Telescope Mechanics

TITLE

Cassegrain Set (CG-Set) Preliminary Design

Code: RPT/TELE/0442-R
Issue: 1.A
Date: 22/06/2017
Nr. of pages: 146
C/D: Yes

Gran Telescopio de Canarias, S.A.

Instituto de Astrofísica de Canarias
Vía Láctea s/n
38200 - LA LAGUNA, TENERIFE, Islas Canarias
Tfno +34 922 315 031  Fax +34 922 315 032

Centro Común de Astrofísica de La Palma
Cuesta de San José s/n
38712 BREÑA BAJA, LA PALMA, Islas Canarias
Tfno +34 922 425 720  Fax +34 922 425 725

http://www.gtc.iac.es  E-Mail: gtc@iac.es
## Approval Control

| Prepared by | Germán Prieto  
| Engineer of Development Group | Signed in the original copy |
| | Benjamin Siegel  
| Engineer of Development Group | Signed in the original copy |
| | Daniel Nauzet Salazar Jorge  
| Engineer of Development Group | Signed in the original copy |
| | Jose Antonio Rodríguez  
| Engineer of Development Group | Signed in the original copy |
| | Himar Viera  
| | Signed in the original copy |
| | Daniel Nauzet Salazar Jorge  
| | Signed in the original copy |

| Revised by |  |
| Approved by | Germán Prieto  
| Engineer of Development Group | Signed in the original copy |
| | Javier Castro  
| Head of Development Group | Signed in the original copy |

| Authorized by | Romano Corradi  
| General Director | Signed in the original copy |

Date: 22/06/2017
Changes record

<table>
<thead>
<tr>
<th>Issue</th>
<th>Date</th>
<th>Section</th>
<th>Change Code</th>
<th>Change Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.A</td>
<td>22/06/17</td>
<td>All</td>
<td>All</td>
<td>First version</td>
</tr>
</tbody>
</table>


Applicable documents

<table>
<thead>
<tr>
<th>N°</th>
<th>Document name</th>
<th>Code</th>
<th>Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Cassegrain Set (CG-Set) Specifications</td>
<td>ESP/TELE/0216-R</td>
<td>1.A</td>
</tr>
<tr>
<td>A2</td>
<td>CG-Set Interface Requirements</td>
<td>DCI/TELE/0061-R</td>
<td>1.A</td>
</tr>
<tr>
<td>A3</td>
<td>CG-Set – Science Instrument Interface</td>
<td>DCI/TELE/0062-R</td>
<td>1.A</td>
</tr>
<tr>
<td>A4</td>
<td>Cassegrain Focal Station Envelopes</td>
<td>DR/GTC/002</td>
<td>1.H</td>
</tr>
<tr>
<td>A5</td>
<td>Cassegrain Rotator – Telescope Tube</td>
<td>DR/I-TL-TL-001/000</td>
<td>1.A</td>
</tr>
<tr>
<td>A6</td>
<td>Cassegrain Instrument Rotator – Instrumentation Interface flange</td>
<td>DR/I-IN-TL-002/000</td>
<td>1.A</td>
</tr>
<tr>
<td>A7</td>
<td>AG Instrument – Probe Arm Linear Stage</td>
<td>DR/I-AG-AG-017/000</td>
<td>1.A</td>
</tr>
<tr>
<td>A8</td>
<td>AG Pick-Off Mirror unit – Probe Arm</td>
<td>DR/I-AG-AG-018/000</td>
<td>1.A</td>
</tr>
<tr>
<td>A9</td>
<td>CG-Set – Cassegrain lifting system</td>
<td>DR/I-SE-TL-013/000</td>
<td>1.A</td>
</tr>
<tr>
<td>A10</td>
<td>Science Instrument – Cassegrain Transportation Cart</td>
<td>DR/I-IN-SE-002/002</td>
<td>1.A</td>
</tr>
</tbody>
</table>

Reference documents

<table>
<thead>
<tr>
<th>N°</th>
<th>Document name</th>
<th>Code</th>
<th>Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 1</td>
<td>Cassegrain Rotator with AG Assembly</td>
<td>DR/TL-IR-CG/000</td>
<td>1.A</td>
</tr>
</tbody>
</table>
# Configuration elements

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL-IR-CG</td>
<td>Cassegrain Instrument Rotator</td>
</tr>
<tr>
<td>AG-CG-AG-200</td>
<td>AG Mechanics Assembly</td>
</tr>
<tr>
<td>CS-IS-CG</td>
<td>Cassegrain Local ISS</td>
</tr>
<tr>
<td>CS-AS-CG-200</td>
<td>Cass. Local Control</td>
</tr>
<tr>
<td>CS-EC-PC-202</td>
<td>Cassegrain Electronics Enclosure</td>
</tr>
<tr>
<td>SE-CG</td>
<td>Cassegrain Support Elements</td>
</tr>
</tbody>
</table>

## Interface elements (only dci’s)

<table>
<thead>
<tr>
<th>Code</th>
<th>Element 1</th>
<th>Element 2</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Acronyms list

AG  Acquisition and Guiding
CG-Set  Set formed by the Cassegrain Instrument rotator, AG-Mechanics, Electronics Cabinet and Support Elements
COG  Centre Of Gravity
EMC  Electromagnetic Compatibility
FE  Finite Elements
FEM  Finite Elements Model
FMECA  Failure Modes Effects and Criticality Analysis
FOV  Field of View
GCS  GTC Control System
GTC  Gran Telescopio Canarias
HMI  Human-Machine Interface
ISS  Interlock and Safety System
LCU  Local Control Unit
LISS  Local Interlock and Safety System
MPMNT  Mean Preventive Maintenance Night-Time
MPMDT  Mean Preventive Maintenance Day-Time
MTBF  Mean Time between Failures
MTTR  Mean Time to repair
M1  Primary Mirror
M2  Secondary Mirror
M3  Tertiary Mirror
PLC  Programmable Logic Controller
POM  Pick-Off Mirror
RAMS  Reliability, Availability, Maintainability and Safety
RCCB  Residual Current Circuit Breaker
RMS  Root Mean Square
TBC  To Be Confirmed
TBD  To Be Defined
CONTENTS

Applicable documents ................................................................. 4
Reference documents ................................................................ 4
Configuration elements .............................................................. 5
Interface elements (only dci’s) .................................................... 5
Acronyms list ............................................................................ 6
CONTENTS .................................................................................. 7
1 INTRODUCTION ...................................................................... 13
2 SCOPE .................................................................................... 16
3 DEFINITIONS .......................................................................... 16
  3.1 CONCEPTS ......................................................................... 16
    3.1.1 Telescope Tube .............................................................. 16
    3.1.2 Science Instrument ....................................................... 16
    3.1.3 AG Instrument ............................................................ 17
    3.1.4 Pick-Off Mirror (POM) Unit ......................................... 17
    3.1.5 AG Mechanics ............................................................. 17
    3.1.6 Rotator (or Instrument Rotator) .................................... 17
    3.1.7 Electronics Enclosure (and Cabinet) ............................. 17
    3.1.8 Cassegrain Set (CG-Set) ............................................... 17
    3.1.9 Mean Preventive Maintenance Night-Time (MPMNT) ...... 17
    3.1.10 Mean Time between Failures (MTBF) .......................... 17
    3.1.11 Mean Time to Repair (MTTR) ...................................... 18
  3.2 COORDINATE SYSTEMS AND REFERENCES ..................... 18
    3.2.1 Elevation Axis .............................................................. 18
    3.2.2 Tube Axis .................................................................... 18
    3.2.3 GTC optical axis .......................................................... 18
    3.2.4 AG optical axis ............................................................ 18
    3.2.5 Cassegrain Coordinate System ..................................... 18
    3.2.6 Pupil ............................................................................ 19
3.2.7  Science Instrument Coordinate System .......................................... 19
3.2.8  AG Instrument Coordinate System ................................................... 19
3.2.9  Virtual AG Instrument Coordinate System ......................................... 20
3.2.10 Understanding Co-ordinate systems and geometric constraints ............ 20
4  MECHANICAL DESIGN ........................................................................... 24
  4.1  INTRODUCTION ................................................................................. 24
  4.2  INSTRUMENT ROTATOR .................................................................... 26
        4.2.1  Bearing and Structure ................................................................. 26
                    4.2.1.1 Instrument Attachment Flange ................................................. 28
                    4.2.1.2 AG Attachment Flange .......................................................... 29
                    4.2.1.3 Bearing Stiffness ................................................................. 29
                    4.2.1.4 Bearing Friction ................................................................. 29
                    4.2.1.5 Rotator Attachment ............................................................. 31
        4.2.2  Rotator Motor ............................................................................. 33
                    4.2.2.1 General ............................................................................ 33
                    4.2.2.2 Estimated torque requirement ............................................... 35
                    4.2.2.3 Cooling .............................................................................. 36
                    4.2.2.4 Mounting ........................................................................... 37
                    4.2.2.5 Protection .......................................................................... 37
        4.2.3  Encoder ...................................................................................... 37
                    4.2.3.1 Interface ............................................................................ 39
                    4.2.3.2 Homing .............................................................................. 39
                    4.2.3.3 Maintenance .................................................................... 40
                    4.2.3.4 Protection .......................................................................... 40
        4.2.4  Brake ......................................................................................... 40
                    4.2.4.1 Required Braking Torque ...................................................... 41
                    4.2.4.2 Required Calliper Number .................................................... 43
        4.2.5  Limits .......................................................................................... 44
                    4.2.5.1 Limit Switches .................................................................... 44
                    4.2.5.2 Hydraulic Shock Absorbers ................................................. 45
        4.2.6  Cable Rotator .............................................................................. 46
4.2.7  Counterweighting .............................................................................. 46
4.3  AG MECHANICS ....................................................................................... 46
4.3.1  Probe Arm ............................................................................................. 49
4.3.2  Arm Rotator .......................................................................................... 51
4.3.3  Turn Table ............................................................................................ 52
  4.3.3.1  Encoder ............................................................................................ 53
  4.3.3.2  Bearing ............................................................................................. 53
  4.3.3.3  Motors .............................................................................................. 54
  4.3.3.4  Structure .......................................................................................... 55
  4.3.3.5  Limits ................................................................................................ 56
4.3.4  Main Structure ...................................................................................... 56
4.3.5  Cable Rotator ......................................................................................... 58
4.4  CABLES AND HOSES ........................................................................... 59
4.5  SUPPORT ELEMENTS ........................................................................... 60
  4.5.1  Science Instrument Dummy ................................................................ 60
  4.5.2  Transport Cart ..................................................................................... 60
4.6  FE-ANALYSIS ............................................................................................ 60
  4.6.1  Simplified Bearings with conventional section .................................. 61
    4.6.1.1  Analysis Object .............................................................................. 61
    4.6.1.2  Model – Nasmyth Bearing ............................................................ 61
    4.6.1.3  Results – Nasmyth Bearing ........................................................... 64
    4.6.1.4  Model – Cassegrain Bearing with conventional section ............. 67
    4.6.1.5  Results – Cassegrain Bearing with conventional Section ........... 68
  4.6.2  Cassegrain Bearing with Customized Section – Rotator Attachment to Telescope ..... 69
    4.6.2.1  Analysis Object .............................................................................. 69
    4.6.2.2  Model – Cassegrain Bearing with customized Section ................ 69
    4.6.2.3  Results – Cassegrain Bearing with customized Section ................ 69
    4.6.2.4  Model – Cassegrain Rotator on Telescope Interface Flange ........... 71
    4.6.2.5  Results – Cassegrain Rotator on Telescope Interface Flange ........... 73
  4.6.3  Cassegrain Rotator and AG-Mechanics ............................................. 77
    4.6.3.1  Analysis Object .............................................................................. 77
4.6.3.2 Model – Cassegrain Rotator and AG -Mechanics .......................................................... 77
4.6.3.3 Results – Cassegrain Rotator and AG -Mechanics ......................................................... 83

4.6.4 Eigen-Frequencies .............................................................................................................. 89
4.6.4.1 Analysis Object .............................................................................................................. 89
4.6.4.2 Model ............................................................................................................................. 89
4.6.4.3 Results ............................................................................................................................ 89

4.6.5 Analysis Main Conclusions .............................................................................................. 93

4.7 ELECTRONICS ENCLOSURE .............................................................................................. 93
4.7.1 General ............................................................................................................................. 93
4.7.2 Frame ............................................................................................................................... 93
4.7.3 Attachment to the Telescope ............................................................................................. 94
4.7.4 Wall Panels ....................................................................................................................... 95
4.7.5 Connections ...................................................................................................................... 98
4.7.6 Cooling system .................................................................................................................. 98
4.7.7 Moisture control ............................................................................................................... 100

4.8 MECHANICAL INTERFACES .............................................................................................. 100

4.9 3D MODEL .......................................................................................................................... 100

5 CONTROL ARQUITECTURE .................................................................................................. 107
5.1 GC-SET LOCAL CONTROL SYSTEM SCOPE .................................................................... 107
5.2 DESCRIPTION ......................................................................................................................... 107
5.3 JUSTIFICATION ..................................................................................................................... 109
5.4 INTERFACES ........................................................................................................................ 110

6 LOCAL INTERLOCK & SAFETY SYSTEM .............................................................................. 112

7 ELECTRICAL AND ELECTRONICS DESIGN .................................................................. 113
7.1 GENERAL ............................................................................................................................ 113
7.2 ELECTRONIC CABINET ....................................................................................................... 114

8 LOGISTIC SUPPORT .............................................................................................................. 116
8.1 ASSEMBLY .......................................................................................................................... 116
8.2 VERIFICATION ...................................................................................................................... 116
8.3 HANDLING .......................................................................................................................... 116
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4</td>
<td>Storage, Packaging and Transportation</td>
</tr>
<tr>
<td>8.5</td>
<td>Integration at the GTC</td>
</tr>
<tr>
<td>8.5.1</td>
<td>Rotator Mounting in the Telescope Structure</td>
</tr>
<tr>
<td>8.5.2</td>
<td>Alignment</td>
</tr>
<tr>
<td>8.5.2.1</td>
<td>Rotator w.r.t. Telescope Structure</td>
</tr>
<tr>
<td>8.5.2.2</td>
<td>AG Instrument w.r.t. Rotator Axis</td>
</tr>
<tr>
<td>8.6</td>
<td>Safety</td>
</tr>
<tr>
<td>8.7</td>
<td>Reliability</td>
</tr>
<tr>
<td>8.8</td>
<td>Maintainability</td>
</tr>
<tr>
<td>9</td>
<td>System Budgets</td>
</tr>
<tr>
<td>9.1</td>
<td>Error Budget</td>
</tr>
<tr>
<td>9.1.1</td>
<td>Relative Pupil Error (Science and AG-Instrument relative orientation towards the pupil)</td>
</tr>
<tr>
<td>9.1.1.1</td>
<td>Relative orientation Error due to Gravity</td>
</tr>
<tr>
<td>9.1.1.2</td>
<td>Relative orientation error due to Fabrication and Mounting Errors</td>
</tr>
<tr>
<td>9.1.1.3</td>
<td>Total Relative Pupil Error. Conclusions</td>
</tr>
<tr>
<td>9.1.2</td>
<td>Absolute Pupil Error (Science Instrument orientation towards the pupil)</td>
</tr>
<tr>
<td>9.1.2.1</td>
<td>Absolute orientation error due to Gravity</td>
</tr>
<tr>
<td>9.1.2.2</td>
<td>Absolute orientation error due to Fabrication and Mounting Errors</td>
</tr>
<tr>
<td>9.1.2.3</td>
<td>Total Absolute Pupil Error. Conclusions</td>
</tr>
<tr>
<td>9.1.3</td>
<td>Positioning Errors (AG Instrument relative to Science Instrument)</td>
</tr>
<tr>
<td>9.1.3.1</td>
<td>Lateral Positioning Error</td>
</tr>
<tr>
<td>9.1.3.2</td>
<td>Axial Positioning Error</td>
</tr>
<tr>
<td>9.1.3.3</td>
<td>Conclusions</td>
</tr>
<tr>
<td>9.1.4</td>
<td>Position stability (AG Instrument relative to Science Instrument)</td>
</tr>
<tr>
<td>9.1.4.1</td>
<td>Lateral Position Stability</td>
</tr>
<tr>
<td>9.1.4.2</td>
<td>Axial Position Stability</td>
</tr>
<tr>
<td>9.1.4.3</td>
<td>Conclusions</td>
</tr>
<tr>
<td>9.2</td>
<td>Mass Budget</td>
</tr>
<tr>
<td>9.3</td>
<td>Electrical Power</td>
</tr>
<tr>
<td>9.4</td>
<td>Thermal Dissipation</td>
</tr>
</tbody>
</table>
10 COMMERCIAL COMPONENTS LIST ................................................................. 144
11 ANNEXES .................................................................................................... 146
1 INTRODUCTION

The Gran Telescopio de Canarias (GTC) is a large optical Telescope with an Alt-azimuth Mount, i.e. one vertical rotating axis (Azimuth Axis) and one horizontal rotating axis (Elevation Axis). See Fig. 1. The Azimuth axis rotates the whole Telescope (Tube and Mount) with regard to the ground. The Elevation Axis rotates the Telescope Tube with regard to the Telescope Mount from the Horizon to the Zenit, i.e. 90°.

