of ±10µm. The upper chord spheres are also equipped with the panel adjuster interface.

Each node has its own identification number, which is part of the name. The identification number is composed of as follows: (Direction of view behind the reflector)

- 0-Plane in the middle of main reflector
- Left side (in optical line of sight): 1021006-DWG-23-22420-XYZ
- Right side (in optical line of sight): 1021006-DWG-23-22420-XYZ-M (Mirrored nodes)

Figure 15 Count up from X (upper chord to lower chord)

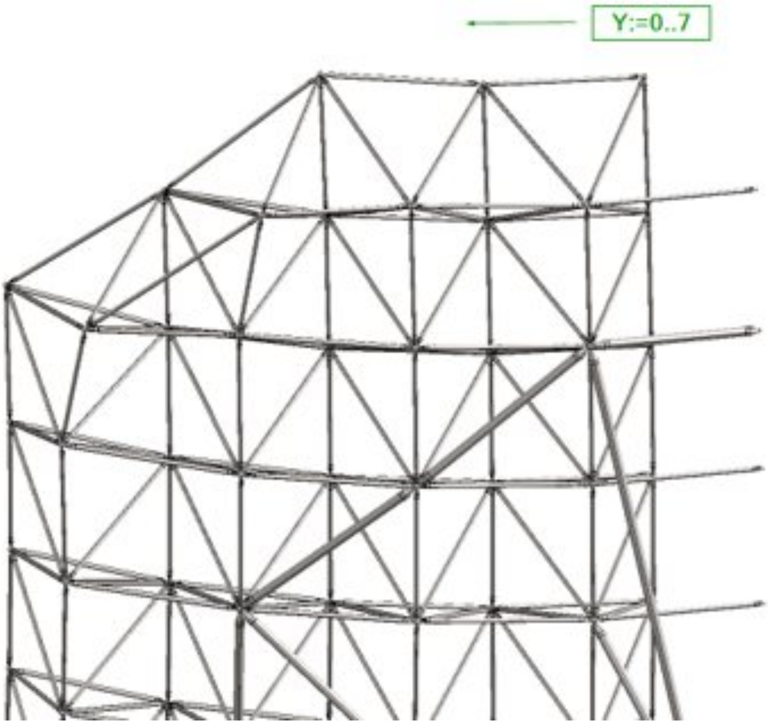


Figure 16 Count up from Y (0-Plane to the left, direction of view behind the reflector)

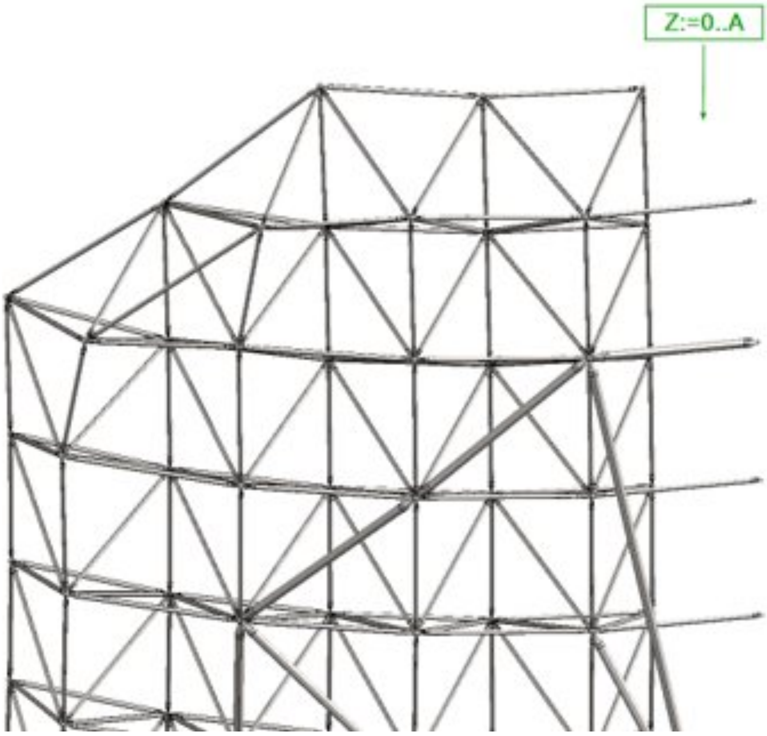


Figure 17 Count up fom Z (Top of reflector to bottom)

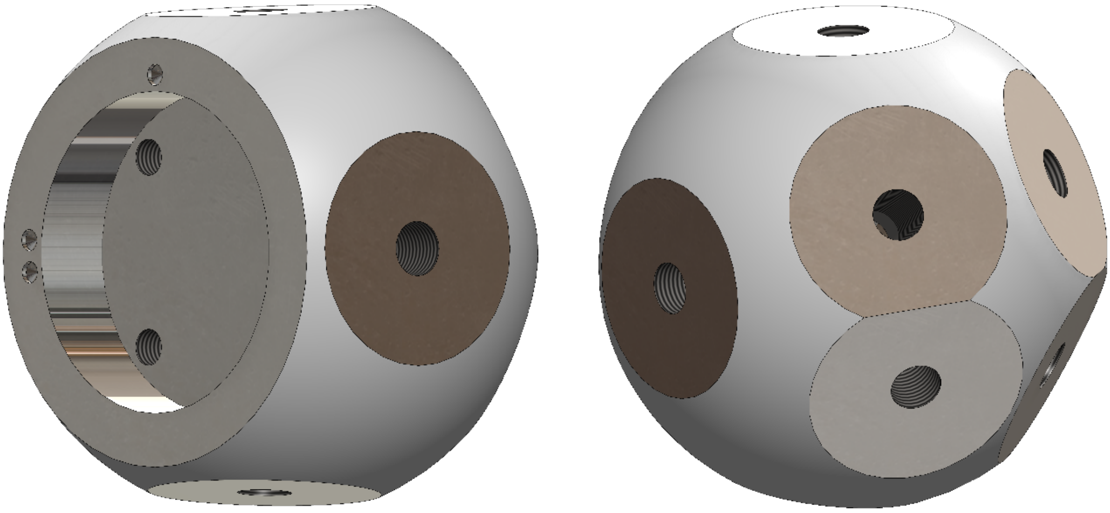


Figure 18 Node 058 Direction of View into the reflector (left), View from behind (right)

Figure 18 shows a node, which is in the upper chord of the reflector. The four threads (left) and the cylindrical surface are used to attach the panel adjustment mount and for clamping in manufacturing. In addition, markings are shown here which point to the center of the reflector (two points) and to the upper edge of the reflector (one point).

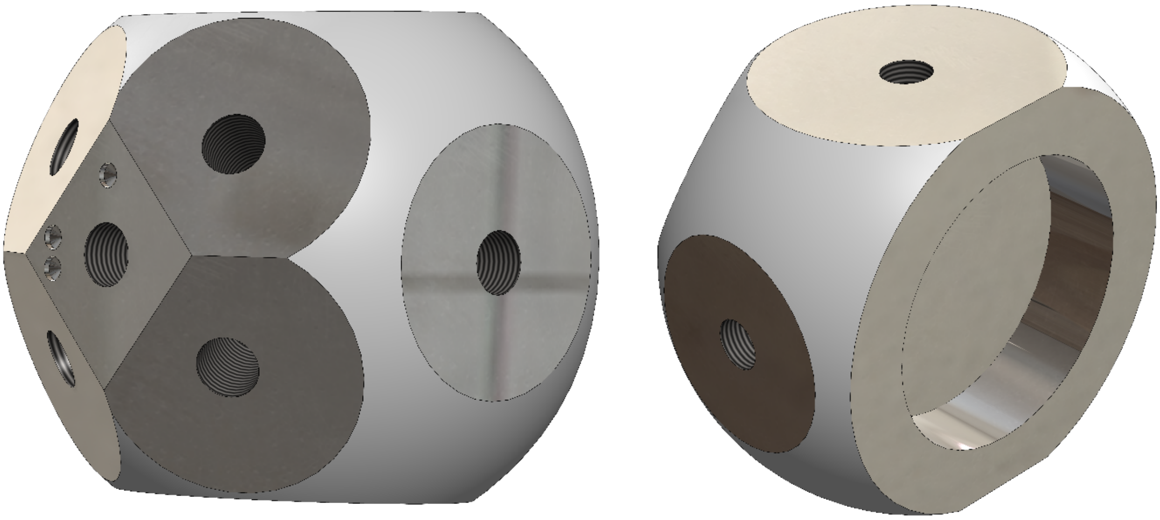


Figure 19 Node 157 Direction of View into the reflector (left), View from behind (right)

Figure 19 shows a node, which is in the lower chord of the reflector. The threads (left) will be used for the fifth adjuster. As mentioned before, the markings here also serve to orient the nodes. Center of the reflector (two points), upper edge of the reflector (one point). The cylindrical surface at this node is used for clamping in manufacturing.

Each surface, which serves as a contact point to a tube, is engraved with the name of the target node, that should help in assembling the BUS.

As the nodes, each tube gets its own identification number. Identification number of the tubes is composed of the source node and the target node e.g., Tube 058157, source node 058 to target node 157

There is an amount of 175 spheres in the reflector system which make a weight of approx. 890kg to the structure.

The described BUS system ends up at a final weight of approx. 22.5 tons (Main Reflector only!)

6.2.2. Panel Adjusters

To ensure superior performance the rectangular panels are support on 5 adjusters.
This means that the panels are not only supported in the 4 corners. They have an additional adjuster in the panel center.
The fifth adjuster is designed vertical on the center of each panel and ends in the lower center of the octahedron segment knot.

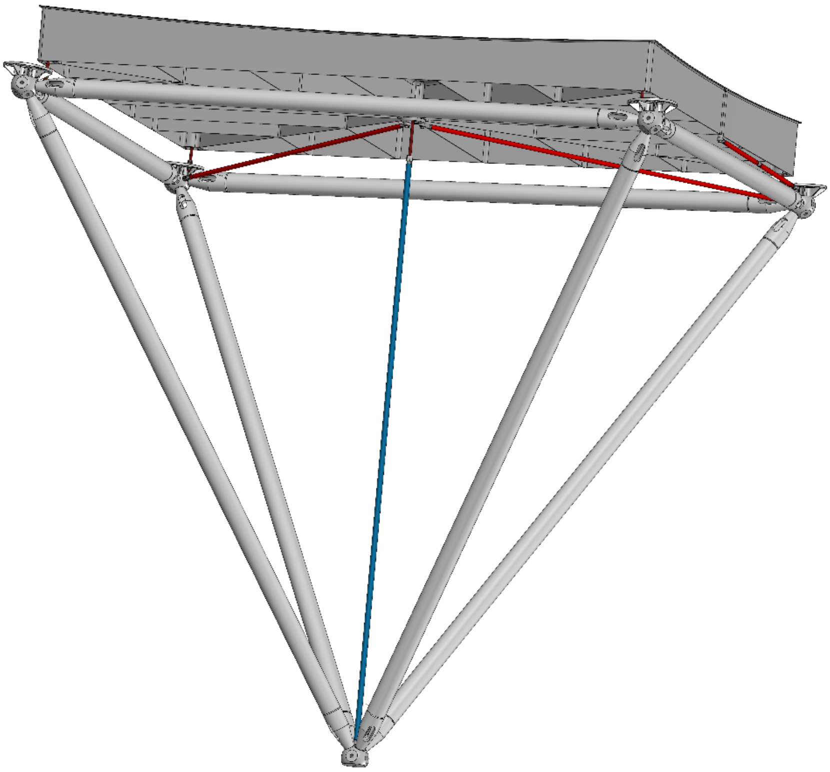


Figure 20 Octahedron BUS Segment with panel

All Panel adjusters are made from M10 stainless steel rods. The corner adjusters of the panels are attached to special designed panel adjuster mounts. These components are aluminum cast items and identical for all upper chord knots. Each of the panel adjuster mount has an outer diameter of 180mm and a weight of 0.7kg.

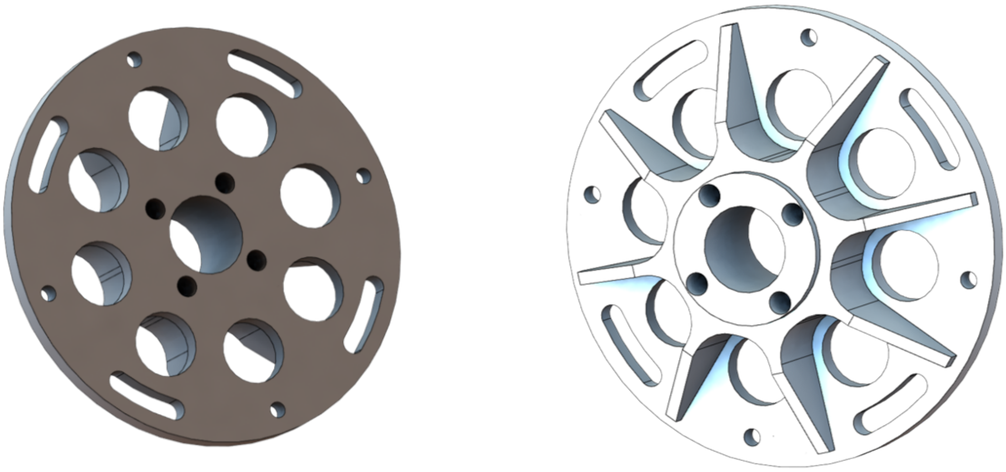


Figure 21 Panel Adjuster Mount

The panel adjuster rods are glued into the main reflector panel and attached to the panel adjuster mount with stainless steel nuts, as well as conical seats and spherical washers to avoid angular stress in the adjuster.

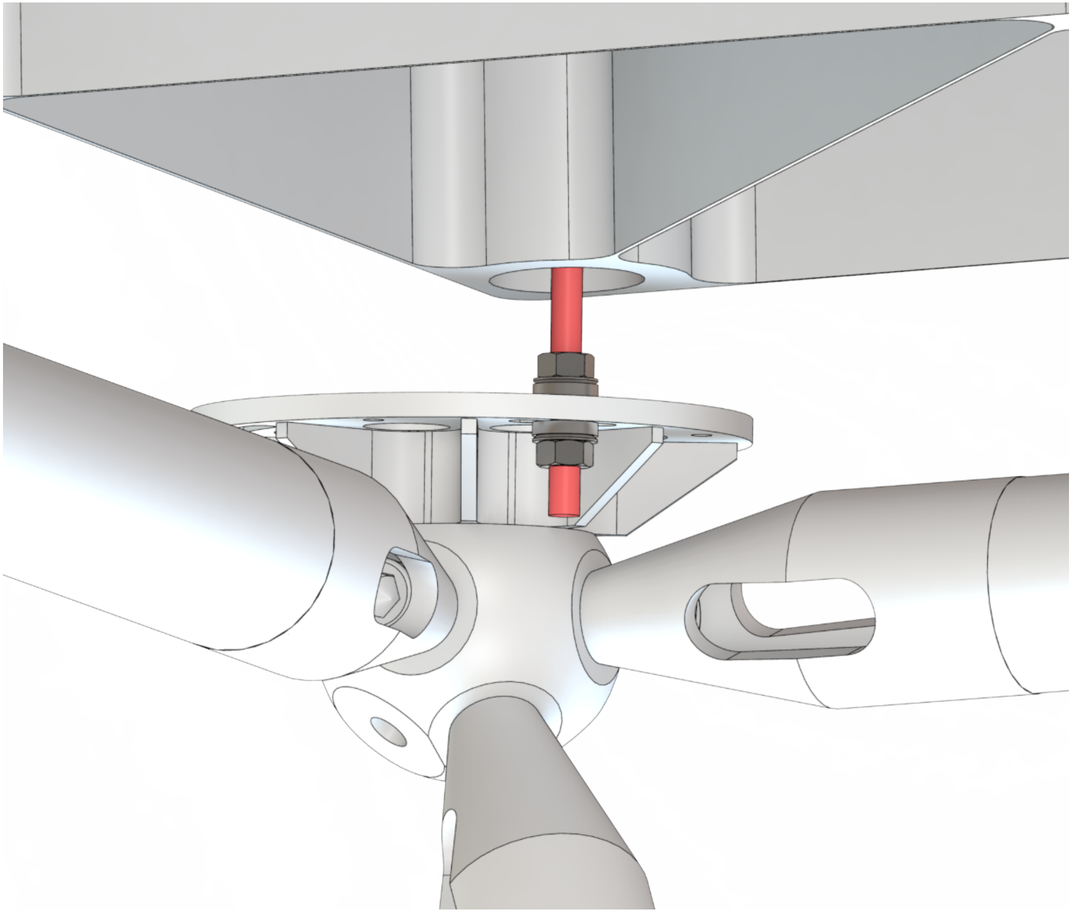


Figure 22 Sample of Panel Adjuster (Corner)

For a more precise adjustment of the panels each of the rectangular panels is equipped with planar and rotational adjusters, too.
The rotational adjusters are arranged as diagonal support which are mounted to the main reflector upper chord spheres on the one hand and close to the panel fifth adjuster on the other hand. The adjusters are designed with left-and right-hand threads to be able to manufacture them all in the same length and to adjust them to the required length.

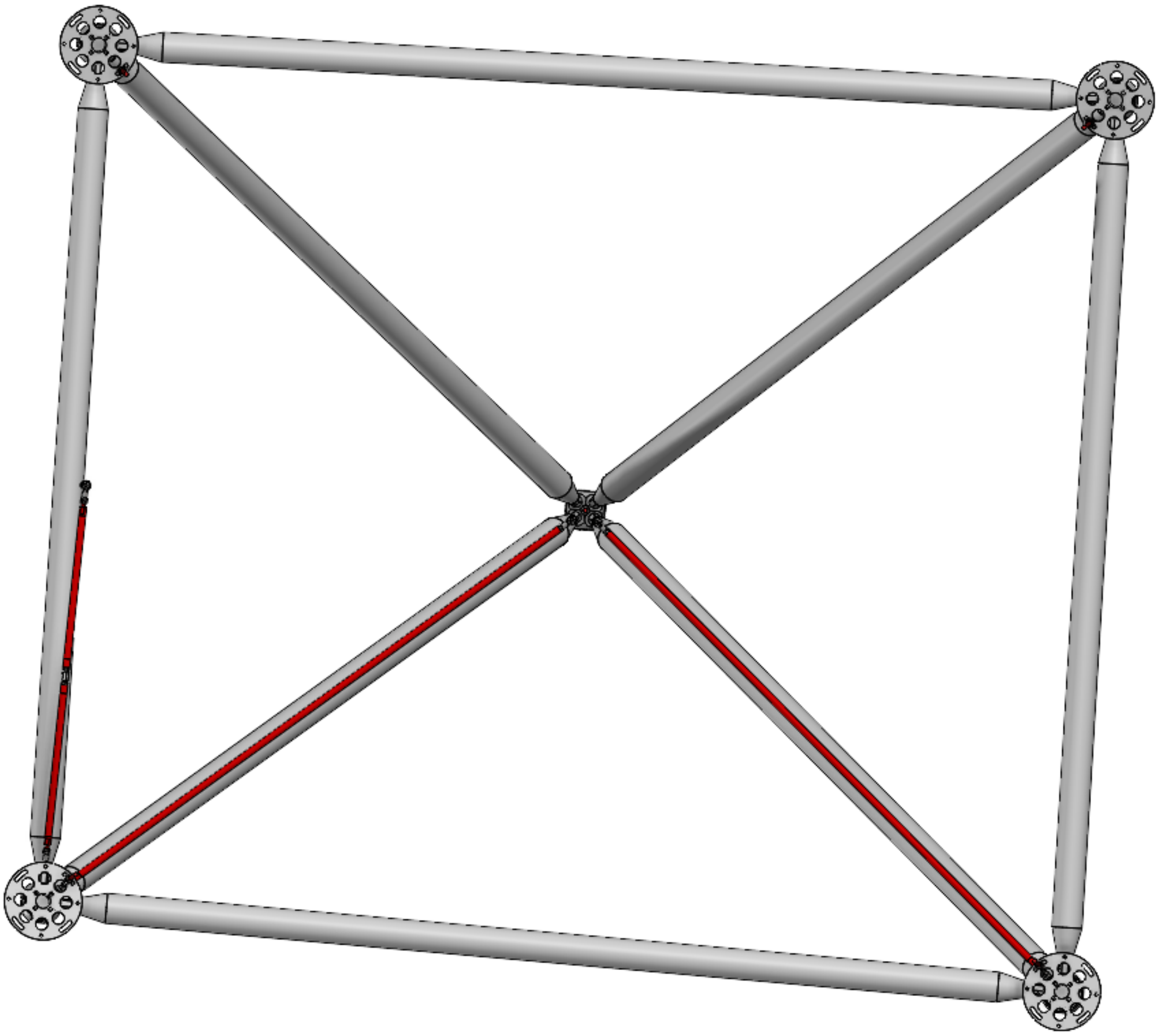


Figure 23 Arrangement of planar and rotation adjusters

The rotational adjuster is shorter than the planar one and is mounted to the panel adjuster mount on the one hand and to the panel itself on the other hand.
All these connections are made with ball joints that are available of the shelf all over the world.

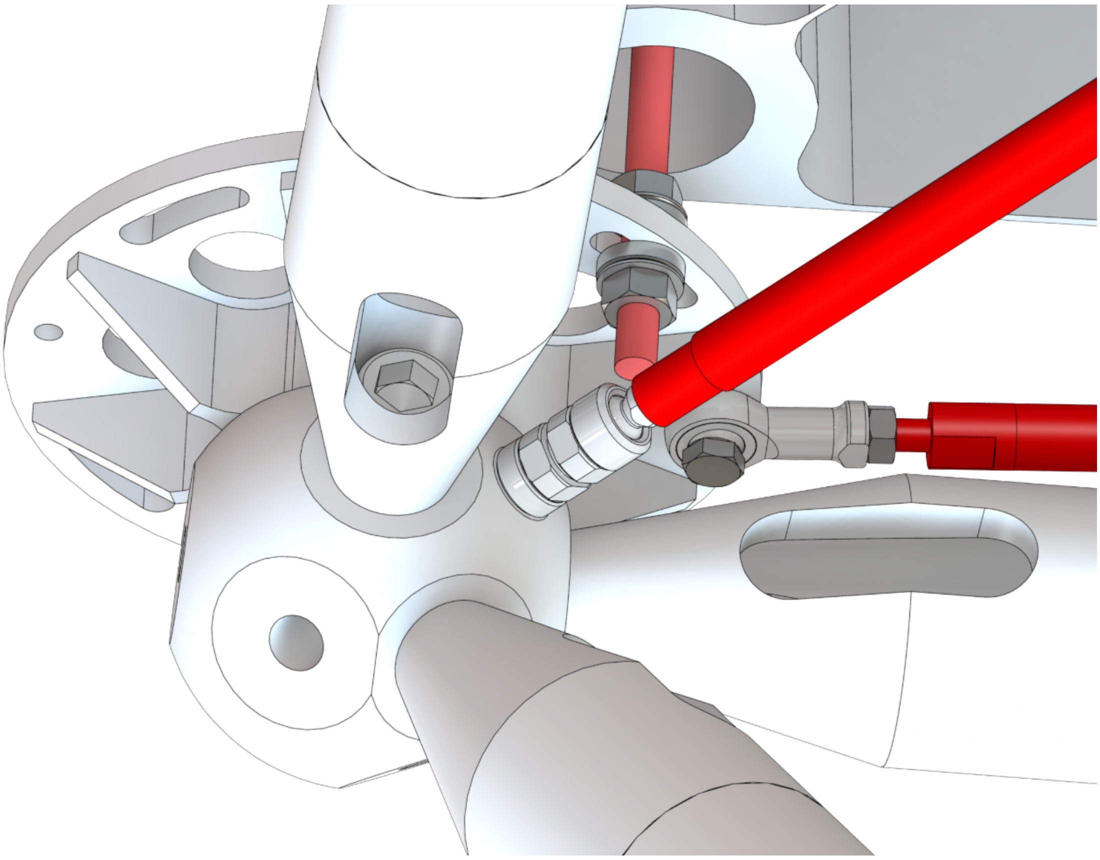


Figure 24 Panel Adjuster Connections BUS knots

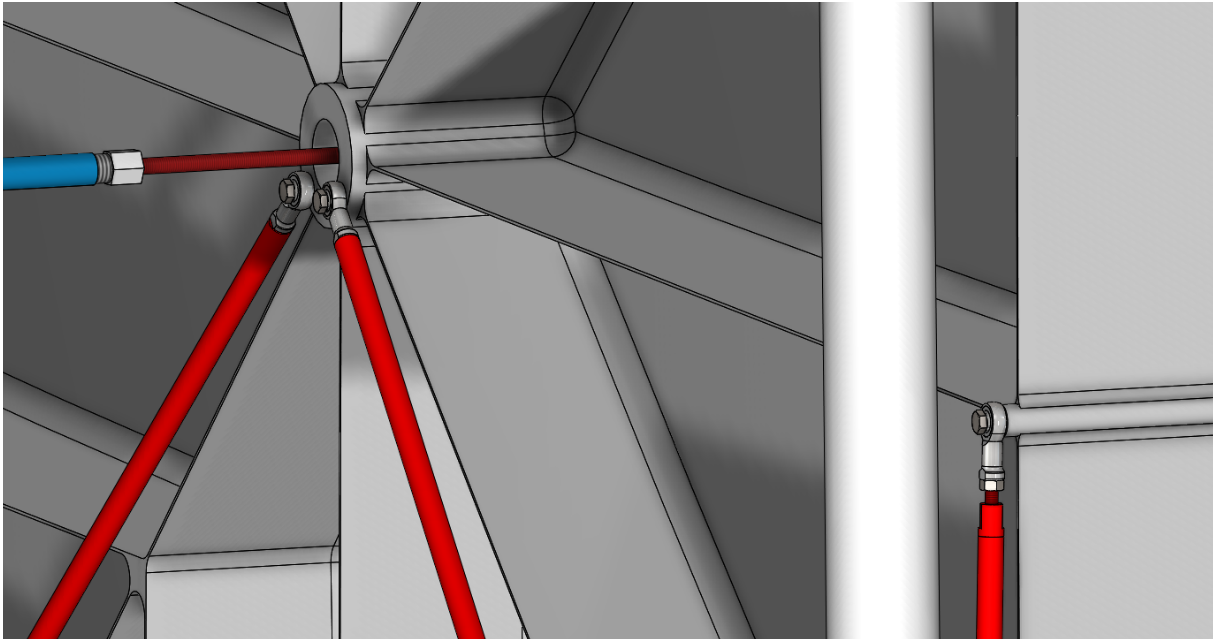


Figure 25 Panel Adjuster Connections Panel

The planar and rotational adjusters are made from steel tubes with an outer diameter of 16mm. Each component is hot dip galvanized and painted in RAL9010.

6.2.3. Panels

The design criteria of the ngVLA main reflector panels are driven by:

"The worldwide trend of transferring higher data volumes from A to B requires in the field of satellite communication, reflector antennas that transmit and receive signal in a larger bandwidth at higher frequencies."

Therefore, antenna reflector surfaces shall operate and fulfill the following specifications:

- Frequencies especially beyond Ka-Band up to 200 GHz
- Large, precise reflecting areas
- Robust, maintenance free and long-term stability
- Cost effective design per sqm
- Suitable for Antennas from 2m up to 40m

To achieve this mtex has developed a low-cost panel design and manufacturing technology that fulfills these requirements and is very suitable for the ngVLA Offset Gregorian radio-antenna.

For the ngVLA application mtex divided the main reflector into 68 square panels which are all with the same outer edge dimension (approx. 2.3 x 2.0m). The reflector corners are closed with 8 triangular panels.

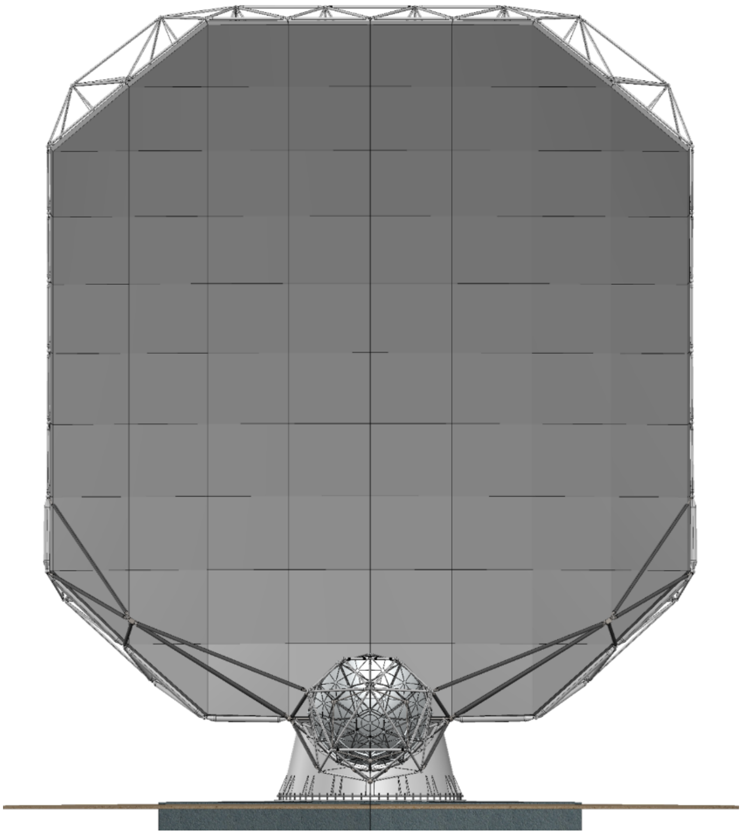


Figure 26 Main Reflector Panel Layout

Due to the optical shaped surface every panel has its own contour. The identical edge length provides the opportunity to create all the rectangular panels with the same supporting rip structure on the rear side
mtex decided to carry out further tests on mtex new panel technology in the original size of the ngVLA telescope. For this we have selected the panel type 2L03.

During manufacturing each panel gets an individual label giving the panel position number and the consecutive Serial number. This shall facilitate panel allocation during panel mount. It is important that the panel labeling is permanent readable and captive (cannot get lost).

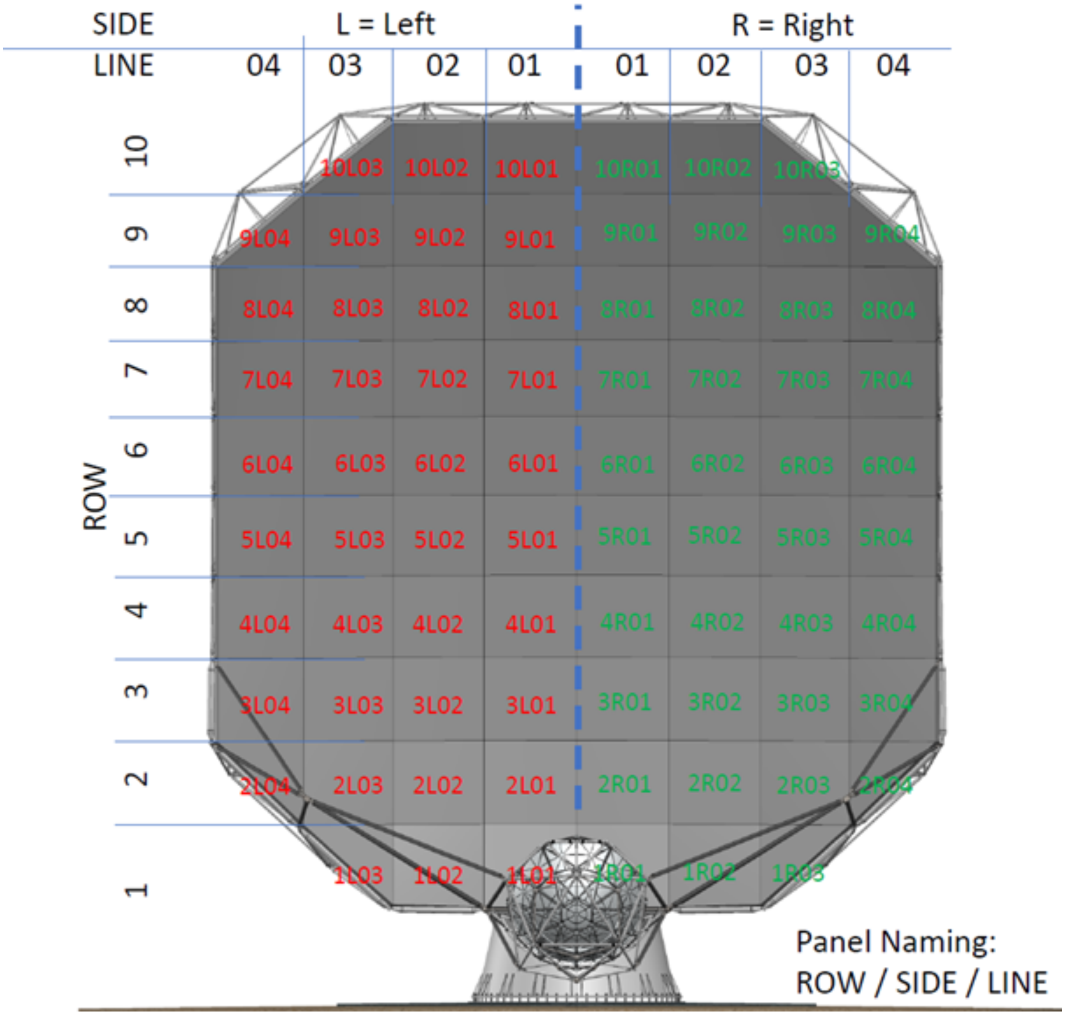


Figure 27 Panel Layout with detailed designation

The following figure shows an example of the panel labeling. Please note that for the serial number 5 digits are required.