The light coming from the stars is reflected on a 10m Primary Mirror, then on a Secondary Mirror, and then to several Focal Stations in different locations on the Telescope by means of different mirrors. Science Instruments are attached and integrated into these focal stations and receive the light gathered by the Telescope.

The Telescope rotates around the mentioned Azimuth and Elevation axes in order to point to the desired angle in the sky placing the image of the target star or celestial object on the Science Instrument detector. The Instrument Rotator, keeps the optical field in the same orienta-
tion as the Earth rotates. The Acquisition and Guiding (AG) Instrument, is an auxiliary instrument used to get the input needed to point to a reference star and guide the Telescope to follow any movement of the image during the observation. It gets also some information on the optical beam used to make real time corrections in the optics of the Telescope. All the previous is needed in order to get the image still and sharp in the Scientific Instrument detector though hours for one single observation.

The AG System consists of a small optical Instrument (AG Instrument) and the AG Mechanics moving and supporting it.

The Science Instrument Rotator, the AG Mechanics of the Cassegrain Focal Station and the corresponding Electronics Cabinet are located at the bottom of the Primary Mirror Cell, in the Telescope Tube. This is called the CG-Set or Cassegrain Set (the complete CG-Set includes the Support Elements as well). See Fig. 2 through Fig. 4. It is grouped in 2 modules:

- Rotator + AG Mechanics
- Electronics Cabinet

These modules are attached to the Primary Mirror Cell structure. Fig. 3 shows the Telescope Structure and other equipment close to the CG-Set constraining the available space for the CG-Set and the access to it.

![Fig. 2 - 3D section of the Primary Mirror Cell showing the Instrument Rotator](image)
Fig. 3 - Detailed cross section of the Primary Mirror Cell

Fig. 4 - Cassegrain Focus envelopes
The Rotator penetrates partially in the Primary Mirror Cell structure. On top of the Rotator the ICM (Instrument Calibration Module) is found. This is a system with 2 possible positions (parking and operation). A lifting system is foreseen in this structure to lift the Rotator and the Scientific Instrument up to the Telescope by means of three hoists.

2 SCOPE

This document describes the preliminary design of the CG-Set, including:

- Instrument Rotator
- AG Mechanics
- Electronics Cabinet (Enclosure + Local Control System HW and SW)
- Support Elements

The GC-Set Product Tree and some of the GTC elements interfacing with it are shown in a tree shape in A1.

The AG instrument and the Pick-off Mirror (which picks and folds the optical beam towards the AG instrument) are out of scope of this document.

This preliminary design has been worked out in the frame of the Tender for the procurement of the CG-Set. Its aim is to give an answer to the main design issues and to demonstrate requirements fulfilment feasibility. It is encouraged to follow the design choices in this document although compliance with it is not mandatory.

Open design issues, if any, are identified through the next sections.

3 DEFINITIONS

3.1 Concepts

3.1.1 Telescope Tube

Is the structural part of the GTC Telescope supporting the Primary Mirror (M1) and Secondary Mirror (M2) as well as the Cassegrain and Folded Cassegrain focal stations. The Telescope Tube interfaces the CG-Set at the Instrument Rotator flange. For the purpose of this specification the Telescope Tube shall be considered a rigid body, as well as its interface flange with the Instrument Rotator.

3.1.2 Science Instrument

Optical Instrument designed to be attached to one of the GTC focal stations and gather astronomical data from celestial targets with Science purposes. The Science Instrument is Out of Scope of this specification. The Telescope Tube interfaces the CG-Set at the Science Instrument flange. For the purpose of this specification the Science Instrument shall be considered as a mass connected to the Science Instrument interface flange of the Instrument Rotator but it will not introduce any stiffness to that flange.
3.1.3 **AG Instrument**

Optical Instrument designed to support astronomical observations with Science Instruments. It consists in an optomechanical assembly and an electronic detector. The AG Instrument is Out of Scope of this specification. The AG Instrument interfaces the CG-Set at the linear stage surface in the Probe Arm. For the purpose of this specification the AG Instrument shall be considered a rigid body with a mass as specified.

3.1.4 **Pick-Off Mirror (POM) Unit**

The POM is a flat mirror used to derive a small field of the GTC light beam to the AG Instrument (3.1). The POM Unit consist on the POM and its mount and interface. The POM Unit is Out of Scope of this specification. The POM unit interfaces the CG-Set at the flange in the Probe Arm end.

3.1.5 **AG Mechanics**

Machine supporting the AG Instrument and Pick-Off Mirror and placing these in the desired place in the optical field of the GTC.

3.1.6 **Rotator (or Instrument Rotator)**

Machine supporting the Science Instrument and the AG Mechanics and rotating these to follow the Earth rotation.

3.1.7 **Electronics Enclosure (and Cabinet)**

The Electronics *Enclosure* includes the thermal and structural envelope and its cooling system, but not the GC-Set electronics inside.

In terms of configuration management, the electronics for the Instrument Rotator is included in the “Instrument Rotator” and the electronics for the AG mechanics is included in the “AG mechanics”.

The Electronics *Cabinet* refers to the *Enclosure* plus the *Electronics* inside.

Sometimes is necessary or useful to refer to the “Cabinet” as a physical unit.

3.1.8 **Cassegrain Set (CG-Set)**

Consists of the Instrument Rotator, AG Mechanics, Electronics Cabinet (including Local Control HW and SW) and Support Elements

3.1.9 **Mean Preventive Maintenance Night-Time (MPMNT)**

The MPMNT is the night-time per year that the system is not available for operation due to planned (preventive) maintenance tasks.

3.1.10 **Mean Time between Failures (MTBF)**

The MTBF for a system is the mean time between two consecutive failures of the system.
3.1.11 **Mean Time to Repair (MTTR)**

The MTTR for a system is the mean time spent in unplanned (corrective) maintenance to repair the system.

3.2 **Coordinate Systems and references**

3.2.1 **Elevation Axis**

Rotation axis of the Telescope Tube (3.1.1). There are physical references at the Telescope defining this axis.

3.2.2 **Tube Axis**

The Tube Axis is the axis of symmetry of the Telescope Tube (3.1.1). It is perpendicular to the Elevation Axis. Their intersection is the origin of the GTC Co-ordinate System. There are physical references at the Telescope defining this axis.

3.2.3 **GTC optical axis**

It is the optical axis of the GTC optics (Primary and Secondary mirrors). Nominally coinciding with the Tube axis.

3.2.4 **AG optical axis**

It is the optical axis of the AG Instrument Optics.

3.2.5 **Cassegrain Coordinate System**

A coordinate system defined as follows (see Fig. 5):

- Origin at the Cassegrain focus of the telescope (in the Tube Axis, 7400 mm “bellow” the Elevation Axis).
- X-Axis is parallel to the Elevation Axis and points towards the Nasmyth A platform.
- Z-axis in the direction of the Tube Axis towards the secondary mirror (M2).
- Y-Axis forms a right-handed coordinate system with the two previous.
The Cassegrain Coordinate System rotates with the Telescope Tube around the Elevation Axis (see 3.1.1).

3.2.6 **Pupil**

As a geometrical reference, the nominal Pupil Plane is fixed to the Telescope Tube, perpendicular to the Cassegrain Z axis, located at \( z = 18139.41 \) mm from the Cassegrain origin. It is taken as reference to define some features of the CG-Set.

3.2.7 **Science Instrument Coordinate System**

Theoretically coincides with the Cassegrain Coordinate System (see 0). In fact, it is subject to small displacements and rotations caused by gravitational deformations and fabrication and mounting errors, taking a different position and orientation from the Cassegrain Coordinate System. The mentioned displacements and rotations are defined by the rigid body motions of the instrument attachment flange.

3.2.8 **AG Instrument Coordinate System**

A coordinate system defined by physical references in the AG Instrument (out of scope) as follows:

- The origin is the centre of the AG Instrument aperture stop.
- The Z-axis runs in direction of the optical axis of the AG Instrument Optics against the incoming light.

*Fig. 5- Detail of the Cassegrain coordinate system*
- The Y-axis is perpendicular to the interface plane between the AG Instrument and the Focusing Mechanism, positive sense of Y-axis going away from the base plate.

- The X-axis forms a right-handed system with the two previous.

It depends therefore exclusively on the position and orientation of physical AG parts, rather than on the incoming light axes.

For practical purposes, the AG Instrument shall be considered rigid and therefore its co-ordinate system can be considered as part of the linear stage focus system in the AG Probe Arm. The relative position of the linear stage and the AG Coordinate System can be seen at drawing DR/I-AG-AG-017/000.

### 3.2.9 Virtual AG Instrument Coordinate System

Is the virtual co-ordinate system obtained by reflection of the AG Instrument Coordinate System (3.1) in the Pick-Off Mirror of the Probe Arm, i.e. it is where the AG Instrument Coordinate System as seen from the Cassegrain Focal Plane (see 3.2.10 Understanding Co-ordinate systems and geometric constraints).

The origins and Z-axes of the Virtual AG Instrument Coordinate System and the Cassegrain Coordinate System coincide when the POM is placed at the centre of the field of view, assuming nominal ideal conditions (no gravity, fabrication and alignment errors).

### 3.2.10 Understanding Co-ordinate systems and geometric constraints

The main references for the design are the Cassegrain Co-ordinates System (3.2.3) and the Pupil (3.2.6). These are fixed to the Telescope Tube, considered rigid for the purposes of this specification.

The nominal Science Instrument Co-ordinate System (3.2.7) is located at the centre of the Instrument focal plane\(^1\) and coincides with the Cassegrain Co-ordinates System.

The aim of the AG Instrument is to scan the Scientific Instrument focal plane. But the AG Instrument cannot by placed directly at the Instrument focal plane. Therefore, the AG optical beam must be folded by a pick-Off Mirror and taken to the AG Instrument in a different position. The AG Instrument Co-ordinate System (3.2.8) represents the actual position of the AG Instrument. The Virtual AG Instrument Coordinate System (3.2.9) represents the position where the AG Instrument “should” be on the Scientific Instrument focal plane. See Fig. 6.

---

\(^1\) Actually, the focal Surface is spherical rather than plane
Requirement RQ/AG-CG-AG-200/¡Error! No se encuentra el origen de la referencia. (Probe Arm rotation axis passing through the Exit Pupil centre) constrains the movement of the Virtual AG Instrument origin to a sphere with the centre in the Pupil and passing through the Scientific Instrument Origin. Since the radius of this sphere is different from the radius of the so called Scientific Instrument “Focal Plane”, a focusing mechanism is needed to scan exactly the Scientific Instrument “Focal Plane”. See Fig. 7
It is not necessary to constrain completely the position of the POM and AG Instrument. The parameters $d$, $\beta$, and $\mu$ in Fig. 8 may vary as long as other requirements are fulfilled. Nevertheless, these parameters have been assigned a nominal value in the preliminary design with the criteria of minimizing the shadow of the Arm over the Scientific Instrument and minimizing the size of the whole system.
Finally, Virtual AG Instrument Coordinate System and Science Instrument Co-ordinate System may deviate from their nominal positions under different gravity orientation, load, temperature, mechanisms position, etc... Some performance requirements hereafter constraint the deviations of these co-ordinate systems from their nominal position within certain limits.
4 MECHANICAL DESIGN

4.1 Introduction

The mechanics of the Cassegrain Set is divided in two main assemblies, one for instrument rotation and the other one for Acquisition and Guiding (AG). Each of these assemblies has different functional components which will be described in the following sections, indicating the most important aspects to be further developed during the subsequent design phases.

Fig. 9 - Cassegrain Rotator, top 3D general view

Fig. 10 - Cassegrain Rotator, bottom 3D general view
Rotator & AG Mechanics Assembly General Characteristics

- External diameter: 2660 mm
- Internal diameter: 780 mm
- Height: 750 mm
- Rotator-unit weight: 1540 kg
- AG-Unit weight: 980 kg
- Total Weight: 2520 kg

The preliminary design 3D model is available. See section 11.

The complete component list for this preliminary design is referred in section 11. This list has to be kept up to date through the design process.

Open Design Issues

- The preliminary design does not comply with the established maximum mass of 2400 kg. The weight should be optimized considering, among others, requirements that are affected by gravitational deformations.
- Component list in section 11 shall be updated and reviewed for completeness and coherence with 3D model, Product Tree, Drawings codes and commercial components references.
4.2 Instrument Rotator

The purpose of the instrument rotator is, as the name says, to rotate the scientific instrument on the Cassegrain focal station. Unlike other focal stations on the GTC, the rotator will not provide general supplies (water, power, air) for the scientific instrument. This must be done by a specific external cable rotator supplied together with the corresponding instrument.

The main components of the rotator are the bearing, which functions as structure at the same time, the direct drive, as well as encoder, brake and limits.

Fig. 12 - Rotator mechanics without AG -Unit

4.2.1 Bearing and Structure

The preliminary design of the instrument rotator is based on a custom made cross roller bearing, manufactured with the required interfaces to be mounted onto the nucleus of the primary mirror cell (PMC), and for carrying the scientific instrument, the AG system and the different subsystems of the rotator. In this way, the bearing provides structural consistence to the system working as static structure, rotating structure and subsystems support.

The principal subsystems integrated on the bearing are the rotator drive and the encoder. The rotator drive is a segmented direct drive motor with the winding segments fixed to the static bearing ring and the permanent magnets fixed to the rotating bearing ring. The same concept is chosen for the encoder with the scanning heads on the static part and the scale tape on the
rotating part. Besides, the supports for brake callipers, switches and end dampers are attached to the bearing.

Because of all that functionality the bearing section is completely adapted to the environment. Rothe Erde manufactures these type of bearing with custom sections and is the principal manufacturer of slewing bearings mounted in other subsystems of the telescopes.

The shape of the bearing section is constrained by:

- the required envelopes
- the dimension of the mounting flange on the primary mirror cell
- the position and shape of the instrument flange
- the design of the AG system and
- the dimension of the rotator drive.

In case that it would not be possible to manufacture a bearing with the required section, due to an elevated complexity, it would be necessary to manufacture a bearing with a standard section and the corresponding companion structures.

Due to the design conditioners, the outer ring of the bearing has a conic shape rising up into the PMC. This shape provides stiffness to the assembly, working as connecting structure between the discrete fixing points on the nucleus of the PMC and the raceway. The bearing must be placed inside the PMC since there is no space on the outside which is occupied by the instrument.
The rotating ring of the bearing includes the interface flanges for mounting the Science Instrument and the AG system, and the interface for the permanent magnets of the drive and the scale tape of the encoder.

**Important note:** The interface flange for the rotator on the PMC is quite weak in almost all the perimeter. The stiffness is mostly provided by the six principal structure nodes surrounding the flange.

### Bearing General Characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>cross roller, preloaded and sealed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>2660 mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>2000 mm</td>
</tr>
<tr>
<td>Height</td>
<td>352 mm</td>
</tr>
<tr>
<td>Raceway diameter</td>
<td>2214 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>1100 kg</td>
</tr>
</tbody>
</table>

#### 4.2.1.1 Instrument Attachment Flange

The interface flange for the Science Instrument at the GTC is also placed inside the PMC nucleus. This position has been chosen to gain some height for the interface structure of the instrument (210 mm in case of OSIRIS²).

The instrument attachment flange has a centring diameter of 2080 mm H7 and a pattern of 36 equip-spaced M16-holes on a diameter of 2150 mm. The flange has 4 pins with conic tip to facilitate the mounting of the instrument, and 8 recesses where extraction screws find contact.

---

² In case of OSIRIS the interface structure is essential since it provides stiffness to the instrument and at the same time permits access the screws which fix the instrument to the rotator. The screws fixing OSIRIS to the interface structure are not accessible once the casing of the instrument is mounted. Because of that, the instrument is mounted to the rotator together with the interface structure and only to that screws access is required.
4.2.1.2 AG Attachment Flange

The mounting flange of the AG system has a diameter of 2060 mm H7 and a pattern of 36 equip-spaced M12-holes on a diameter of 2030 mm. This flange also has 4 pins with conic tip to facilitate the mounting of the AG system, and 8 recesses where extraction screws find contact.

4.2.1.3 Bearing Stiffness

The stiffness of the bearing is an important characteristic since it has direct influence on the image movements. These movements have been analysed by means of a FE model for vertical and horizontal tube position (see 4.6), as well as for different rotation angles of the rotator.

The results show a pupil movement of about 1mm due to the flexibility of the bearing which is a reasonable value considering a maximum permissible pupil movement of 5.9mm, and that other error sources will intervene like fabrication errors, alignment errors, bearing runout and wobble, etc.

For detailed description of the analysis and the results see chapter 9.1.

4.2.1.4 Bearing Friction

The bearings of Nasmyth rotators have a raceway diameter of about 2825 mm with a friction moment of 668,9Nm (A) and 713,9Nm (B), measured without load. The dynamic idle load indicated by the manufacturer was 304 and 331Nm (with 60x10kN load).
The race way diameter of the Cassegrain rotator bearing is 2214 mm. Scaling the friction moment over the diameter a value of about 540 Nm is obtained. However, for preliminary calculations a value of 700 Nm can be taken (more conservative respect to the required motor torque, less conservative for the required brake torque).

The load on the rotator due to the Science Instrument causes an additional friction torque which can be calculated with the equation, shown farther down, indicated by Rothe Erde. The obtained friction torque is an approximation and can be 25% higher. Additionally, the starting friction torque can increase the friction torque in up to 20%.

\[ M_r = \frac{\mu}{2} \cdot \left( 4,1 \cdot M_k + D_L \cdot (F_a + 2,05 \cdot F_r) \right) \]

\[ M_r = 400 \text{ Nm} \]

- Mr: Friction Moment due to load
- Mk: Bending Moment (0,668 m \cdot 2800 kg \cdot 9,81 m/s^2)
- Fa: Axial Load (-)
- Fr: Radial Load (2800 kg \cdot 9,81 m/s^2)
- DL: Nominal bearing diameter (2,214 m)
- \( \mu \): Friction coefficient (indicated by Rothe Erde with 0,004 for the RD 800 series)

The maximum friction torque can be estimated in:

\[ M_{\text{max}} = 1,2 \cdot (M_i + 1,25 \cdot M_r) \]

\[ M_{\text{max}} = 1440 \text{ Nm} \]

- Mi: Idle friction torque mounted in the rotator structure (700 Nm)
- Mr: Friction Moment (400 Nm)

For preliminary calculations, a total maximum bearing friction torque of 1450 Nm is taken. This torque can be higher since the interface on the telescope structure is not an ideal companion structure. There are only 6 stiff zones close to the structure nodes of the primary mirror cell. The intermediate zones between these points have less stiffness and cannot support the rotator structure in the same way.
Open Design Issues

- Evaluate a possible negative effect on the bearing friction torque or life-span due to the irregular stiffness of the interface of the telescope structure, and due to low number of load points of the Science Instrument.
- Possible negative effects of the shape of inner ring and outer ring on the bearing friction and local raceway loads, due to a thin structure with large diameter.
- The re-greasing of the bearing should be done automatic- or semi-automatically. The idea is to install a greasing unit that, together with a determined motion sequence of the rotator axis (and simultaneously the turn table axis), re-greases the bearings by demand. This maintenance task should be started only in local mode forcing the supervision by an operator. Besides, the exit of the grease should be defined in such a way that it can be removed easily, by means of a lower preload of one of the sealing lips and access apertures or by exit channels.

4.2.1.5 Rotator Attachment

Based on the results of the FE analysis the attachment of the rotator to the PMC is defined by means of 48 bolts of the existing pattern of 90, corresponding to 18 contact zones instead of the 12 analysed zones. At each of the 6 principal structure nodes 4 bolts will be placed and 2 bolts at each of the intermediate stiffener plates of the attachment flange of the nucleus of the PMC. In these zones calibrated adjustment plates are placed between rotator and attachment flange in order to provide the possibility of alignment of the rotator in axial direction (piston) and orientation (tip-tilt), independently of the state of the attachment flange.

![Attachment Flanges on rotating part.](image-url)
Attachment of the Science Instrument Cable Rotator and other non-rotating parts

There is the possibility to use countersunk screws as attachment bolts for mounting the rotator to the PMC, creating in this way a completely flat mounting surface for attaching static parts of the Scientific Instrument. In this case, the effect of the countersink drills on the stiffness of the flange should be analysed.

**NOTE. The Instrument Cable Rotator is out of scope of the GC-Set Tender. The paragraphs below are included as additional information.**

In case of the cable rotator for the Science Instrument), it is difficult to foreseen the needs for all possible instruments which could be developed for being installed on the Cassegrain focal station. Besides, the needs for access to the different parts of the instruments are also unpredictable. Because of that, it is proposed to not install a general cable rotator for the instruments. Instead, each instrument shall bring its own cable rotator adapted to their needs.

In case of OSIRIS which has its electronic cabinets hanging on the proper instrument, the needs for cabling between the static part and the rotating part are contained. The proposed design for this case is based on a cable rotator like that one proposed for the AG -System, located around the instrument in such a way that it does not disturb the access for maintenance. Due to the reduced number of cables to rotate in this case, the section of the cable chains will be similar to that one of the AG cable chains. Making easier the mounting of the cable rotator, the slot structure could be fabricated in segments, so that the cable rotator can be installed once the instrument is mounted on the focal station. The last step would be the installation of the cable chains and the intermediate roller structure.

On the mounting flange of the rotator to the PMC, threaded holes are foreseen (36 holes M16 equispaced on a diameter of 2630 mm) allowing the attachment of the static part of the cable rotator of the instrument. These holes also could be used to attach a scientific instrument that does not need field de-rotation.
4.2.2 Rotator Motor

4.2.2.1 General

The selected rotator drive is a commercial direct motor from IDAM available with a nominal rotor diameter of 2150 mm. For these dimensions, the manufacturer offers different rotor heights varying the required torque but does not offer variations in diameter.

In case of requiring a different rotor diameter a custom solution has to be chosen such as offered by PHASE MOTION which develops custom torque motors as per specified dimensions.

The motor selected for the preliminary design is an IDAM RI11-3P-2150x175-HD1 (see datasheets referred in section 11). This motor consists of a permanent magnet ring with a diameter of 2150 mm and a height of 175 mm and a segmented stator composed by 14 winding section covering the full circumference.
Optionally it could be considered to fabricate the rotor as an integral part of the bearing, gluing the permanent magnets directly to the rotating ring. However, the manufacturer recommends fabricating the rotor as an independent component to screw onto the bearing, facilitating the fabrication and allowing the dismantling in case of any possible damage of the rotor or the bearing.

The stator is segmented being an important advantage during maintenance allowing the exchange of windings in case of damage without dismantling the rotator, like in case of the Nasmyth rotators.

<table>
<thead>
<tr>
<th>Magnet Height</th>
<th>[mm]</th>
<th>200</th>
<th>100</th>
<th>50</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Torque</td>
<td>[Nm]</td>
<td>73000</td>
<td>36500</td>
<td>18250</td>
<td>9125</td>
</tr>
<tr>
<td>Mnk (with cooling)</td>
<td>[Nm]</td>
<td>56000</td>
<td>28000</td>
<td>14000</td>
<td>7000</td>
</tr>
<tr>
<td>Mn (without cooling)</td>
<td>[Nm]</td>
<td>27000</td>
<td>13500</td>
<td>6750</td>
<td>3375</td>
</tr>
</tbody>
</table>

*Table 1 Resulting torque values for different motor heights at nominal air gap diameter of 2 m and windings on the complete circumference, indicated by the manufacturer.*

Additionally, it is possible not to install all 14 winding segments which complete the whole circumference, reducing the torque of the motor in function of the removed segments. According to the manufacturer, if only the half of the windings are mounted, it is possible to control the motor with only one amplifier, meanwhile another fraction is installed, each motor section must be controlled by its own amplifier.
An advantage of not installing windings over the whole circumference is that the free space can be used for mounting subsystems like encoder reading heads, brake callipers, limits, etc. making the design of the rotator more compact. On the other side, the cogging torque will increment from 5 Nm (14 segments) to 48 Nm (7 segments). However, the declared values for the cogging torque are smaller than the measured cogging torques of the Nasmyth rotator which are 500 Nm in case of rotator A and 350 Nm in case of rotator B (typical values declared by PHASE MOTION 18-500 Nm).

**Motor General Characteristics**

- **Model**: IDAM RI11-3P-2150x175-HD1
- **Number Winding Segments**: 7
- **Nominal Diameter**: 2150 mm
- **Air Gap**: 2 mm
- **Nominal Torque (without cooling)**: 6750 Nm

**Open Design Issues**

- Determine phase commutation procedure. The wake-and-shake type is excluded since it can fail due to a possible high unbalance of the rotator axis. Besides, possible negative effects of the knocking on the scientific instrumentation should be avoided.

**4.2.2.2 Estimated torque requirement**

- **Bearing friction**: 1450 Nm
- **Cable Rotator**: 500 Nm
- **Unbalance (maintenance)**: 1000 Nm
- **Inertia (2220 kgm², 5°/s²)**: 195 Nm
- **Total**: 3145 Nm

The proposed motor has 7 winding sections and a magnet height of 100 mm creating a nominal torque without cooling of 6750 Nm and a peak torque of 18250 Nm. The design margin to the lowest magnet height of 50 mm seems to be too small.

---

3 Nasmyth rotators 10000 Nm nominal and 24000 Nm peak torque.
4.2.2.3 Cooling

The supplied winding sections do not come with liquid cooling what does not mean a problem from a point of view of the required torque. But since the thermal management is important avoiding the degradation of the seeing, extracting the heat by liquid cooling is necessary.

To realize the cooling, it is proposed to mount cooling plates on the backside of the windings, for example LYTRON CP10GP (see technical data sheets referred in section 11). This heat exchanger could be fixed directly to the static ring of the bearing faced to the windings optimizing heat flow with thermal grease. Another possibility would be to glue the heat exchangers directly to the backside of the windings, although guarantee is lost drilling threaded holes in the stators.

Fig. 18 - Heat exchanger attached to the backside of the motor winding sections
Fig. 19 - Lytron cold plate CP10GP

The regulation of the cooling flow is realized by means of a motorized electro valve that continuously regulates the flow in function of the motor temperature indicated by the built-in PTCs. The electro valve is mounted on the rotator on the side which faces downwards when the telescope tube is in horizontal position, the same place where the hydraulic connection is located (not represented in the dimensional model). Close to the electro valve a flowmeter is installed monitoring the flow for the GTC control system.

Open Design Issues

- Calculation of the required cooling flow, extracted heat by cooling liquid and remaining heat dissipation to the telescope structure and the air.

4.2.2.4 Mounting

The interface between the motor components and the bearing must be confirmed. The possibility is desired of removing winding sections without dismantling the rotor, why an axial mounting of the winding on the rotator is proposed. In this way, it is possible to extract windings from the central maintenance platform.

4.2.2.5 Protection

To protect the exposed magnets, a protection cover is proposed avoiding the attraction of objects by the magnets or contamination of the motor components. The protection cover shall be segmented for easy handling.

4.2.3 Encoder

The proposed encoder system comes from Heidenhain, ERA series, for inner slot mounting. This type of encoder is used in other instrument rotators installed on the telescope and is also mounted on the telescope main axes. The actual model is an ERA 7400 C tape with reference marks for determining the absolute position during the initialization of the axis. The reading heads are AK ERA 7480, also mounted on the Folded Cassegrain rotators.
In a preliminary estimation based on data of other subsystems mounted in the telescope, the accuracy of the encoder has been determined in 5 arcsec with two scanning heads mounted diametrically opposed. This error can be reduced by calibration estimating the final error in about 1.3 arcsec. The repeatability is estimated in about 0.3 arcsec.

For the calibration of the encoder, additional scanning heads must be mounted, therefore additional scanning head supports could be foreseen.

However, the final configuration has to be determined in function of mounting conditions, bearing run-outs, gravitational deformations, tracking error, etc.

**Encoder General Characteristics**

<table>
<thead>
<tr>
<th>Model</th>
<th>Heidenhain ERA 7480</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Scanning Heads</td>
<td>2</td>
</tr>
</tbody>
</table>
Total Error (without calibration, est.) 5"
Total Error (with calibration, est.) 1,3"
Repeatability (estimated) 0,3"

4.2.3.1 Interface
The encoder tape is placed inside a slot which is directly machined in the rotating ring of the bearing. The reading heads are mounted on supports which are attached to the static ring of the bearing between the winding sections. The supports shall allow to align the reading heads with respect to the scale tape according to the tolerances established by the manufacturer.

The final angular position of the scanning heads must be determined but probably will be in the horizontal plane when the telescope tube is in horizontal position. In vertical position, the differential motion between scanning head and scale tape could exceed the mounting tolerances established by the manufacturer.

Besides, the relative motion between scanning head and scale tape due to gravitational deformations must be analysed. In the preliminary design, a tangential relative movement of 1,7 µm between scanning head and scale tape has been determined changing the telescope tube from horizontal to vertical position with maximum Science Instrument mass. This leads to an angular error of about 0,3" but could be compensated with a second scanning head on the opposite.

4.2.3.2 Homing
In case of the Folded Cassegrain Rotators the homing procedure consists in a slow movement in a defined direction, starting from the parking position towards the homing switch. Once the homing switch is actuated, the axis inverts the moving direction searching for a reference mark on the encoder tape. In this moment, the 0-position is known by help of an off-set value, which was calculated during integration determining the centre of the range between both limit switches and the reference reading.

The disadvantage of this procedure is that it does not work well in every situation, and it is slow. Depending on the starting position, the axis could first touch a limit switch disabling the drive. An operator had to go to the control cabinet bringing back manually the axis.

An alternative could be using the reference switch (absolute switch) for the homing procedure. Since the absolute switch indicates in which half on the total range the rotator is, the initial homing movement can be programmed always towards the centre of the rotation range. Just after passing two reference marks of the encoder the absolute position can be determined using interface electronics from the Heidenhain EIB series.

Comment: There are interface electronics from Heidenhain EIB-series for connecting 1 or 2 scanning heads. The model for 2 scanning heads does not supply a usable signal if one of both scanning heads fail, but it would be an interesting option if the electronics could keep working in this case. Using two interface electronics, a mean value has to be formed out of both signals by means of additional electronics.
4.2.3.3 Maintenance
In the preliminary design the reading heads has been placed in that manner that access from
the maintenance platform is possible adjusting the reading heads or cleaning them. In the final
design phase the maintenance of the encoder shall be studied and optimized.

4.2.3.4 Protection
Both, reading heads and scale tape are protected by segmented covers in order to avoid dam-
age or contamination of the system. Removing the covers shall be possible in a straight for-
ward manner from the maintenance platform.

4.2.4 Brake
A brake for parking and emergency functions is foreseen. The type should be fail-safe, prefera-
ble mechanically actuated and pneumatically released, since compressed air is available (5
bar).

For constructional simplicity, the brake disc can be included directly into the AG -structure. In
case of dismounting the AG system the brake callipers had to be dismounted as well. This solu-
tion is acceptable since the brake is not an operational brake in which case the disc also had to
be exchangeable.

The selected brake callipers are RINGSPANN DH010FPM corresponding to the callipers chosen
for the Folded Cassegrain rotators. They are mounted on secondary supports attached to the
static part of the rotator bearing.

The number of callipers has to be determined in function of the required brake torque for inte-
gration, maintenance and emergencies, taking into account the final inherent friction of the
rotator.

Fig. 22 - Brake Calliper Ringspann DH 010 FPM – 012 M – 12
The pneumatic circuit shall contain filter, pressure regulator, electric valve, pressure indicator and flow regulator (on the release line). The pressure indicator is to control if the brake callipers really are opened, meanwhile the flow regulator is for adjusting the braking time. The brake time is of interest since the braking torque to maintain an unbalanced rotator could be too much for sensible scientific instrumentation closing the brakes at one blow.

Fig. 23 Pneumatic circuit brake.

The pneumatic components can be mounted on a separate panel inside the electronic cabinet. The advantage of that solution is a cheerful design, the cabling is maintained short and the screen light of the pressure switch has not to be obscured.