3L04-00001

Green- panel position
Blue- consecutive serial number

6.2.4. Feed arm with Front-End equipment

The feed arm is designed as a space truss framework and connects the sub-reflector with the main reflector BUS.
It also carries the front-end equipment of NRAO, the feed indexer actuator and the sub-reflector hexapod.

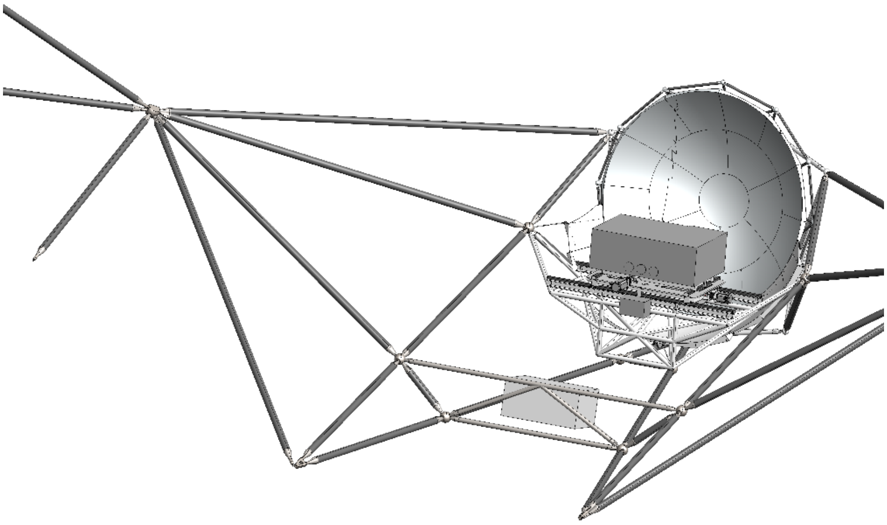


Figure 28 Feed Arm with Equipment

Cabling from the main reflector to the sub-reflector is routed below the feed arm on both sides. The fully equipped feed arm has a weight of approx. 3.1 tons.

6.2.4.1. Feed Arm Structure

The feed arm structure is made from CFRP and structural steel. All elements that are routed from the main reflector along the optical axis to the sub-reflector are made from CFRP. The structures that are perpendicular to the CFRP structure are made from structural steel. This contains the support truss, the front-end equipment support frame and the sub-reflector support structure.
In difference to the main reflector BUS the structural steel items in the feed arm structure are made as one-piece welded structures that are bolted to the carbon fiber.
The CFRP connections are made like the sphere/truss connections in the main reflector system.
In Figure 30 you can see the feed arm structure with the CFRP elements shown in black and the structural steel elements in white/grey.

The structural weight of this mix-material structure is only 1600 kg at a length of approx. 10,5m.

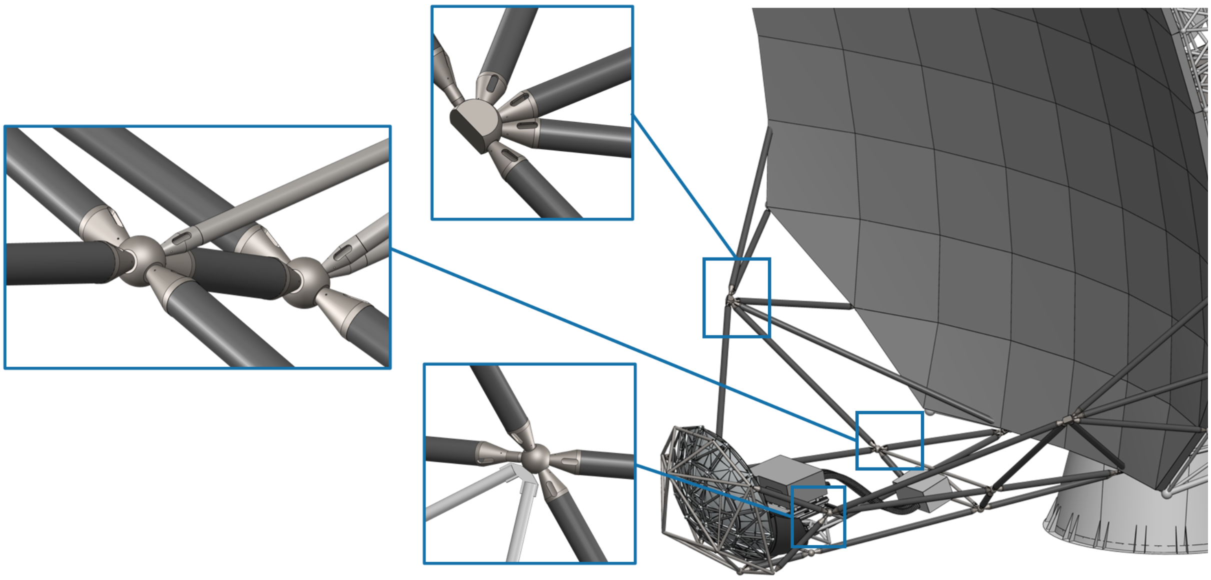


Figure 29 Detailing of Feed Arm

Naming schema similar to Main Reflector BUS (right side nodes mirrored, Direction of view behind the reflector)

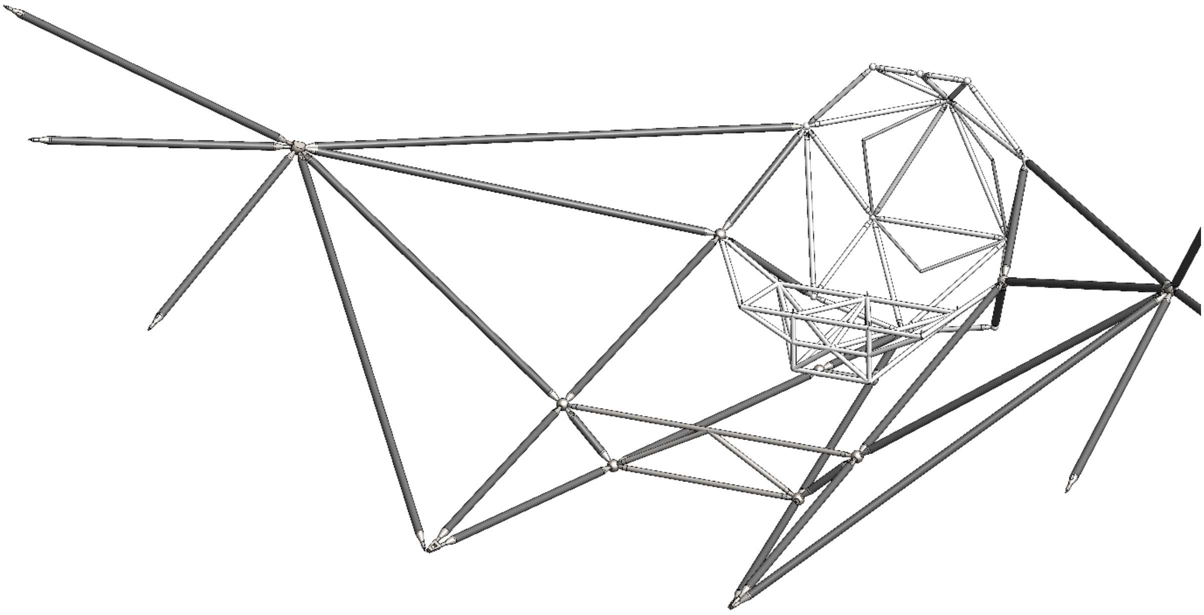


Figure 30 Feed Arm Structure (without equipment)

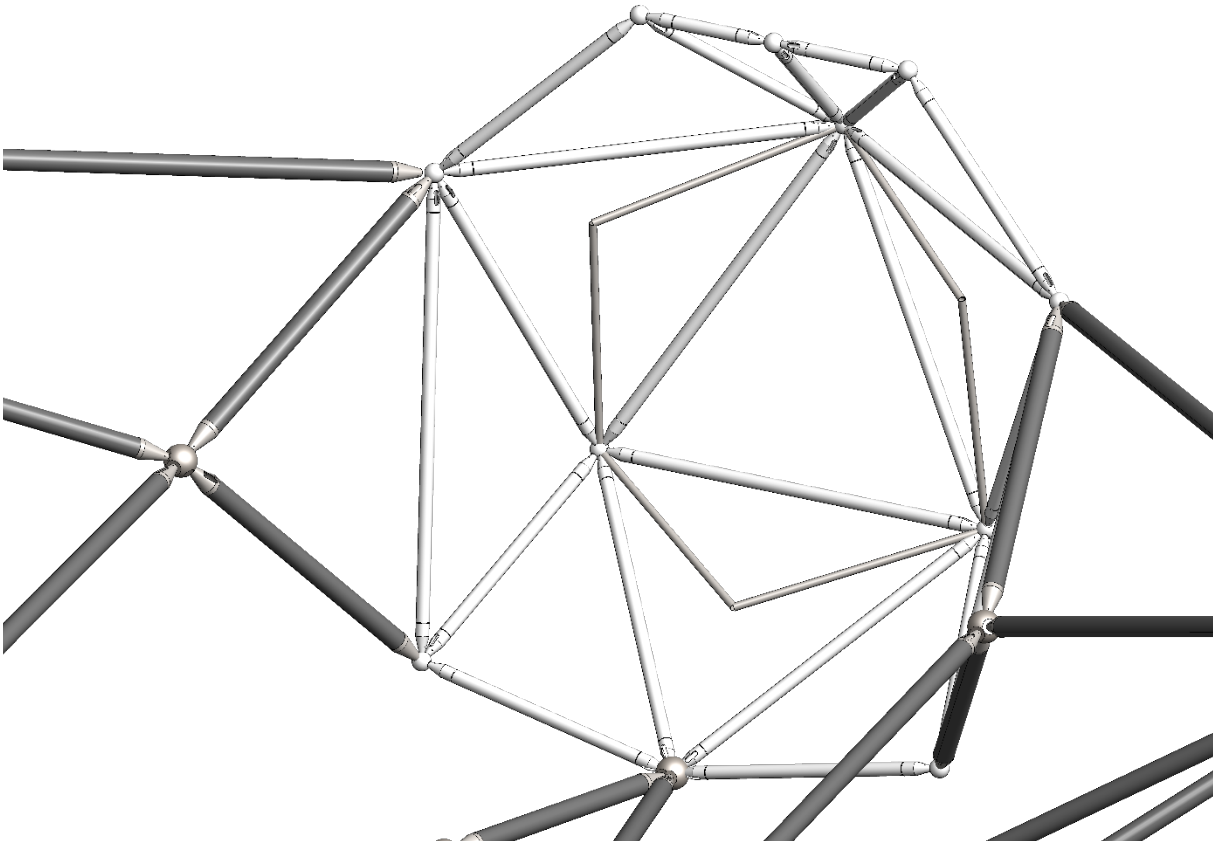


Figure 31 Sub-reflector Support Structure

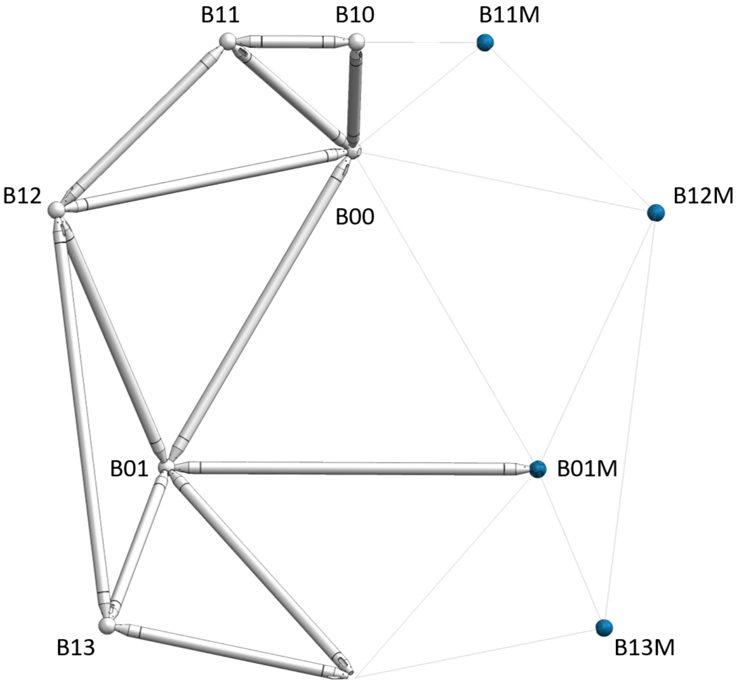


Figure 32 Description node and tube naming in sub-reflector support structure

Similar to the main reflector each node and tube has its own identification number, which is part of the name. The identification number is composed of as follows: (Direction of view behind the main reflector)

- 0-Plane in the middle of main reflector
- Left side (in optical line of sight): 1021006-DWG-23-22440-BXY
- Right side (in optical line of sight): 1021006-DWG-23-22440-BXY-M (Mirrored nodes)

As the nodes, each tube gets its own identification number. Identification number of the tubes is composed of the source node and the target node e.g., Tube B10B11, source node B10 to target node B11.

This structure consists of tubes with an outer diameter of Ø70mm, cones and nodes.
The total weight of this structure is approx. 550kg. The final coating is RAL 9010.

6.2.4.2. Feed Indexer Actuator

The feed indexer actuator is designed to move the feed system in the values specified by NRAO. It can move the feed in the optical Z-axis within a travel range of ±150mm and along the Y-axis within a travel range of ±675mm.

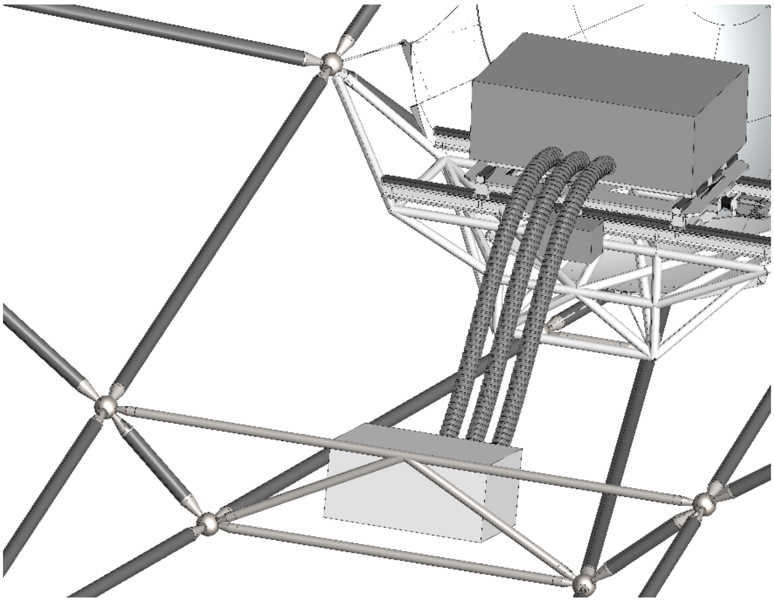


Figure 33 Feed Indexer Actuator Overview

The feed indexer actuator is based in a massive, welded steel frame with machined mounting interfaces that connect the base frame to the feed indexer support frame which is located in the feed arm structure.
On top of the base frame there are two linear rails for precise movement in Y-direction. The system is driven by a servo motor with a planetary gearbox that drives a high-precision spindle with a preloaded nut to avoid any backlash. For positioning a tape encoder is foreseen.
The Z-axis movement is done in the same way as described for the Y-axis.

All the linear rails are protected with bellows against environmental impacts. The linear rails and slides require a low awareness of maintenance.
To reduce the overall feed indexer actuator weight the connection plates between the moving axes are made from high quality and milled aluminum.

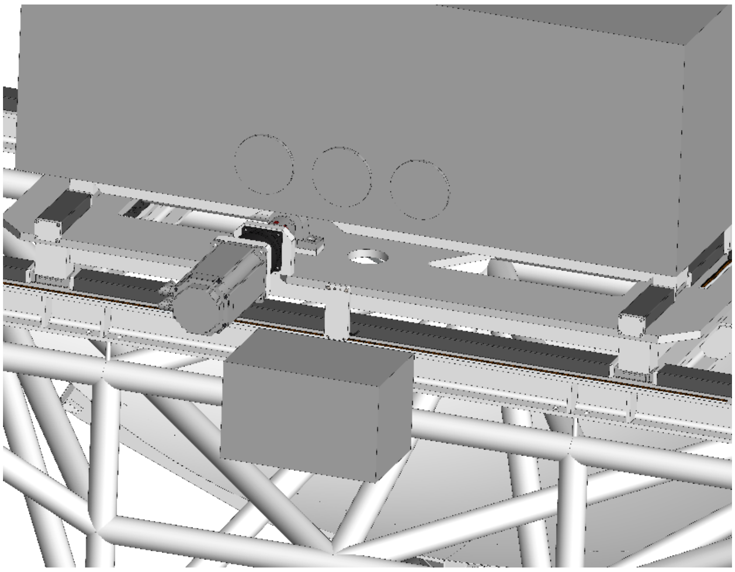


Figure 34 Feed Indexer Actuator (detail view)

In difference to the information provided by NRAO, mtex suggest the use of a 3D robotic cable chain to ensure proper cable routing between the front-end receiver and the auxiliary box. The figure below shows the sample of such a robotic cable chain made by IGUS.

Figure 35 Sample of IGUS Triflex R robot chain

These types of cable chain are well proven throughout different industries which require a large amount of movement and flexibility.
The weight of the feed indexer actuator without the front-end receiver is approx. 385kg.

The arrangement of the front-end receiver and the front-end auxiliary box was chosen by mtex to improve the overall FEA results. The receiver support structure is connected to the CFRP feed arm structure in the center of gravity of the feed indexer actuator and the sub-reflector system.
The alternative solution with an arrangement like specified by NRAO is shown in Figure 36 and has already been added to the main design (Figure 33) as a preliminary solution.

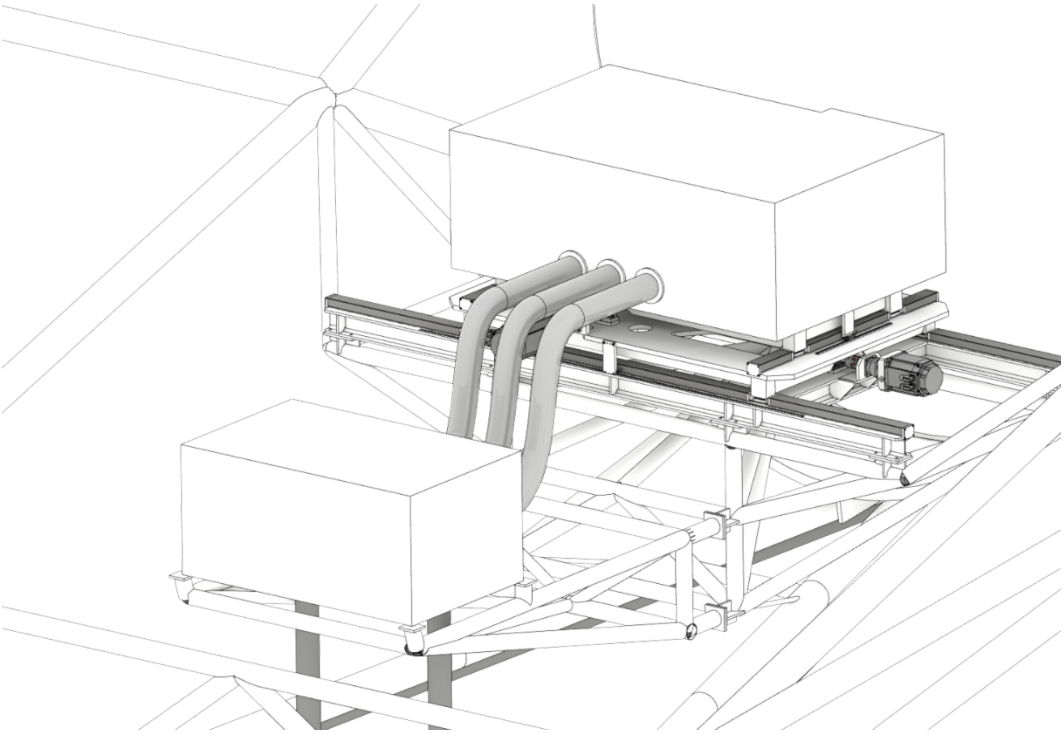


Figure 36 Alternative Front-End equipment arrangement

6.2.5. Sub-reflector

The sub-reflector for the ngVLA antenna is designed as an aluminum panel structure like the main reflector. Compared to the main reflector the sub-reflector is supported with a CFRP tubes. Due to the sub-reflector contour it was decided to design the sub-reflector with 19 panels. Each panel uses 4 vertical and 3 horizontal adjusters.

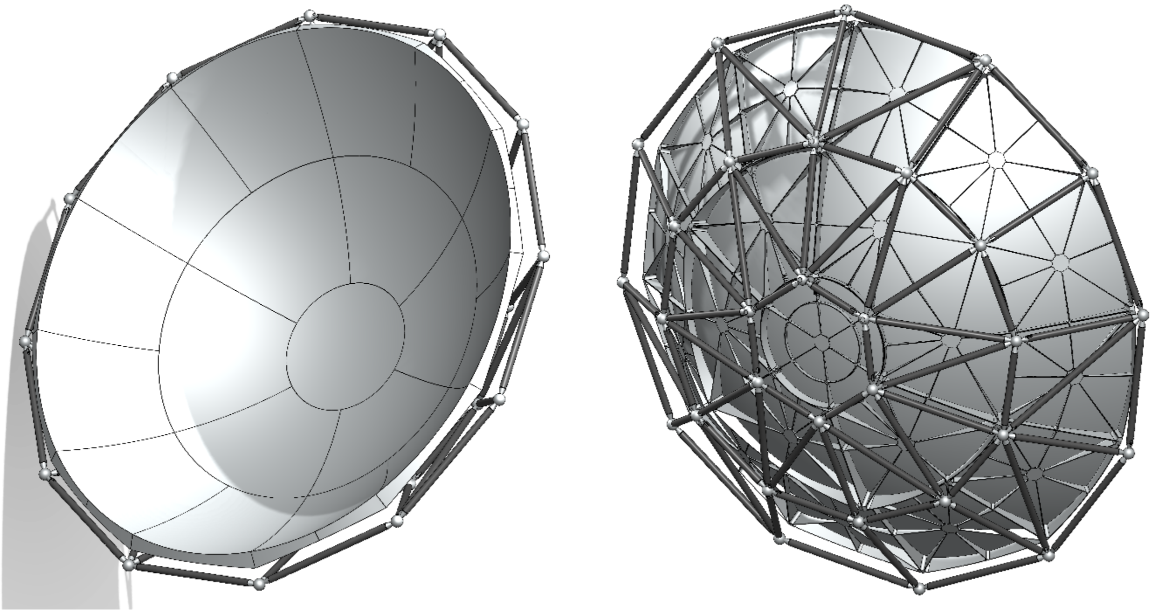


Figure 37 CFRP Sub-reflector (front-and rear view)

The sub-reflector is connected to the sub-reflector BUS, which is connected by a hexapod to 3 points at the sub-reflector support structure.

The final surface will be inspected with metrology methods to ensure the developed surface accuracy.

6.2.5.1. Sub-reflector BUS

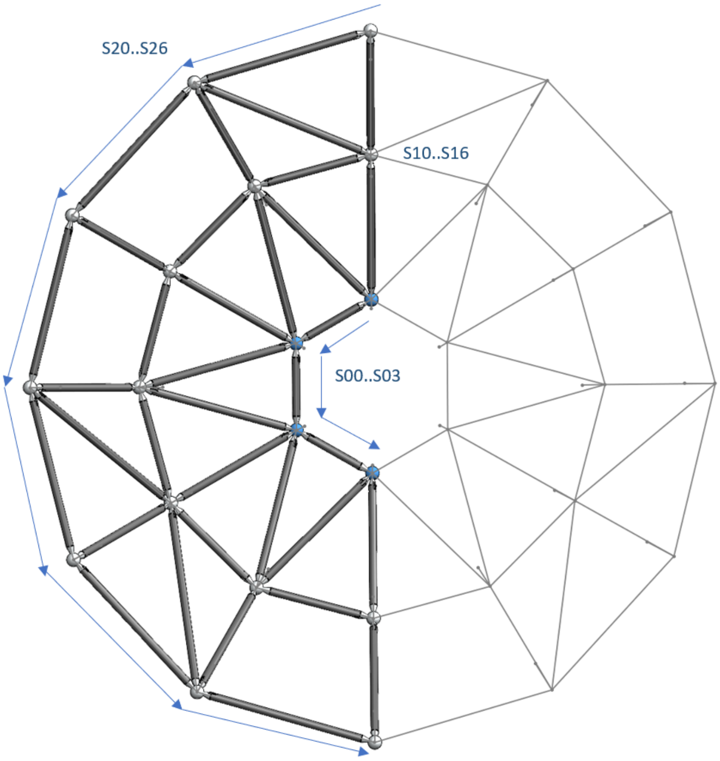


Figure 38 Description node and tube naming in sub-reflector BUS

The sub-reflector BUS is a bolted structure similar to the main reflector BUS. The structure has interfaces to the feed-arm structure, the sub-reflector noise shield and the sub-reflector hexapod. Similar to the main reflector each node has its own identification number, which is part of the name. The identification number is composed of as follows: (Direction of view behind the main reflector)

- 0-Plane in the middle of main reflector
- Left side (in optical line of sight): 1021006-DWG-23-22453-SXY
- Right side (in optical line of sight): 1021006-DWG-23-22453-SXY-M (Mirrored nodes)

As the nodes, each tube gets its own identification number. Identification number of the tubes is composed of the source node and the target node e.g., Tube S20S10, source node S10 to target node S20.

This structure consists of tubes with an outer diameter of Ø50mm, cones and nodes.
The total weight of this structure is approx. 65kg. The final coating is RAL 9010.

6.2.5.2. Sub-reflector Hexapod

The sub-reflector hexapod is designed as a mechanical hexapod with 6 identical legs. One side of the hexapod is bolted to the sub-reflector BUS with 3 identical welded brackets.
Sphere-like knots, similar to those used for the main reflector BUS, connect the legs with the sub-reflector. These ball joints will reduce the angular stress to the structure.

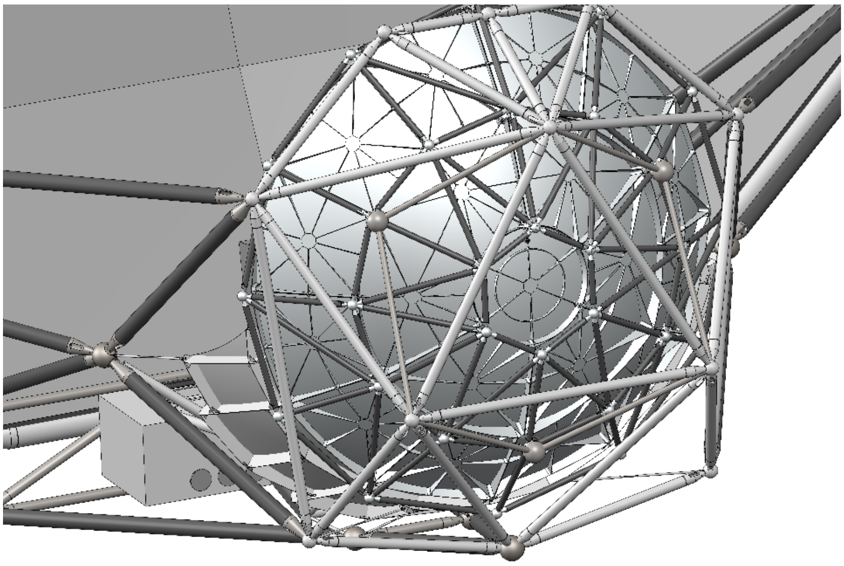


Figure 39 Sub-reflector Hexapod (overview)

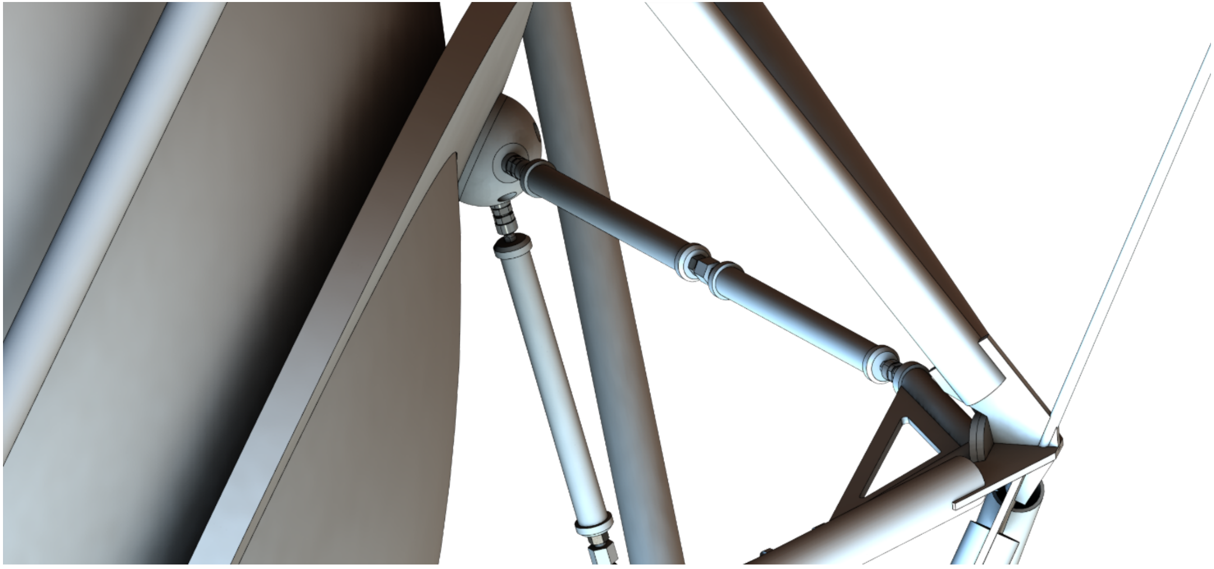


Figure 40 Sub-reflector Hexapod (detail view)

To adjust the length of each leg, the middle threads of the legs are manufactured with left-hand threads on the one end and right-hand threads on the other end. To ensure the position will stay fixed after adjustment, every interface is designed with Loctite jamb nuts.

6.2.5.3. Sub-reflector Shroud/Noise Shield

To protect the sub-reflector from ground noise and radiation it is equipped with a noise shield made from segmented aluminum sheets.

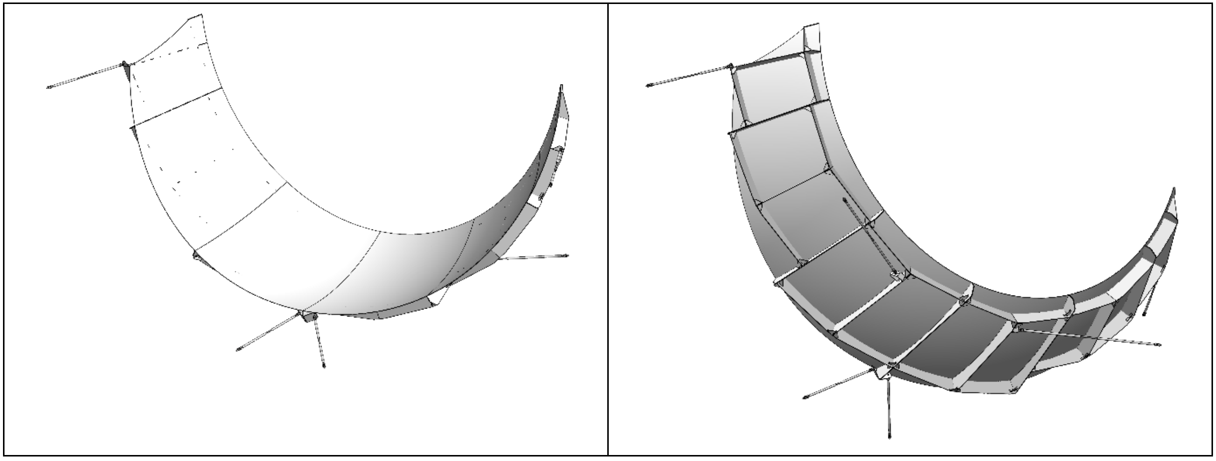


Figure 41 Sub-reflector Noise Shield

During the detailed design phase, the decision of six-piece or three-piece component will be finalized. The noise shield is designed that it is not touching the sub-reflector in any position and not interfering the beam, of course.
The new optical design file provided with the RFP shows an even enlarged extension.

6.2.6. Counterweights

The counterweights are designed as 3 different massive steel plates per side. Each plate is designed to a thickness of 100mm.

It was decided to make 3 counterweight plates per side to be able to trim the reflector system in the final configuration and to simplify the installation because it is possible to use smaller equipment for lifting and installation.

Each of the plates is mounted with M24 bolts and the plates are connected with each other with M24 bolts, too.

To ensure a proper connection in every elevation position of the antenna the counterweights are connected to the welded structure with a tongue and feather design.

The counterweight plates end up with a total weight of approx. 8350 tons (4175 kg per side).