4.2.4.1 Required Braking Torque

Moment of inertia, Instrument Rotator (IR) \( 1220 \text{ kgm}^2 \)

(3D Model Preliminary Design)

Moment of inertia, Scientific Instrument (SI)\(^4\) \( 615-1000 \text{ kgm}^2 \)

\(^4\) 615 kgm\(^2\) OSIRIS, 1000 kgm\(^2\) requirement
Unbalance, Instrument Rotator (IR) 50-100 Nm  
(ESP Cassegrain)

Unbalance, Scientific Instrument (SI) 750-1000 Nm  
(DCI for instrument)

Maximum Braking Time (y minimum) 0,5-1,0 s  
(ESP Cassegrain, adjustable)

Maximum Rotation Velocity 1-10 °/s  
(ESP Cassegrain)

Rotator Bearing Friction Torque (DCI/STMA/0017-R, 5.2.6; unnormal operation conditions) 1040-1200 Nm  
(Estimation based on Nasmyth)

Cable Rotator Friction Torque 300-500 Nm  
(Estimation based on FC)

\[ \delta_{\text{min}} = \frac{\omega_{\text{max}}}{t_{\text{max}}} = \frac{10^\circ}{0,5s} \cdot \frac{\pi}{180^\circ} = 0,349 \frac{rad}{s^2} \]

Maximum required Braking Torque, considering maximum inertia and unbalance, maximum slewing speed and minimum friction:

\[ M_{\text{req}} = M_{\text{inertia}} + M_{\text{unbalance}} - M_{\text{friction}} \]

\[ M_{\text{req}} = (J_{\text{rotator}} + J_{\text{instrument}}) \cdot \delta_{\text{min}} + M_{\text{unbalance}} - M_{\text{friction}} \]

\[ M_{\text{req}} = (1220 \text{ kgm}^2 + 1000 \text{ kgm}^2) \cdot 0,349 \frac{rad}{s^2} + 1100 \text{ Nm} - 1340 \text{ Nm} \]

---

5 540 Nm to 700 Nm scaled from Nasmyth plus 1,25·400 Nm due to load. Starting torque increase is not considered.
Minimum required Braking Torque, considering foreseen inertia (OSIRIS), minimum unbalance, tracking speed, longest braking time and maximum friction:

\[ M_{req} = M_{inertia} + M_{unbalance} - M_{friction} \]

\[ M_{req} = (J_{rotator} + J_{instrument}) \cdot \delta_{min} + M_{unbalance} - M_{friction} \]

\[ M_{req} = \rightarrow 0 \text{Nm} + 100 \text{Nm} - 1700 \text{Nm} \]

\[ M_{req \ max} = 535 \text{Nm} \]

\[ M_{req \ min} = -1600 \text{Nm} \]

The calculations above have to be taken as an example.

The required brake torque varies, above all, due to friction and unbalance, but also due to the speed. Besides, the final friction torque of bearing and cable rotator is difficult to estimate, why an adjustable brake torque is desirable.

4.2.4.2 Required Calliper Number

The final number of brake callipers must be determined taking into account friction torques and unbalances, but also different operation conditions (observation, maintenance) which could require adapted brake performance.

Braking torque for one calliper:

Model: Ringspann DH 010 FPM – 012 M – 12

<table>
<thead>
<tr>
<th>Tangential Force per Calliper(^6)</th>
<th>300 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensation factor static application(^7)</td>
<td>0,5</td>
</tr>
</tbody>
</table>

\(^6\) Friction Coefficient 0,4

\(^7\) The standard brake pads are for dynamic applications why a reduction factor of 0,5 have been applied. The manufacturer RINGSPANN offers also brake pads for static applications which would be more adequate and probably had a better brake performance. For the Folded Cassegrain Rotators the standard brake pads were used
Effective Disc Radius: 0.965 m

\[ M_{\text{Brake}} = F_t \cdot r_{\text{effective}} \cdot f_{\text{static}} \]

\[ M_{\text{Brake}} = 300 \, N \cdot 0.965 \, m \cdot 0.5 \]

\[ M_{\text{Brake}} = 145 \, Nm \, (\text{brake pad option dynamic}) \]

\[ M_{\text{Brake}} = 290 \, Nm \, (\text{brake pad option static}) \]

### 4.2.5 Limits

The proposed system for the rotator axis limits is the same as in case of the Folded Cassegrain rotators, with three steps: the first limit is electronically controlled by encoder readings, the second limit is determined by electrical switches and the last one by hydraulic shock absorbers.

The electric limit switches shall be located at a certain angle (TBD) behind the electronic limits at ±270°. The shock absorbers shall be placed with sufficient distance to the electrical switches, so that the brakes are able to stop the axis, once the signal of the switches is received by the control electronics, without touching the shock absorbers. In this way, all three limit types work independently.

#### 4.2.5.1 Limit Switches

On the rotator axis, there are three electric switches, one with double lever detecting in which section of the total movement range the rotator actually is, and two switches with simple lever stopping the axis only together with the corresponding position of the double lever switch (also called absolute switch or reference switch). The switches are operated by a pin mounted on the brake disc at a certain angle outside of the nominal operation range of ±270°.

The only task of the absolute switch is to detect in which section the rotator actually is, it does not give precisely the absolute position of the rotator axis what has to be done by the absolute marks of the encoder.
Open Design Issues

- The absolute switch shall be protected against intentional or unintentional manipulation.

4.2.5.2 Hydraulic Shock Absorbers

In case of failure of one of the electric limit switches, the rotator axis will be stopped by physical end stops in the form of hydraulic shock absorbers. A slider ring with a limit actuator, rotating approximately $\pm 178^\circ$, together with the position of the shock absorbers, determines the overall gross rotation range. This gross rotation range determines the rotation range of the rotator cable chain.

As in case of the brakes, the limit system will not work if the AG-system is dismounted since the limit slider ring and the actuator of the shock absorber are located on the AG-structure.

In this preliminary design, the shock absorbers (NUMATICS WEB-M1.0) and the limit switches (Telemecanique XCMD) are the same as in case of the Folded Cassegrain rotators. For final design, it must be justified its suitability for the Cassegrain rotator.

All components of the mechanical limits shall survive an impact under all operations conditions (maximum velocity, load, unbalance, etc.).
4.2.6 **Cable Rotator**

In the preliminary design, all the components of the rotator which require cables or hoses are located on the static part of the rotator (motor windings, encoder reading heads, brakes, switches, etc.). Hence, no rotation is required for the rotator components. The rotating components which need cables and hoses to be rotated are part of the AG -System or the scientific instrument (see 4.3.5 and 0).

4.2.7 **Counterweighting**

The rotator axis shall be counterweighted with a residual unbalance of less than 100 Nm (50 Nm goal) reducing unnecessary power consumption and reducing heat generation in the telescope chamber. An additional margin of ±50 Nm shall be provided for small future modifications.

**Open Design Issues**

- For the material of the counterweights, normal construction steel is preferred, lead shall only be used if technically justified.
- If small weight-units are used for counterweighting, they should be placed over cross.

4.3 **AG Mechanics**

The core of the AG -System consists of an arm containing the AG -Instrument, which is the same instrument as in Folded Cassegrain. The arm can position a pick-off mirror in any position of a Ø15 arcmin FOV and move back keeping the field completely unobstructed. Unlike the FC focus, in this case the instrument is installed inside the Probe Arm, like in the Nasmyth foci. The arm moves over the field by a combination of the rotations of the turn table around the field and the arm rotator, like in the other instrument rotators. The axis of the arm rotator is slightly inclined pointing to the centre of the secondary mirror (M2), so that the pick-off mirror draws a spherical segment with centre on M2.

The AG -Instrument is mounted on a linear actuator with a focal range of 100 mm, +70 mm towards the pick-off mirror and -30 mm backwards. The required net-range is 40 mm remaining
±30 mm as safety margin. The selected translation stage is a PI-M404-42S from Phyisk Instrumente, the same as in FC but with bigger range.

Fig. 26 - General view from above of the AG-Unit

Fig. 27 - General view from below of the AG-Unit (protection cover not shown)
Fig. 28 - Section view of the AG Unit

Fig. 38 – Load path AG main structure – bearing – turn table – Probe Arm.
The load path between AG main structure and Probe Arm is not the shortest one inversing its direction. In case of the AG mechanics, this is not a disadvantage but more an advantage. AG main structure and turn table work as two opposed cantilevers whose rotations due to gravity are almost compensated remaining the axial displacement of the Probe Arm as the principal motion. This leads to a very small pupil displacement when the tube points to the zenith.

4.3.1 Probe Arm

The AG Instrument has a FOV of Ø20 arcsec with a commercial mirror for pick-off (EDMUND 89-460) (out of scope of the CG-Set Tender) which complies with the required dimensions.
The mount and the adjustment system of the pick-off mirror (out of scope of the CG-Set Tender too) were designed with a regulation range of ±2 mm (net) allowing to align the mirror in piston and tip-tilt. The present design defines the interface between the arm and the pick-off mirror on the fixed closing plate of the mirror support (plate inclined 45°, fixed with 4 screws M3 and 2 reference pins to the extreme of the Probe Arm. The small difference between the 45°-angle and the required angle can be achieved with the regulation screws of the mirror mount).

The pick-off mirror together with its mount is not part of the supplies of the AG-mechanics.

It is proposed to construct the arm starting from a machined steel block forming the instrument housing, a machined head for supporting the pick-off mirror with its mount and a tube connecting both elements by welding. The instrument housing includes also a cover machined from a thick steel plate. In the final design of the arm, the thicknesses of the components and the location of possible stiffener ribs should be optimized, analysing the effects of gravitational deformations of the arm over the image movement of the AG-Instrument.

The counterweighting of the arm respect to its rotations axis also shall be considered, reducing weight and adding counterweights where it will be necessary. The arm should be balanced for intermediate positions of the focus positioner and for intermediate positions of the cable chain.

For the arm tube a commercial tube NPS2-SCH40 (Øext60, Øint52) is foreseen, with the outer diameter turned to Ø56 mm reducing mass and dimensions, including flanges on both sides for welding to the instrument housing and the arm head supporting the pick-off mirror.

The complete AG-Instrument is installed as a whole inside the arm and can be dismounted as a whole loosening 4 screws which fix the base of the instrument to the translation stage. The interface between arm and arm rotator is defined by the moving flange of the arm rotator and a locating pin. To remove the arm, it will be necessary first to remove the AG-System to access to the screws holding the arm on the arm rotator. Dismounting the arm is only foreseen for substituting or repairing the arm rotator.

However, the flexion of the Probe Arm itself is not considered in the structural analysis of this preliminary design and slightly will worsen the results. With the actual design proposal, the flexion will be about 30 µrad resulting in 0.5 mm (0.09%) pupil displacement.

In horizontal tube position a similar compensation effect is observed as that referred in 4.3. Independently if the Probe Arm is in “hanging” or “standing” position, the weight of its mechanics causes a rotation in the same direction as the science instrument, keeping low the resulting relative pupil displacement.

---

8 The deformation of the mirror due to the mount was not analyzed. Depending on the analysis results a modification of the mount could be required.
Open Design Issues

- The actual combination of AG-Instrument and linear positioner can lead to a collision of the AG-Instrument with the rear wall of the arm casing.
- The safety margin for the pick-off mirror inside the arm head is too small. Using the complete adjustment range of +/-3 mm the mirror can touch the inner wall of the arm head.
- Both, arm and linear positioner shall have mechanical references which guarantee the position after removing for maintenance or repair.
- The position of the rotation axis could be optimized reducing counterweights.
- Access and maintenance of the AG-Instrument is no well solved. This point should be further developed, mounting for example the AG-Instrument on a lateral cover of the AG-Arm while keeping the required mounting repeatability.

4.3.2 Arm Rotator

The selected arm rotator is a RV160HAT rotation stage from NEWPORT, with encoder on the load axis. This rotation stage is from the same series as that one chosen for the FC rotator (RV120HAT) but bigger in size increasing the stiffness.
The arm rotator is mounted on an inclined plane of the rotating structure of the turn table, machined with the needed angle assuring that the rotation axis points to the centre of M2. The arm rotator shall be mounted on the turn table by means of a mounting aid assuring its position. It is preferable to define the position of the arm rotator without mounting aid, for example by a centring diameter and a location pin.

The arm rotator has to be ordered from NEWPORT with the limit switches located in the right place (±55° in the preliminary design), so that the arm can reach the border of the field of view and can be parked without the danger of collision. For additional security two hydraulic absorbers are installed.

Between the arm and the turn table a cable chain is mounted guiding the cables required for the AG-Instrument.

Open Design Issues

- Self-locking of the arm rotator should be checked.
- Calibration of the encoder should be checked.

4.3.3 Turn Table

The turn table, similar to the systems in FC and Nasmyth, consists of cross roller slewing bearing (aprox. 1 m in diameter) with external toothing moved by two servomotors with reducers working in anti-backlash mode.
4.3.3.1 Encoder

The outer ring of the bearing includes the scale tape of the turn table encoder which is the same model as in case of the rotator axis. On the rotating ring two reading heads are mounted on opposite positions. As in case of the encoder of the rotator axis the required number of scanning heads has to be determined to guarantee the required positioning precision of the turn table. Segmented protection covers shall be foreseen avoiding unintentional damaging or pollution of the encoder.

Determining the absolute position shall be done as fast as possible since night-time for observation is valuable. Instead of installing a home switch, it is proposed to place a double-lever switch in the centre of the rotation range of the turn table to indicate in which section the axis actually is. With this information and an adequate interface electronics the absolute position can be determined moving the axis always towards the centre and over two reference marks.

In a preliminary estimation based on data of other subsystems mounted in the telescope, the accuracy of the encoder has been determined in 6,5 arcsec with two scanning heads mounted diametrically opposed. This error can be reduced by calibration estimating the final error in about 1,6 arcsec. The repeatability is estimated in about 0,7 arcsec.

4.3.3.2 Bearing

In the preliminary design, it was tried to use an existing bearing (stored on GTC site) which includes a tape slot for a Heidenhain encoder. The bearing corresponds to a standard catalogue bearing from ROTHE ERDE with reference 161.25.0980.890.11.1503, whose external gearing has been modified from M8 to M4. Due to lack of time the bearing has not been opened for revision of its state to determine if it is reusable. GTC does not dispose of the original drawing of the bearing but has a drawing from the manufacturer of the subsystem in which the bearing was mounted, indicating dimensions and stiffnesses (DR/SE-CM-CA-120-0108). Regarding the external gearing, the existing drawing shows a M4 gearing with 278 teeth without profile offset, meanwhile ROTHE ERDE normally uses profile offset obtaining stronger teeth. It is not
known if the existing bearing has been manufactured without profile offset or if the drawing does not show it.

Open Design Issues

- Finally, the reuse of the bearing mentioned before has been discarded since a bearing adapted to the actual design could probably has a reduced section and diameter saving space and weight. This last argument is very important since the whole focal station suffers overweight. As in case of the rotator bearing, a customized section could be considered substituting part of the static structure of the AG -System of part of the turn table or both. The modulus of the gearing also could be reduced increasing the number of teeth of the pinions.

- The re-greasing of the bearing should be done automatic- or semi-automatically. The idea is to install a greasing unit that, together with a determined motion sequence of the rotator axis (and simultaneously the turn table axis), re-greases the bearings by demand. This maintenance task should be started only in local mode forcing the supervision by an operator. Besides, the exit of the grease should be defined in such a way that it can be removed easily, by means of a lower preload of one of the sealing lips and access apertures or by exit channels.

4.3.3.3 Motors

The same components as in FC has been chosen, servomotors from KOLLMORGEN combined with reducers from PARKER BAYSIDE, which are similar also to that ones installed in Nasmyth. The servomotors include brakes which maintain the position of the turn table when it does not move, so that the motors can be shut of avoiding unnecessary power consumption and heat generation.

The dimensioning and suitability of this components has to be analysed in function of the appearing loads and the available space. Additionally, it has to be taken into account that these servomotors (DBL-series) are declared obsolete by the manufacturer, why probably a model form the actual AKM-series has to be selected.
4.3.3.4 Structure

The rotating ring of the bearing carries the turn table plate on which the arm rotator is mounted. This structure consists of a thick steel plate machined with the required interfaces and weight-reducing pockets close to the arm rotator. On the opposite of the arm rotator material is left on the structure compensating the weight of the Probe Arm and the arm rotator. In the preliminary design this counterbalance has not been analysed in detail. The distribution of material shall be optimized balancing the turn table, as well as possible, over the whole rotation range, keeping low the weight at the same time and respecting the required stiffness.

The turn table has also a cable rotator consisting in a cable chain and two guiding slots, one fixed to the static structure of the AG-System and the other one fixed to the rotating structure of the turn table.