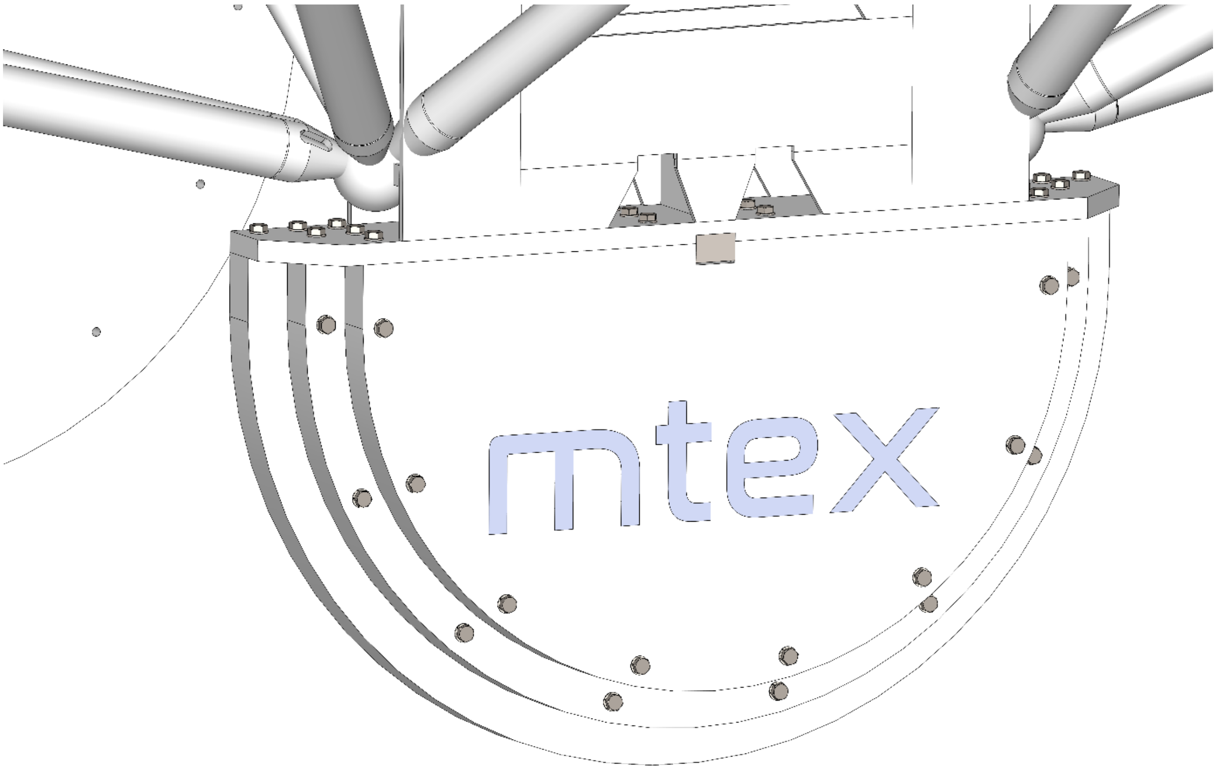


Figure 42 Counterweights mounted to welded structure

6.3. Aperture Blockage

The blockage of the main reflector and sub reflector was calculated considering a panel gap of 4mm in the main reflector area, as well as a 1mm panel gap for the panels of the subreflector segments.

Main Reflector area:

without panel gaps	351.2 m²
with panel gaps	350.0 m²
blockage	**0.338%**

Subreflector area:

without panel gaps	10.63 m²
with panel gaps	10.61 m²
blockage	**0.188%**

Full Aperture area:

without panel gaps	361.83 m²
with panel gaps	360.62 m²
blockage	**0.33´3%**

6.4. Pedestal

The antenna pedestal is defined as the fixed part from the foundation up to azimuth bearing.

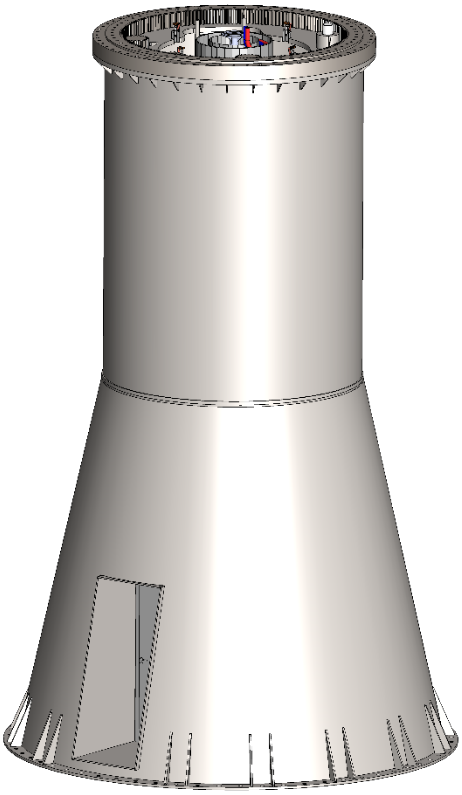


Figure 43 Pedestal Overview

The pedestal mainly consists of two large, welded steel structures, the lower and the upper pedestal. These structures are bolted in the middle to ensure easier transport to site.
To enter the structure the pedestal is designed with a standard door size that is 850 mm wide and 2000 mm high. This allows easy access for maintenance personnel. To make it even easier to get in and out with heavy equipment there is a removeable ramp that can be stored inside the pedestal.
The fully assembled pedestal contains a large amount of equipment such as the EMI drive cabinet, back-end rack, azimuth drives, azimuth cable wrap, etc.
To adjust the azimuth axis the pedestal is mounted to an anchoring with 64 bolts.
The gap that is created here will be closed with an adjustable gap cover that can handle the flatness issues of a concrete foundation surface.

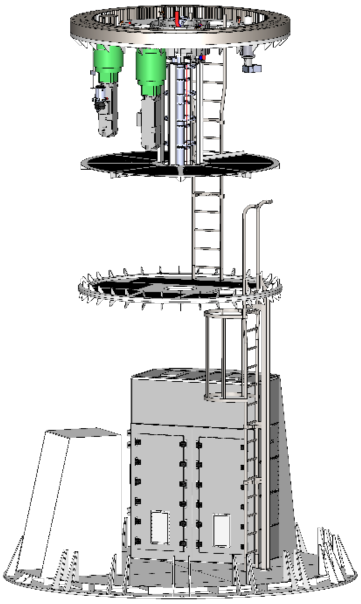


Figure 44 Pedestal without outer steel walls

The floors inside the pedestal are steel grating. This ensures airflow and can be removed for maintenance or assembly reasons. A removeable grating floor provides the opportunity to lift and lower a complete gearbox or other heavy equipment.

Inside the pedestal there is one ladder from ground floor to the first floor and another ladder from first floor to the maintenance platform in the upper pedestal section.

The ladder from ground floor to first floor is equipped with a safety rail and fall protection according to local safety regulations.

All ladders are fixed to the structure and not removeable.

6.4.1. Foundation

The foundation will have a hexagonal shape with 12 meters flat to flat size (see Figure 43), it will be 1 meter thick as this, it is a field proven design.

- More efficient than square or round configurations
- High factor of safety vs. overturning/sliding
- Allows for low soil pressure requirement values
- Results in higher spring rates
- Easily scalable for actual site soil conditions
- 125 m^3 of concrete
- 300,000 kg of concrete/reinforcement
- mtex/KTF supplied Foundation Template /Anchor bolt cages (see Figure 45)
- must be reviewed/modified for each site per Geotech investigation and local engineering firm

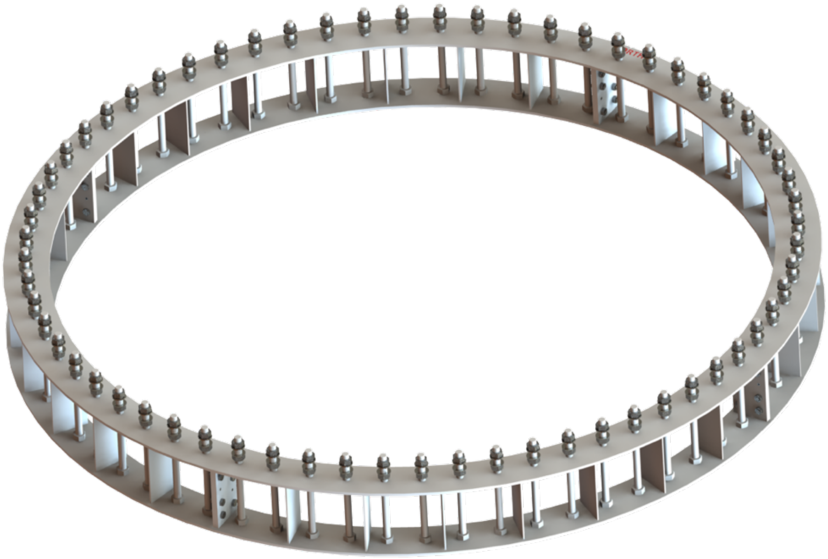


Figure 45 Foundation anchor ring and template

6.4.2. Lower Pedestal

The lower pedestal steel structure is designed as a cone with a foundation interface diameter of 5150 mm and a top interface diameter to the upper pedestal steel structure of 2950 mm.
It is designed and calculated with a wall thickness of 20mm.
This creates a total steel structure weight of approx. 14 tons.

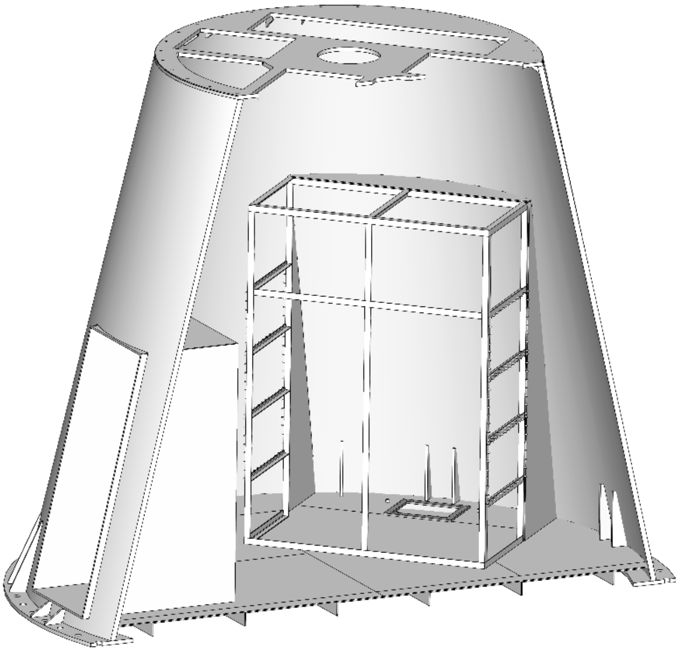


Figure 46 Lower Pedestal Steel Structure (Cross Section)

The lower pedestal is designed with a standard steel entrance door for easy and comfortable access. This door is also fire resistant and has a free opening with 740 mm width and a height of 1945 mm.
Inside the pedestal there is the welded EMI drive cabinet base frame that will be equipped with sidewalls, doors, and EMI gaskets during commissioning.
It is also possible to store the removeable ramp inside the pedestal.
The lower pedestal also houses the back-end equipment rack and the air-handler.

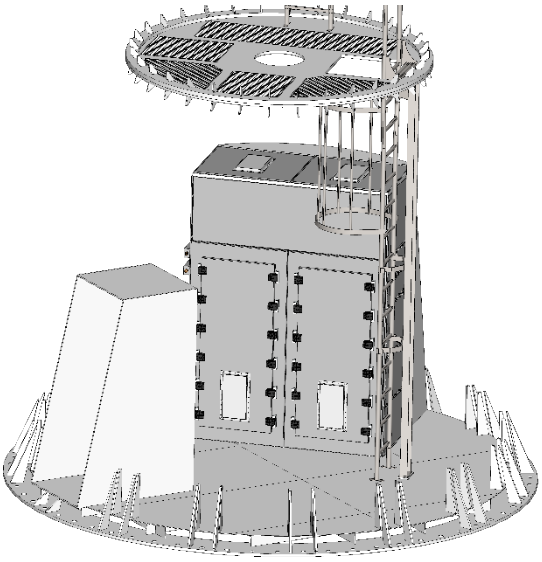


Figure 47 Lower Pedestal without Back-End Rack

6.4.3. Upper Pedestal

The upper pedestal steel structure is designed as a cylinder with a 2950 mm interface diameter at the bottom and 3200 mm interface diameter on top. The lower interface is suited for the lower pedestal and the upper interface is designed according to the azimuth bearing.

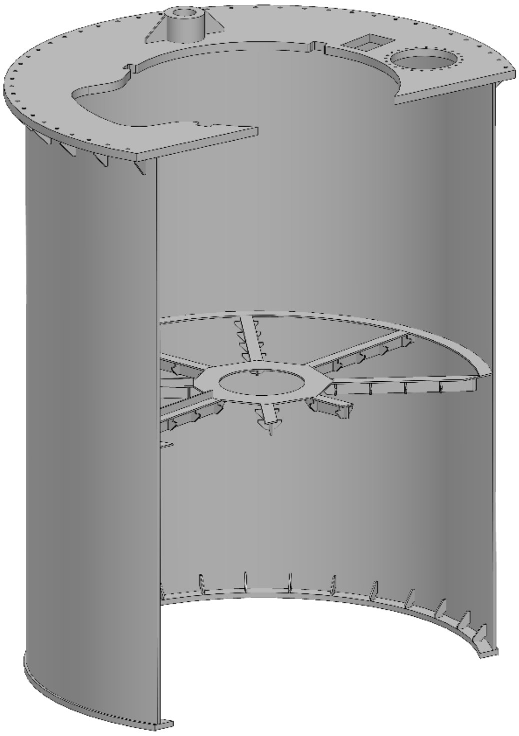


Figure 48 Upper Pedestal Steel Structure (Cross Section)

The upper steel plate interfaces to a lot of mechanical equipment like azimuth drives (two pieces), azimuth lightning protection (four pieces), azimuth stow pin, azimuth automatic lubrication system and the oil compensating reservoirs of the azimuth gearboxes. All the mentioned equipment is mounted to the interface plate from the bottom.
The azimuth bearing is set up on the top and bolted to the structure from the bottom.
In the middle of the steel structure cylinder there is a maintenance platform that ensures easy access to the equipment installed in the upper steel plate.
Grating which is installed on the steel profiles of the maintenance platform can be removed for equipment lifting reasons.
The platform also interfaces to the fix holders of the azimuth cable wrap.
Below the platform there is the interface for the azimuth I/O Unit.

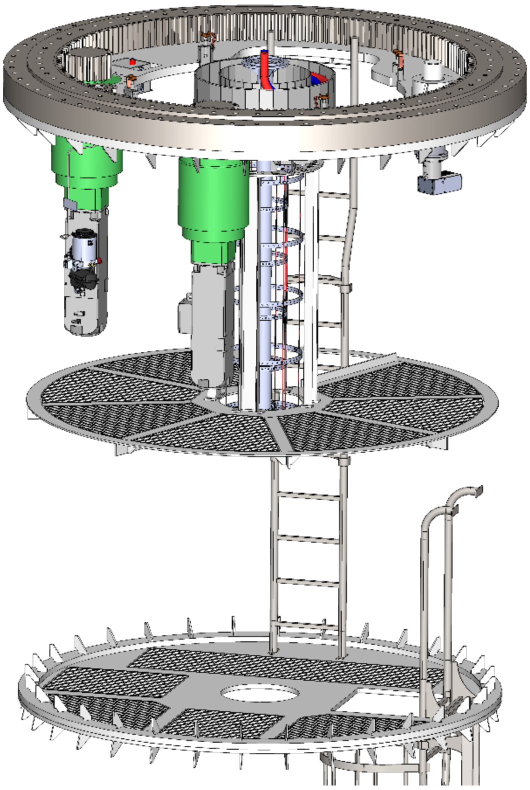


Figure 49 Upper Pedestal with Equipment

All the mechanical components above will be described in more detail in section 6.6.
The weight of the upper pedestal steel structure is approx. 8500 kg.

6.5. Turnhead

The Turnhead is the connection structure between the pedestal and the main reflector system. It interfaces to the top of the azimuth bearing and the elevation bearings mounted to the Turnhead “arms”. Access to the Turnhead structure is given through an opening in the bottom plate. Two hatches on the top are made for climbing out of the structure and for fitting and removing of equipment.

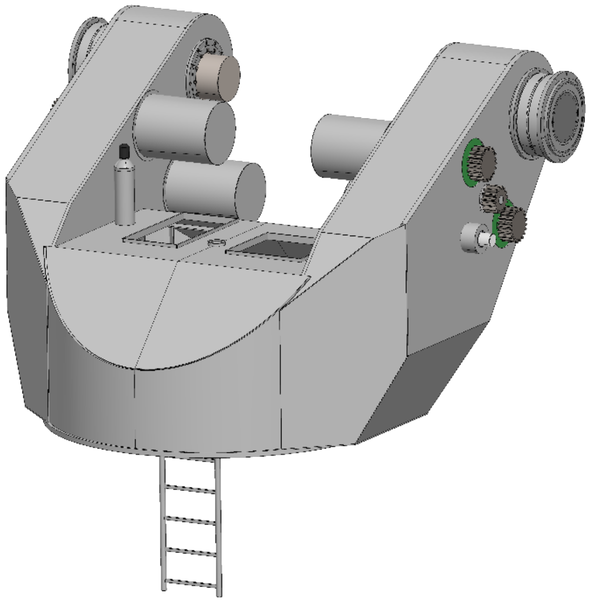


Figure 50 Turnhead with Equipment (rear view)

In addition to the bearing interfaces the Turnhead is also equipped with the following mechanical items and interfaces:

- Elevation drives (gearboxes and motors, 2 per side)
- Elevation automatic lubrication (1 per pinion per side, 1 pump for both bearings)
- Elevation stow pins (1 per side)
- Elevation buffer system
- Elevation I/O unit
- He-Bottle for operation (exchangeable)
- Elevation cable loop interfaces
- Environmental CFI (inside Turnhead)
  - He-Compressor
  - He-buffer-bottle
  - He-Compressor control unit
  - RFI Enclosure

The weight of the Turnhead steel structure is approx. 12 tons.

- For safety reasons the top of the Turnhead is equipped with a safety post, as well as an emergency stop button close to the access hatch. The safety post allows moving on top of the Turnhead without changing the fixing point. It can be reached directly when exiting the Turnhead access hatch. The safety post and its anchor point are EN 795 certified of the shelf safety equipment. With regards to the hazard analysis in the detail design phase, mtex might add additional anchor points to the Turnhead top. A replacement of the safety post is feasible, and another safe anchor point according to the osha standard will be provided instead. The access ladder to the Turnhead is mounted to the Turnhead itself and rotating close to the azimuth cable wrap in the upper pedestal. For installing and removing equipment the equipment hatch is closed with bolts and EMI gaskets. The access hatch is a foldable hatch with easy-to-remove hinges in case it is required to remove it quickly.

To ensure lightning protection for the azimuth bearing a copper slip rail is mounted below the bottom plate of the Turnhead.

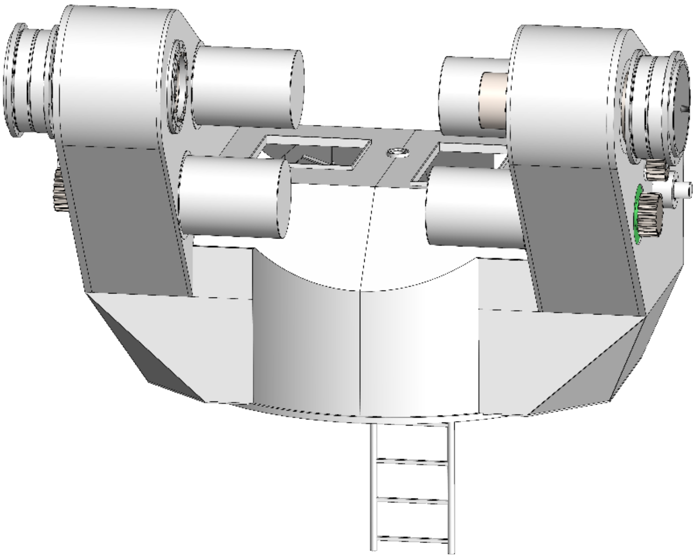


Figure 51 Turnhead with Equipment (front view)

To install the main reflector system to the Turnhead it is required to install the elevation buffer consoles after the main reflector system is connected to the elevation bearings.

6.6. Mechanical Equipment

The following sections are intended to provide detailed information about the main mechanical components.

6.6.1. Main Bearings

6.6.1.1. Azimuth Main Bearing

mtex made the decision to go for a three-row-roller bearing for the azimuth bearing.
This design is well proven and recommended for antenna use by the manufacturer.
To achieve high stiffness for the overall system the azimuth bearing raceway will have a diameter of 3000mm with a current design weight of approx. 4,100kg.

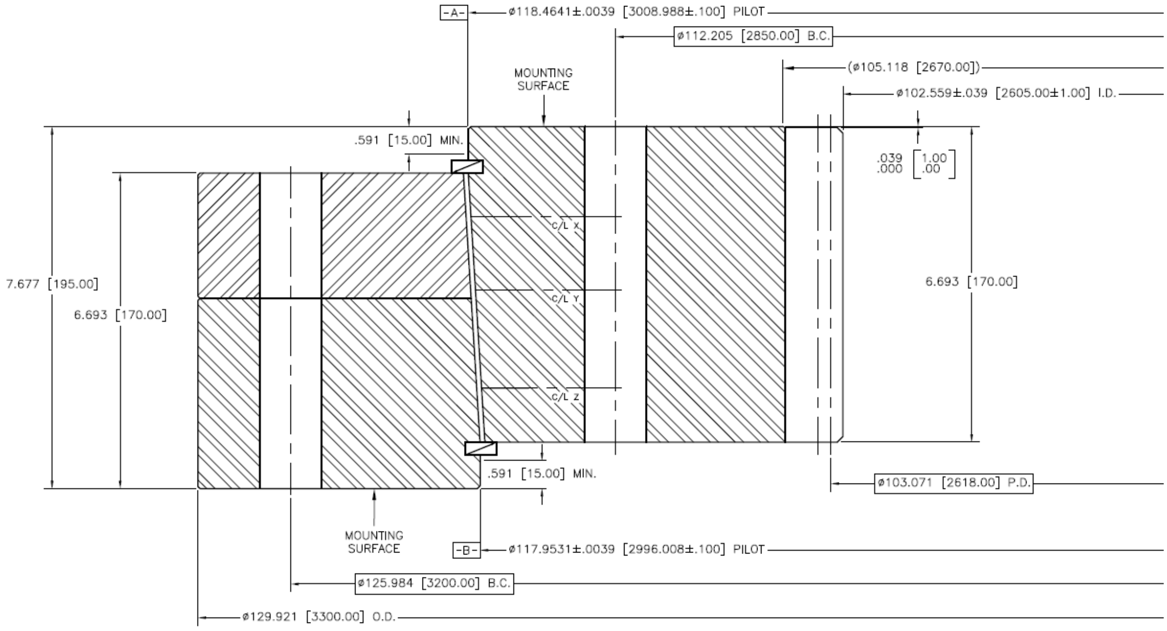


Figure 52 Three-Row-Roller Bearing (Sample, dimensions not applicable to ngVLA)

The final design will be with inner toothing and lubrication interfaces from the top.

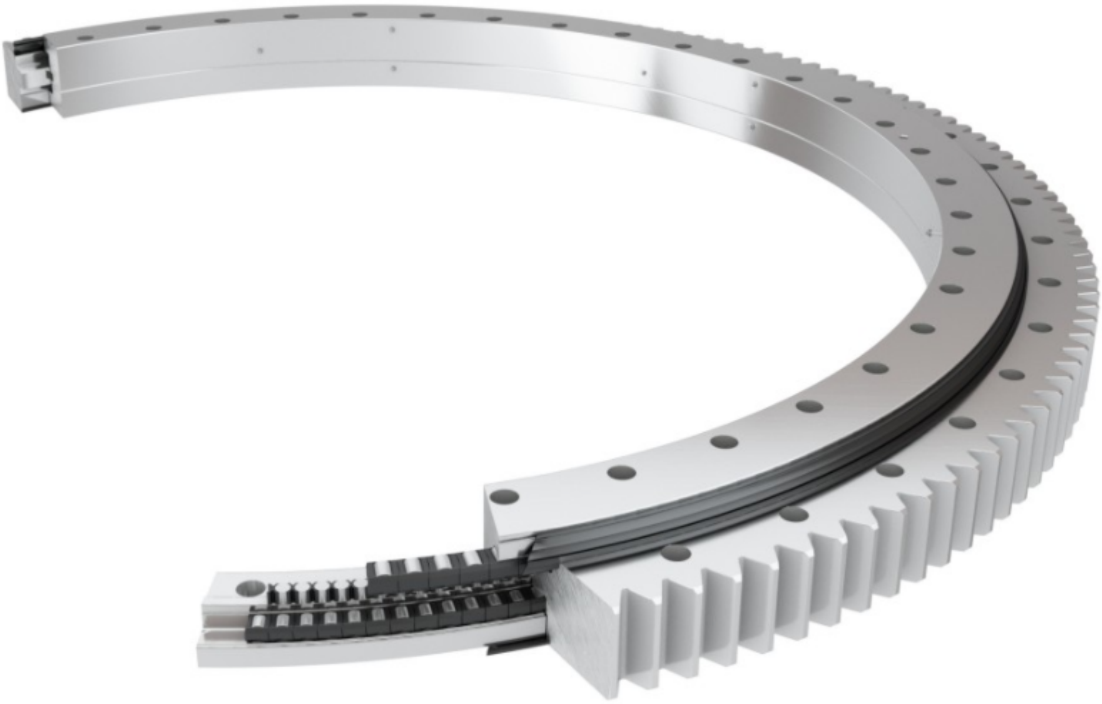
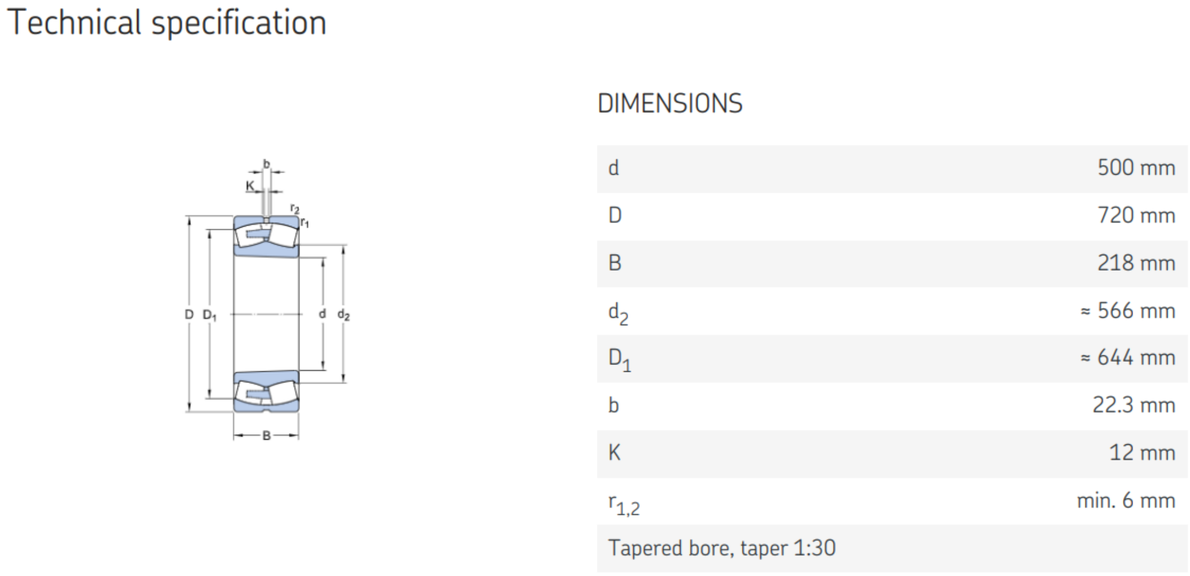


Figure 53 Three-Row-Roller Bearing Sample (Rothe Erde Website)

6.6.1.2. *Elevation Main Bearing (TW)*

The two elevation bearings are planned as spherical roller bearings from the standard delivery program.



Technical specification

DIMENSIONS

d	500 mm
D	720 mm
B	218 mm
d_2	≈ 566 mm
D_1	≈ 644 mm
b	22.3 mm
K	12 mm
$r_{1,2}$	min. 6 mm
Tapered bore, taper 1:30	

Figure 54 Bearing Dimensions (240/500 ECAK30 W33)

This bearing needs to be installed with a clamping collar which is standard.
Each bearing has a weight of 290kg.
The bearings are mounted to the antenna with a massive elevation axis on each side.

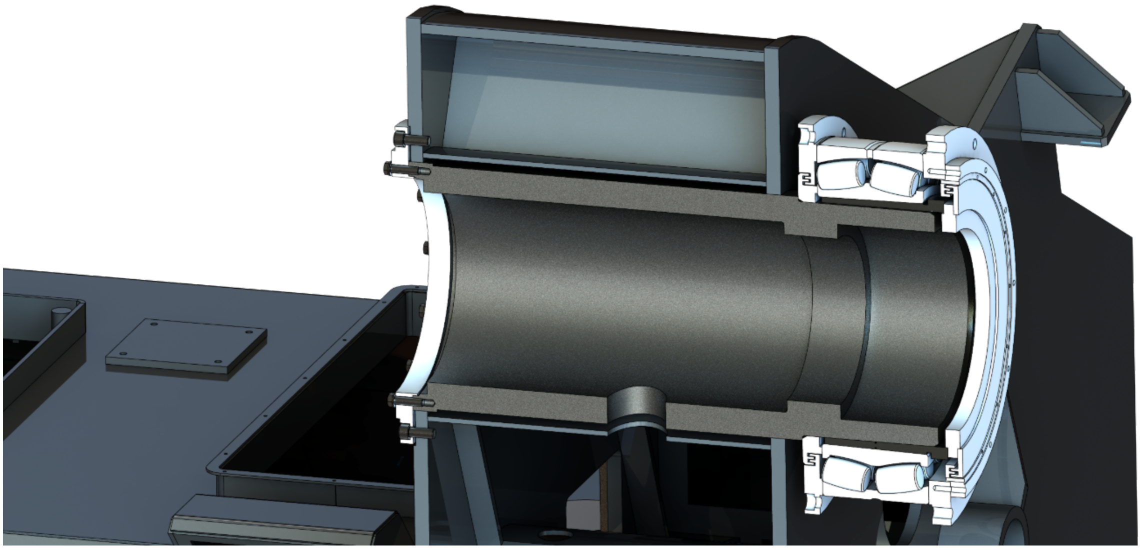


Figure 55 Elevation Bearing Assembly (Cross Section, Left Side)

The bearing axis is designed with the interface to the elevation I/O box, as well as cable feed through inside the Turnhead to ensure that no cable needs to be routed outside the antenna.
Bearing details:

6.6.1.3. Feed Indexer Y- and Z- axis rails

The feed indexer linear rails for Y-axis, as well for the Z-axis are chosen as identical types. There are a lot of different manufacturers available on the market.
The current design is made with SSR25 rails and slides that can handle dynamic loads of 31,5 kN. The SSR rail system has been chosen due to their capability of low friction, long-term maintenance-free operation, and superb high-speed response abilities.
The slides use a caged ball linear motion guide.

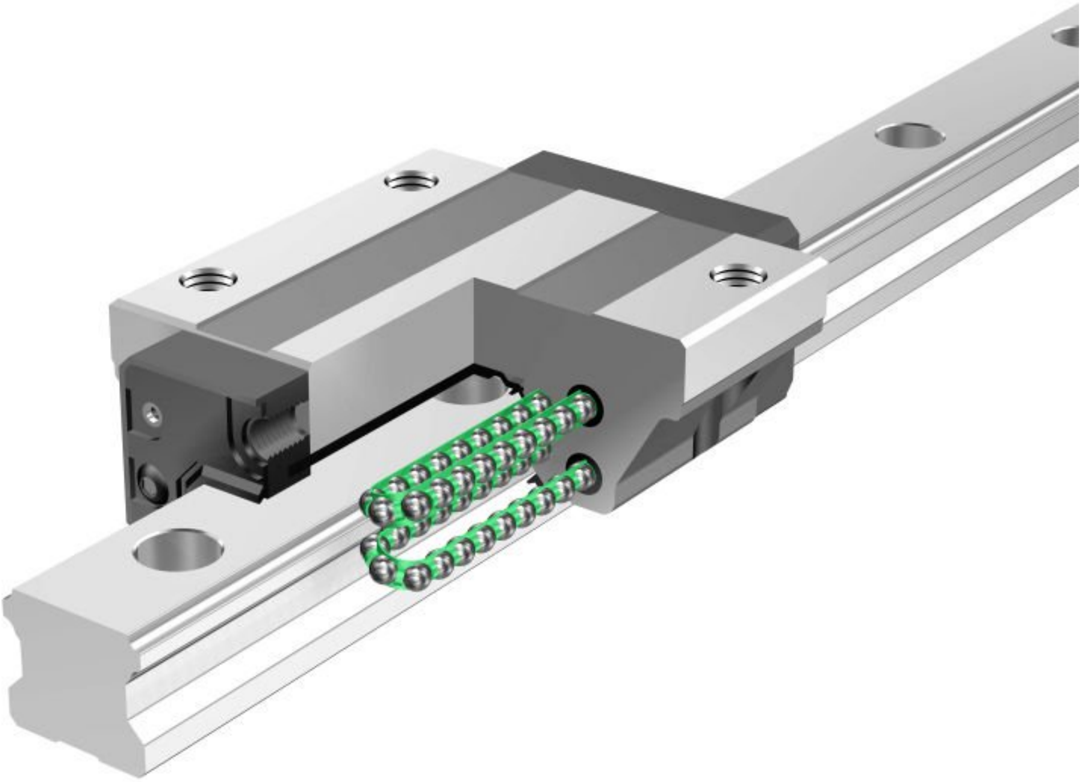


Figure 56 Caged Ball Linear Motion Guide (Cross Section, THK)

To protect the linear rails from environmental impacts the rails will be covered with bellows.

6.6.2. Gearboxes

6.6.2.1. Azimuth Gearboxes

The gearboxes are not off-the-shelf, they are specially designed for the ngVLA application for high stiffness.
There are two azimuth gearboxes that are mounted to the top interface plate of the upper pedestal hanging below the Turnhead.

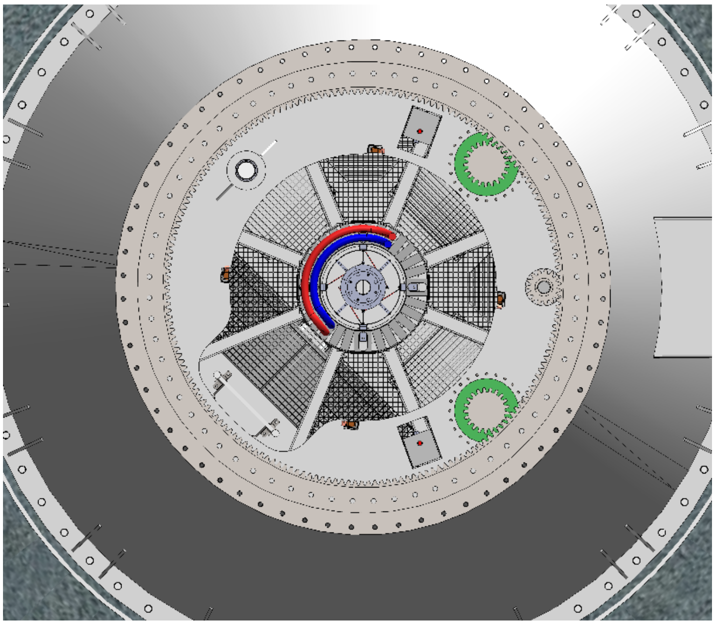
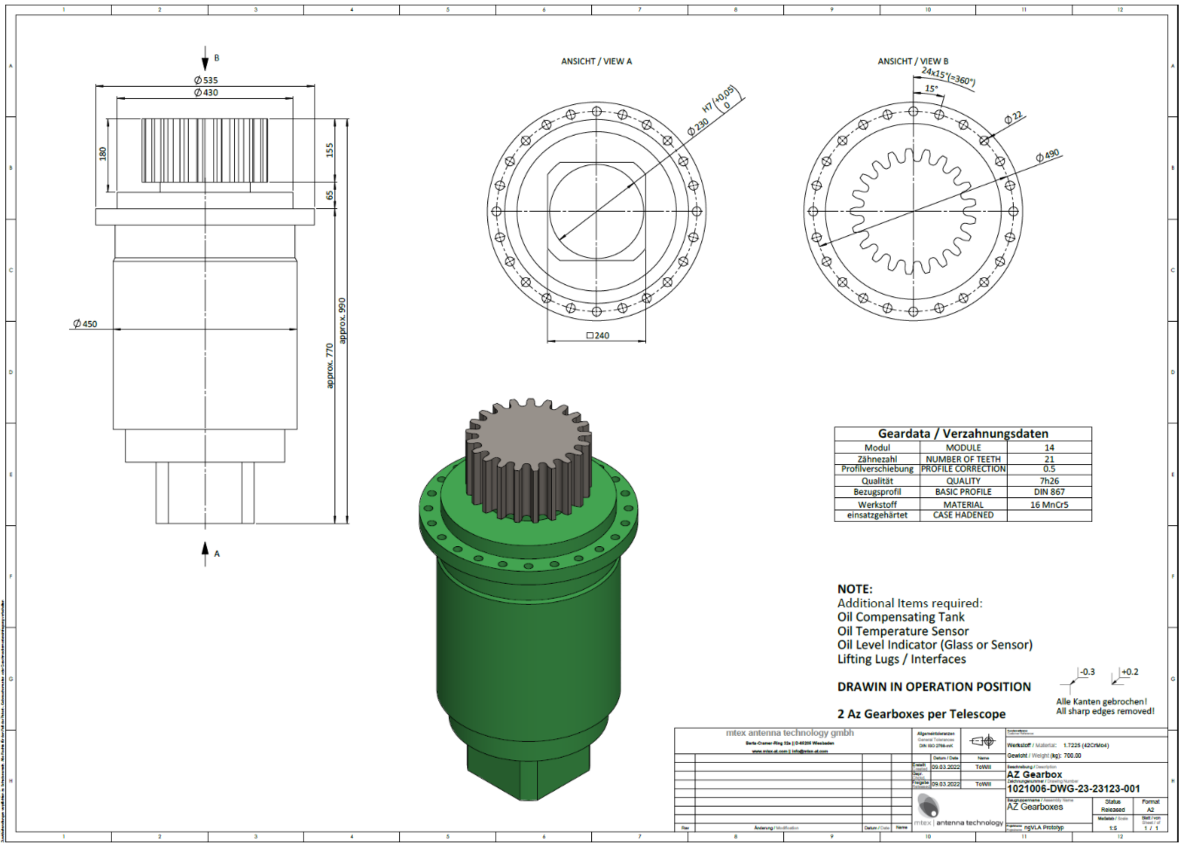


Figure 57 Azimuth Drive Arrangement

Due to the mounting orientation both gearboxes are equipped with oil compensating tanks which are installed close to the appropriate gearbox.
Each gearbox is estimated to weigh approx. 700kg.
Additional equipment that comes with the gearbox are oil level indicators, oil temperature sensor and lifting lug interfaces.
The drive pinion is designed to the following parameters:

Table 4 Azimuth Drive Pinion Geardata

#	DESCRIPTION	PARAMETER
1	Module	14
2	Number of teeth	21
3	Profile correction	0.5
4	Quality	7h26
5	Basic profile	DIN 867
6	Material	16 MnCr
7	Case hardened	



Geardata / Verzahnungsdaten		
Modul	MODULE	14
Zähnezahl	NUMBER OF TEETH	21
Profilverschiebung	PROFILE CORRECTION	0.5
Qualität	QUALITY	7h26
Bezugsprofil	BASIC PROFILE	DIN 867
Werkstoff	MATERIAL	16 MnCr5
einsatzgehärtet	CASE HADENED	

NOTE:
Additional Items required:
Oil Compensating Tank
Oil Temperature Sensor
Oil Level Indicator (Glass or Sensor)
Lifting Lugs / Interfaces

DRAWIN IN OPERATION POSITION

2 Az Gearboxes per Telescope

Figure 58 Azimuth Gearbox Preliminary Drawing

6.6.2.2. Elevation Gearboxes

The gearboxes are not off-the-shelf, they are specially designed for the ngVLA application. There are four elevation gearboxes. Two gearboxes are mounted to each side plate of the Turnhead.

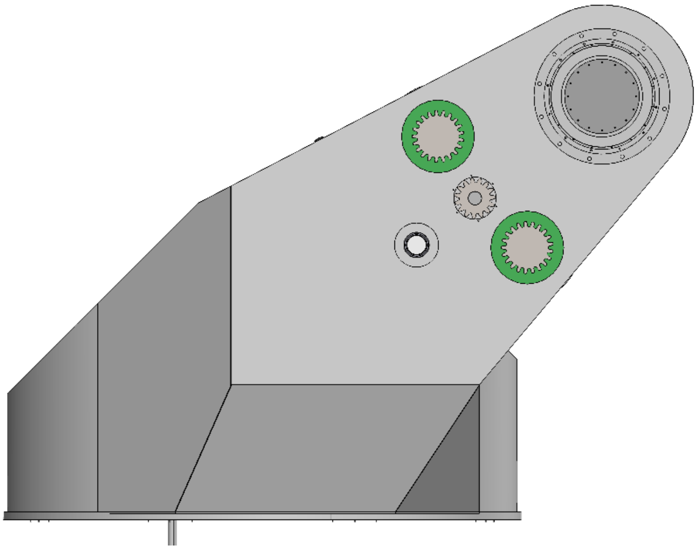


Figure 59 Elevation Drive Arrangement

Each gearbox is estimated to weigh approx. 600kg.

Additional equipment that comes with the gearbox are oil level indicators, oil temperature sensor and lifting lug interfaces.

The drive pinion is designed to the following parameters:

Table 5 Elevation Drive Pinion Gear data

#	DESCRIPTION	PARAMETER
1	Module	14
2	Number of teeth	21
3	Profile correction	0.5
4	Quality	7h26
5	Basic profile	DIN 867
6	Material	16 MnCr
7	Case hardened	

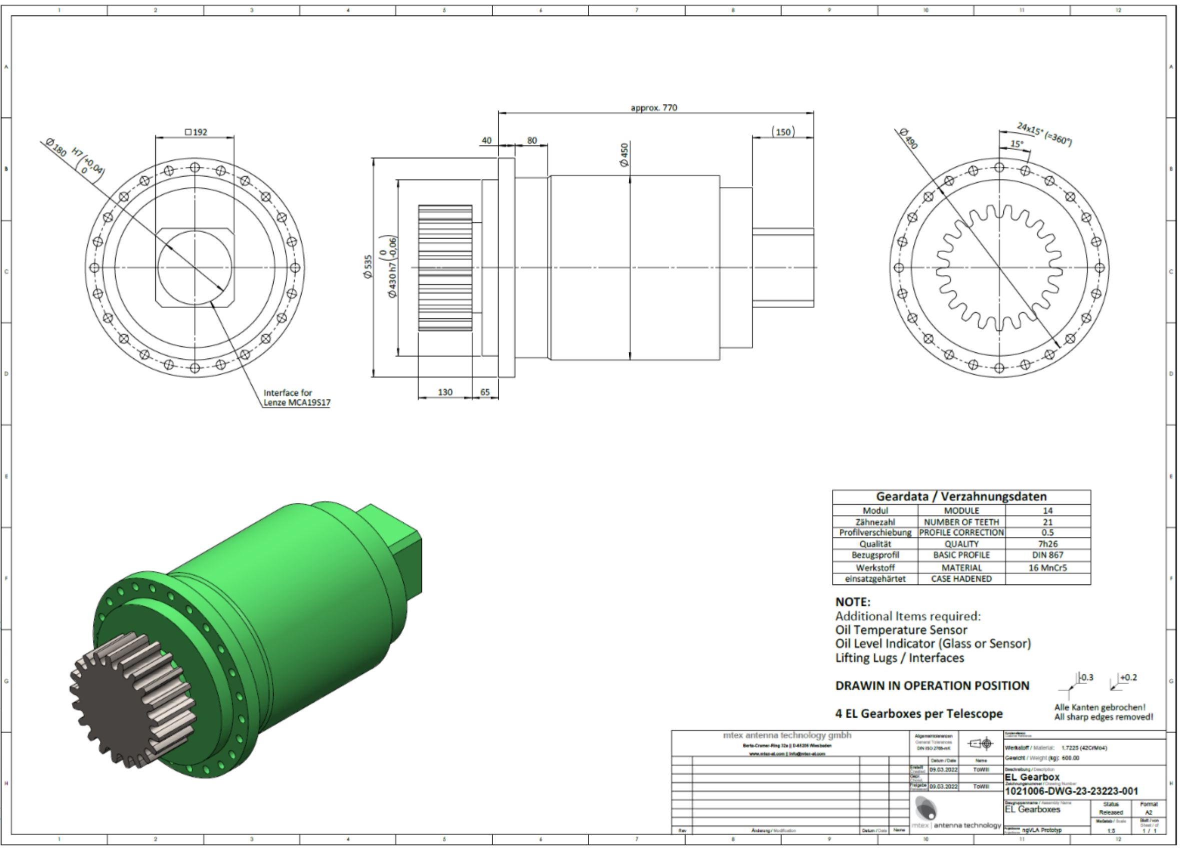


Figure 60 Elevation Gearbox Preliminary Drawing

6.6.2.3. *Feed Indexer Y- and Z- axis linear actuators*

For the feed indexer actuator Y-axis and Z-axis incorporate planetary gearboxes.
These items are off-the-shelf
At this design stage there are two different gearboxes as the required torque is quite different.
The Z-Axis drive train requires much more torque than the Y-Axis drive train due to the unbalanced load in the appropriate elevation positions of the telescope.
The Y-Axis drive train only needs to move the feed indexer actuator and front-end receiver weight along the linear rails.

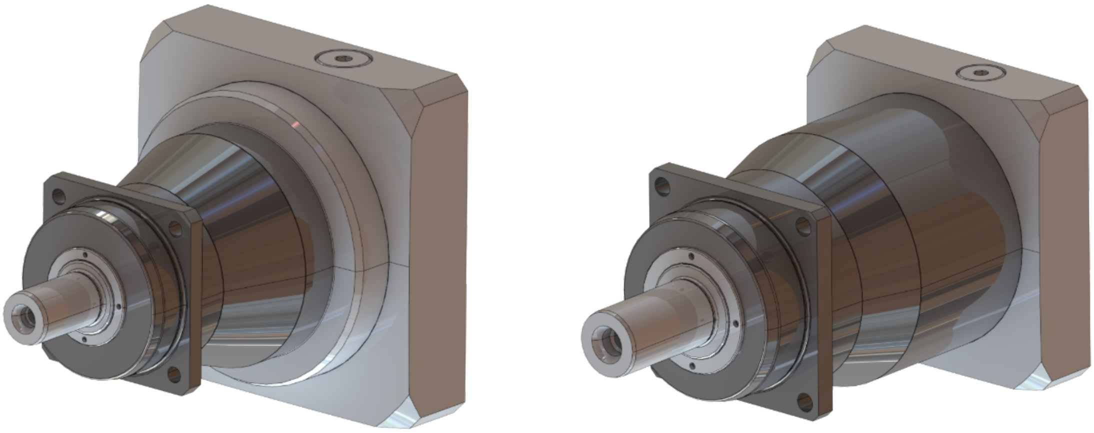


Figure 61 3D CAD Model of Gearboxes (Y-Axis, left | Z-Axis, right)

The Y-Axis is designed to an output torque of approx. 65 Nm.
The Z-Axis is designed to an output torque of approx. 250 Nm.
Both gearbox output shafts are connected to the high precision jackscrews with elastomer couplings similar like R+W Couplings type EK2.

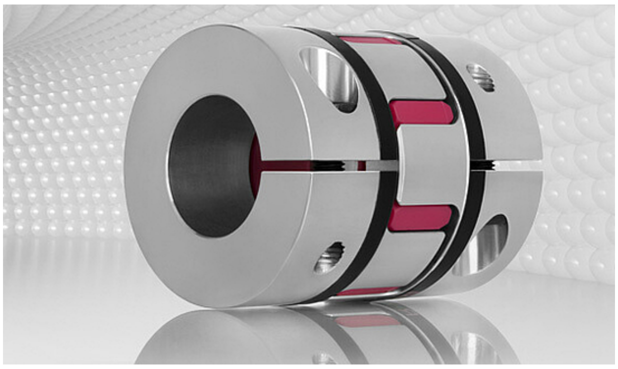


Figure 62 R+W EK2 Coupling sample (www.rw-couplings.com)

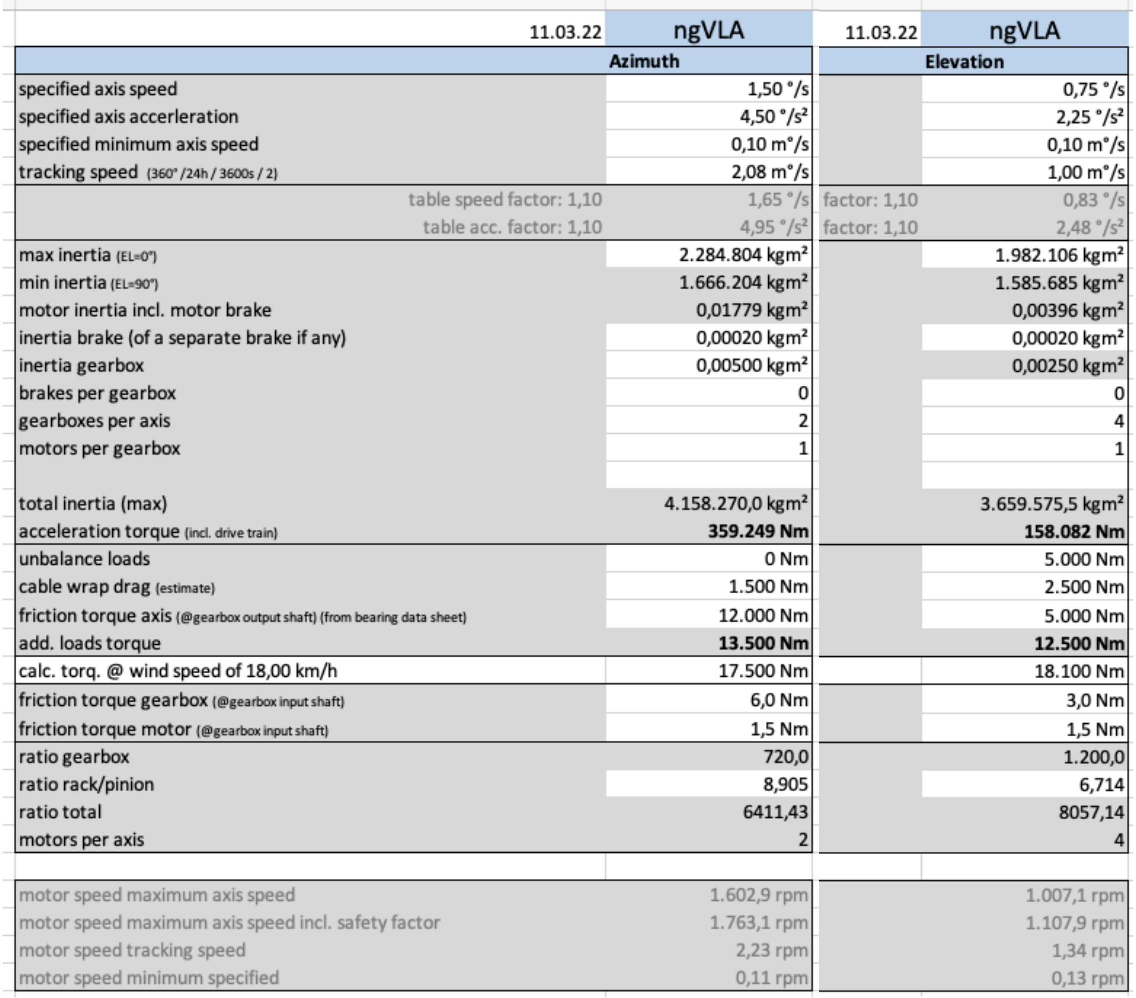
Due to the different required torques, there are two different couplings used.

6.6.3. Motors

A torque budget defines the required size and the dimensioning of the motors and amplifiers for the main axes (see Table 6), as well as the motors for the Feed Indexer, (see Table 9).
As a result, the described motors and amplifiers have been selected, see following sub-sections.

As Table 6 presents the budget input data for the main axes, defines additional operational points for the main axes. Those operational points support to select a proper motor and amplifier system when put in conjunction with the motor and amplifier torque-over-speed diagram. Those points illustrate the selected motors, see Figure 63 and Figure 64.

Table 6 Azimuth and Elevation torque budget input data



11.03.22	ngVLA	11.03.22	ngVLA
	Azimuth		**Elevation**
specified axis speed	1,50 °/s		0,75 °/s
specified axis accerleration	4,50 °/s²		2,25 °/s²
specified minimum axis speed	0,10 m°/s		0,10 m°/s
tracking speed (360° / 24h / 3600s / 2)	2,08 m°/s		1,00 m°/s
table speed factor: 1,10	1,65 °/s	factor: 1,10	0,83 °/s
table acc. factor: 1,10	4,95 °/s²	factor: 1,10	2,48 °/s²
max inertia (EL=0°)	2.284.804 kgm²		1.982.106 kgm²
min inertia (EL=90°)	1.666.204 kgm²		1.585.685 kgm²
motor inertia incl. motor brake	0,01779 kgm²		0,00396 kgm²
inertia brake (of a separate brake if any)	0,00020 kgm²		0,00020 kgm²
inertia gearbox	0,00500 kgm²		0,00250 kgm²
brakes per gearbox	0		0
gearboxes per axis	2		4
motors per gearbox	1		1
total inertia (max)	4.158.270,0 kgm²		3.659.575,5 kgm²
acceleration torque (incl. drive train)	**359.249 Nm**		**158.082 Nm**
unbalance loads	0 Nm		5.000 Nm
cable wrap drag (estimate)	1.500 Nm		2.500 Nm
friction torque axis (@gearbox output shaft) (from bearing data sheet)	12.000 Nm		5.000 Nm
add. loads torque	**13.500 Nm**		**12.500 Nm**
calc. torq. @ wind speed of 18,00 km/h	17.500 Nm		18.100 Nm
friction torque gearbox (@gearbox input shaft)	6,0 Nm		3,0 Nm
friction torque motor (@gearbox input shaft)	1,5 Nm		1,5 Nm
ratio gearbox	720,0		1.200,0
ratio rack/pinion	8,905		6,714
ratio total	6411,43		8057,14
motors per axis	2		4
motor speed maximum axis speed	1.602,9 rpm		1.007,1 rpm
motor speed maximum axis speed incl. safety factor	1.763,1 rpm		1.107,9 rpm
motor speed tracking speed	2,23 rpm		1,34 rpm
motor speed minimum specified	0,11 rpm		0,13 rpm

The diagrams in see Figure 63 and Figure 64, one color reflects an environmental scenario which combines the following 3 operational points regarding torque demand:

constant wind speed, no acceleration and no wind gusts (lower point)
constant wind speed plus acceleration and no wind gusts (mid-point)
constant wind speed plus acceleration and plus wind gusts (upper point).

The points are reflecting the acting motor pair and the crossed points are reflecting the counter-torque motor pairs.

The selection should ensure that all lower points are below (with some margin) the S1-characteristics line of the motor, which represents the continuous maximum torque threshold.

The selected Azimuth and Elevation motors are synchronous servo motors incl. holding brake and high precision motor encoder. The high precision motor encoder provides a very accurate velocity feedback and its safe motion characteristic support the safety functions described below. The motors are operated by a variable frequency drive amplifier which provides the dynamic current control loop and interfaces to the PLC control loops via deterministic real-time fieldbus.

The details of the individual motors and amplifiers are mentioned in the following sections.

6.6.3.1. *Azimuth Motors from Lenze*

Table 7 Azimuth motors and amplifiers of drive system by Lenze

Motor			Amplifier	
MCA20X14H		2 motors	i950-C11/480-3	2 amplifiers
Nominal speed n_N	[rpm]	1420	Mains input voltage 480 VAC ±10%	
Nominal torque M_n	[Nm]	61.0	Continuous power per motor	11 kW
Nominal power P_N	[W]	9.1	Continuous current per motor	27 Aeff
Nominal current I_N	[A]	23.0	Peak current per motor	54 Aeff
Maximum torque M_{max}	[Nm]	250	Nominal switching frequency	8 kHz
Maximum current I_{max}	[A]	92.0	Possible switching frequencies	2 / 4 / 8 kHz
Maximum speed n_{max}	[rpm]	6500		
Moment of inertia J	[kgcm2]	171		
Weight without brake m	[kg]	64		
Holding torque of brake M_{Br}	[Nm]	90		
Mass of brake	[kg]	13.0		
Moment of inertia of brake J_{Br}	[kgcm2]	6.88		

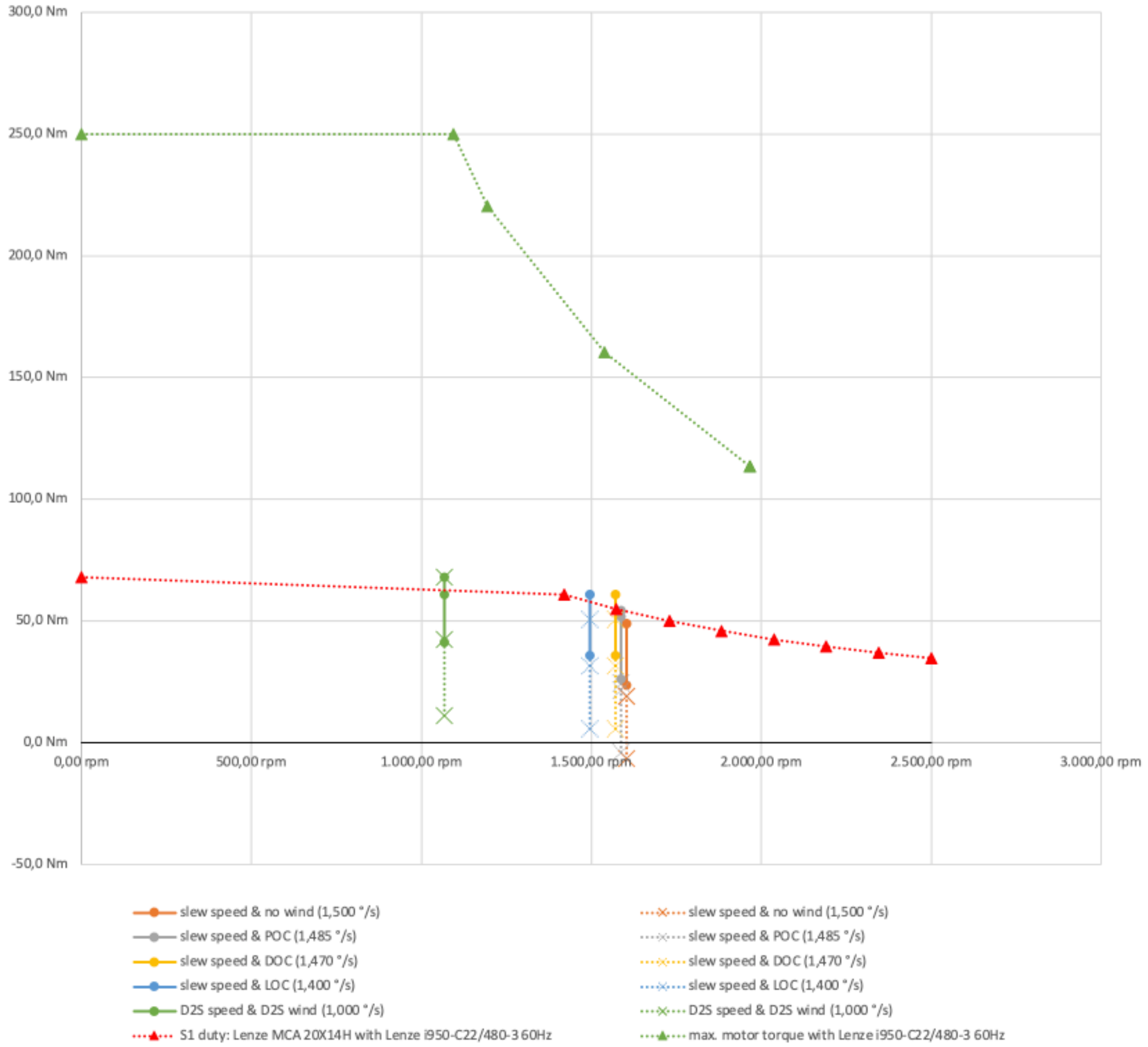


Figure 63 Azimuth torque-over-speed diagram and operating points of drive system by Lenze, the gearbox ratio is changed to 720:1

6.6.3.2. Elevation Motors from Lenze

Table 8 Elevation motors and amplifiers of drive system by Lenze

Motor			Amplifier	
MCA19S17-S1SP1	4 motors		i950-C7.5/400-3	4 amplifiers
Nominal speed n_N	[rpm]	1700	Mains input voltage 480 VAC ±10%	Continuous
Nominal torque M_n	[Nm]	36.3	power per motor	7.5 kW
Nominal power P_N	[W]	6.4	Continuous current per motor	14.0 Aeff
Nominal current I_N	[A]	13.9	Peak current per motor	28 Aeff
Maximum torque M_{max}	[Nm]	180	Nominal switching frequency	8 kHz
Maximum current I_{max}	[A]	68.9	Possible switching frequencies	2 / 4 / 8 kHz
Maximum speed n_{max}	[rpm]	8000		
Moment of inertia J	[kgcm2]	72		
Weight without brake m	[kg]	48.2		
Holding torque of brake M_{Br}	[Nm]	40		
Mass of brake	[kg]	5.0		
Moment of inertia of brake J_{Br}	[kgcm2]	19.5		

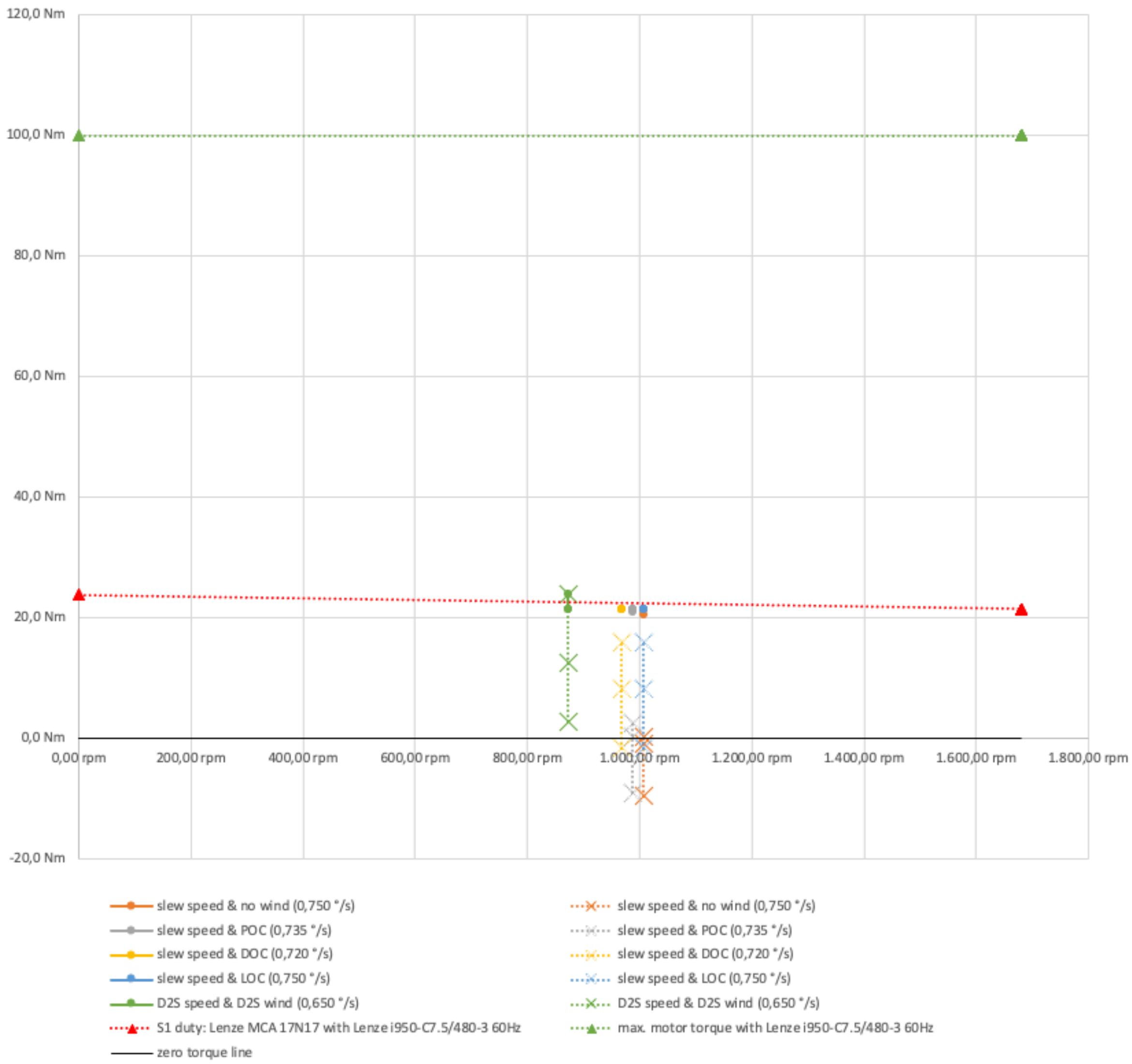
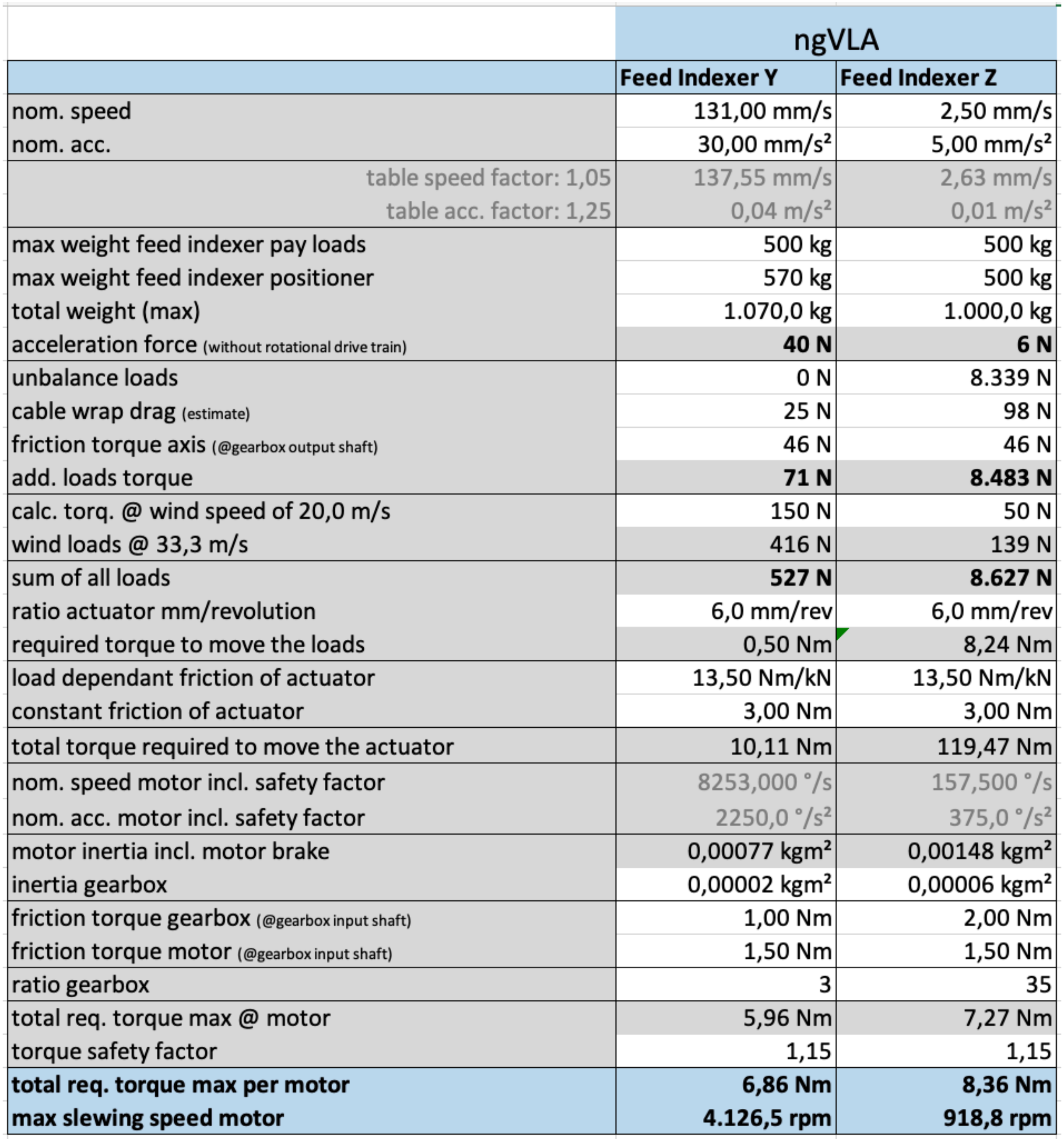


Figure 64 Elevation torque-over-speed diagram and operating points of drive system by Lenze, the gearbox ratio is changed to 1200:1

6.6.3.3. *Feed Indexer X- and Y- axis motors*

The selection for the Feed Indexer motors is relying on the torque budget as maximum operating point only, the loads are not varying as much as those of the main axes, therefore the maximum operating point defines the drive train sizing for continuous operation, see following table.