Finally, the Relative Pupil error can be drastically improved by placing a spacer at the Arm rotator interface which could be machined according to the dimensional verifications of the assembled rotator.
Open design issues

- Foresee a machinable spacer for the Arm Rotator Interface

4.3.3.5 Limits

Analogous to the rotator axis, the turn table includes electrical limit switches and hydraulic end dampers limiting the rotation range, apart from the defined encoder limits. The rotation range in the preliminary design has been defined in ±115° guaranteeing that the pick-off mirror can reach every position of the field of view, including a certain margin. The finally required rotation range and the positions of the limit switches and end dampers have to be confirmed, as well as the range of the cable rotator. Both, the limit switches (Telemecanique XCMD) and the end dampers (NUMATICS WEB-M0.15) are the same used for the AG-System of FC but have to be confirmed to be suitable for the actual system.

Apart, it is proposed to install an additional switch indicating the section in which the axis is, making faster the determination of the absolute position of the axis. Reading the position of this switch, the movement to determine the absolute position always can be done towards the centre of the rotation range without touching end stops.

Open Design Issues

- The absolute switch shall be protected against intentional or unintentional manipulation.

4.3.4 Main Structure

The whole AG-System is integrated in a structure which is mounted on the rotating part of the instrument rotator, so that it rotates simultaneously with the Science Instrument. The structure has a bell-shaped form with a nominal wall thickness of 10 mm and increased wall thicknesses on the interfaces with the different components attached to it.

It is proposed to fabricate this piece out of a forged and turned steel ring (one or two), although it could be possible to use formed and welded steel plates with machined interfaces. In this last case, maybe a tailored bottom could be used with the required interfaces welded on.

The AG-structure has a flange with an outer diameter of 2060 mm adjusting to the rotating part of the instrument rotator and an inner diameter of 870 mm where the turn table bearing is mounted. Besides, the structure has interfaces with the cable rotator of the turn table, the external cable rotator for the AG-System, turn table motors and limits, among others.

For closing the AG-System between the rotator and the Science Instrument a protection cover is foreseen which keeps unobstructed the 15°-FOV for the Science Instrument, so that the AG-System is protected during the installation of the Science Instrument. On the other side, this protection plate shall include a simple mechanism to close the central hole for maintenance taking place above the Science Instrument. The central hole cover shall withstand the weight of an operator. At the same time, the protection covers defines the limit between the envelopes of the instrument and the AG-System avoiding any unintentional interference between both systems due to the reduced space.
Fig. 36 - AG Main Structure top view

Fig. 37 - AG Protection Cover (inner shutter not shown)
Open Design Issues

- The protection cover should have a shutter mechanism (electrically actuated or released) to protect the Science Instrument and to make easier maintenance. In this sense, the shutter should withstand the weight of a person.

4.3.5 Cable Rotator

In case of the AG-System, which is located inside the nucleus of the PMC, it is easier to place a specific cable rotator for this system inside the PMC. On other instrument rotators installed on the telescope the externally placed cable chain carries supplies for the instrument and supplies for the AG-System, solution that complicates maintenance.

The cable rotator of the AG-System rotates directly the cables between the nucleus of the PMC and the AG-Structure fixed to the rotating part of the instrument rotator. The proposed design is leaned on the solution used for the FC-rotators, scaled to the reduced needs in case of the Cassegrain-rotator.

![AG Cable Rotator Diagram](image)

This cable rotator consists of two cable chains, an inner guiding slot, a preloaded intermediate roller structure and attachment points on the fixed part behind the connection panel. Both cable chains start from a certain point on the rotating structure following the guiding slot on both sides. Coming together again on the opposite of the starting point they are fold back by the main rollers of the intermediate roller structure running back until reaching the fixed points.
The intermediate roller structure is closed by means of two threaded rods between the main rollers. Two springs are located on the rods determining the preload. This preload should be adjusted in shop but should not vary if the cable rotator is opened and closed again. On the opposite of the main rollers counterweights are installed compensating the unbalance created by the main rollers.

Meanwhile the secondary rollers, just as the main rollers, are custom plastic rollers, the smaller guiding rollers proposed are DualVee from BishopWisecarver, distributed by HEPCO MOTION.

Chapter 4.4 contains a preliminary cable count for the AG -System which shall occupy maximum three quarters of the total capacity of the cable rotator.

The fixed ends of the cable chains are attached to a support structure with a connection panel. All supplies of the rotator, except the hydraulic, are going over this connection panel independently if the supply is for the static of the rotating part of the rotator. In this way, the rotator is a plug and play device easy to handle during tests and final integration.

The support structure for the cable chains and the connection panel is attached to the static part of the rotator bearing.

Open Design Issues

- The available section for cables and hoses inside the cable chain, as well as the available space on the connection panel, shall be increased to allow for future modifications.

4.4 Cables and Hoses

A preliminary cable count has been realized for all required cables and houses between the electronic cabinet and the Cassegrain Rotator (see section 11). The idea is to have one connection panel situated on the rotator where all supplies are connected, independently if they go to the static or rotating part of the rotator. All connectors are different avoiding false connections. The cable strand between rotator and electronic cabinet goes through a cable transit in the cabinet wall directly to the control electronics inside the cabinet. Overlengths of the cables are stored in the bottom of the cabinet. All supplies coming from the GTC enter the cabinet through a connection panel in the cabinet wall.

In this way, the handling of the rotator during tests and integration is easier and faster and no connection schemas are required.

Besides, distribution boxes are foreseen in the different cable strands, reducing the amount of cables in general.
4.5 Support Elements

4.5.1 Science Instrument Dummy

Once the instrument rotator and the AG-System are installed at the Telescope and aligned, a dummy for the instrument should be installed until the real instrument is mounted. This dummy is necessary for counterbalancing the telescope tube and allowing to operate the telescope using the other focal stations, although no instrument is installed on the Cassegrain focal station. The dummy used for shop tests could fulfil this task. Ideally, the dummy is configurable in weight, for example in 1600 kg plus 2x400 kg. For storage, it can be reduced in size and has its own transport rollers.

Open Design Issues

- Dummy Instrument design

4.5.2 Transport Cart

For initial Rotator testing and POM Unit alignment at the GTC or for maintenance operations, a transport cart is required. This cart will also be used for carrying the rotator to the telescope chamber for its integration on the telescope structure. Later, the cart is used to transport or to store the scientific instrument OSIRIS. If OSIRIS is installed and in operation, the transport cart should be stored using as less space as possible, being foldable or dismountable.

At the upper part, the cart shall have a removable structure supporting a mirror used to align the POM. At the lower part of the transport cart a horizontal interface should be foreseen to be able to exchange the movement system. Initially, the transport cart might have conventional industrial wheels. Later, it might be more convenient to use a different movement system like a pneumatic transport system.

Open Design Issues

- Transport Cart Design

4.6 FE-Analysis

The aim of the FE-analysis in the preliminary design phase is to determine the absolute image motion seen from the Science Instrument and the relative image motion between Science Instrument and AG-Instrument, due to gravitational bending. These deformations are caused by the rotation of the telescope tube, the rotation of the Instrument Rotator and subsequent change in orientation of the Probe Arm with regard to gravity. Finally, the AG Probe Arm can be moved as well. The deformation results from the FE analysis contribute to the general error budget for absolute and relative orientation errors towards the pupil.

Additionally, the first five eigen-frequencies were calculated under full load.

Stress analyses were not performed.
Analyses performed:

- Creation of a simplified bearing model with scaled stiffness based on data from the Nasmyth Rotator bearing (see chapter 4.6.1).
- Analysis of the stiffness of the Cassegrain Rotator bearing based on the results obtained with the simplified model (see chapter 4.6.2).
- Determination of movements due to gravity for Science Instrument focal plane, AG focal plane and pick-off mirror (see chapter 4.6.3).
- Determination of the first five eigen-frequencies (see chapter 4.6.3).

4.6.1 Simplified Bearings with conventional section

4.6.1.1 Analysis Object

Determine the stiffness of a bearing with the required diameter for the Cassegrain Rotator but with conventional section.

Based on the dimensions and stiffness of the Nasmyth Rotator bearing a model was created reproducing its characteristics. This model was scaled to obtain a representative bearing for the Cassegrain Rotator.

4.6.1.2 Model – Nasmyth Bearing

The model of the Nasmyth Rotator bearing consists of two simple concentric rings with rectangular section and a small slot between them. Inside the slot a third ring is located, representing the rolling elements, with a modified young modulus to obtain the corresponding general stiffness of the bearing.

The dimensions and mechanical characteristics of this third ring, i.e. the rolling elements, are used to create first a bearing for the Cassegrain Rotator with conventional section and later with customized section (see chapter 4.6.2).

Stiffness values of the Nasmyth Rotator Bearing indicated by the manufacturer:

- **k-flection**: \(1.75 \cdot 10^{10}\) Nm/rad
- **k-radial**: \(9.10 \cdot 10^9\) N/m
- **k-axial**: \(1.28 \cdot 10^{10}\) N/m

General Dimensions of the Nasmyth Rotator bearing model:

- **Outer diameter**: 2953 mm
- **Inner diameter**: 2716 mm
- **Medium diameter rolling elements**: 2833 mm
- **Section rolling elements**: 40x10 mm
All three rings have been meshed with hexahedron elements (solid 186) and the contacts between the rings are defined as bonded.

**Boundary Conditions – Tilt Stiffness**

For the analysis of the tilt stiffness the one face of the inner ring was fixed and on the same side of the outer a remote force of 10000 N was applied at a distance of 650 mm.

**Boundary Conditions – Radial Stiffness**

For the analysis of the radial stiffness one face of the inner ring was fixed. On the same side, the face of the outer ring was restricted in axial direction and a remote force of 10000 N was applied considering the surface completely stiff.

*Fig. 39 - Boundary conditions, analysis of tilt stiffness*
Boundary Conditions

**Boundary Conditions – Axial Stiffness**

For the analysis of the axial stiffness one face of the inner ring was fixed and on face of the outer ring a remote force of 10000 N was applied considering the surface completely stiff.
4.6.1.3 Results – Nasmyth Bearing

The tilt stiffness was obtained by the following equation:

\[
\theta = \tan^{-1}\left(\frac{\delta_z}{r}\right) \rightarrow k_{\theta} = \frac{M}{\theta}
\]

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (flexible zone) [Mpa]</th>
<th>(\delta_z) [(\mu)m]</th>
<th>(\theta_y) [(\mu)rad]</th>
<th>(k_{\theta\text{obtained}}) [Nm/rad]</th>
<th>(k_{\theta\text{theoretical}}) [Nm/rad]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flection</td>
<td>1520</td>
<td>5.48 (\times) 01</td>
<td>3.713 (\times) 01</td>
<td>1.7507 (\times) 10</td>
<td>1.75 (\times) 10</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 2 Results of the analysis for tilt stiffness (Nasmyth).

The radial and axial stiffness was obtained by the following equation:

\[
k_r = \frac{F}{\delta_x}
\]

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (flexible zone) [Mpa]</th>
<th>(\delta_x) [(\mu)m]</th>
<th>(k_{r\text{obtained}}) [N/m]</th>
<th>(k_{r\text{theoretical}}) [N/m]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>1520</td>
<td>2.72 (\times) 01</td>
<td>3.67 (\times) 10</td>
<td>9.10 (\times) 09</td>
<td>+303</td>
</tr>
</tbody>
</table>

Table 3 Results of the analysis for radial stiffness (Nasmyth).

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (flexible zone) [Mpa]</th>
<th>(\delta_z) [(\mu)m]</th>
<th>(k_{r\text{obtained}}) [N/m]</th>
<th>(k_{r\text{theoretical}}) [N/m]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>1520</td>
<td>5.49 (\times) 01</td>
<td>1.82 (\times) 10</td>
<td>1.28 (\times) 10</td>
<td>-42</td>
</tr>
</tbody>
</table>

Table 4 Results of the analysis for axial stiffness (Nasmyth).

In all three previous cases the relative error was calculated as follows:

\[
\varepsilon = \text{abs}\left(\frac{K_{\text{requerida}} - K_{\text{obtenida}}}{K_{\text{requerida}}}\right) \times 100\%
\]
The finally obtained stiffnesses for the bearing differ quite from the desired ones in axial (-42%) and radial (+303%) direction. This is not considered to be critical, since the axial and radial stiffnesses do not have too much influence on the pupil error. More important is the tilt stiffness which was well adjusted without considerable error.
Fig. 43 Displacements with radial load.

Fig. 44 Displacements with axial load.
4.6.1.4 Model – Cassegrain Bearing with conventional section

The simplified model of the Cassegrain Rotator bearing is modelled in the same way as the Nasmyth Rotator bearing, but with modified diameter. The flexible ring in the middle, representing the rolling elements, was directly overtaken keeping unmodified its section and mechanical characteristics (Young modulus).

General Characteristics of the Cassegrain Rotator bearing model:

- Outer diameter: 2360 mm
- Inner diameter: 2070 mm
- Medium diameter rolling elements: 2214 mm
- Section rolling elements: 40x10 mm

![Simplified model for Cassegrain Rotator bearing.](image)

**Boundary Conditions**

For calculation of the stiffnesses of the bearing the same boundary conditions as in case of the Nasmyth bearing has been used (see chapter 4.6.1.2).
4.6.1.5 Results – Cassegrain Bearing with conventional Section

The results were obtained analogously to that ones of the Nasmyth Rotator (see chapter 4.6.1.3)

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (zona flexible) [Mpa]</th>
<th>δx [µm]</th>
<th>θy [µrad]</th>
<th>kθobtained [Nm/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>1520</td>
<td>9.31E-01</td>
<td>7.894E-01</td>
<td>8.29E+09</td>
</tr>
</tbody>
</table>

Table 5 Results of the analysis for tilt stiffness (Cassegrain conventional).

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (zona flexible) [Mpa]</th>
<th>δx [µm]</th>
<th>kθobtained [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>1520</td>
<td>3.76E-01</td>
<td>2.66E+10</td>
</tr>
</tbody>
</table>

Table 6 Results of the analysis for tilt stiffness (Cassegrain conventional).

<table>
<thead>
<tr>
<th>Load Type</th>
<th>E (zona flexible) [Mpa]</th>
<th>δx [µm]</th>
<th>kθobtained [N/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>1520</td>
<td>7.14E-01</td>
<td>1.40E+10</td>
</tr>
</tbody>
</table>

Table 7 Results of the analysis for tilt stiffness (Cassegrain conventional).

According to the obtained results, the tilting stiffness of the Cassegrain bearing (8.29E+09) is about 53% lower than the tilting stiffness of the Nasmyth bearing (1.75E+10).

Having a look only on the rolling elements (middle ring) of the simplified bearing model, the following moments of inertia are obtained:

\[
I_{Nasmyth} = \frac{\pi}{64} (D_{ext}^4 - D_{int}^4) = (2.838^4 - 2.828^4) = 0.909 \frac{\pi}{64}
\]

\[
I_{Cassegrain} = \frac{\pi}{64} (D_{ext}^4 - D_{int}^4) = (2.219^4 - 2.209^4) = 0.434 \frac{\pi}{64}
\]

The resulting factor of both moments of inertia and hence the stiffnesses is:

\[
\frac{I_{Cassegrain}}{I_{Nasmyth}} = \frac{K_{Cassegrain}}{K_{Nasmyth}} = 0.477
\]
This is consistent with the factor obtained by the bearing model:

\[
\frac{K_{\text{cass}	ext{grain-FE}}}{K_{\text{Nasmyth-FE}}} = \frac{8.29 \times 10^9 \text{Nm/rad}}{1.75 \times 10^9 \text{Nm/rad}} = 0.474
\]

4.6.2  **Cassegrain Bearing with Customized Section – Rotator Attachment to Telescope**

4.6.2.1  **Analysis Object**

Determine the stiffnesses for the Cassegrain Rotator bearing with customized section, first isolated and later taking into account the attachment flange on the telescope.

4.6.2.2  **Model – Cassegrain Bearing with customized Section**

The section of this bearing model corresponds to the present preliminary design for the Cassegrain Rotator using the same flexible middle ring modelled before (see chapter 4.6.1), representing the rolling elements of the bearing.

The modelling procedure of the bearing itself is analogues to that one presented in chapter 4.6.1, but here the boundary conditions are different representing the attachment method of the rotator to the telescope structure.

*Fig. 46  FE-Model of the Cassegrain Rotator bearing with customized section.*
The outer ring of the bearing is fixed in discrete zones equispaced over the whole perimeter. To cases have been analysed:

Case 1: The rotator is fixed in 6 zones corresponding to the main nodes of the primary mirror structure.

Case 2: The rotator is fixed in 12 zones corresponding to the main nodes and the secondary nodes of the primary mirror structure.

In both cases, the tilting remote force of 10000 N is attached to the inner ring at a distance of 650 mm considering the surface of the rotator on which it acts completely stiff.
4.6.2.3 Results – Cassegrain Bearing with customized Section

The results were obtained analogously to that ones of the Nasmyth Rotator (see chapter 4.6.1.3)

<table>
<thead>
<tr>
<th>Boundary Type</th>
<th>E (zona flexible) [Mpa]</th>
<th>$\delta_z$ [µm]</th>
<th>$\theta_y$ [µrad]</th>
<th>$k_{\text{obtained}}$ [Nm/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1 (6 zones)</td>
<td>1520</td>
<td>5.128</td>
<td>4.653</td>
<td>$1.40 \times 10^9$</td>
</tr>
<tr>
<td>Case 1 (12 zones)</td>
<td>1520</td>
<td>4.436</td>
<td>4.026</td>
<td>$1.61 \times 10^9$</td>
</tr>
</tbody>
</table>

Table 8 Results of the analysis for tilt stiffness (Cassegrain customized).

The tilt stiffness obtained for the rotator attached in 12 zones is 15% higher than for the rotator attached in 6 zones.

The following images show the deformations for both cases of boundary conditions.
Fig. 49 Displacements under flexion for the Cassegrain Rotator with customized section, attached in 6 zones.

Fig. 50 Displacements under flexion for the Cassegrain Rotator with customized section, attached in 12 zones.
4.6.2.4 Model – Cassegrain Rotator on Telescope Interface Flange

This model of the Cassegrain Rotator includes the attachment flange of the telescope structure. In this way, the local stiffness between the Cassegrain Rotator and the structure nodes of the primary mirror cell can be taken into account.

Between both, the Cassegrain Rotator and the attachment flange on the telescope, adjustment shims with a thickness of 5 mm are modelled.

Three cases with different boundary and attachment conditions have been analysed.

**Note:**

In this context, the constraint zones refer to how the model is constrained and the attachment zones refer to how the rotator is attached to the interface flange on the telescope.

**Case 1:** 6 constraint zones coinciding with the principal nodes of the PMC, and 6 attachment zones between rotator and interface flange, coinciding as well with the principal nodes of the PMC.
Case 2: 6 constraint zones coinciding with the principal nodes of the PMC, and 12 attachment zones between rotator and interface flange, coinciding with the principal and the secondary nodes of the PMC.

Case 3: 12 constraint zones coinciding with the principal nodes of the PMC, and 12 attachment zones between rotator and interface flange, coinciding with the same nodes of the PMC.

In both cases, the tilting remote force of 10000 N is attached to the inner ring at a distance of 650 mm considering the surface of the rotator on which it acts completely stiff.

Fig. 52 Boundary and attachment conditions, case 1.

Fig. 53 Boundary and attachment conditions, case 2.
4.6.2.5 Results – Cassegrain Rotator on Telescope Interface Flange

The results were obtained analogously to that ones of the Nasmyth Rotator (see chapter 4.6.1.3)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>E (flexible zone) [Mpa]</th>
<th>( \delta_z ) [µm]</th>
<th>( \theta_y ) [µrad]</th>
<th>( k_{\text{obtained}} ) [Nm/rad]</th>
<th>Variation to case 1 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1520</td>
<td>9.493</td>
<td>8.615</td>
<td>7.55E+08</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>1520</td>
<td>8.465</td>
<td>7.682</td>
<td>8.46E+08</td>
<td>12</td>
</tr>
<tr>
<td>Case 3</td>
<td>1520</td>
<td>5.918</td>
<td>5.37</td>
<td>1.21E+09</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 9 Results of the analysis for tilt stiffness (Cassegrain customized with telescope interface flange).

The following images show the deformations for all three cases.
Fig. 55. Deformations due to flexion, 6 constraint zones and 6 attachment zones.

Fig. 56. Deformations due to flexion, 6 constraint zones and 12 attachment zones.
4.6.3 **Cassegrain Rotator and AG -Mechanics**

4.6.3.1 **Analysis Object**

Determine the movements of the Science Instrument focal plane, the AG focal plane and the Pick-off Mirror due to gravity, under any working condition, i.e. any position of the telescope tube and the AG -Mechanics.

The used geometry corresponds to a simplified model of the preliminary mechanical design of the CG-Set.

4.6.3.2 **Model – Cassegrain Rotator and AG -Mechanics**

The model is built up with 3D-elements (solid186) including the interface flange of the telescope tube structure, instrument rotator, AG main structure, turn table bearing, turn table and arm rotator. To simplify the model, the arm is considered a rigid body represented only by a lumped mass to which another small mass, the pick-off mirror, is linked.

The focal planes of the Science Instrument and the AG -Instrument were not modelled (unlike in other analyses realized with linked points). Instead, their motions are calculated based on the motion of lumped masses placed in the model. So, the Science Instrument is modelled with a mass of 2,4 t at 0,425 mm behind the focal plane and an auxiliary mass of 1 g in the centre of the attachment flange of the Science Instrument to the rotator. The AG -arm is represented by a mass of 11 kg and the pick-off mirror by one of 1,5 kg.

![Diagram of deformations due to flexion, 12 constraint zones and 12 attachment zones.](image-url)
In both cases, the focal planes lie between the mass pairs and their translations and rotations can be determined.

The instrument rotator is attached to the telescope structure in 12 attachment zones represented with 5 mm thick shims.

The Science Instrument is attached to the rotator in only 3 points to avoid introducing stiffness to the rotator structure. Besides, the attachment points do not coincide in angular position with the structure nodes of the primary mirror cell.

The bearing of the turn table, as well as the arm rotator, were modelled with the same principle as the rotator bearing, using known stiffness values.

The following table shows the principal characteristics of the different components of the FE-Model. All components, excepting the lumped masses, were modelled with solid186-elements and a density of 7850 kg/m$^3$.

<table>
<thead>
<tr>
<th>Part</th>
<th>Masa [Kg]</th>
<th>Material</th>
<th>$E$ [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotator Bearing, fixed ring</td>
<td>617</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>Rotator bearing, rotating ring</td>
<td>428</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>Rotator bearing, rolling elements</td>
<td>22</td>
<td>Custom</td>
<td>1520</td>
</tr>
<tr>
<td>Attachment Shims</td>
<td>5.9</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>Telescope Tube Attachment Flange</td>
<td>261</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>AG main structure</td>
<td>335</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>AG turn table</td>
<td>105</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>AG Bearing, fixed ring</td>
<td>77</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>AG bearing, rotating ring</td>
<td>67</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>AG bearing, rolling elements</td>
<td>6.3</td>
<td>Custom</td>
<td>210</td>
</tr>
<tr>
<td>Arm Rotator, fixed ring</td>
<td>2.8</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>Arm Rotator, rotating ring</td>
<td>4.4</td>
<td>Steel</td>
<td>2e+05</td>
</tr>
<tr>
<td>Arm Rotator, rolling elements</td>
<td>1.6</td>
<td>Custom</td>
<td>107</td>
</tr>
<tr>
<td>Science Instrument</td>
<td>2400</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Auxiliary mass</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 10 Resume of the properties of the FE-Model

<table>
<thead>
<tr>
<th>Instrument</th>
<th>k_f [N/m]</th>
<th>k_x [N/m]</th>
<th>k_θ [Nm/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG Instrument</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pick-Off Mirror</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 11 shows the stiffnesses used for the turn table bearing and the arm rotator.

<table>
<thead>
<tr>
<th>Bearing</th>
<th>k_f [N/m]</th>
<th>k_x [N/m]</th>
<th>k_θ [Nm/rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing de AG</td>
<td>2,10e+08</td>
<td>3,22e+08</td>
<td>7,452e+07</td>
</tr>
<tr>
<td>Rotator Newport RV160</td>
<td>5,50e+08</td>
<td>3,17e+08</td>
<td>1,667e+06</td>
</tr>
</tbody>
</table>

Table 11 Stiffnesses of the turn table bearing and the arm rotator.

Fig. 58 shows the completely meshed FE-model with lumped masses and the used coordinate system whose orientation coincides with the Cassegrain focal station coordinate system.
A total of 8 cases have been analysed with different working conditions (telescope tube and arm positions) and different constraint configurations (6 or 12) of the attachment flange to the telescope structure. In all cases, the rotator was attached to the interface flange in 12 zones (shims).

<table>
<thead>
<tr>
<th></th>
<th>Telescope Tube vertical</th>
<th></th>
<th>Telescope Tube horizontal</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 constraints</td>
<td>12 constraints</td>
<td>6 constraints</td>
<td>12 constraints</td>
</tr>
<tr>
<td>Arm horizontal</td>
<td>Case 1</td>
<td>Case 5</td>
<td>Case 2</td>
<td>Case 6</td>
</tr>
<tr>
<td>Arm hanging</td>
<td>-</td>
<td>-</td>
<td>Case 3</td>
<td>Case 7</td>
</tr>
<tr>
<td>Arm standing</td>
<td>-</td>
<td>-</td>
<td>Case 4</td>
<td>Case 8</td>
</tr>
</tbody>
</table>

Table 12: Reference table for the calculated cases. Gravity applied in -Z for vertical tube position and in +Y for horizontal tube position. All cases have 12 attachment points between rotator and telescope structure.
Fig. 60 Boundary conditions, case 2.

Fig. 61 Boundary conditions, case 3.

Fig. 62 Boundary conditions, case 4.
Fig. 63 Boundary conditions, case 5.

Fig. 64 Boundary conditions, case 6.

Fig. 65 Boundary conditions, case 7.
4.6.3.3 Results – Cassegrain Rotator and AG-Mechanics

In the following tables the displacements of the lumped masses are shown, as well as the resulting displacements and rotations of the focal planes of the Science Instrument and the AG-Instrument.

### Science Instr. – Displacement and Rotations

<table>
<thead>
<tr>
<th>Case</th>
<th>Subsystem</th>
<th>$\delta_x$ [µm]</th>
<th>$\delta_y$ [µm]</th>
<th>$\delta_z$ [µm]</th>
<th>$\theta_x$ [µrad]</th>
<th>$\theta_y$ [µrad]</th>
<th>$\theta_z$ [µrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Science Instr.</td>
<td>0</td>
<td>0</td>
<td>-46</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Auxiliary Mass</td>
<td>0</td>
<td>0</td>
<td>-46</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 2-4</td>
<td>Science Instr.</td>
<td>0</td>
<td>70</td>
<td>0</td>
<td>51</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Auxiliary Mass</td>
<td>0</td>
<td>38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 5</td>
<td>Science Instr.</td>
<td>0</td>
<td>0</td>
<td>-34</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Auxiliary Mass</td>
<td>0</td>
<td>0</td>
<td>-34</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 6-8</td>
<td>Science Instr.</td>
<td>0</td>
<td>54</td>
<td>0</td>
<td>37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Auxiliary Mass</td>
<td>0</td>
<td>31</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 13 Science Instrument; Displacements and Rotations due to gravity.*

### AG-Instrument and Pick-off Mirror – Displacements and Rotations

<table>
<thead>
<tr>
<th>Case</th>
<th>Subsistema</th>
<th>$\delta_x$ [µm]</th>
<th>$\delta_y$ [µm]</th>
<th>$\delta_z$ [µm]</th>
<th>$\theta_x$ [µrad]</th>
<th>$\theta_y$ [µrad]</th>
<th>$\theta_z$ [µrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>AG-Instr.</td>
<td>3</td>
<td>0</td>
<td>-46</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Pick-Off Mirror</td>
<td>3</td>
<td>0</td>
<td>-41</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>AG-Instr.</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>43</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Pick-Off Mirror</td>
<td>0</td>
<td>23</td>
<td>0</td>
<td>43</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 14  AG -Instrument and Pick-off-Mirror; Displacements and Rotations due to gravity.

The rotations were calculated by the differential motion of the lumped masses or by displacements of selected points of the structure. In case of the Science Instrument, the rotations over z are determined by tangential displacements of the attachment flange, and in case of the AG - Arm some rotations are determined by displacements of the attachment flange of the arm rotator (rotx with arm at 9 o’clock and roty with arm at 6 and 12 o’clock).

Some important notes:

- The overall mass of the rotator is about 2,3 t in the FE-model but 2,5 t in the 3D-model. Hence, the results for gravitational deformations and eigen-frequencies are more likely optimistic.
- The lateral stiffness of the rotator bearing is about 300% higher as the stiffness of a comparable bearing why the lateral displacements of the focal plane will be slightly higher.
- The AG -arm is considered a rigid body. Although the deformations of the arm contribute to the pupil error, its portion on the overall error caused by the AG -structure is assumed to be small.
- Likewise, the translation stage of the AG -Instrument and the pick-off mirror unit are not modelled but finally will contribute to the errors as well.

The following images show gravitational deformations of the CG-Set for cases 1 to 4.
Fig. 67 Case 1, in-axis view.

Fig. 68 Case 1, section view.
Fig. 69 - Case 2, in-axis view

Fig. 70 - Case 2, section view.
Fig. 71 Case 3, in-axis view.
Fig. 72 Case 3, section view.

Fig. 73 Case 4, in-axis view.
4.6.4 Eigen-Frequencies

4.6.4.1 Analysis Object

Determine the first five eigen-frequencies of the rotator under full load and with telescope tube in horizontal position.

4.6.4.2 Model

The used model corresponds to case 2 (see chapter 4.6.3.2).

4.6.4.3 Results

The first two eigen-frequencies are tilt modes over different axes perpendicular to the rotation axis. The values of these modes depend on the angular position of the three attachment points of the Science Instrument. Considering a more realistic attachment configuration of six points, the frequencies will be higher. The third mode is a torsion mode over the rotation axis.

The forth and the fifth modes are local wave modes of the AG turn table.

\begin{align*}
\text{f1} &= 59 \text{ Hz} \quad \text{tilt (y-axis)} \\
\text{f2} &= 59 \text{ Hz} \quad \text{tilt (x-axis)} \\
\text{f3} &= 75 \text{ Hz} \quad \text{piston (z-axis)}
\end{align*}
\(f_4 = 112 \text{ Hz}\)  local tilt (y-axis)

\(f_5 = 121 \text{ Hz}\)  local piston (z-axis)

\(f_6 = 136 \text{ Hz}\)  local tilt (x-axis)

Fig. 75  First mode, 59 Hz, global tilt (y-axis).

Fig. 76  Second mode, 59 Hz, global tilt (x-axis).
Fig. 77 Third mode, 75 Hz, global piston (z-axis).

Fig. 78 Fourth mode, 112 Hz, local tilt (y-axis).
Fig. 79  Fifth mode, 121 Hz, local piston (z-axis).

Fig. 80  Sixth mode, 136 Hz, local tilt (x-axis).
4.6.5 Analysis Main Conclusions

The most important results of the previous FE-analysis are the expected motions of the Science Instrument and the AG-Instrument, due to gravitational deformations. The obtained values (from FE-analysis chapter 4.6.3.3) are used for the error budgets of relative and absolute pupil errors (see chapters 9.1.1 and 9.1.2).

Having a closer look on the numbers, the gravitational deformations of the Cassegrain rotator itself make about only 5% of the relative orientation (pupil) error between Science Instrument and A&G-Instrument (see Table 19 in chapter 9.1.1.3). In case of the absolute pupil error, the contribution of the Cassegrain rotator is slightly higher but still low with 34% (see Table 19 in chapter 9.1.1.3).

The conclusion is that, regarding pupil error, the Cassegrain rotator is sufficiently stiff and there is even margin left that could be used for weight saving. The results of the dynamic analysis emphasize this circumstance with a high first eigen-frequencies of 59 Hz.

Although the flexibility of the Probe Arm was not considered during the preliminary design, contribution of the gravitational deformations to positioning errors are quite low.

Regarding position stability of the AG Instrument with regard to the Science Instrument, gravitational deformations have a significant contribution to the final result and the flexibility of the Probe Arm must be included to confirm requirements compliance.

4.7 Electronics Enclosure

4.7.1 General

This section deals only with the mechanical and thermal aspects of the Enclosure. For electrical/electronics design refer to section 7.

There might be commercial enclosures fulfilling all the requirements in A1, nevertheless, this design is based in the last electronic cabinets built for the GTC. The design of these cabinets is described in Grantecan internal documents RPT/TELE/0421-R and NTE/STMA/0480-R. These can be made available if required (in Spanish).