Table 9 Feed Indexer Y and Z torque budget

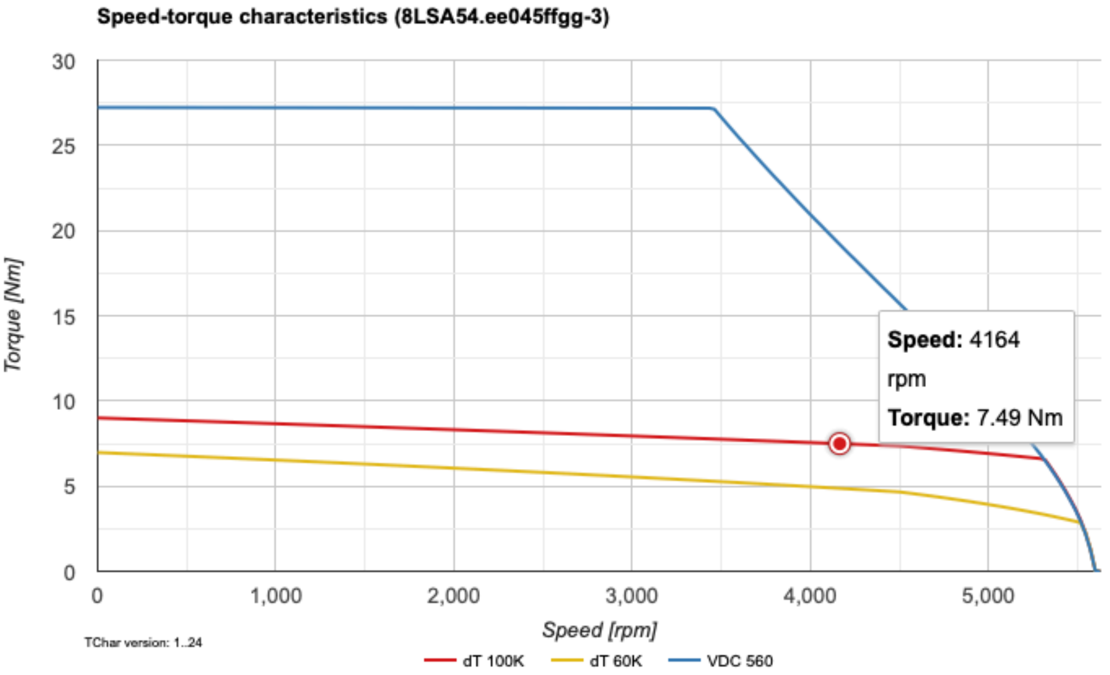


	ngVLA	
	Feed Indexer Y	**Feed Indexer Z**
nom. speed	131,00 mm/s	2,50 mm/s
nom. acc.	30,00 mm/s²	5,00 mm/s²
table speed factor: 1,05	137,55 mm/s	2,63 mm/s
table acc. factor: 1,25	0,04 m/s²	0,01 m/s²
max weight feed indexer pay loads	500 kg	500 kg
max weight feed indexer positioner	570 kg	500 kg
total weight (max)	1.070,0 kg	1.000,0 kg
acceleration force (without rotational drive train)	**40 N**	**6 N**
unbalance loads	0 N	8.339 N
cable wrap drag (estimate)	25 N	98 N
friction torque axis (@gearbox output shaft)	46 N	46 N
add. loads torque	**71 N**	**8.483 N**
calc. torq. @ wind speed of 20,0 m/s	150 N	50 N
wind loads @ 33,3 m/s	416 N	139 N
sum of all loads	**527 N**	**8.627 N**
ratio actuator mm/revolution	6,0 mm/rev	6,0 mm/rev
required torque to move the loads	0,50 Nm	8,24 Nm
load dependant friction of actuator	13,50 Nm/kN	13,50 Nm/kN
constant friction of actuator	3,00 Nm	3,00 Nm
total torque required to move the actuator	10,11 Nm	119,47 Nm
nom. speed motor incl. safety factor	8253,000 °/s	157,500 °/s
nom. acc. motor incl. safety factor	2250,0 °/s²	375,0 °/s²
motor inertia incl. motor brake	0,00077 kgm²	0,00148 kgm²
inertia gearbox	0,00002 kgm²	0,00006 kgm²
friction torque gearbox (@gearbox input shaft)	1,00 Nm	2,00 Nm
friction torque motor (@gearbox input shaft)	1,50 Nm	1,50 Nm
ratio gearbox	3	35
total req. torque max @ motor	5,96 Nm	7,27 Nm
torque safety factor	1,15	1,15
total req. torque max per motor	**6,86 Nm**	**8,36 Nm**
max slewing speed motor	**4.126,5 rpm**	**918,8 rpm**

The selected motors and amplifier are as follows:

Table 10 Feed Indexer motors and amplifier

Motor			Amplifier	
8LSA54.ee045ffgg-3			8EI8X8HWDS0.XXXX-1	
Nominal speed n_N	[rpm]	4500	Mains input voltage 3x 200 VAC to 480 VAC ±10%	
Nominal torque M_n	[Nm]	7.3	Continuous power per motor	4 / 4 kW
Nominal power P_N	[W]	3440	Continuous current per motor	8.8 / 8.8 Aeff
Nominal current I_N	[A]	6.7	Peak current per motor	24 / 24 Aeff
Maximum torque M_{max}	[Nm]	27.6	Peak power output	10 kW
Maximum current I_{max}	[A]	33	Nominal switching frequency	5 kHz
Maximum speed n_{max}	[rpm]	9000	Possible switching frequencies	5 / 10 / 20 kHz
Moment of inertia J	[kgcm2]	6.04		
Weight without brake m	[kg]	8.5		
Holding torque of brake M_{Br}	[Nm]	15		
Mass of brake	[kg]	1.4		
Moment of inertia of brake J_{Br}	[kgcm2]	1.66		



Speed rated: 4500 rpm, Torque rated: 7.300 Nm

6.6.4. Automatic Lubrication System

The ngVLA antenna is equipped with four independent automatic lubrication systems (ALS).

- Azimuth bearing raceway
- Azimuth bearing toothing
- Elevation bearing raceway
- Elevation gear rim

All these automatic lubrication systems use the same type of grease pump.
For azimuth axis lubrication system, the grease pumps are located in the upper pedestal structure between the two azimuth gearboxes.
The grease pumps for the elevation portion are located in the main cylinder of the Turnhead, located in feed arm direction.

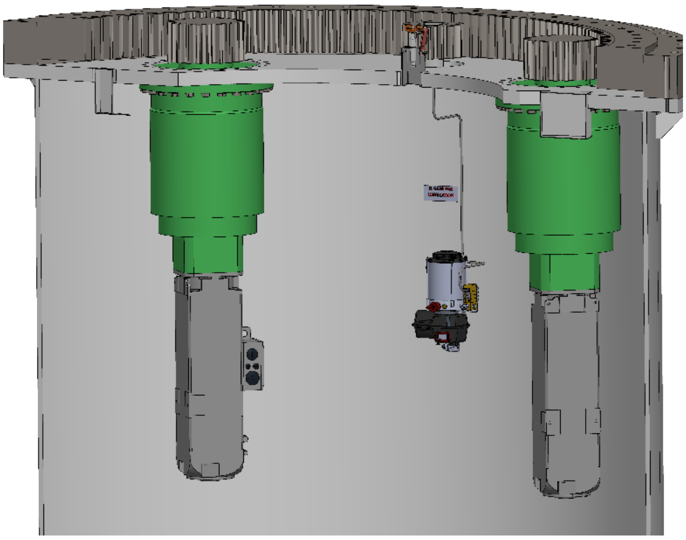


Figure 65 Grease Pump Location of AZ ALS (inside upper pedestal)

This means that access to the pumps for maintenance or refill is given from inside the antenna structure.
The grease line routings will be made from stainless steel pipes with mounting interface at the steel structures. No flexible transitions are required for the routing of the grease lines.

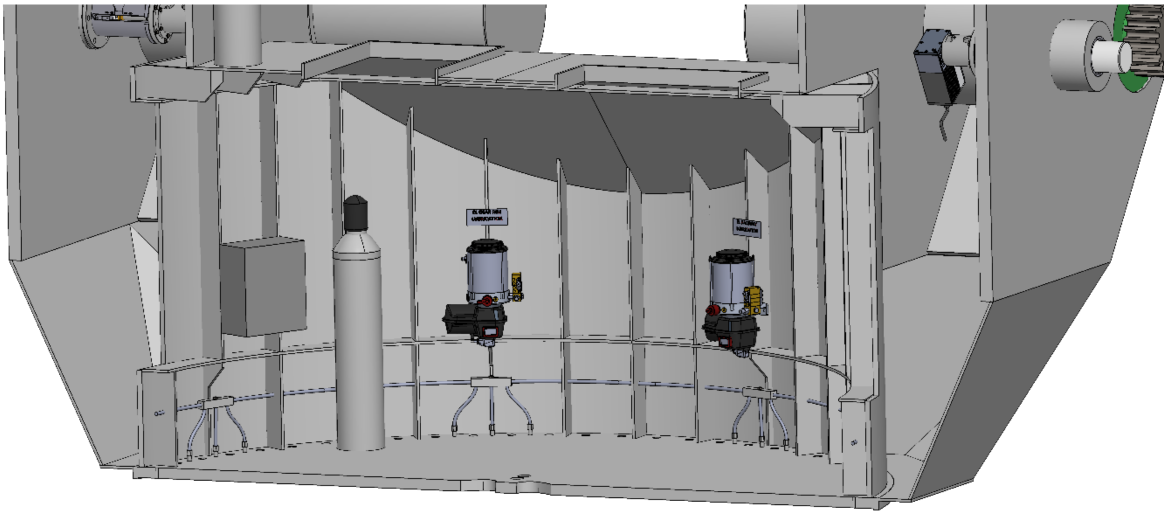


Figure 66 Grease Pump Location of EL ALS (inside Turnhead)

The elevation ALS will be equipped with progressive distributors to ensure identical amounts of grease at each grease inlet.
The final design will include grease channels on the antenna outside to keep the structure clean of grease.

6.6.5. Lightning Protection

For Lightning protection, the antenna is equipped with appropriate components.
There are 3 aluminum lightning rods on the upper edges of the main reflector system, another 3 lightning protection rods are mounted to the sub-reflector BUS.

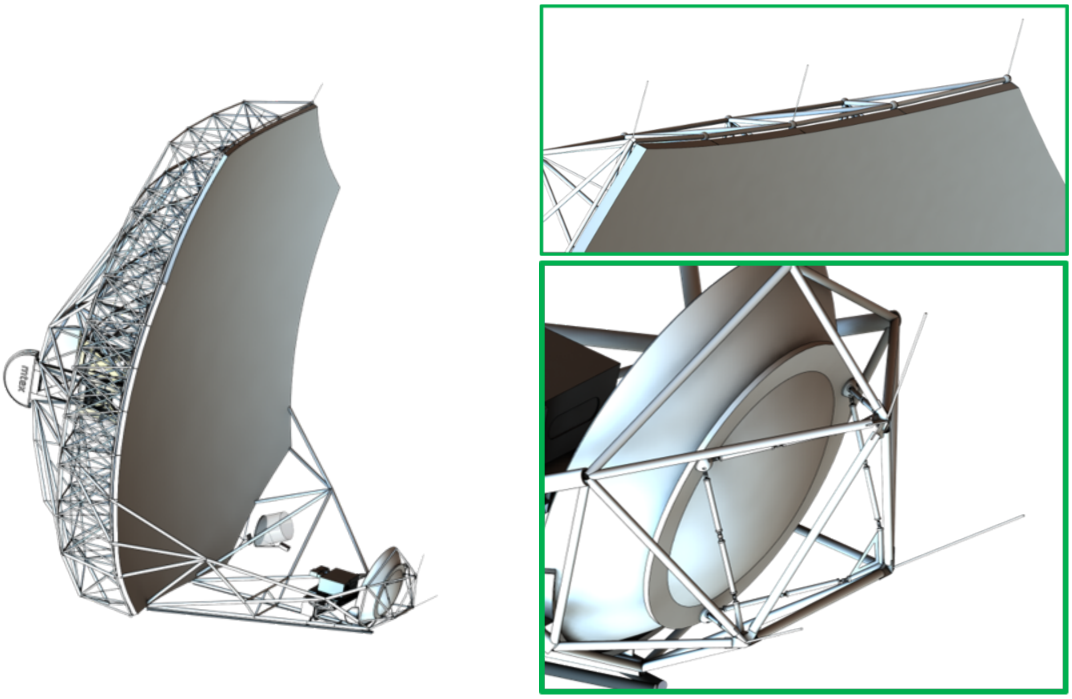


Figure 67 Main Reflector Lightning Protection

For azimuth bearing lightning protection a well-proven high voltage spring-loaded contact bridges rotating and non-rotating structures using copper slip rails and high-quality cast bronze contacts. Every bearing will be equipped with 4 of these high voltage contacts which are equally spaced. Each unit can handle a permanent load of 350 amps.

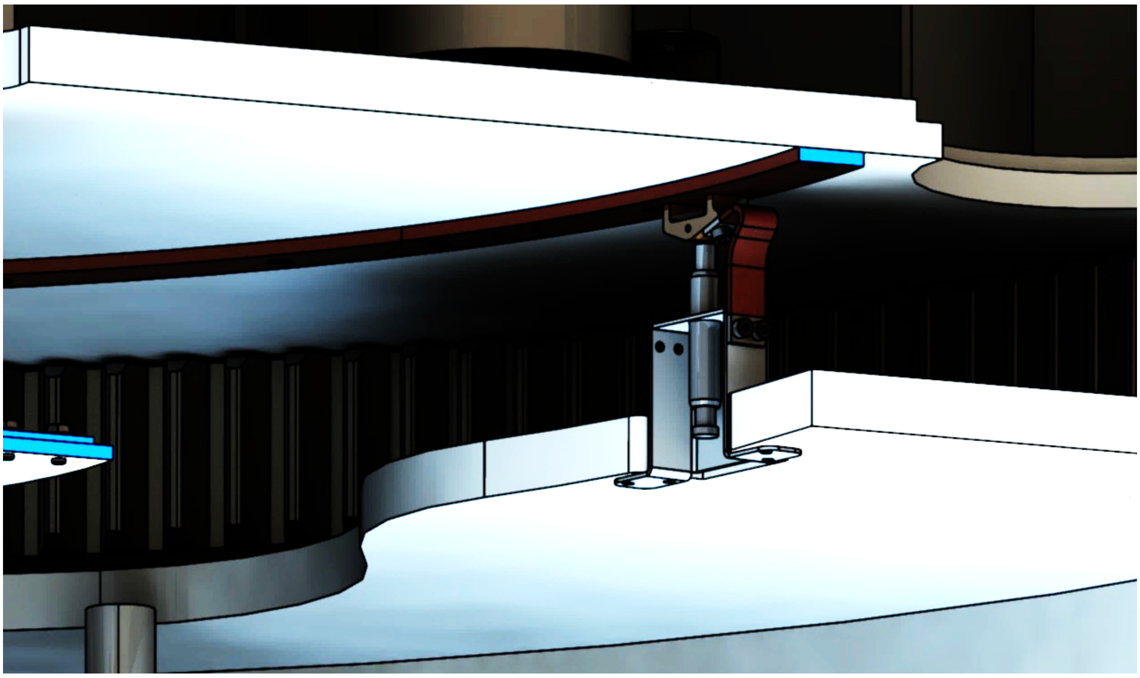


Figure 68 AZ Bearing Lightning Protection

The copper slip rail segments are divided by 60deg cuts to ensure easy sliding of the high voltage contacts in the segment transition areas. This ensures long lifetime of the high voltage contacts.

The high voltage contacts are mounted with brackets, so they can be assembled as single pieces before they are installed to the antenna.

6.6.6. Stow Pins

For safety reasons the mtex ngVLA antenna is designed with stow pin systems for azimuth, as well as elevation. Identical stow pin units for azimuth and elevation for commonality, spares, etc.

All stow pin units are designed with a hand crank system for manual movement during power failure.

Limit switches for both positions ensure to communicate the stow pin position to the servo system.

Each stow pin axis has a diameter of 115mm.

6.6.6.1. Azimuth Stow Pin

The azimuth stow pin is mounted to the top plate of the upper pedestal and engages in the bottom plate of the Turnhead. At the current design level, it is planned to have one azimuth stow position at 0° azimuth.

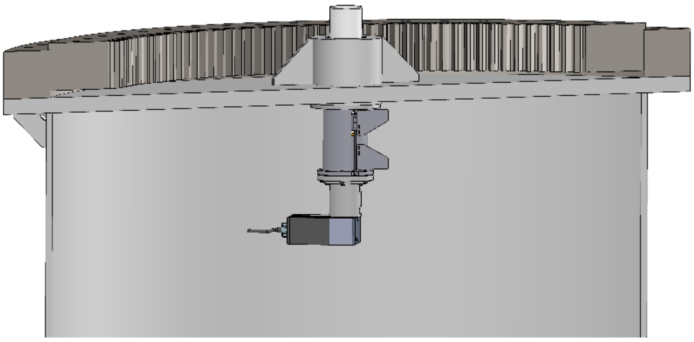


Figure 69 Azimuth Stow Pin

6.6.6.2. Elevation Stow Pins

For elevation movement there is one stow pin on each side to lock the antenna from moving in elevation.

Elevation locking position is designed at 88° elevation and at 12° for maintenance purpose.

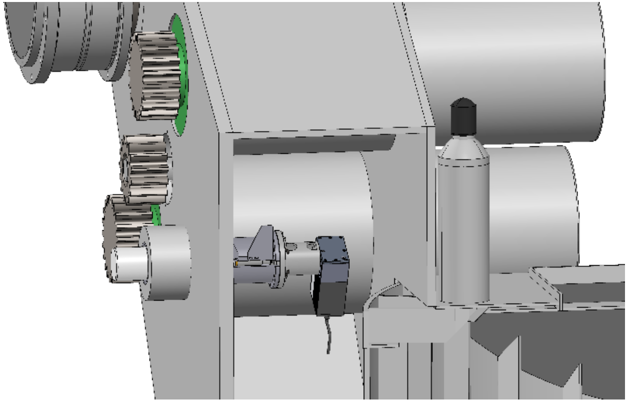


Figure 70 Elevation Stow Pin (left side)

Access to the elevation stow pins is provided from inside the Turnhead arms.

6.6.7. Preventive Maintenance Crane

mtex suggest equipping some antennas (remote locations spiral arms + long baseline) with a preventive maintenance crane, that is attached to the main reflector BUS. This crane is designed as an electric winch that can lift and lower, e.g. the He-operation bottle which is located on top (or inside) of the Turnhead. Nevertheless, the crane is designed to a capacity that allows only lifting all necessary equipment that is required for preventive maintenance as toolboxes, He-supply bottle or similar.

It is assumed that most of the antennas in the array core does not require this preventive maintenance crane, because access and lifting of equipment will be carried out with service equipment (truck with forklift or manlifts).

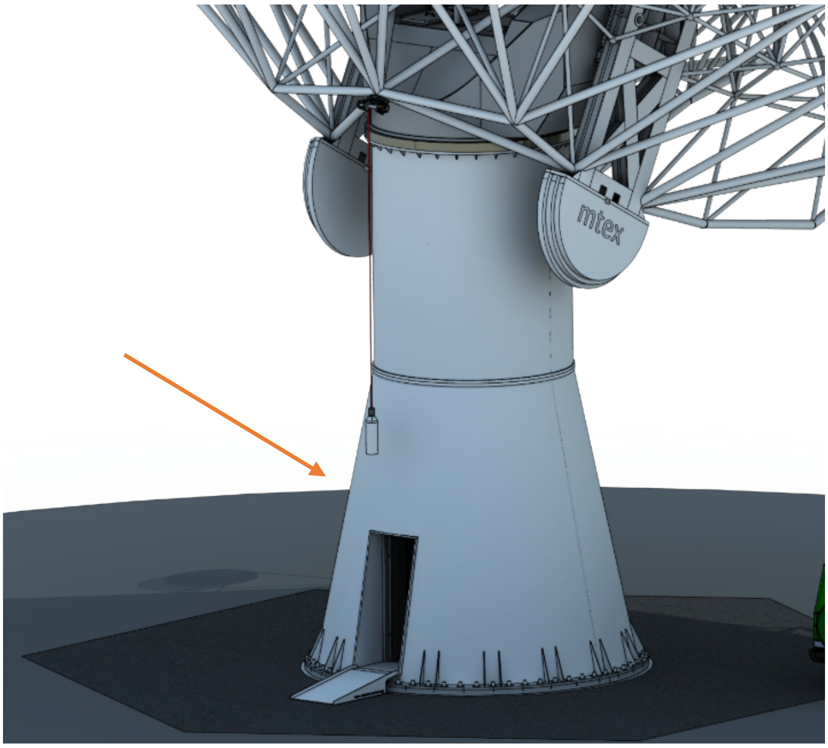


Figure 71 He-Operation Bottle during lifting

The maintenance crane can reach equipment on the ground as soon as the reflector is driven to an elevation angle of 88 degrees.

As soon as the equipment is lifted with the winch the reflector elevation angle can be lowered, so the equipment reaches the top of the Turnhead.

A tradeoff study is recommended to decide, if the crane capacity should be enlarged to support also corrective action (LRU replacements).

6.6.8. Cable Routing Concept

The cable routing concept chosen by mtex for ngVLA can be divided into several topics:

Inside steel structure
Outside steel structure
Azimuth Cable Wrap
Elevation Cable Wrap

For cable routing inside the steel structure there are two different plans in place. Long cable runs with the greatest amount of different cables will be routed using wire mesh cable tray systems that are available all over the world. Cables can be added and removed easily.

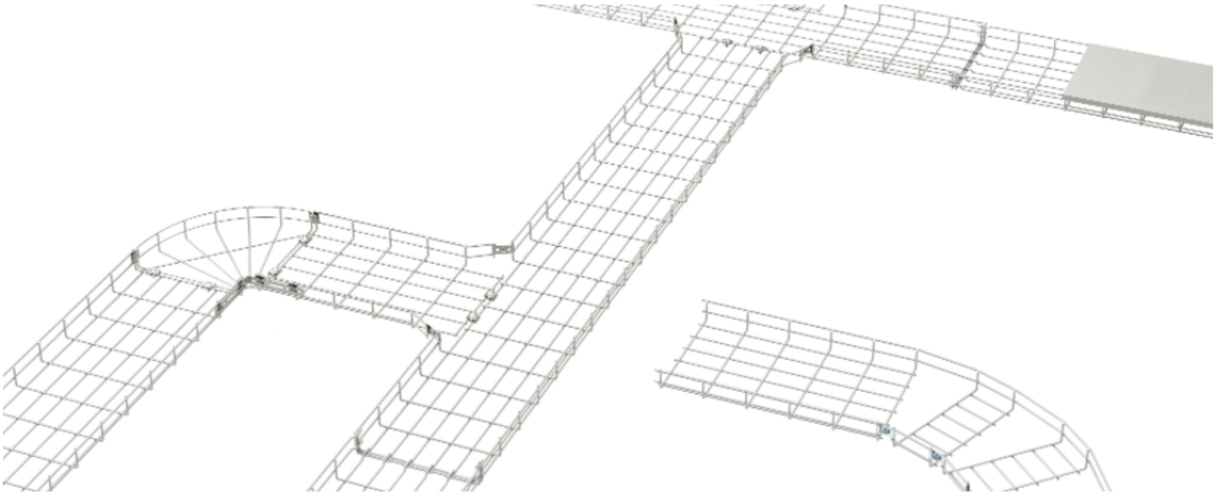


Figure 72 Sample of Wire Mesh Cable Tray System

Single cable that leave these wire mesh cable trays will be routed along the steel walls using cable finger brackets. These brackets are mounted to the steel structure walls with welded studs.

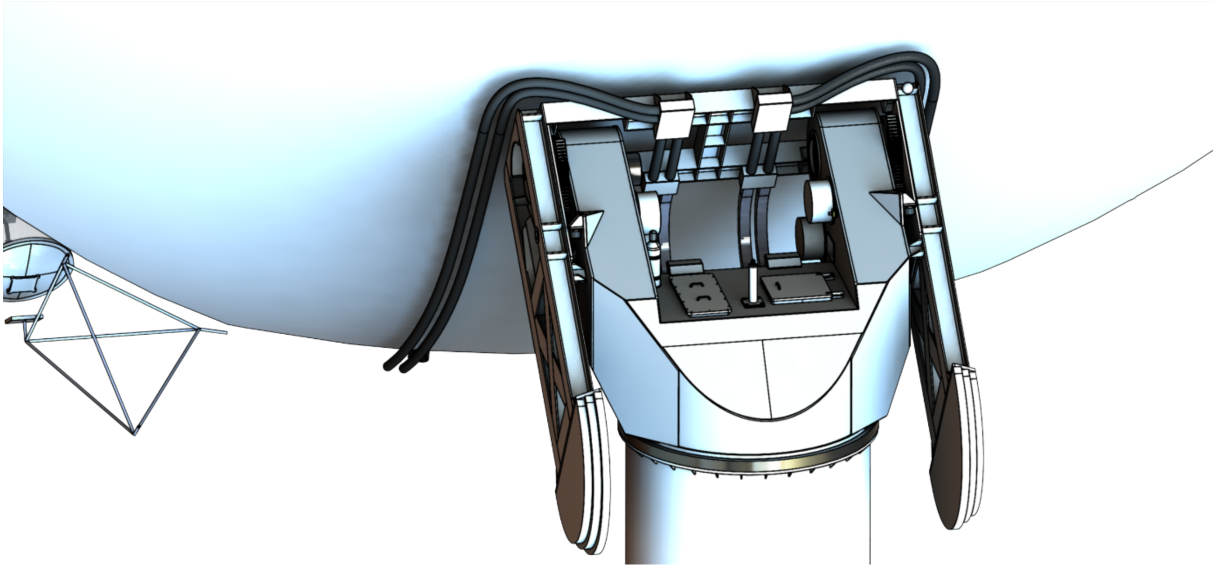


Figure 73 Main Reflector Cable Routing (without BUS)

The main reflector cable routing shown above is just to highlight the designed ways and length. All cable trays which are installed outside the antenna are intended as closed cable trays with covers.

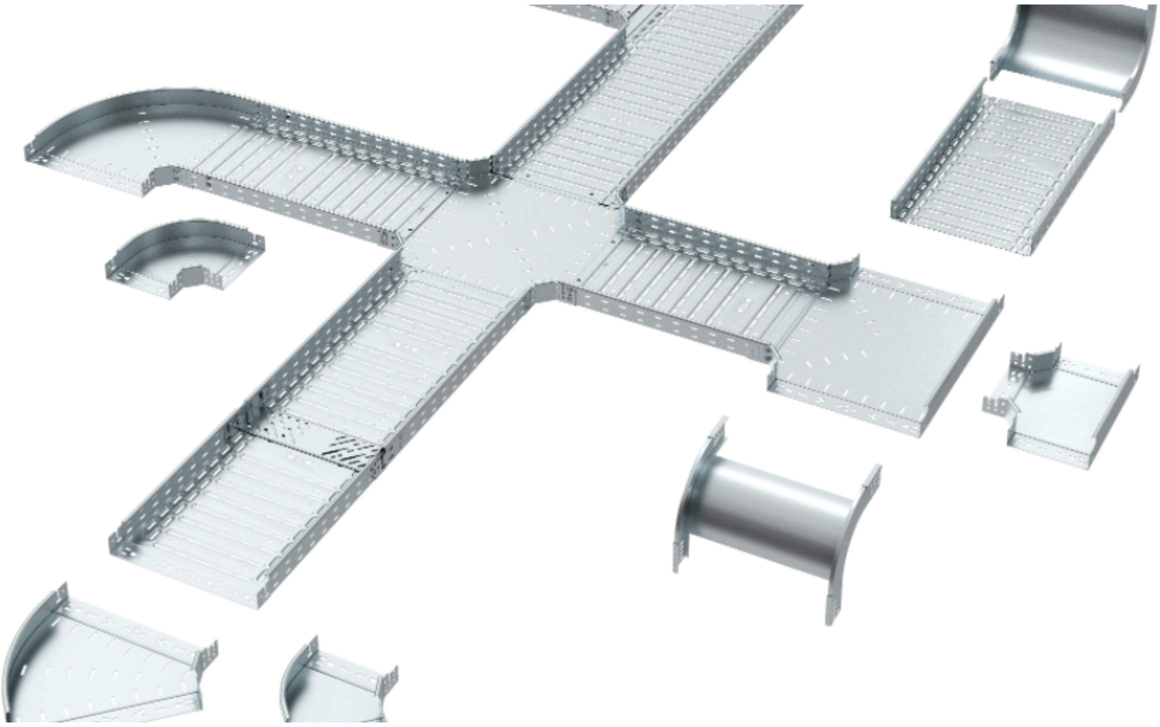


Figure 74 Sample of closed cable tray system

The elevation cable loops start at the front cable interfaces of the Turnhead. It is planned as a closed, flexible steel tube system that is well-know from any other antenna and antenna applications. The close steel tube ensures environmental protection, as well as EMI protection.

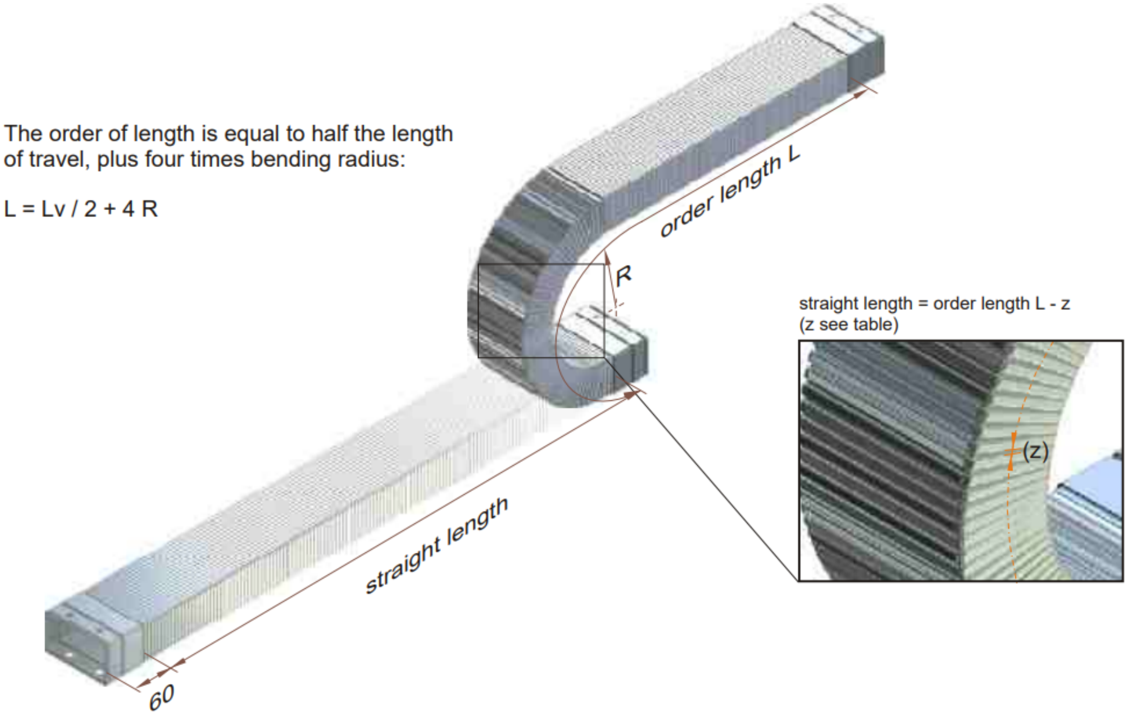


Figure 75 Sample of Steel Tube Cable Loop

At the current design stage there are four elevation cable loops with a cross section area of 115mm x 100mm each.

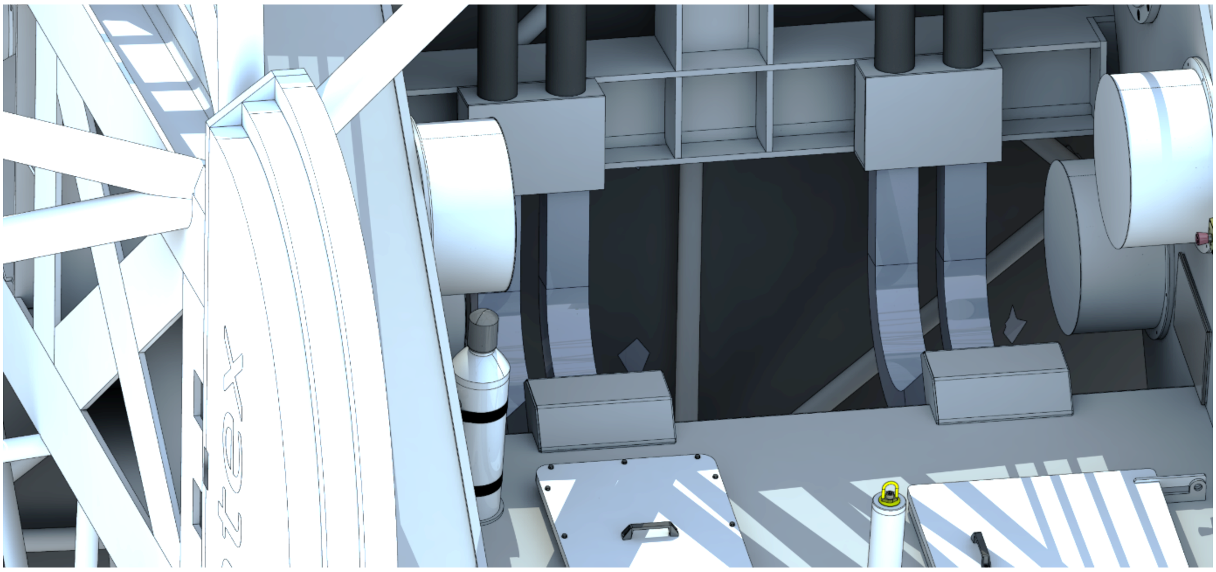


Figure 76 EL Cable Loop at 12deg elevation

The azimuth cable wrap is a well-proven, simple, and robust system from a lot of antennas installed all over the world.
There is a drive tube that is mounted to the bottom of the Turnhead. The drive tube is equipped with steel rings that carry single cables. The outer rings are connected to each other with steel wires, so that they can move up and down while the inner rings turn along azimuth with the antenna. The upper, outer ring is mounted to a fixed steel frame.

This steel frame that is mounted to the top of the maintenance platform inside the upper pedestal routes the cables to the top of the azimuth cable wrap. From here each cable runs down along the outer rings before they jump to the inner ring at the lower end of the cable wrap. From the lower end the are routed straight up into the Turnhead.

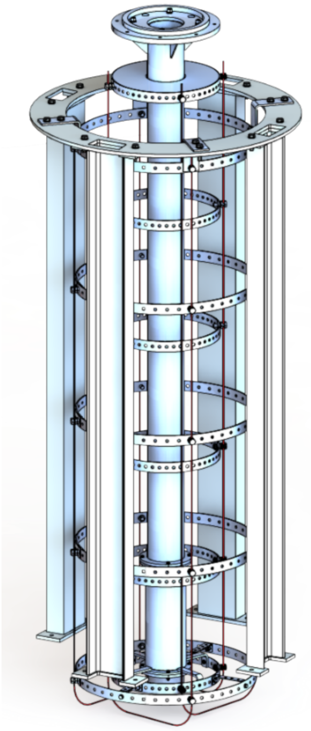


Figure 77 Azimuth Cable Wrap

6.6.9. AZ Tiltmeter

The AZ Tiltmeter is located in the Turnhead, above the AZ cable wrap and centered to the AZ axis.

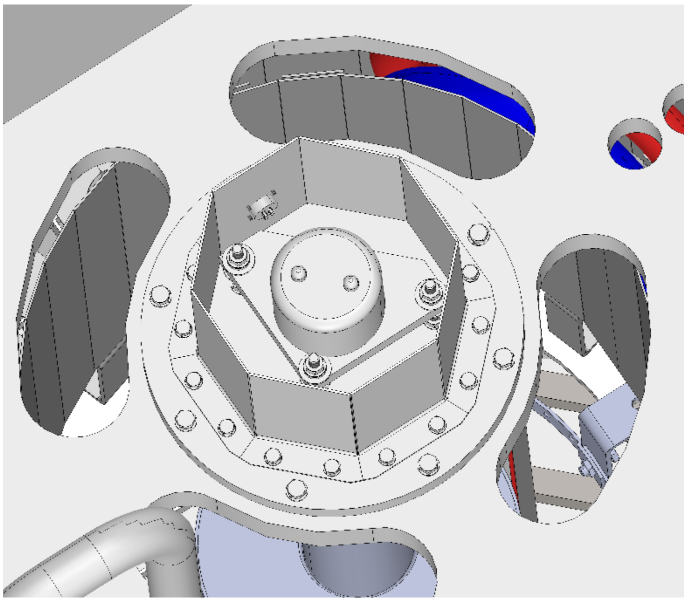


Figure 78 AZ Tiltmeter

6.7. Antenna Ventilation Concept

The ventilation, better the temperature control of the antenna internal environments will be realized by an HVAC system as specified in ⍰.

A closed glycol system with an outside of the antenna installed water-to-air heat exchanger will provide the temperature-controlled glycol to all consumers.
A defined rate of air exchange will be realized by simple fans taking the outside air on the top of the antenna Turnhead and pushing the fresh air into the antenna. A filter in the antenna door will serve as air exhaust.

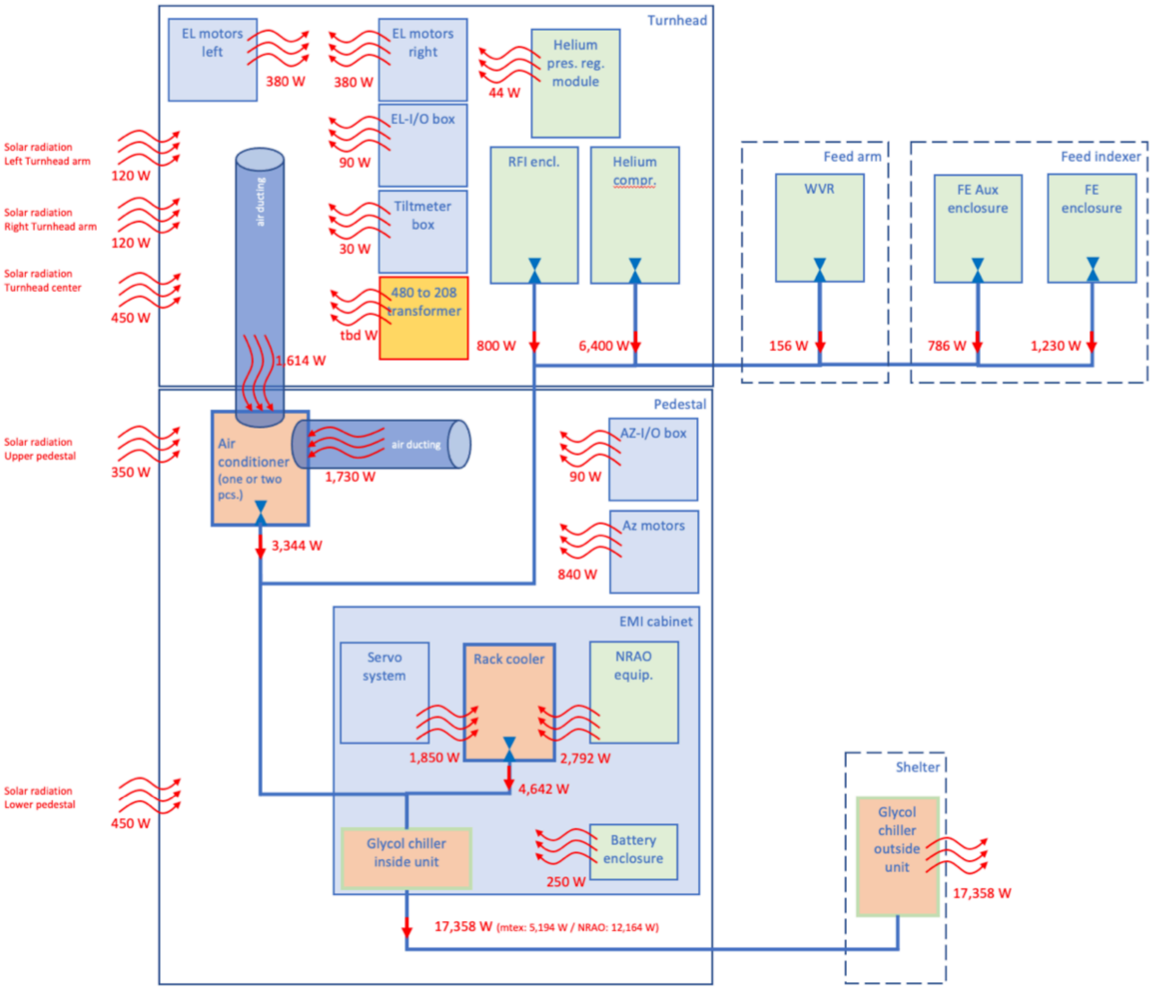


Figure 79 Copy of the specified system according ⍰

6.8. EMI Design Concept

mtex focused in their product development on an EMI reduced servo system. The findings of this development workflows into the ngVLA servo design and are described in the following sections.

6.8.1. Filters and Cable Pass-Throughs

The Emi filters are made for the mtex antenna control system. The filters made in cooperation with the manufacturer of mtex Servo components and the Filter manufacturer himself. The Filters run through several components tests in a EMI Test Chamber (reverberation chamber).

The Filters are mounted on a new designed interface plate that holds the filter and the cable can go through the interface to the inside/outside of each cabinet, control box or I/O Units.
The interface is also made to give best RFI shielding.

6.8.2. Fiber-Optic Pass-Throughs

The Fiber-Optic-Interface in the EMI Cabinet is also an improved design. The final design is the result of lesson learned and tests also from other Projects.
The interface is tested several times separate (build in) and together with Servo Components. On the I/O Units are mounted calculated waveguides to pass through fiber optic cables. These wave guides also holds the fiber safely in position by good RFI shielding effectiveness. As a result of experience all mtex interfaces are made for easy installation and maintenance.

6.8.3. Honeycomb Filters for Ventilation openings

The EMI cabinet allows fresh air inlet through the honeycomb EMI filter which are in the doors. The hot air that the cabinet created inside is pushing out by fans over the to mounted RFI Honeycomb filters
The EMI Cabinet is also a part of the ventilation concept as you can see in Section 9.6.4.
Several EMI tests have been performed with these RFI Honeycombs to find a Filter that allows also a good airflow through it.

Figure 80 Door/Roof Filter during EMI Tests

6.8.4. mtex EMI Cabinet / Enclosure

The mtex EMI Cabinet is built from different sections that bolted together to a closed RFI sealed compartment. The cabinet is part of the lower tower segment as shown in the picture below. The steel frame and the roof plate are welded into the lower tower segment.

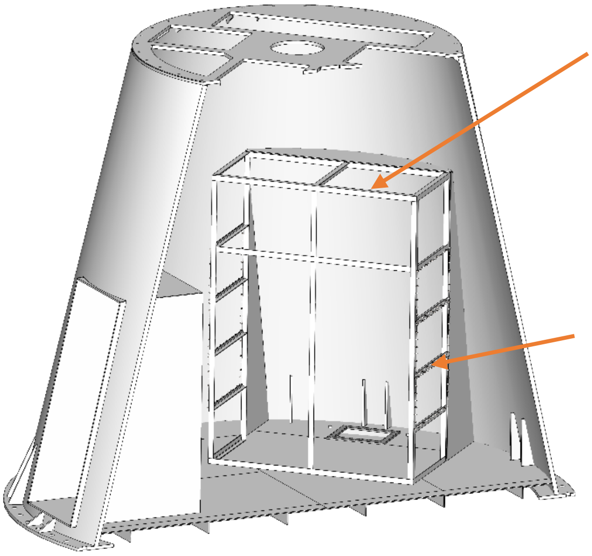
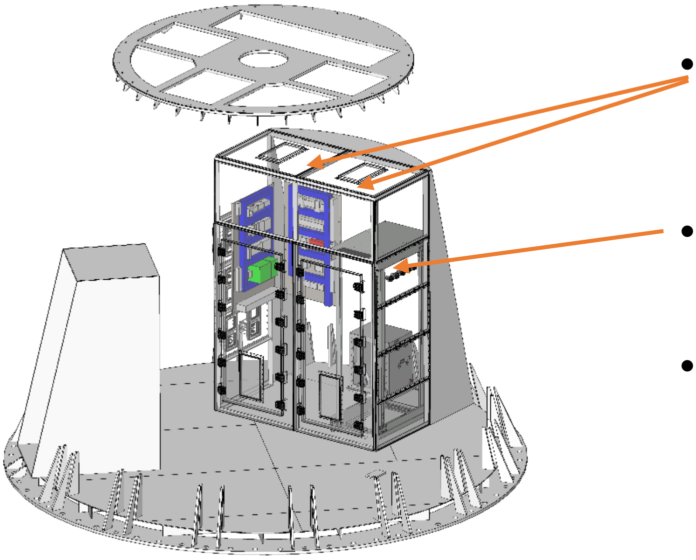


Figure 81 Lower pedestal

Filters and Interfaces are installed in the side plates which mounted to the right/left side onto the frame structure. In the front plate are 2 doors are integrated for entry into the welded cabinet.
Special hinges allow these 2 doors to open right or left. The doors can be removed easily for improved access for maintain or control tasks. The cabinet size is chosen to have space for customer equipment and space for safe work/control/maintenance inside, especially on electrical equipment.



- EMI Honeycombs with fan for ventilation
- Side plates with interfaces
- Cabinet doors equipped

Figure 82 Details of the mtex EMI enclosure

6.8.5. Azimuth I/O Box

The azimuth I/O box is a stainless-steel body, that houses the azimuth encoder and the I/O units inside. It is connected to the servo system using fiber optic. The main encoder is mounted to a very stiff bearing unit that interfaces to the azimuth I/O box as well as to an adjustable steel structure below the maintenance platform. All bolted interfaces are equipped with high performance EMI gaskets to ensure to meet the EMI specification.

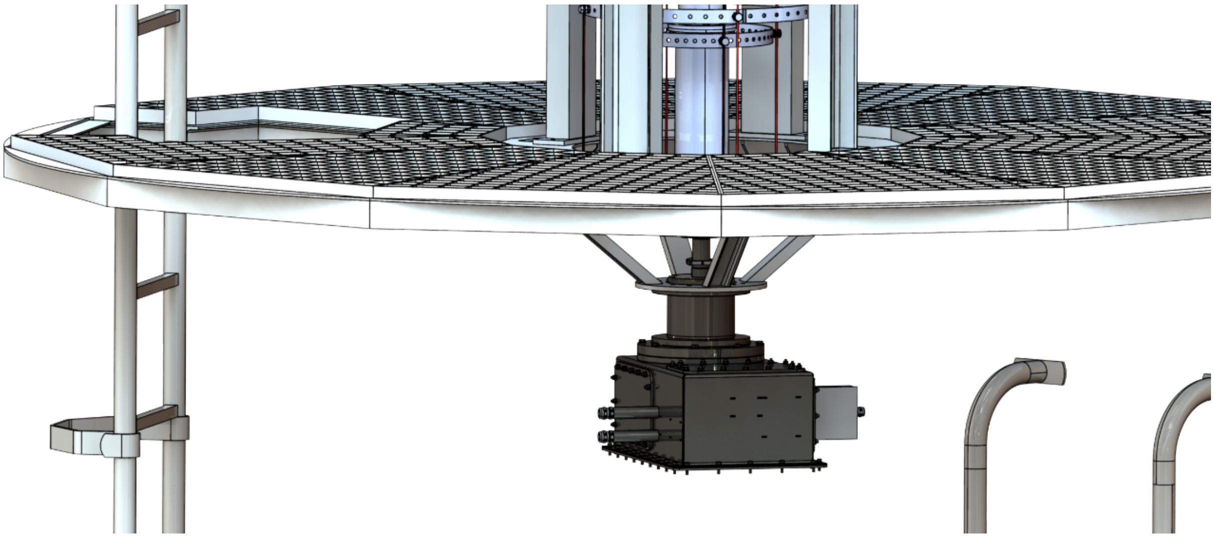


Figure 83 Azimuth I/O Box mounted to Maintenance Platform

Fiber feed through and EMI filter interfaces have been proven during EMI testing. The connection to the rotating azimuth part is ensured by a metal bellow coupling. The rotating encoder shaft is EMI protected by a special gasket. The complete I/O unit can be assembled and tested as one piece. It is designed as an LRU.

6.8.6. Elevation I/O Box

The elevation I/O box is located inside the left elevation bearing axis (looking to the antenna from the rear). The elevation I/O box consists of a stainless-steel encoder bearing unit, a safety encoder adapter, stainless steel housing, drive shaft and a connection membrane to the rotating main reflector system.

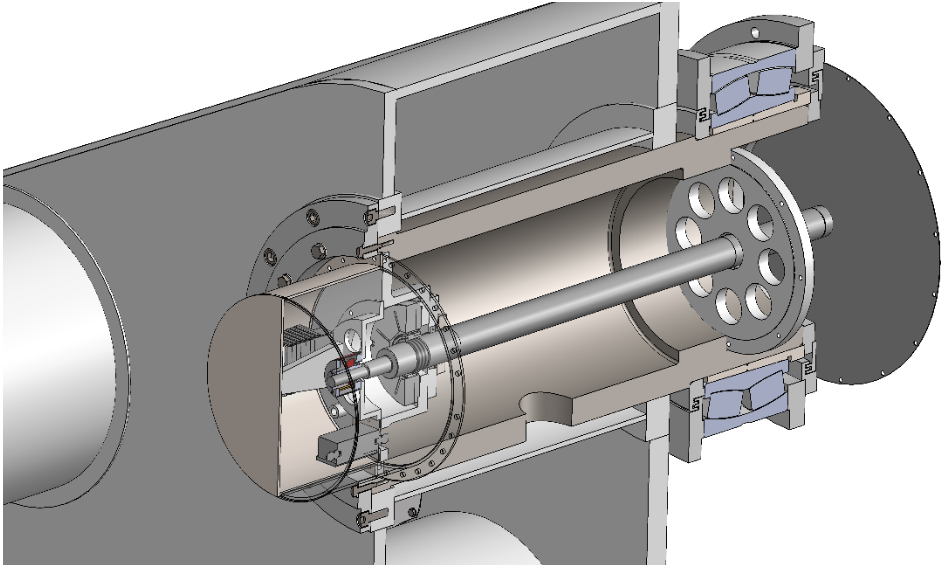


Figure 84 EL I/O Box (Cross Section)

The drive shaft has a main bearing close to the encoder, as well as a support bearing close to the elevation bearing. The membrane connection is ensured by a form fit. The elevation main encoder shaft is EMI protected using a gold-plated copper beryllium ball seal EMI gasket.
Cable and fiber feed throughs are made to the design concepts that mtex has confirmed during extensive testing.
All bolted connections are equipped with high performance EMI gaskets.
The complete I/O unit can be assembled and tested as one piece. It is designed as an LRU.

6.8.6.1. EMC Test Plan

The following plans illustrate the main steps for RFI, which shall be taken and followed during whole project:

The RFI investigation activities during Design phase:

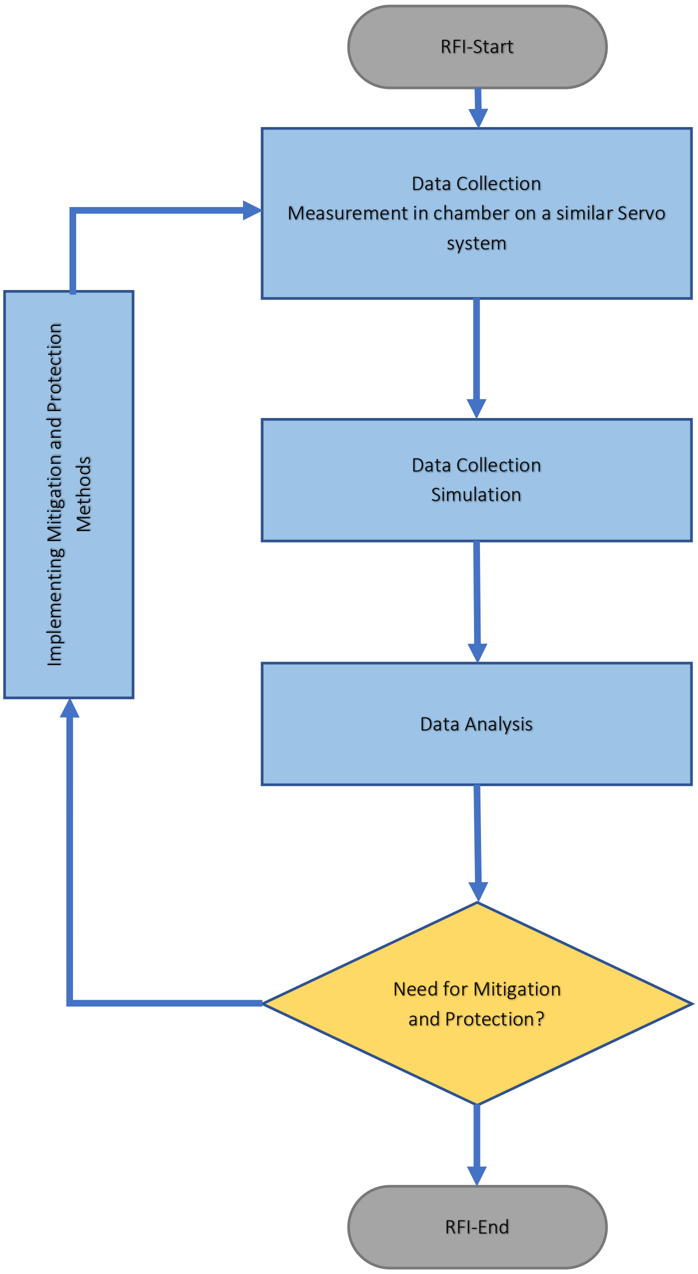


Figure 85. Flow chart of activities during Design phase

The servo system will be a system consisting of main components of a servo system similar to the final one for ngVLA antenna. This part of work shall be finished before starting with building prototype antenna system, which will have the final servo system. The main propose of having the practical works on RFI during design phase is to save time and to match the tight schedule plan. Thus, the above set of activities can be considered as preparation for final RFI investigation activities on the final system.

The RFI investigation activities during Prototype building phase:

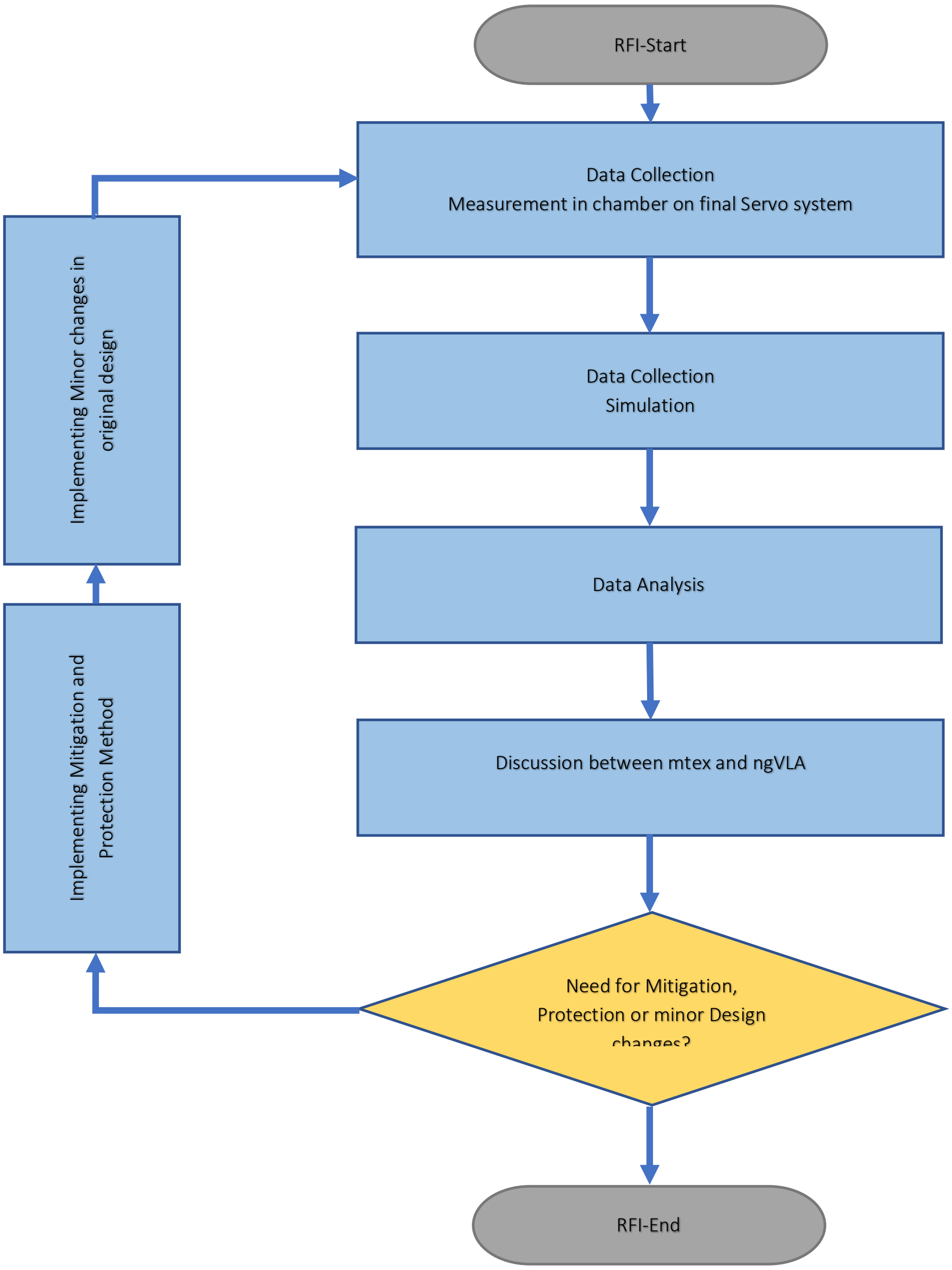


Figure 86. Flow chart of activities during prototype building phase

The additional step, implementing minor changes in design, which only concerns electrical and electronical units, is inserted in the above chart after mitigation and protection. It is considered only as needed if the other precautions are not sufficient or the changes provide better and faster outcomes to reach the goal specification. This is estimated to be a rare case and it is included in planning in case of encountering unexpected RFI issue, which can only be emerged due to the fact of using similar servo system during design phase.
The EMI, EMS and LEMP are simply a set of steps, which shall be followed after each other. Therefore, the plans for them are implicitly in each section correspondingly. These activities shall be done before starting with RFI works on prototype building phase of the project.
More detail version of all test plans will be issued at the next phase of the work, which is going to be mutually agreed on.

6.8.6.2. EMC Test Report

The following short section list off the preliminary test reporting for the EMC management:

- RFI
    - Chamber measurement procedures, once in each working phase of project, unless some modification require updating this part
    - Chamber measurement results, one per measurement session
    - Chamber calibration procedures, once in each working phase of project, unless some modification require updating this part
    - Chamber calibration results, one per measurement session
    - Simulation procedures, once in each working phase of project, unless some modification require updating this part
    - Simulation results, one per Simulation session
    - Data Analysis and Summary report. The report will be issued one per session.
    - RFI Final Report, summarizing the whole activity, once at the end of the work.
- EMI & EMS
    - measurement procedures, once
    - measurement results, one per measurement session
    - calibration procedures & results, once
    - Earthing System, design and structure, once
    - EMI & EMS Final Report, once
- LEMP
    - Simulation procedures, once
    - Simulation results, one per Simulation session
    - Lightning Protection System, design and structure, once
    - Lightning system Analysis, once
    - Lightning data Analysis, once
    - LEMP Final Report, once

6.9. Software ACU and real-time PLC concept

6.9.1. Software context and package overview

mtexM&C+ automation software is separated in low-level real-time relevant modules and higher-level non-real-time modules interfacing via OPC-UA® as illustrated in Figure 87, a cross-platform communication protocol for industrial automation. For the ngVLA project, it was agreed that the low-level real-time modules will be interfacing directly of the ngVLA control system relying on the OPC-UA interface.

Figure 88 shows an overview of the software structure. mtexM&C+control is the non-real-time component of mtex core software package, which is based on a mtex framework using Docker and Python. The real-time abstraction layer modules, which represent the real-time modules with their defined status and commanding variables, will be provide as interface support to NRAO for their further continued development.

Using Microsoft Visual Studio with the TwinCAT plugin, the real-time component mtexM&C+rt was developed, which incorporates low-level functionalities and the hardware communication layer.

Furthermore mtexM&C+webApp is the web-based Graphical User Interface (GUI) which communicates to mtexM&C+control software modules, or as a second version via OPC-UA to mtexM&C+rt enabling low-level control directly on the real-time PLC software.

While the mtexM&C+ is setup to be an open-source project with all its components, the real-time PLC code (mtexM&C+rt) is made available, changes within this software package are performance related and not recommended without mtex involvement. The safety system configuration is also made available but is protected from any change by other entities apart from mtex to prevent any safety issue.

On top of these core software components ngVLA specific modules will be implemented, in order to fulfill additional project specific requirements.