4.7.2 Frame

The frame is a RITTAL series TS8 (2000x800x800). This has the advantage of using the same accessories as in other enclosures in the GTC. Alternatively, a customizable aluminium frame system can be used, as NORCAN. This is more flexible but requires more design resources.

The size is estimated based in the electronics envelope calculated in section 7.

Is pending to analyse whether some reinforcement is needed in the frame to withstand the enclosure load at the attachment points in every position.
4.7.3 **Attachment to the Telescope**

It is proposed to use an intermediate frame between the cabinet and the telescope structure. This contributes to stiffen the enclosure structure as well.

![Fig. 81 - Enclosure attachment to the Telescope structure (schematic view). Enclosure (grey), Intermediate frame (orange), Silent block (rose), Silent block interface (green), Telescope structure (blue)](attachmentimage)

The load of the enclosure shall lay on elastomer silent blocks. The final design of the interface will depend on the silent block chosen.

![Fig. 82 - Silent block and interface example](attachmentimage)
The attachment system of previous cabinet to the Telescope Tube is included in Grantecan drawing DR/I-TL-CS-015/000. This can be made available if required.

The silent block choice shall take into account the different gravity orientations. The first eigen frequency must be well below 30 Hz but keeping a certain stiffness to the assembly at the same time.

The parameters to consider are:
- Maximum load in 3 axes
- Stiffness in 3 axes

The first eigenfrequency shall be calculated from the cabinet weight and the silent block stiffness.

The silent block must be failure-proof, i.e., if the elastomer material breaks or the bonding fails, the silent block design prevents the enclosure from falling.

4.7.4 Wall Panels

In order to minimize the heat paths to external surfaces exposed to the ambient air, the wall insulating panels are fixed to the most external part of the frame literally surrounding its whole volume. With a correct panel overlapping, almost the only heat path are the screws to fix the panel to the frame. See Fig. 83 and Fig. 84.

Such a solution has been thermally tested to fulfil the thermal requirements on A1.

The panels are made from painted folded steel (1.5 mm thick) or anodized aluminium (2 mm thick). The chosen insulating material is polisocyanurate, 30mm thick, covered with aluminium foil (PIRALU). This material is bonded to the panel.

Careful attention must be given to some details in order to limit the heat flow:
- Insulating material bonding to panel: using a flexible glue, adequate for the environmental conditions of the ORM. Weight shall be used during the bonding process.
- Screws: as less as possible, preferably from stainless steel with a low thermal coefficient
- Reinforcement of screws areas using non-conductive materials- see proposed solution in Fig. 84.
- Insulating of overlapping areas between panels using soft materials (weather-strips, armaflex) on both sides so that panels can be pressed against each other. See Fig. 84.
- Door hinges, locks or fasteners, dampers: careful design to limit the heat paths from the inside to the outside of the enclosure
- Cable through sealing system: Roxtec in order to keep uniformity with other thermal enclosures in the GTC
- Earthing of the panels: A copper screw is welded to the metallic part of the panel and shall be connected to the frame by means of a copper braid. See Fig. 85.
- Any hole in the panels must be carefully closed at the end in order to prevent air or heat to flow through.
Fig. 83 - Cross sections of thermal enclosure and door hinge detail

Fig. 84 - Panel overlapping detail showing polyamide spacers to reinforce screw areas.

Fig. 85 - Copper screws for panel earthing
The chosen solutions shall be validated by thermal calculation taking into account the worst case for heat conduction (20°C in the cabinet, -2°C outside).

4.7.5 Connections

The idea is that any connections to the Enclosure internal equipment are kept externally to the Enclosure. There are mainly 2 cases:

- Connections to Rotator and AG. Cables form the Enclosure internal equipment, through the cable glands with the necessary length to reach the Rotator connection panel and with aerial connectors at the panel end. The cables remain at the Cabinet side for transportation.

- Connections to GTC systems and services. The baseline is to provide connectors at the enclosure wall in a place TBD. These connections are defined in document A2. Thermal isolation and water tightness have to be ensured somehow. This is left for the detailed design.

As an alternative, these connections could be at the Rotator connection panel but this is for the time being already too populated and it is not advisable to add more connections unless there is a way to make the panel bigger while maintaining accessibility to connectors.

4.7.6 Cooling system

It consists basically in a water-air heat exchanger, one or more ambient temperature sensors, a fan and a solenoid valve. The fan is connected to a door switch that powers on the fan as the door closes. The solenoid valve is controlled based on the temperature values by means of a control loop running in the LCU.

Two options are considered for the heat exchanger:
- Wall mounted heat exchanger- less compact, but water connections can be designed so that leaks cannot reach electronics and more space inside the cabinet.

![Wall mounted heat exchanger](image1)

**Fig. 87 - Wall mounted heat exchanger**

- Internal heat exchanger- easily customizable

![Internal heat exchanger with fans attached](image2)

**Fig. 88 - Internal heat exchanger with fans attached**

The heat exchanger and fan shall be chosen based on the heat dissipation estimated for the foreseen electronics, considering that most of the heat must be removed by the cooling system (only 150W dissipation to surrounding air is allowed). This can be calculated following the manufacturer tables or charts using the following parameters:

- Inside ambient temperature (20°C)
- Water temperature (10°C) (TBC)
- Water flux (8l/min)
- Air flux

Some manufacturers, like Lytron offer charts that showing some heat exchangers and fans so that the set can be chosen at once.

It is important to correct air flux, since air density is 25% lower at 2400m.
4.7.7 **Moisture control**

Moisture in the internal air is controlled by special desiccants that absorb moisture when air is above 40% relative humidity and release moisture when relative humidity is lower. Dry-bag, from Anders Bendt has been used for other cabinets in the GTC.

In order to avoid condensation on the electronics when the door is opened, the cold-water flow must be stopped some 15 min before, so that temperature of the surfaces inside the cabinet is more or less equalized with ambient temperature.

4.8 **Mechanical Interfaces**

The CG-Set interfaces mechanically with the following GTC items:

- The Primary Mirror Cell, at the Rotator attachment flange (see A5)
- The Science Instrument, at the Instrument flange (see A6)
- The AG Instrument, at the Focus Linear Stage of the Probe Arm (see A7)
- The Pick-Off Mirror, at the Probe Arm end (see A8)
- The Cassegrain Lifting System, at the lifting points in the AG structure (see A9)

Additionally, the Transport Cart interfaces with the Science Instrument at the corresponding support points (see A10).

4.9 **3D Model**

The 3D model has been structured according to the product tree defined in document A1 and the Component list (referred in section 11).

The general assembly is named “000-GENERAL_ASSEMBLY” and is divided in six main assemblies:

- PMC_OUT_OF_SCOPE
- TL-IR-CG_000_CASSEGRAIN_ROTATOR
- OSIRIS_GLOBAL_OUT_OF_SCOPE
- PRIMARY_MIRROR_CELL_OUT_OF_SCOPE
- OPTICAL_BEAM
- ENVELOPES

Out of scope assemblies are included (identified as such within their names) in order to have a more realistic view of the interfaces and envelope constraints defined in the drawings and to put the GC-Set into context in the GTC.

The following image shows the general assembly:
The mechanics of the Cassegrain Set is divided in two main assemblies, one for the Instrument Rotator and the other one for Acquisition and Guiding (AG).

The coding of the parts and assemblies which are in scope have the following format, as an example:

- TL-IR-CG-100_000 corresponds to the Rotator Mechanics Assembly
- AG-CG-AG-200_000 corresponds to the AG Mechanics Assembly

Furthermore, the coding of commercial components has the following format:

- “Commercial Name_Commercial reference number”, for example (“NEUMATICBRAKE_RINGSPANN_DH10FPM”).

The following images show the main assemblies and sub-assemblies which are within the scope of work:
Fig. 2 TL-IR-CG_000 CASSEGRAIN ROTATOR MAIN ASSEMBLY.

Fig. 3 TL-IR-CG-100_000 ROTATOR MECHANICS ASSEMBLY.
The parts and assemblies out of scope are not coded with the product tree coding, except for the AG Instrument, Cassegrain SICM, OSIRIS Instrument and the Pick-Off Mirror assembly.

The name of this parts and assembly have the following format:

- Part Name_OUT_OF_SCOPE, for example "PRIMARY_MIRROR_CELL_OUT_OF_SCOPE"
- Assembly Name_Out_OF_SCOPE, for example "OSIRIS_GLOBAL_OUT_SCOPE"

In the case of the OSIRIS instrument, the main assembly, all sub-assemblies and secondary parts are out of scope of the Tender.

The following images show the main assemblies and sub-assemblies out of scope:
Fig. 5 Assembly of the Primary Mirror Cell Nucleus out of scope.

Fig. 6 OSIRIS Instrument Assembly out of scope.
Fig. 7 Primary Mirror Cell out of scope.

Fig. 8 Pick-Off Mirror Unit out of scope.
Fig. 9 AG Instrument out of scope.
5 CONTROL ARQUITECHTURE

5.1 GC-Set Local Control System scope

The CG-Set Control system shall include any HW and SW for the GCT-Set to work autonomously (Local Control System), and to communicate with the GTC Control System (GCS) for full functionality.

Out of scope of this design (and of the GC-Set Tender) are:

- GTC Control System (GCS)
- Remote LCU’s (hosting the GCS)
- Buses from remote LCU’s to the GC-Set Electronics Enclosure

5.2 Description

There shall be two control modes: Local (from HMI) and Remote (from remote LCU, out of scope of the Tender). Main functionalities are (see A1 for a more detailed functionality description):

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Local (HMI)</th>
<th>Remote (GCS)</th>
<th>Remote (ISS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode Switching</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Motion</td>
<td>X(1)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Start-up</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Electronics Enclosure Temp.</td>
<td>X</td>
<td>X(1)</td>
<td>X(2)</td>
</tr>
<tr>
<td>Rotator Motor Temperature</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Structural Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bearings grease sequence</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Motor cooling valve switching</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Breaks Air pressure monitoring</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Shutter</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Emergency Stop</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Emergency power switch off</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

(1)- Reduced functionality
(2)- The loop runs locally, but it is configured remotely
(3)- The shutter can be closed from a local button in a near location

Table 15 - Functionality of the Local Control System and interfaces with GCS and ISS

The HW architecture, including preliminary safety functions implementation, is shown in Fig. 89.
Fig. 89 - CG-Set control HW architecture. In blue, out of scope of GC-Set Tender. In Red Interface with GTC.

The hardware design consists of a single LCU, which includes a PLC, communication terminals, a safety terminal and digital and analogue input / output terminals. The LCU components shall be from Beckhoff.

The selected drives are:

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Drives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotator</td>
<td>One drive Servostar 700</td>
</tr>
<tr>
<td>AG Turn Table</td>
<td>Two drives Servostar 700 (master/slave)</td>
</tr>
<tr>
<td>AG Arm</td>
<td>One drive iPOS XXX(TBD)</td>
</tr>
<tr>
<td>AG Focus</td>
<td>One drive iPOS XXX(TBD)</td>
</tr>
</tbody>
</table>

There shall be 2 HMI screens for Local Control. One shall be wireless, located at a place accessible from the Rotating Floor of the Telescope. The other shall be located at the Primary Mirror Cell, close to the Rotator. HMI shall be used for maintenance Motion Control as well as other maintenance operations. The Local Interlock & Safety System shall be monitored through the HMI’s as well. The HMI’s shall include Emergency stop buttons and interlock shall keys.
The communication bus for the Local Safety System shall be PROFIBUS, for the Local HMI TBD(wireless) and for the rest of functionality would be CAN (from GCS to GC-Set, from Cabinet LCU to drives).

**Open Design Issues**

- Cabinet LCU HW components selection (Beckhoff)
- Cabinet LCU SW components selection (Beckhoff) and preliminary configuration and programming aspects
- Mode switch implementation for Drives (The final decision shall be agreed with Grantecan).
- Trade-off between PROFIBUS and PROFISAFE as protocol for the Local Safety System. (The final decision shall be agreed with Grantecan).
- HMI panels selection and connection to the Cabinet LCU
- Final drive models selection

### 5.3 Justification

Beckhoff has been selected because it allows an off the shelf integration of PLC, safety module, I/O in one platform. Furthermore, it has been used already successfully in other subsystems of the GTC. Finally, the prices are substantially lower than other equivalent systems used in the GTC in the past.

In order to take advantage of the accumulated experience and developments in Motion Control, drives Servostar700 & iPOS, already used in other GTC subsystems, have been selected.

Additionally, when using an integrated servo drive all the elements of the motion system are connected directly to it: motor, resolver, encoder, limits and home, which does not require additional electronics.

Although local motion control could use the capability of the Servostar 700 to respond through predefined behaviours when receiving signals on some of its digital inputs, it would be preferable to do so through a CAN bus to make communication more standard for the case of that the servo drive would have to be replaced.

As integrated servo drives based on the CANOpen standard, replacement of the Servostar700 or iPOS by another device from another manufacturer would imply a reduced cost and would be limited to the development of the manufacturer’s specific software, that is, the non-standard software.

Both the S700 and the iPOS offer a simple debugging environment. That is, the S700 allows simultaneous access through its RS-232 interface (DriveGUI) and its CAN interface (GCS). The iPOS also allows simultaneous access through its RS-232 interface (EasyMotion) and its CAN interface (GCS).

Both the S700 and the iPOS offer a simple operating environment, that is, both maintains referencing after a disable.

When questioning Kollmorgen in case there are reasons for the Servostar 700 series to be replaced by the new AKD series, the answer we have been given is that they are equivalent and
used interchangeably for most applications, therefore, based on our experience already acquired with the S700, this change would not be justified. Specifically, we have been informed that the S700 series has been developed for the European market to replace the S600, while the AKD series is developed for the US market. The only advantage of the AKDs is that they are more compact in size (~10 cm height).

Concluding, the selected alternative allows to reuse the development performed for other GTC subsystems (Servostar 700 / iPOS / Beckhoff) and the homogenization in the platform that implements the input / output and safety functions in a single unit (Beckhoff), will allow to reduce the development and integration cost.

The philosophy behind that election is based on the platform that adapts to the required functionality and aims to lay the groundwork for future updates on the rest of the analog systems of the different focal stations of the telescope.

### 5.4 Interfaces

The interfaces between GCS and the GC-Set Local Control are the following:

<table>
<thead>
<tr>
<th>Functional description</th>
<th>Type</th>
<th>Protocol</th>
<th>From</th>
<th>To</th>
<th>Trough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode switching</td>
<td>Monitoring</td>
<td>CANOpen</td>
<td>Cabinet LCU</td>
<td>GCS</td>
<td></td>
</tr>
<tr>
<td>Motion Control (various)</td>
<td>Control</td>
<td>CANOpen</td>
<td>GCS</td>
<td>Drives</td>
<td></td>
</tr>
<tr>
<td>Motion Control (various)</td>
<td>Monitoring</td>
<td>CANOpen</td>
<td>Drives</td>
<td>GCS</td>
<td></td>
</tr>
<tr>
<td>Start-up (various)</td>
<td>Control</td>
<td>CANOpen</td>
<td>GCS</td>
<td>Various</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Start-up (various)</td>
<td>Monitoring</td>
<td>CANOpen</td>
<td>Various</td>
<td>GCS</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Electronics Enclosure cooling (various)</td>
<td>Control</td>
<td>CANOpen</td>
<td>GCS</td>
<td>Valve, fan</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Electronics Enclosure cooling (various)</td>
<td>Monitoring</td>
<td>CANOpen</td>
<td>Valve, fan</td>
<td>GCS</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Structure Temp#1</td>
<td>Monitoring</td>
<td>CANOpen</td>
<td>PT100</td>
<td>GCS</td>
<td>Cabinet LCU</td>
</tr>
</tbody>
</table>

The interfaces between HMI and GC-Set Local Control (internal interfaces for contractor):

<table>
<thead>
<tr>
<th>Functional description</th>
<th>Type</th>
<th>Protocol</th>
<th>From</th>
<th>To</th>
<th>Trough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode switching</td>
<td>Control</td>
<td>TBD</td>
<td>Cabinet LCU</td>
<td>HMI</td>
<td></td>
</tr>
<tr>
<td>Component</td>
<td>Type</td>
<td>TBD</td>
<td>HMI</td>
<td>Drives</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>-----------</td>
<td>-----</td>
<td>------</td>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>Local Motion Control (various)</td>
<td>Control</td>
<td>TBD</td>
<td>HMI</td>
<td>Drives</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Local Motion Control (various)</td>
<td>Monitoring</td>
<td>TBD</td>
<td>Drives</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Rotator motor Temp#i</td>
<td>Monitoring</td>
<td>TBD</td>
<td>PT100</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Rotator motor Water Valve</td>
<td>Control</td>
<td>TBD</td>
<td>HMI</td>
<td>Valve</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Rotator motor Water Valve</td>
<td>Monitoring</td>
<td>TBD</td>
<td>Valve</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Rotator motor Air Pressure</td>
<td>Monitoring</td>
<td>TBD</td>
<td>P. Switch</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Electronics Enclosure Temp#i</td>
<td>Monitoring</td>
<td>TBD</td>
<td>PT100</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Electronics Enclosure Fan state</td>
<td>Monitoring</td>
<td>TBD</td>
<td>Fan relays</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>Rotator Bearing Grease Sequence</td>
<td>Control</td>
<td>TBD</td>
<td>HMI</td>
<td>Greasing system</td>
<td>Cabinet LCU</td>
</tr>
<tr>
<td>AG Bearing Grease Replacement</td>
<td>Monitoring</td>
<td>TBD</td>
<td>Greasing system</td>
<td>HMI</td>
<td>Cabinet LCU</td>
</tr>
</tbody>
</table>

During the detailed design the mapping between the functional data and the CAN objects shall be specified.
6 LOCAL INTERLOCK & SAFETY SYSTEM

The Local Interlock and Safety System (LISS) shall provide the GC-Set with any Safety Systems needed to work as an autonomous system from the Safety point of view. The design of the LISS is out of scope of this document (although it is in the scope of the Tender). As stated in A1, it requires a Safety Assessment according to the applicable regulations before proceeding with its design.