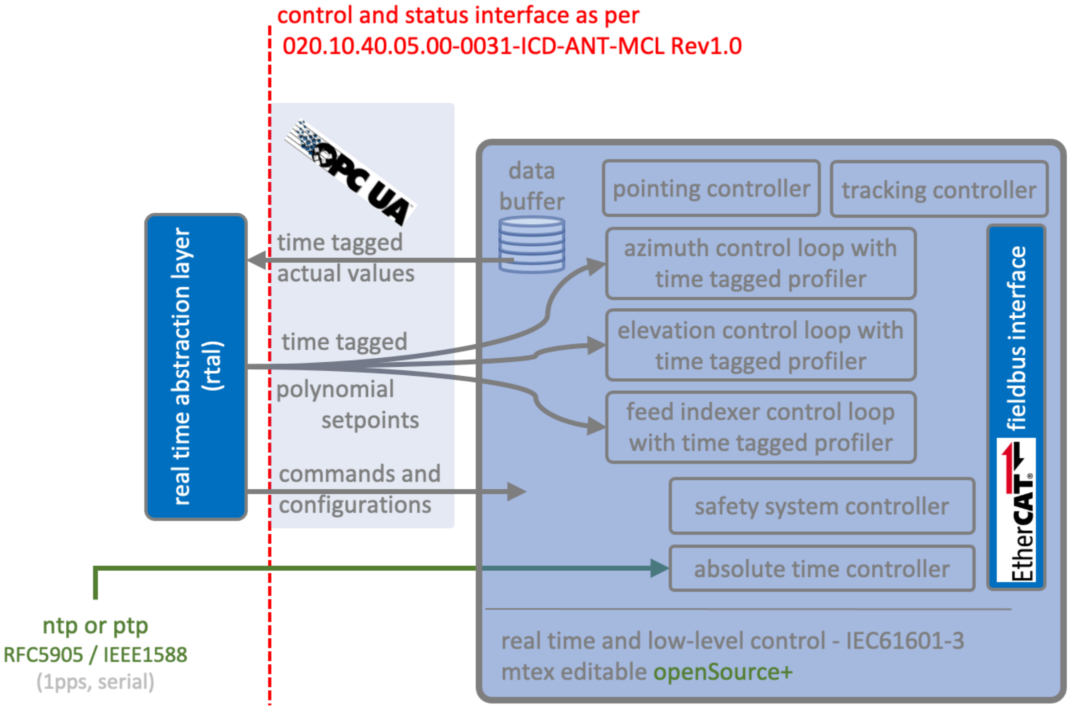


Figure 87 Details of the software structure ACU and real-time PLC

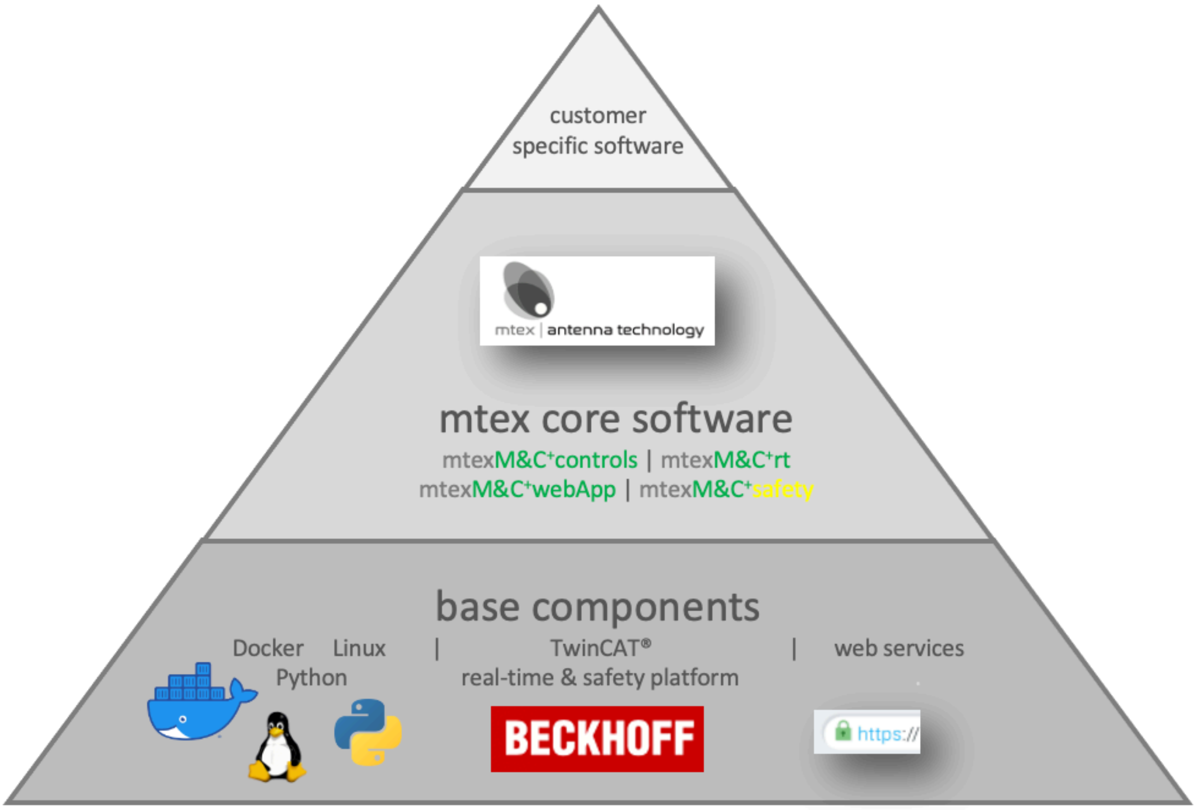


Figure 88: Overview software structure

6.9.2. mtexM&C$^+$rt - low-level real-time PLC software package

Real-time software is developed in structured text using Beckhoff TwinCAT, including integrated OPC-UA® server and visualization library, a web-based GUI to interface with real-time software modules (basis for the mtexM&C$^+$webApp that communicates to the real-time directly). mtexM&C$^+$rt core software modules deployed within the real-time PLC provide low-level functionality on subsystem level and interface with the subsystem's hardware components via the distributed real-time I/O system.

Functionalities implemented within the mtexM&C$^+$rt software package:

- setpoint modules
    - manual/fixed setpoint for az/el/fi (stow, service, bore sight tower, …)
    - program track (table of <az/el>time with interpolation)
    - stream track (polynomial stream <az/el-coefficients>time with interpolation)
- offsets modules
    - constant (az/el or el/xel)
    - program track
    - stream track
- corrections
    - gravity correction
    - ambient temperature correction
    - pointing model
- general modules
    - system time
    - safety system handling (communication from, to & for the safety system)
    - autostow for azimuth and elevation based on provided wind data
    - Fault detection and Monitoring of connected devices

6.9.3. Version control with GitLab

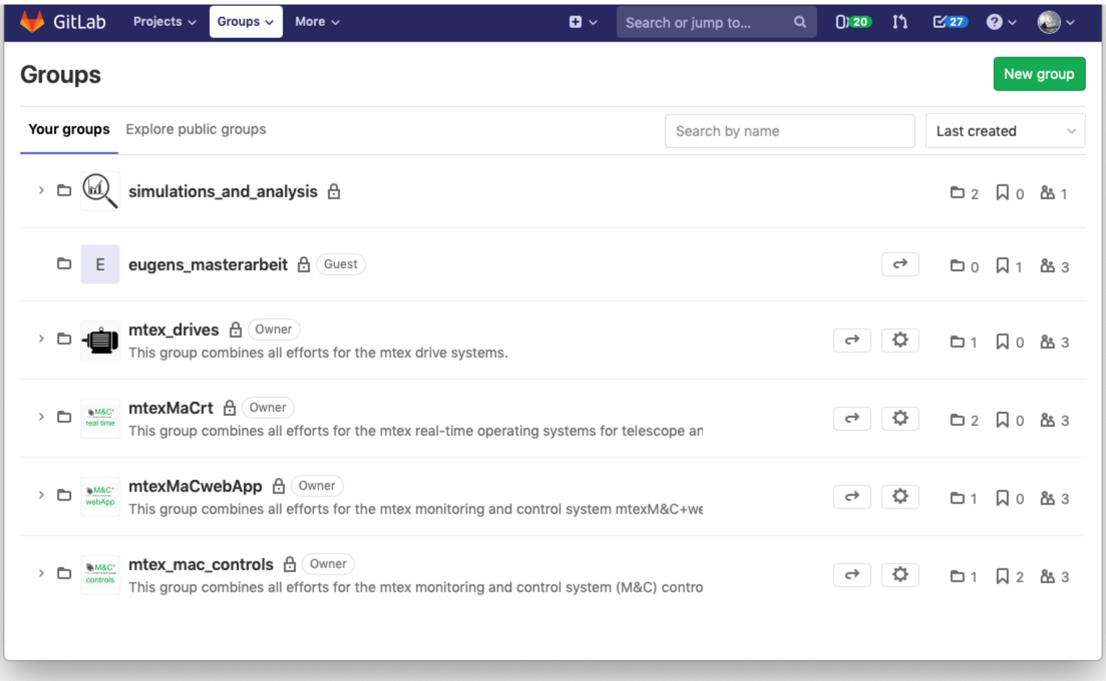
Regarding Servo subsystem software, the software revisions are tracked and tagged and after testing within mtex GitLab system for quality assurance. During commissioning on-site software changes will be documented and relevant tests from the In-Plant Testing will be repeated, where applicable. As mtex heavily relies on automated software testing, such repetition of software testing on-site is a straightforward process.

6.9.4. Servo and Control System Simulator

An antenna simulator will be provided to NRAO well in advance to the start of any commissioning and testing activity to jointly be ready for any acceptance testing activities (factory or site testing) to ensure proper behavior of both software systems. This approach helps to identify software issues early during the development phase.

The mtex GitLab system is used to support the following tasks during software projects:

structuring of all tasks in topics related groups
structuring software modules and sub modules linked within GitLab
work planning and issue tracking via SCRUM and CANBAN-boards
software versioning and release control
software quality verification via unit testing and CI (automated code testing through GitLab)
access to external entities to jointly collaborate and provide access to the issues and status



Groups

simulations_and_analysis — 2 0 1

eugens_masterarbeit Guest — 0 1 3

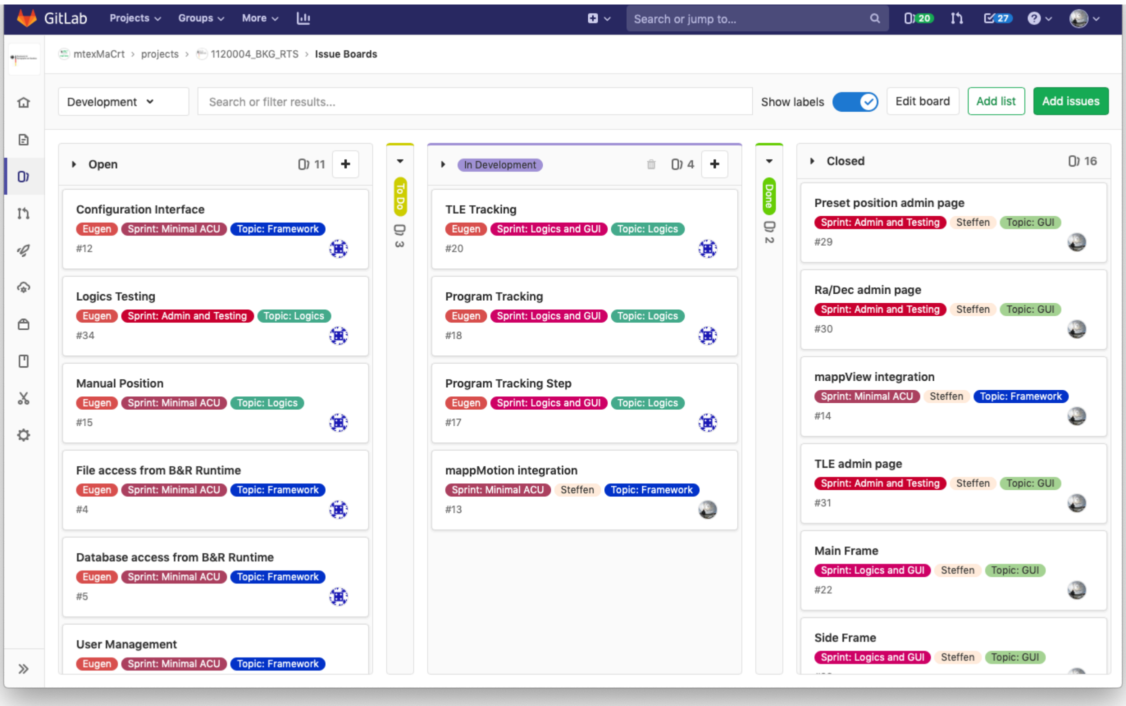
mtex_drives Owner — 1 0 3
This group combines all efforts for the mtex drive systems.

mtexMaCrt Owner — 2 0 3
This group combines all efforts for the mtex real-time operating systems for telescope an

mtexMaCwebApp Owner — 1 0 3
This group combines all efforts for the mtex monitoring and control system mtexM&C+we

mtex_mac_controls Owner — 1 2 3
This group combines all efforts for the mtex monitoring and control system (M&C) contro

Figure 89 mtex Gitlab tasks and development organization



Open 11

- Configuration Interface — Eugen, Sprint: Minimal ACU, Topic: Framework — #12
- Logics Testing — Eugen, Sprint: Admin and Testing, Topic: Logics — #34
- Manual Position — Eugen, Sprint: Minimal ACU, Topic: Logics — #15
- File access from B&R Runtime — Eugen, Sprint: Minimal ACU, Topic: Framework — #4
- Database access from B&R Runtime — Eugen, Sprint: Minimal ACU, Topic: Framework — #5
- User Management — Eugen, Sprint: Minimal ACU, Topic: Framework

In Development 4

- TLE Tracking — Eugen, Sprint: Logics and GUI, Topic: Logics — #20
- Program Tracking — Eugen, Sprint: Logics and GUI, Topic: Logics — #18
- Program Tracking Step — Eugen, Sprint: Logics and GUI, Topic: Logics — #17
- mappMotion integration — Sprint: Minimal ACU, Steffen, Topic: Framework — #13

Closed 16

- Preset position admin page — Sprint: Admin and Testing, Steffen, Topic: GUI — #29
- Ra/Dec admin page — Sprint: Admin and Testing, Steffen, Topic: GUI — #30
- mappView integration — Sprint: Minimal ACU, Steffen, Topic: Framework — #14
- TLE admin page — Sprint: Admin and Testing, Steffen, Topic: GUI — #31
- Main Frame — Sprint: Logics and GUI, Steffen, Topic: GUI — #22
- Side Frame — Sprint: Logics and GUI, Steffen, Topic: GUI

Figure 90 mtex Gitlab Issue Board

6.10. Servo System

6.10.1. Hardware

This section provides the required overview and context of the Antenna Servo System hardware and software. It describes the main hardware components as well as the structure of the software.

The hardware for all mtex servo control systems is based on common-off-the-shelf (COTS) hardware of well-established companies in the field of the automation industry. Relying on world-wide conveniently available, widely used and tested - and more important - standardized hardware enables mtex to concentrate on the special tasks when designing and building servo and control systems for antennas and communication antennas still being flexible and mostly hardware independent.

Our customers take great benefit of this as well when dealing with repairs, or future extensions and adaptations as standardization, in the use of proven interfaces, communication protocols and hardware platforms simplifies to a great extend upcoming tasks/challenges. In addition, customers maintenance staff can rely on mtex support as first level and the support of the companies involved in the project as manufacturers from the automation industry as second level.

Defined product lifecycles guarantee long-term availability of spares as products will be selected accordingly. Even in case of end of product lifetime during the operational phase of the systems, manufacturers can easily provide alternatives relying on their standardization.

6.10.2. Context overview

The context of the Antenna Servo subsystem is provided in Figure 91 and is structured in the following subsystems:

- Real-time PLC incl. low level real-time software
- Safety System PLC incl. configuration
- Amplifier systems incl. configuration
- Distributed I/O system (normal and safe I/Os)
- Portable Control Unit, (PDCU)

The **real-time PLC** is implementing basic low-level control and the real-time control loops of all axes of motion as described in Section 6.9.2. Details are provided in Section 6.10.4. The real-time PLC is controlled either via OPC-UA, or via PDCU and operates the individual motion axes.
The details and the functionality of the **Safety System** will be defined by the hazard analysis that will be performed and updated during the design phases of the project. Details regarding that process are described in section 6.10.8, the participation of the customer is required, during design review meetings and official project milestones the hazard analysis and the Safety System Specification will be updated and released.
The **PDCU** is a tablet-based device running under iOS extended with an industrial case including an emergency stop push button and the means to charge the tablet, see section 6.10.7.

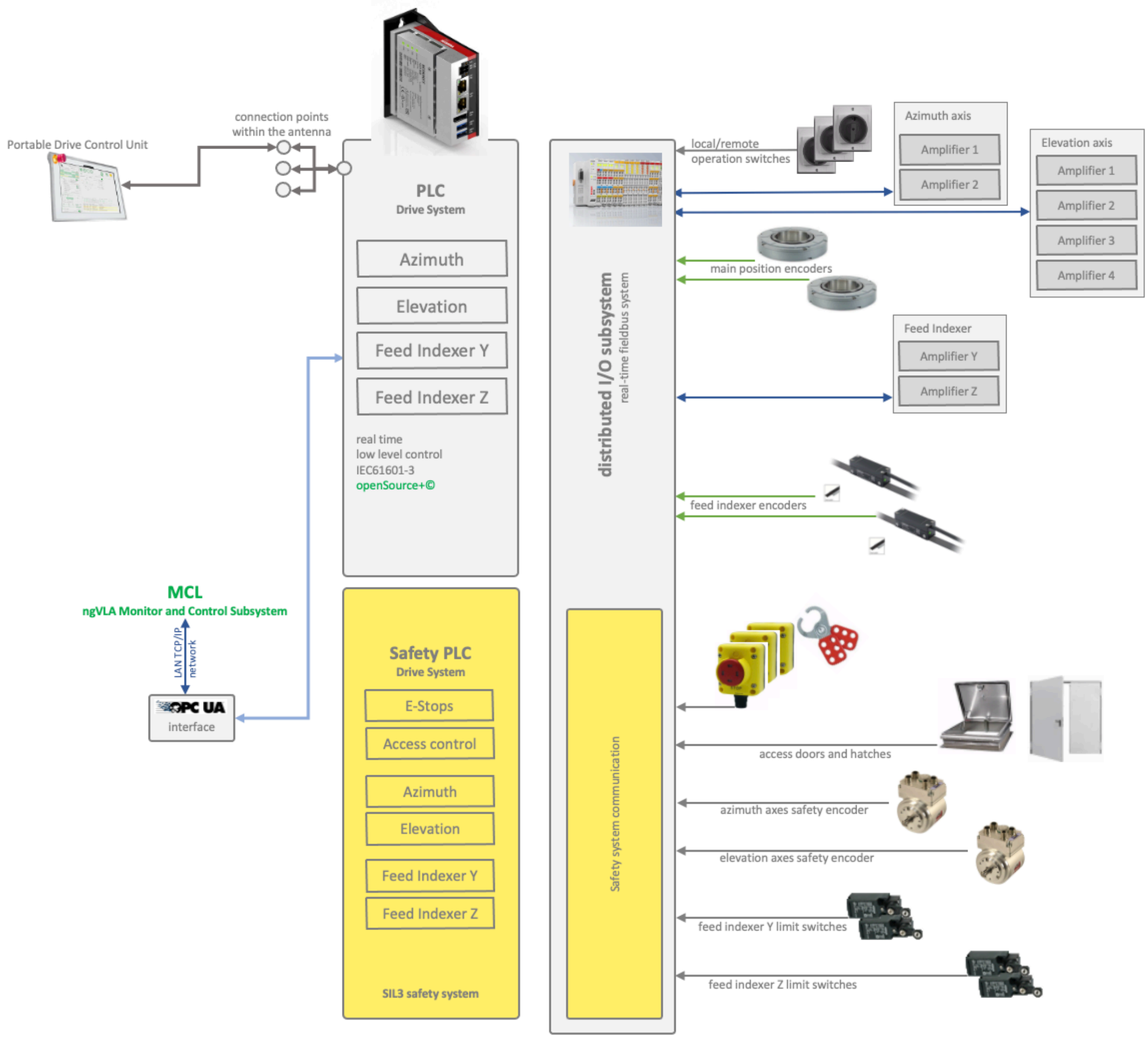
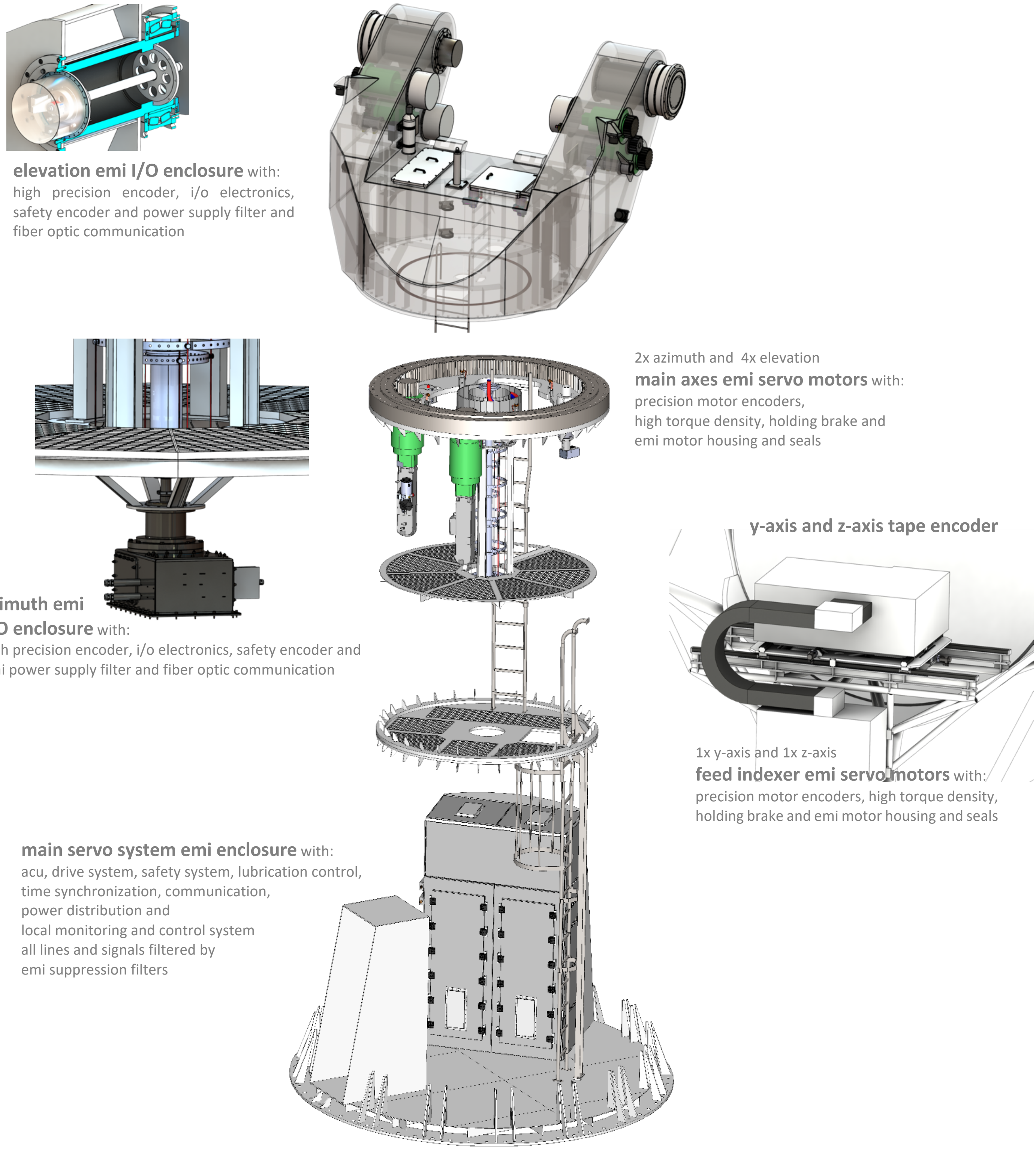


Figure 91: Servo System hardware context

The locations and places of installation of several components are shown in Figure 92 Servo System components locations.



elevation emi I/O enclosure with:
high precision encoder, i/o electronics, safety encoder and power supply filter and fiber optic communication

2x azimuth and 4x elevation
main axes emi servo motors with:
precision motor encoders,
high torque density, holding brake and
emi motor housing and seals

y-axis and z-axis tape encoder

azimuth emi I/O enclosure with:
high precision encoder, i/o electronics, safety encoder and emi power supply filter and fiber optic communication

1x y-axis and 1x z-axis
feed indexer emi servo motors with:
precision motor encoders, high torque density, holding brake and emi motor housing and seals

main servo system emi enclosure with:
acu, drive system, safety system, lubrication control,
time synchronization, communication,
power distribution and
local monitoring and control system
all lines and signals filtered by
emi suppression filters

Figure 92 Servo System components locations

6.10.3. Operational modes and functionality summary

The Antenna Servo subsystem will provide several modes of operation for the individual axes and as a complete antenna system.

Table 11 Operational modes summary

Operation mode	Control via	Comments
Slewing	MCL, Local M&C (PDCU)	slewing with closed position loop slewing with velocity loop only
Manual Positioning		absolute positioning relative positioning position-select for 10 predefined positions
Auto stow on/off (azimuth and elevation only)		the azimuth and elevation will be stowed automatically based provided wind sensor data
Program-Tracking incl. Offsets		az/el-timetable
Scan pattern as offsets		spiral, raster or lissajous
Stream tracking		polynomial stream of <az/el- coefficients> over time with interpolation
Follow pointing model correction on/off (azimuth, elevation and feed indexer z-axis)		The positions for azimuth, elevation and the feed indexer z-axis are automatically corrected based on a pointing model

6.10.3.1. *Remote control via MCL*

Remote control will be available through the OPC-UA® interfaces of all subsystems, incorporated by mtexM&C+rt.

6.10.3.2. *Control via mtexM&C+webApp as local M&C*

The mtexM&C+webApp acts as the local MMI. It displays all status and configuration parameters as well as the controllable parameters of each software module required for maintenance activities. An example of the mtexM&C+webApp design and capabilities is shown in Figure 93. It should be noted that this screenshot is taken from a design, that manages all ground station hardware. The local MMI for the maintenance activities will be of the same design and concept, but will be limited in functionality to the required functions only necessary for maintenance.
The left frame shows a general overview of all devices' health, as well as several quick actions which can be adapted to project specific requirements. The top frame acts as a tab bar, where each button represents a view in the main frame. The main screen seen in the example is the tab for low-level management of all included devices. “Motor #1” is the selected device in the example and its status parameters are monitored. Each field provides additional information on unit, allowed range and meaning of the status variable. Furthermore, writeable status parameters can be set directly from this view by specifying the value and clicking the green arrow button right next to the input field (see parameter “set speed”). In addition to that, below the status parameters, writeable parameters are grouped in command structures in order to

facilitate commanding of the devices. On the bottom of the screen there is an event view, where predefined incoming events are listed and can be sorted and filtered in various ways. In addition to the low-level control provided by this view, there are views for subsystems, that facilitate the control by incorporating quick commands and adding visualization. Furthermore, data logging and configuration views are available.

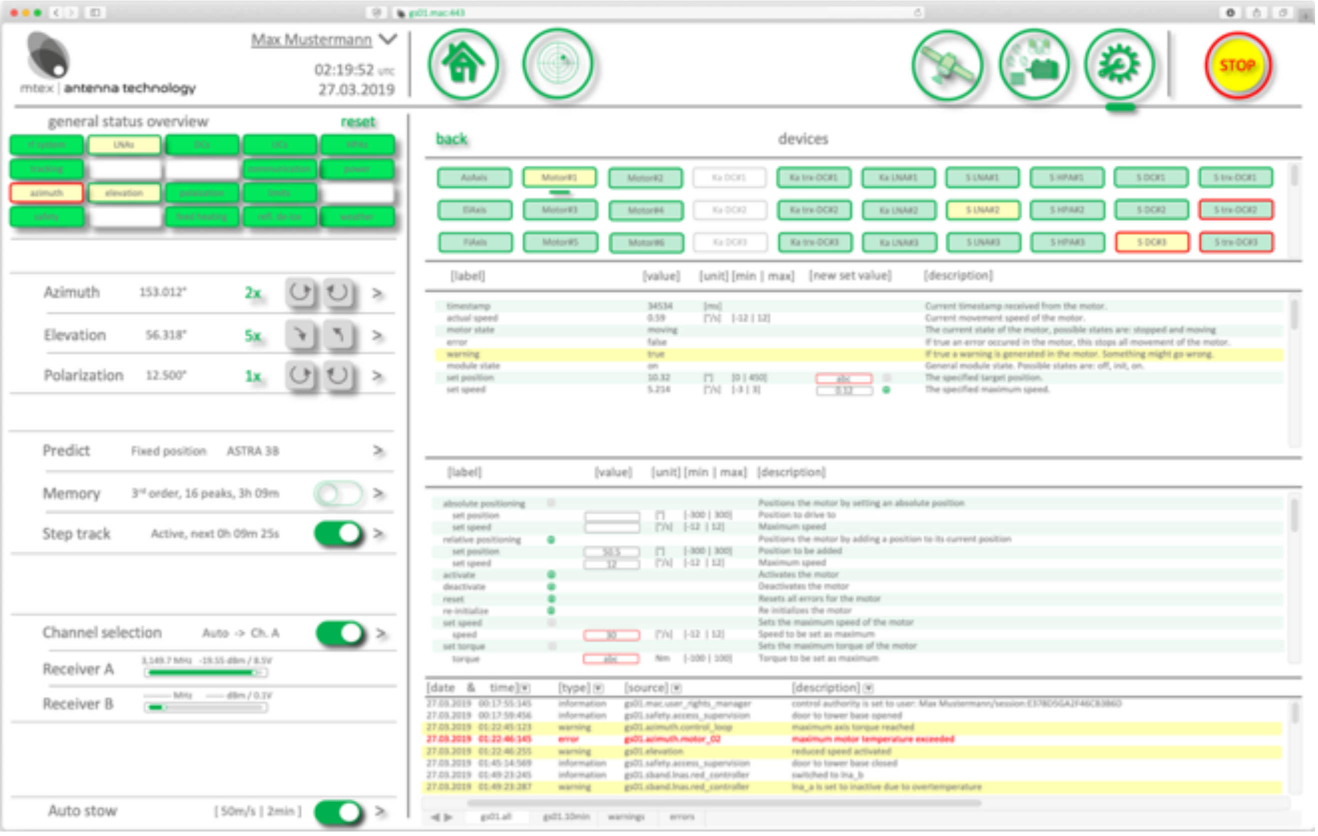


Figure 93: Example screenshot of the mtexM&C⁺webApp.

6.10.4. Real-time PLC hardware

The real-time PLC is based on the industrial PC platform by Beckhoff. This CPU is based on Intel Atom processor technology and used for applications with the highest performance requirements.
The configuration of the selected unit, C6015-0020, includes USB3.0, 2x Gigabit-Ethernet and a DisplayPort.

The selected unit main features are:

- Ultra-compact control cabinet PC
- Intel Atom® E3845 1.91 GHz, 4 cores (TC3: 50) and 4 GB DDR3L RAM
- Hard disk/flash: 1 slot for M.2 SSD with 40 GB
- Ethernet: 2 x 100/1000BASE-T on-board
- Graphic adapter: integrated in the processor
- Cooling: passive with single side cooling plate
- Power supply: 24VDC
- Operating system: FreeBSD

Figure 94: Drive system PLC

6.10.5. Redundant 24VDC power supplies

Another single point of failures are power failures either in power supplies or cabling. This is addressed by using redundant power supplies.

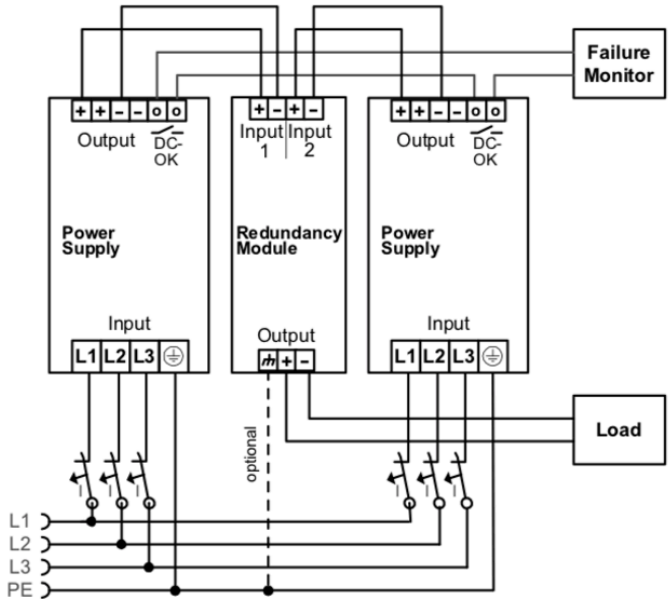


Figure 95 Redundancy concept for 24VDC power supply and distribution to loads

Two power supplies convert the 400VAC power to 24VDC power, the distribution of the 24VDC to the loads is handled by a redundancy module with much higher MTBF value as the individual power supplies, see Figure 95.

This setup is used twice to provide high available 24VDC power within the systems. “Dirty-24VDC” to supply relays and brakes with the required power to operate is separated from “Clean-24VDC” that supplies the electronics.

6.10.6. Position encoders

The position encoders for the individual axes of motion will be high precision encoders from *Johannes Heidenhain GmbH* as accurate position feed-back. Installed within the I/O boxes, two RCN8311 disc encoders with high single-turn resolution and accuracy for azimuth and elevation axis. Those encoders are also safety rated and can be used to feedback a safe signal to the safety system.

Figure 96 Precision Encoder

Also installed within the Azimuth I/O box is a multiturn encoder from Heidenhain to determine in which revolution the antenna azimuth axis is currently working in.

The two axes of motion of the Feed Indexer will be equipped with either high resolution motor encoders that can be used as absolute position feedback or an absolute tape encoder (LA11) from RLS to accurately measure the position of the feeds. EMI/RFI testing will show, if the digital version will have to be replaced with an analogue incremental version (LM10).

Figure 97 Linear Absolute Encoder

6.10.7. Portable Drive Control Unit

The PCU (**P**ortable **D**rive **C**ontrol **U**nit) is realized as a mobile panel handheld device based on an iOS device shown in Figure 98. In compliance with requirements, low-level control will be available using mtexM&C$^+$webApp displayed on the PDCU.
The PDCU will be supplied with a cable of 25m length to connect to the connection boxes.

Figure 98: PDCU with example GUI (e-stop will be incorporated)

Figure 99: PDCU connection box

Connection boxes (see Figure 99) for the PDCU are installed on appropriate locations within the antenna. The following are foreseen:

Next to the pedestal entrance door
Up on the Turnhead outside at elevation gearboxes
At the Feed Indexer

6.10.8. mtexM&C$^+$safety as safety system

The Safety System is based on the modules of the Beckhoff TwinSafe platform. The safety controller module is equipped with safety functionality that allows it to safely execute applications designed in within TwinCAT Safe Designer. The module can be used in safety-related applications up to PL e or SIL 3.
In addition, the module coordinates the safety-related communication of all modules involved in the application. In this context, the module also monitors the configuration of these modules and carries out autonomous parameter downloads to the modules whenever necessary. This guarantees a consistent and correct module configuration in the network from a safety standpoint in all scenarios involving module replacement and service.

Figure 100: TwinSafe safety plc controller

Figure 101: Safety rated I/O modules 8purely safety (left) and single channel (right)

The safety system sensors (E-Stops, door and hatch switches) will all be spread throughout the antenna. The distributed I/Os as shown in Figure 101 will be used to interface to those elements heavily reducing cabling and maintenance effort.

A hazard analysis performed during all project phases and reviewed within the project team including customer participation will define the exact functionality of the Safety System and locations for E-Stops, doors and hatch supervision. The functionality and locations presented in the following subsections are based on the experience of the project team members and present the expected measures. Nevertheless, the basis for the safety system specification will be the hazard analysis.

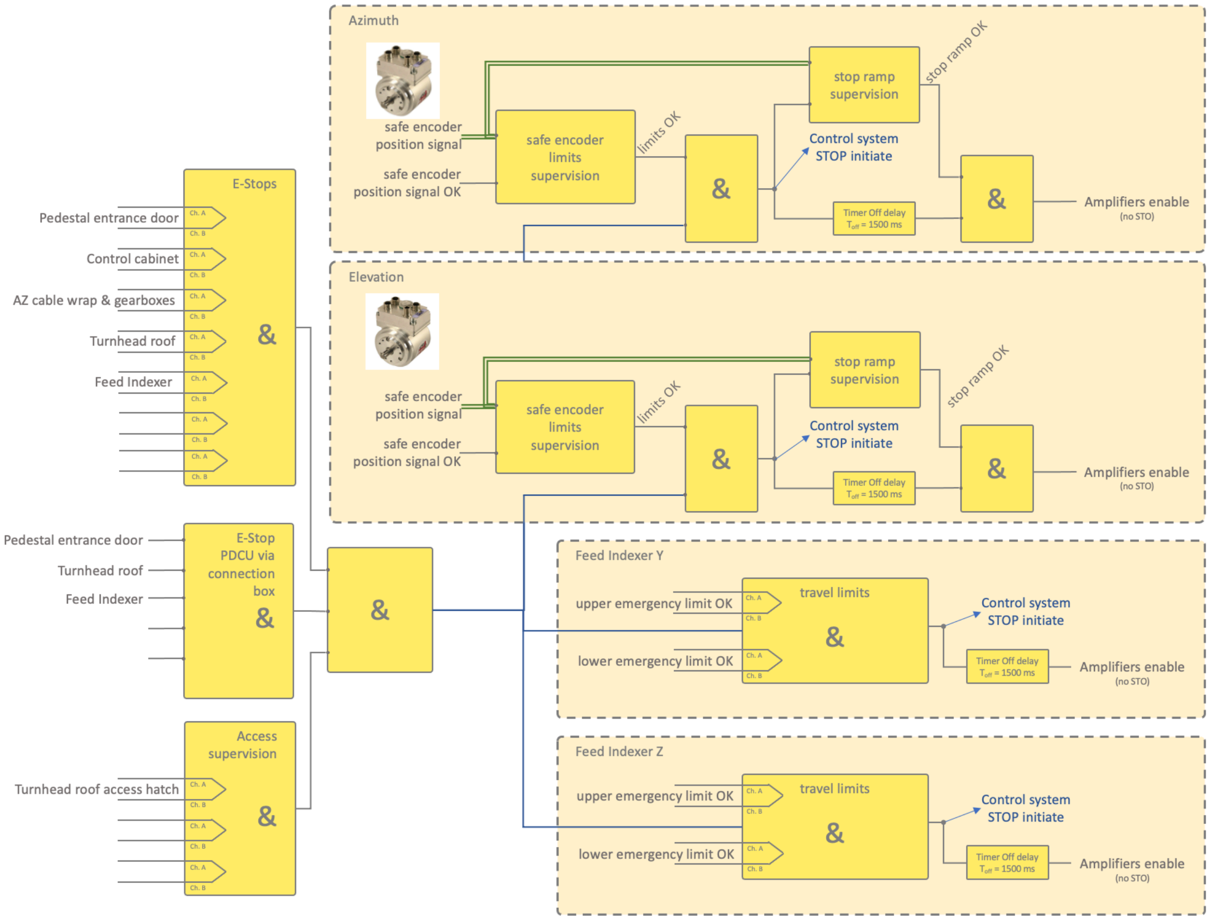


Figure 102: General safety system logic overview

The PDCU will also be equipped with an e-stop push button. When the PDCU is not connected, a blind plug will bridge the e-stop circuit on the connection box where usually the PDCU e-stop would close that circuit. To facilitate connecting and disconnecting the PDCU and removing and putting back the blind plug, an override timer can be activated via push button to not send all antenna systems in e-stop when connecting or removing the PDCU (Figure 103).

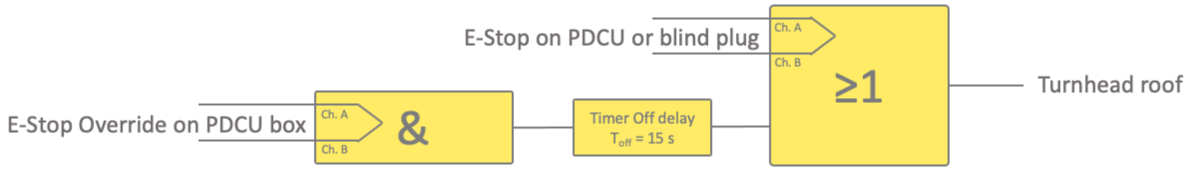


Figure 103: PDCU E-Stop override when connecting/disconnecting PDCU

6.10.8.1. Motion limit switches

As the control system operates the antenna systems and implements all the required functionality, the safety system supervises each axes of motion with respect to its safe range of travel. Two main concepts are implemented to perform the supervision of limits. For the main axes as Azimuth and Elevation an application incorporating a safety encoder will be implemented within the servo system. The auxiliary axes of motion like the feed indexer will rely on limit switches.
The benefits of a safety-rated encoder system are that a continuous supervision of the actual state of motion can be performed, whereas using limit switches only trigger at the end of travel. The concept for the safety-rated encoder system is explained in section 6.10.8.1.2.

6.10.8.1.1. Standard limit switches for the auxiliary axes

Axes with small inertia and/or fairly low speeds do not contain high amount of kinetic energy when operated, stopping ramps are fairly short in time and travel range and therefore do present a lower risk.
Two limit switches will be installed, one at each end of travel to supervise that the axis of motion does not leave its safe operating range with respect to its position, see Figure 104 for *CCWemergency limit* and *CWemergency limit*. For a translational axis those switches would be upper and lower limit switch.
The switches are triggered when the axis passes the switch and the signal OK circuit will be opened starting the safe timer to disable the amplifiers when the timer has expired and immediately notifying the control system to bring the axis to a complete stop with the motors. When the timer has expired, the safety system disables the motors via Safe Torque Off (STO) and closes the brakes. This ensures that the axis will also be stopped even when the control system has not brought the axis to a stop due to some malfunction. Under normal conditions, all axes are brought to a complete controlled stop via the control system with motors.
The same sequence is started as well when an E-Stop push button is triggered, that signal is the one line to the left of Figure 104, see also Figure 102.

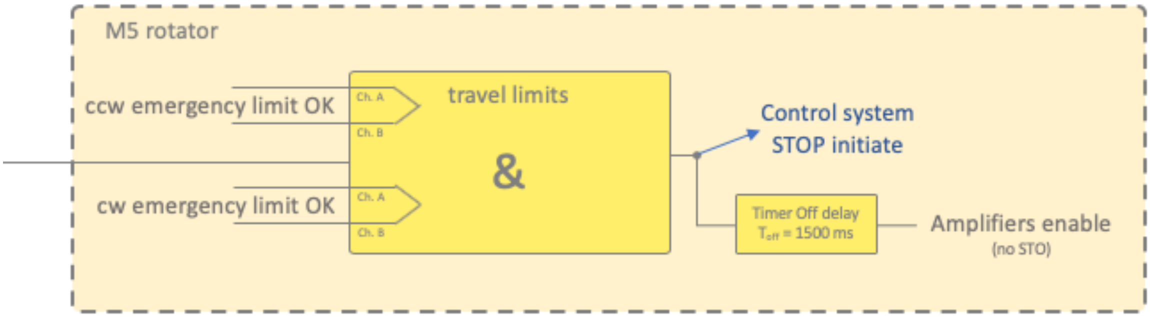


Figure 104: Standard limit switch for travel range

6.10.8.1.2. Safe encoder application for the main axes

The main axes of azimuth and elevation will be equipped with a safety encoder not only supervising the limits of motion with respect to positions, but also supervises the speed and stopping behavior. Figure 106 to Figure 111 show the individual motion characteristics that will be supervised by this application.
Based on the feedback of a safety-rated encoder installed on the main axis a safe position and velocity signal can be used within the safety system to activate different supervisions under individual operating conditions.
The following situations are supervised under normal operation:

- Approaching the end of travel, the position dependent maximum speed threshold ensures that the axis speed will be reduced in the direction of travel end, realized by Safe Limited Speed (Figure 111) where SLS equals 0°/s at t1 and Safe Direction behind the travel limit (Figure 110).
- Safe Maximum speed, ensuring that the antenna never exceeds its speed limit (Figure 109)
- Stopping behavior after activation of an emergency stop push button to ensure that the axis will be stopped correctly by the control system (Figure 107)

During maintenance activities and in addition to the above the following additional supervisions can be activated:

- Safely Limited Position, ensuring that the axes do not leave an even more reduced range of travel (Figure 108)
- Safe Limited Speed, when performing maintenance on bearings or gearboxes (Figure 111)
- Safe Direction, when the axes shall not be allowed to move further in one direction (Figure 110)

As the safe encoder application is only supervising the above, the control system is still the first level to keep the system in a safe state. As result of a violation of the above supervisions is that the safety system will immediately disable the motors and close the brakes of the respective axis (STO from Figure 106), ensuring that the antenna still remains in a safe state.

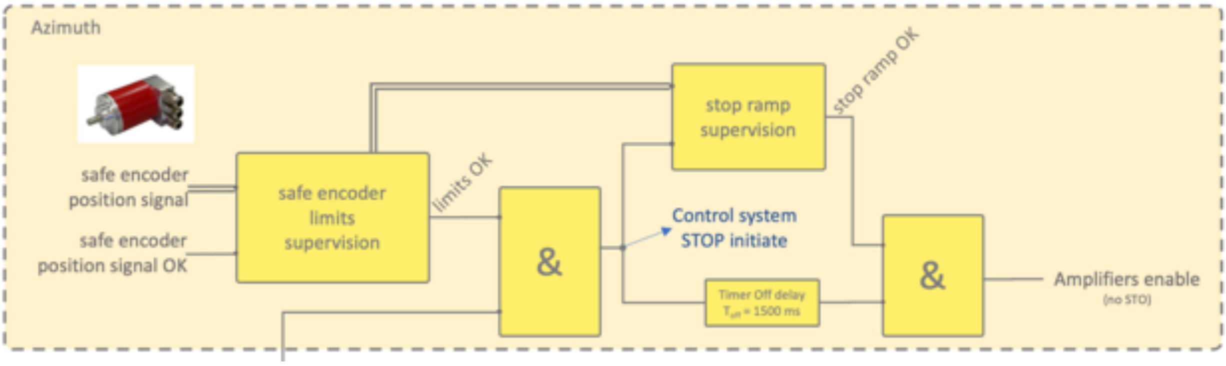


Figure 105: Azimuth motion limits

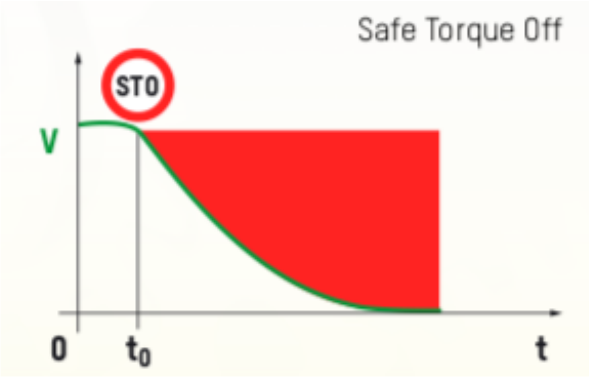


Figure 106: Safe Torque Off, STO

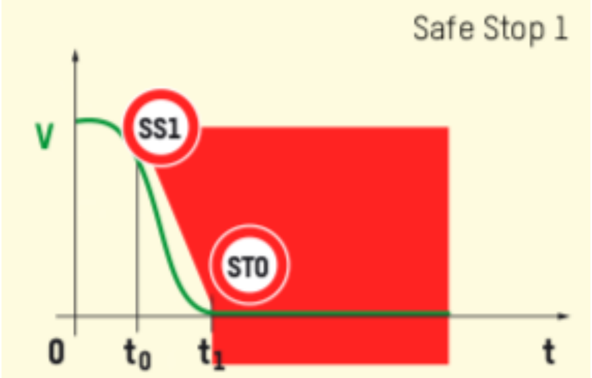


Figure 107: Safe Stop 1, SS1

Figure 108: Safe Limited Position, SLP

Figure 109: Safe Maximum Speed, SMS

Figure 110: Safe Direction, SDI

Figure 111: Safe Limited Speed, SLS

6.11. Power Distribution Supervision

The incoming power line will be supervised by a device that provides the following functionality:

continuous measurement and logging of power quality and consumption
logging of events like passing configured thresholds
event based actions on digital outputs to shut down power to the antenna
configurable recovery

With this device it will be possible to protect the antennas systems from any hazardous voltages coming from the grid and which are not filtered by the infeed filter or overvoltage protection. The distribution of the main power is then provided by the mtex cabinet throughout and for all antenna subsystems.

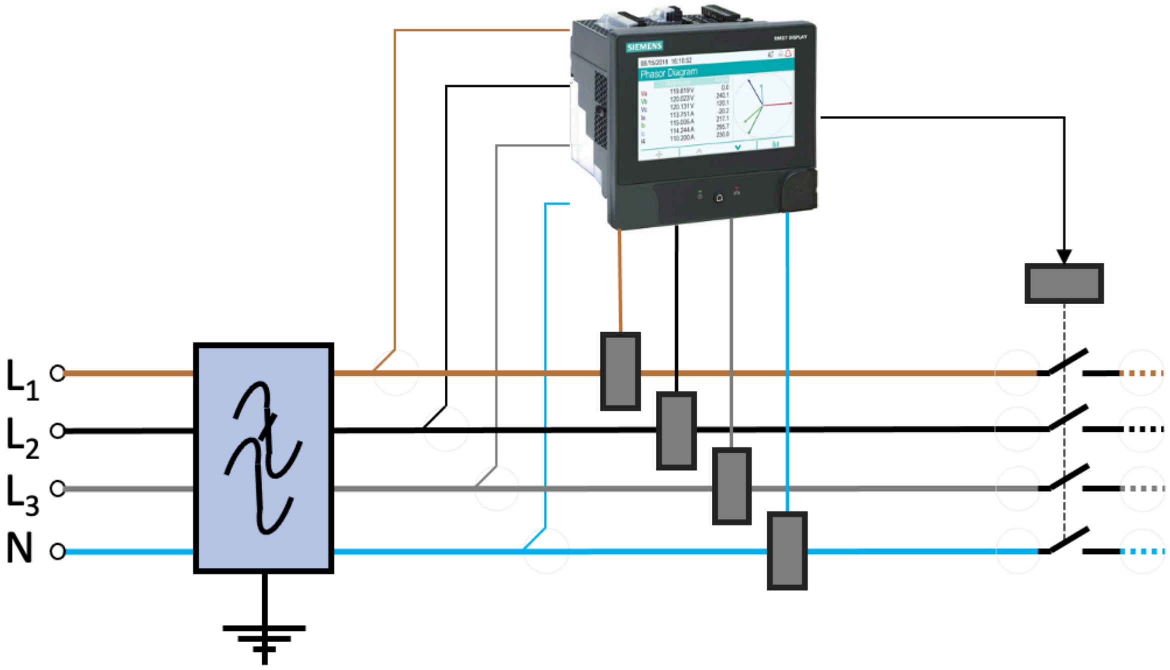
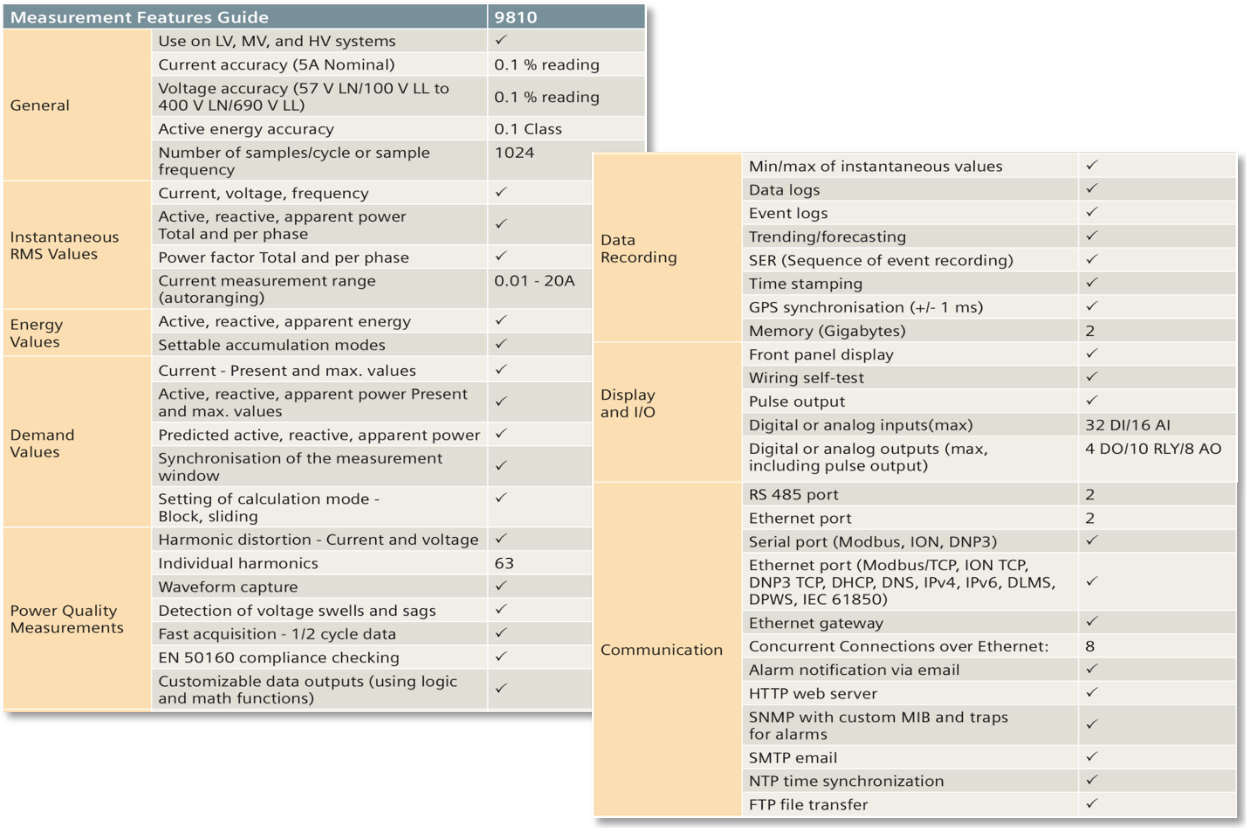


Figure 112 Power Supervision Device

Further distribution and generation of 24VDC is described within the servo section.



Measurement Features Guide		9810
General	Use on LV, MV, and HV systems	✓
	Current accuracy (5A Nominal)	0.1 % reading
	Voltage accuracy (57 V LN/100 V LL to 400 V LN/690 V LL)	0.1 % reading
	Active energy accuracy	0.1 Class
	Number of samples/cycle or sample frequency	1024
Instantaneous RMS Values	Current, voltage, frequency	✓
	Active, reactive, apparent power Total and per phase	✓
	Power factor Total and per phase	✓
	Current measurement range (autoranging)	0.01 - 20A
Energy Values	Active, reactive, apparent energy	✓
	Settable accumulation modes	✓
Demand Values	Current - Present and max. values	✓
	Active, reactive, apparent power Present and max. values	✓
	Predicted active, reactive, apparent power	✓
	Synchronisation of the measurement window	✓
	Setting of calculation mode - Block, sliding	✓
Power Quality Measurements	Harmonic distortion - Current and voltage	✓
	Individual harmonics	63
	Waveform capture	✓
	Detection of voltage swells and sags	✓
	Fast acquisition - 1/2 cycle data	✓
	EN 50160 compliance checking	✓
	Customizable data outputs (using logic and math functions)	✓
Data Recording	Min/max of instantaneous values	✓
	Data logs	✓
	Event logs	✓
	Trending/forecasting	✓
	SER (Sequence of event recording)	✓
	Time stamping	✓
	GPS synchronisation (+/- 1 ms)	✓
	Memory (Gigabytes)	2
Display and I/O	Front panel display	✓
	Wiring self-test	✓
	Pulse output	✓
	Digital or analog inputs(max)	32 DI/16 AI
	Digital or analog outputs (max, including pulse output)	4 DO/10 RLY/8 AO
Communication	RS 485 port	2
	Ethernet port	2
	Serial port (Modbus, ION, DNP3)	✓
	Ethernet port (Modbus/TCP, ION TCP, DNP3 TCP, DHCP, DNS, IPv4, IPv6, DLMS, DPWS, IEC 61850)	✓
	Ethernet gateway	✓
	Concurrent Connections over Ethernet:	8
	Alarm notification via email	✓
	HTTP web server	✓
	SNMP with custom MIB and traps for alarms	✓
	SMTP email	✓
	NTP time synchronization	✓
	FTP file transfer	✓

Figure 113 Datasheet of the Power Supervision Device

6.12. Fire Alarm System

Fire- and smoke detectors will be installed in the antenna to detect any potentially dangerous situation and to inform the maintenance staff (and/or local fire department).
Detectors are planned to be installed in the following locations as minimum:

- Inside of the lower Pedestal
- Inside of the EMI/RFI Main Cabinet enclosure
- Inside of the Turnhead center

The fire hazard will also be analyzed as part of the hazard analysis, additional detectors and/or different locations my result and influence the design.

6.13. Customer Equipment

This section is intended to explain the decisions mtex made to place the equipment that has been defined by the customer. Appropriate CAD data has been provided by NRAO.

6.13.1. Front-End Equipment

The Front-End equipment consists of the Front-End Receiver Enclosure and the Front-End Auxiliary Enclosure. Both items are defined in ⍰.

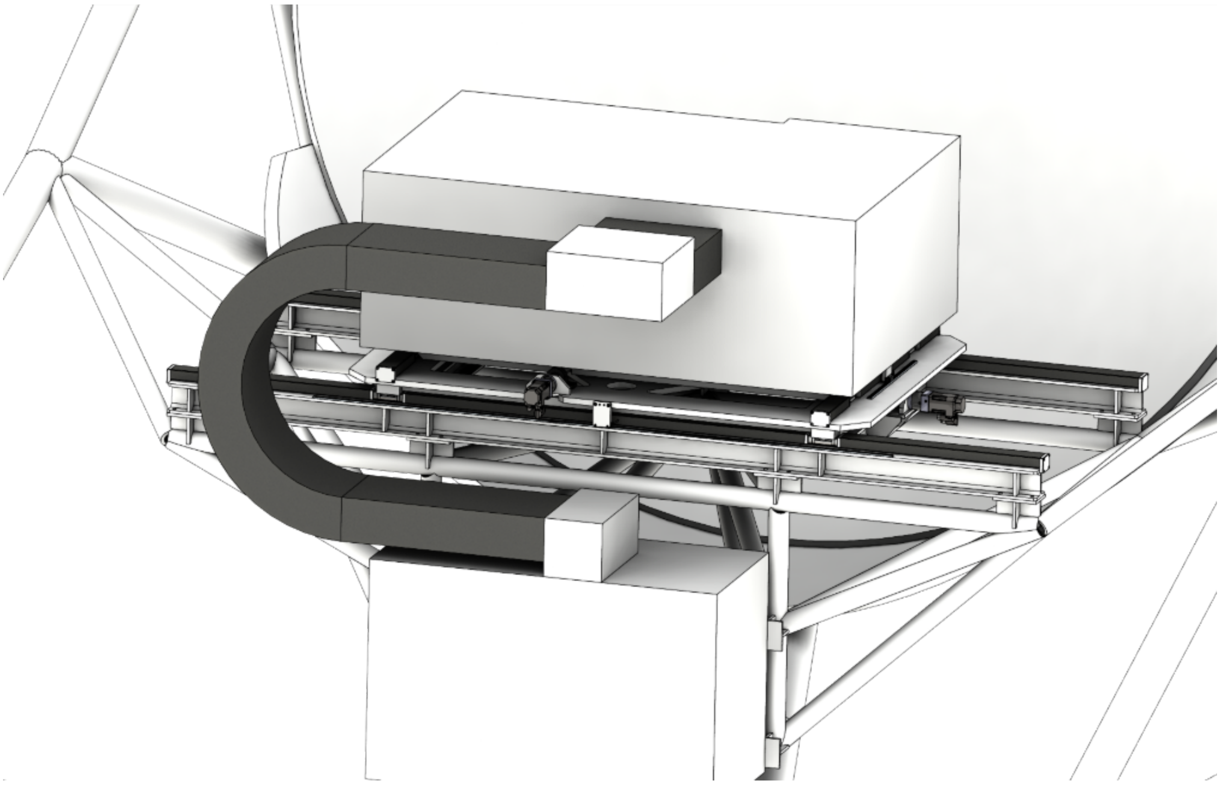


Figure 114 Front End Equipment at Feed Indexer Actuator

The Front-End Receiver Enclosure is mounted to the top plate of the feed indexer actuator. It can be moved as specified by NRAO including some spare travel range. The Front-End Auxiliary Enclosure is mounted to the steel structure frame that carries the feed indexer actuator and connects the left and right side of the feed arm structure.

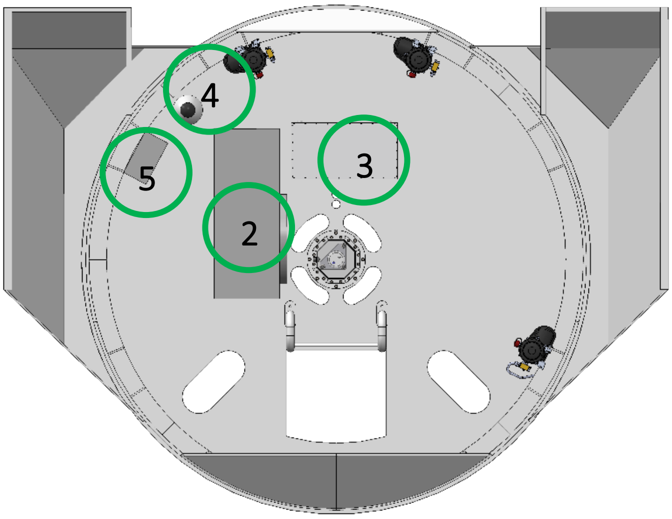
Depending on the recommended type of cable wrap, mtex decided to move the position of the Front-End Auxiliary Enclosure closer to the Front-End Receiver Enclosure.

6.13.2. Environmental Control Equipment

The Environmental Control Equipment is defined by NRAO in ⍰.
This equipment includes:

- Glycol chiller
- Helium compressor
- Helium pressure regulation assembly
- Helium buffer tank
- Helium supply tank
- RFI Enclosure

mtex managed to incorporate all these items inside the Turnhead, except the helium supply tank. The helium supply bottle needs to be changed on a regular basis, so mtex made the decision to set this bottle on top of the Turnhead for the most comfortable maintenance access.
Installation inside the Turnhead requires a certain sequence to get the bigger parts in place.
The final design of the RFI enclosure can be discussed in the detail design phase.



(1) Glycol Chiller (Lower Pedestal / not shown)

(2) Helium compressor

(3) Helium pressure regulation assembly

(4) Helium buffer tank

(5) RFI enclosure

(6) Helium supply tank (outside and not shown)

Figure 115 Environmental Control Equipment Locations

There are several options for mounting / positioning the helium supply tank for the cryo system. Depending on the final dimensions and mass of the distributed system there may be suitable clearance inside the Turnhead or external near the access hatch. This is an area that requires further discussion and collaboration with NRAO and the cryo IPT. Refer to Figures and for tradeoffs and comparisons.

6.13.3. Back-End Equipment

The Back-End Equipment is defined by NRAO in ⍰.
Back-End Equipment consists of:

- Back-End Rack electronics rack
- Backup Battery for P500

All the components are in the lower pedestal inside the EMI drive cabinet.
Mtex modified the arrangement of the components to fit them inside the cabinet.
At the current design stage there are a lot of possibilities to define the optimal layout together with NRAO.

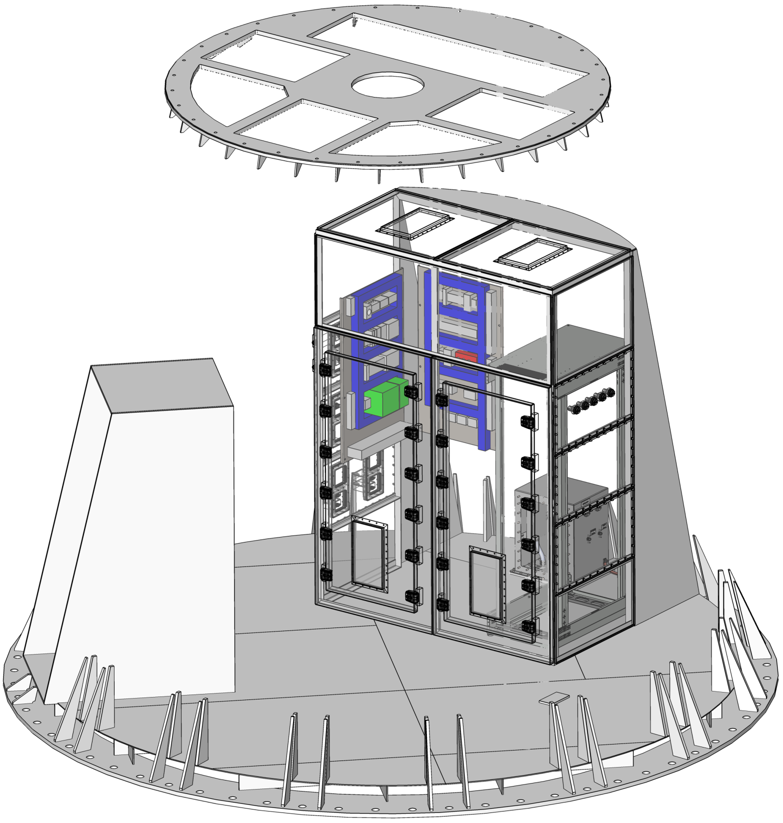


Figure 116 Back-End Equipment configuration inside emi cabinet (left side inside an 19" cabinet) and mtex servo system items (right side)

Airflow through the customer Back-End rack is still in the same way as it was defined by NRAO.

6.13.4. WVR

Details of the WVR are defined by NRAO in ⍰.
The WVR is located outside the feed arm structure close to the main reflector edge.
This location ensures that there is no blockage to the optical beam of the antenna. The location also provides easy access to align the WVR parallel to the main reflector optical beam.
Mtex designed an additional support structure for the WVR which uses the rear mounting plate specified by NRAO in ⍰.

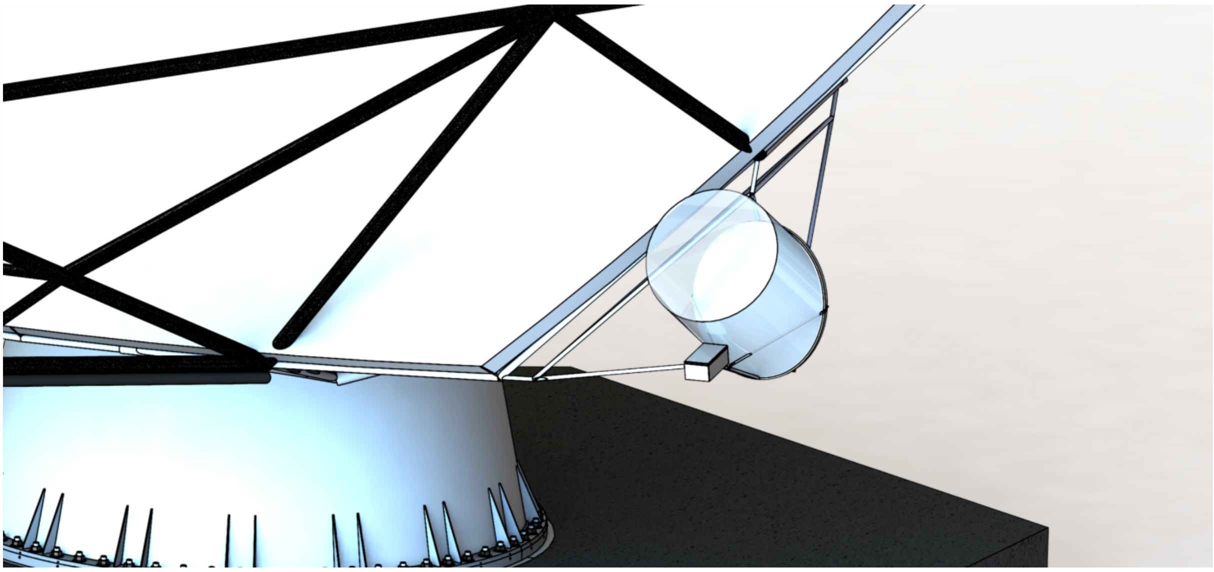


Figure 117 WVR Location