Few additional requirements are given therefore in A1 for the LISS, being perhaps the most important that any safety function that is not implemented in the Drives shall be integrated in the Beckhoff Cabinet LCU. See Fig. 89.

For the Interfaces of the LISS with the ISS, see Table 15.

Open Design Issues

- Basically, the whole design of the LISS, according to the applicable regulations.
7 ELECTRICAL AND ELECTRONICS DESIGN

7.1 General

The following is a suggested basic scheme. Each motor will have its own drive and each drive will have its own electrical protection.

As shown in the scheme, five drives will control the five motors, as mentioned in section 5. The desirable choice for Rotator motor is a Kollmorgen Servo drive from S700 series (e.g. S712). Also, for the two motors of the Turn table mechanism a Kollmorgen Servo drive is suggested (e.g. 703 or 706). These two drives must work in a Master/Slave configuration to prevent backlash effects. IPOS series from Technosoft are suggested for the Probe Arm and the Linear Positioning Stage.

All the mechanisms have two limit switches, installed each at the end of their movement range. The limit switches have to stop the corresponding mechanism when any of the limits is reached. Motors proposed for Probe Arm and Linear Positioning have its own limits installed on itself.

Encoder sets (tape and heads) are required for both Rotator and Turn table. These are necessary to define the position of the device and for referencing them.

A pneumatic brake system is necessary to ensure undesirable movements when the Rotator is stopped.

There shall be Emergency stops located inside the Electronics Cabinet, on top of the Rotator and in the HMI panels. Interlock keys shall be on the HMI panels.

A safety switching device like a disconnector shall be installed outside the cabinet to allow power off the cabinet.

All the drives must have an individual electrical protection. Subsystems shall have 30mA individual differential protection apart from the magnetothermal usual ones. Smaller IPOS drives will be benefit from the 24V power supply protection.
Independent power supplies with PFC for AG Instrument, for IPOS servos and for cooling system items are suggested. Power supplies from Phoenix Contact TRIO-PS series are preferred.

Some requirements apply to the devices mounting and connection on the back panel. See A1.

A cable and connectors list has been compiled. See table and corresponding drawing in 11.

### 7.2 Electronic Cabinet

The aim at this phase is to determine whether one cabinet 2000x800x800mm (the standard in the GTC) is enough for the equipment and lets still some margin for future implementations.

Following you can see the dimensions of the typical devices inside the cabinet.

<table>
<thead>
<tr>
<th>Device</th>
<th>Height(mm)</th>
<th>Width(mm)</th>
<th>Depth(mm)</th>
<th>Weight(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Servo Drive S700</td>
<td>345</td>
<td>70</td>
<td>243</td>
<td>4400</td>
</tr>
<tr>
<td>IPOS Drive</td>
<td>139</td>
<td>25</td>
<td>94</td>
<td>250</td>
</tr>
<tr>
<td>Beckhoff</td>
<td>100</td>
<td>50</td>
<td>80</td>
<td>500</td>
</tr>
<tr>
<td>Contactors</td>
<td>70</td>
<td>45</td>
<td>90</td>
<td>200</td>
</tr>
<tr>
<td>Differential</td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>300</td>
</tr>
<tr>
<td>Power Supply</td>
<td>140</td>
<td>60</td>
<td>150</td>
<td>1500</td>
</tr>
</tbody>
</table>
Fig. 91 shows that a cabinet 1600mm(H)x600mm(W)x500mm(D) would be enough for the estimated volume and foreseen distribution. Nevertheless, a 2000x800x800mm is needed to ensure enough margin.

Power and Control devices should be installed in different areas, power devices at the bottom of the cabinet. A galvanized steel sheet shall be installed between both areas to minimize electromagnetic interferences.

A weight of 40Kg is estimated for the Electronics (without the back plane).

The estimate power consumption will be in the range 1000-1500VA.

Open Design Issues

- Complete electrical distribution design including all protections required in A1.
- Start-up system HW design and selection (contactors)
- Once components have been selected:
  - Final layout and free area for future implementation
  - Power consumption budget and compatibility with the electrical power available
  - Heat dissipation budget (input for the Enclosure cooling system calculations)
8 LOGISTIC SUPPORT

8.1 Assembly

Some assembly aspects have been considered during the preliminary design described in chapter 4.

Open Design Issues

- Complete assembly sequence shall have to be composed in further steps.

8.2 Verification

Verification of each requirement and interface is outlined in documents A1, A2 and A4. No problem has been identified with testability of requirements so far but this should be checked further as design proceeds.

Some Test Bench is needed to support the Rotator and AG Mechanics probably in 3 different orientations:

- Nominal Vertical Rotation Axis (as in the GTC with the Tube pointing to the Zenith)
- Inverted Vertical Rotation Axis
- Horizontal Rotation Axis

The Test bench must allow to handle the Rotator with the Instrument dummy attached, at least for the Horizontal Rotation Axis position.

Finally, the system must be stiff enough to ensure that no external effects are affecting the results (e.g. tracking performance).

In order to test motion control functionalities of the Drives not available from the HMI, the Drives manufacturer GUI could be used to generate the required profiles and obtain the corresponding results.

Interfaces with the GCS are foreseen to be tested at factory by GTC personnel who will take the needed HW and SW with them.

Safety functionality shall be tested according to the applicable regulation.

8.3 Handling

The Rotator + AG Mechanics assembly shall be handled as a whole at the GTC facilities mounted on the Transport Cart (see 4.5.2). The transport cart shall carry the Cassegrain Science Instrument as well.

There are main two open issues to be solved by Grantecan (out of scope of the CG-Set Tender):

- The selection of a general-purpose system for easy handling of any kind of loads up to 5 ton on the different surfaces of the GTC building and Telescope floor.
- The adaptation of the OSIRIS Instrument turning tool to attach the Cassegrain Rotator
While this is not solved a Transportation Cart must be built specifically for both Cassegrain Rotator and Cassegrain Scientific Instrument.

Once the GC-Set is downloaded at the GTC facilities it shall be installed on the Cart and taken to another room for Site Testing. When ready, it shall be taken with the Cart to the Telescope floor below the Telescope Tube. Then it will be lifted by the lifting system as described in 8.5.2.1.

8.4 Storage, Packaging and Transportation

This point has not been studied during the preliminary design.

Open Design Issues

- Foresee storage, packaging and transportation according to the requirements in A1

8.5 Integration at the GTC

8.5.1 Rotator Mounting in the Telescope Structure

*NOTE: this mounting operation is out of scope of the GC-Set Tender. The paragraphs below are written here as additional information.*

The installation of the instrument rotator, as well as its maintenance, is proposed to be realized with the telescope tube in vertical position, reaching from the bottom.

For lifting the rotator 3 electrical winches are available (out of scope of the CG-Set Tender) which are installed in the lower part of the primary mirror cell. Once the rotator is aligned and fixed, the winches are used for lifting and lowering the Science Instruments to be mounted on the rotator. For this purpose, the static ring of the rotator bearing has apertures for guiding through the cables of the winches. Once the Science Instrument is mounted, the cable load is almost completely released but the cables itself will remain fixed on the instrument (in case of OSIRIS on its interface structure).

Regarding the AG -System, since it is mechanically independent from the rotator, it shall have lifting points, so that it can be dismounted form the rotator (lifting system for that case is not included in this work).
8.5.2 Alignment

8.5.2.1 Rotator w.r.t Telescope Structure

The rotator shall have adjustment mechanisms to move the rotator laterally with respect to the telescope structure. It is proposed to place these mechanisms close to the main structural nodes of the primary mirror cell achieving a stiff response.

NOTE: alignment operation is out of scope of the GC-Set Tender. The paragraphs below are written here as additional information.

Once the rotator is provisionally fixed on the telescope structure it will be necessary to align its rotation axis with the optical axis of the telescope (tube axis) pointing to the centre of the secondary mirror. For this, the rotator includes 8 radial M12 set screws for centring the rotator and calibrated alignment shims of different thickness (overall nominal thickness 5 mm and 0.05 mm smallest), mounted between rotator attachment flange and telescope interface flange, for controlling axial position and the orientation of the rotator.

These rotations are the most critical degrees of freedom during the alignment of the rotator since their variations has the biggest influence on the absolute pupil error to the telescope pupil (distance between focal plane and M2 is 18139.41 mm). Lateral and axial deviations do not have so much influence since the first one has the same magnitude on M2 and the second one can be compensated by the telescope optics (but causes an orientation error of the rotation axis of the AG arm rotator).
For the alignment of the rotator with respect to the tube axis it is proposed to use the dimensional measurements of the Cassegrain interface flange, realized during the construction of the telescope structure. There are measurements of the radial oscillations and the decentring with respect to the tube axis, as well as axial deviations. There is no information about the medium diameter of the centring flange.

Using the measurements of the radial oscillation it is possible to centre the rotator with respect to the tube axis measuring the distance between the static ring of the rotator and the attachment flange on the telescope by means of a gauge through radial holes. Additionally, there are axial holes for verifying the distance between both flange with help of calibrated pins.

Although there are measurements of the axial deviations of the Cassegrain attachment flange, it is recommended to repeat this measurement for all screw locations compensating these deviations by shims. In this way, unnecessary stress in the rotator structure and above all in the attachment flange are far-reaching avoided.

For verification of the inclination of the rotator respect to the tube axis a precision clinometer can be used (WYLER Clino 2000, 5 arcsec sensibility). Knowing the exact tube position (inclination) reading the encoder of the elevation axis and touching the attachment flange of the rotator with the clinometer the angle of the rotator with respect to the tube axis can be determined. Considering the measurement errors and settlings during the tightening of the fixing screws a final error of 0,1 mrad is expected, corresponding to a pupil error of 1,7 mm or 0,3%.

According to the realized measurements during the construction of the telescope, the inclination of the Cassegrain attachment flange is about 0,04 mrad.

<table>
<thead>
<tr>
<th>Flange centre w.r.t tube axis</th>
<th>X=0,95 mm</th>
<th>Y=-0,2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance flange plane to elevation axis</td>
<td>Z=-7290,8 mm</td>
<td></td>
</tr>
<tr>
<td>Inclination w.r.t. tube axis</td>
<td>RotX=0,00 mrad</td>
<td>RotY=-0,04 mrad</td>
</tr>
<tr>
<td>Axial oscillation</td>
<td>0,46 mm</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>Not measured.</td>
<td></td>
</tr>
<tr>
<td>Radial oscillation w.r.t. tube axis</td>
<td>3,18 mm</td>
<td></td>
</tr>
<tr>
<td>Residual radial oscillation</td>
<td>1,67 mm</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 93 Cassegrain Attachment Flange position, inclination and form deviations.
Fig. 94 Cassegrain Attachment Flange radial deviations.

Fig. 95 Cassegrain Attachment Flange radial deviations.
8.5.2.2 AG Instrument w.r.t Rotator Axis

NOTE: this alignment operation is out of scope of the GC-Set Tender. The paragraphs below are written here as additional information.

Once the GC-Set is at the GTC, and prior to the integration in the telescope, the AG -Instrument has to be integrated inside the arm and the pick-off mirror has to be aligned. It will be necessary to align the pick-off mirror on ground with help of a total station, similar to the procedure followed in case of the Nasmyth foci. For this purpose, the complete AG -System has to be available mounted on a test bench with the rotation axis of the turn table in horizontal position and a reference installed in the AG -Instrument.

The alignment of the pick-off mirror could also be done with the rotator in horizontal position using an auxiliary folding mirror.

Open Design Issues
- Interfaces for alignment aids should be foreseen.

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Position [dec]</th>
<th>Z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRIDA_CASS_LV1</td>
<td>20</td>
<td>-7290.74</td>
</tr>
<tr>
<td>BRIDA_CASS_LV2</td>
<td>60</td>
<td>-7290.63</td>
</tr>
<tr>
<td>BRIDA_CASS_LV3</td>
<td>100</td>
<td>-7290.78</td>
</tr>
<tr>
<td>BRIDA_CASS_LV4</td>
<td>160</td>
<td>-7290.96</td>
</tr>
<tr>
<td>BRIDA_CASS_LV5</td>
<td>200</td>
<td>-7290.75</td>
</tr>
<tr>
<td>BRIDA_CASS_LV6</td>
<td>240</td>
<td>-7290.74</td>
</tr>
<tr>
<td>BRIDA_CASS_LV7</td>
<td>280</td>
<td>-7291.09</td>
</tr>
<tr>
<td>BRIDA_CASS_LV8</td>
<td>340</td>
<td>-7290.92</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>-7290.83</td>
</tr>
<tr>
<td>RMS</td>
<td></td>
<td>0.12</td>
</tr>
</tbody>
</table>

*Fig. 96 Cassegrain Attachment Flange position w.r.t. elevation axis.*
8.6 Safety

All safety features have been left to the GC-Set Tender contractor and shall be according to the applicable regulation.

Open Design Issues

- Identify applicable standards and regulations
- Safety functions, as well as their implementation and testing, shall be done according to those regulations

8.7 Reliability

Reliability is a main driver of the whole GTC design and it has been taken into account in every regard throughout the design, e.g. by using fail-safe elements, design margins or proved components.

Open Design Issues

- Quantify reliability by a RAMS analysis

8.8 Maintainability

Maintainability is a main driver of the whole GTC design and it has been taken into account in every regard throughout the design.

One of the main points considered so far is accessibility. To this regard, the items identified needing access for either preventive or corrective maintenance are:

- Bearings- grease replacement, depending on the final grease replacement system
- Rotator Motor windings- substitution
- AG motors- repairs, substitution
- Water connections at windings cooling system- repairs
- Encoder heads- substitution
- Braking system- air connections, clean braking disc, etc...
- Electrical Limits- repairs, substitution
- Dampers- repairs, substitution, visual control
- Connection Panels- repairs, substitution of cables, substitution of connected parts, unmounting of Rotator from the Telescope, etc...
- Probe Arm drive- substitution
- Focus linear table- substitution
- AG Instrument and electronics box- repairs, adjustments, upgrades
- Cable chains- cable substitutions, new cables, etc...
- Electronics Enclosure- repairs, upgrades, checks, ...

All these items shall be accessible from either one of the following:

- Central shutter platform- access to the innermost part of the AG system and the Rotator
- Scissors Platform at the Telescope floor- access to the outermost parts of the Rotator and to the Electronics Enclosure. See Fig. 97 and Fig. 98.
- Primary Mirror Cell beam structure- access to the outermost parts of the Rotator (to this regard Grantecan shall study the installation of an additional platform between beams external to the rotator). See Fig. 99.
Further, a preliminary list of spares has been identified. See spares list in A1.

Finally, other maintainability criteria have been taken on account throughout the preliminary design as stated in A1.
Open Design Issues

- Preliminary definition of main maintenance operations
- Assessment of corresponding accessibility and spares needed, between others
- Quantify maintainability (MTTR and Day time preventive maintenance) with the corresponding analysis
9 SYSTEM BUDGETS

9.1 Error Budget

Six errors are controlled:

- **Relative pupil error (Science and AG-Instrument relative orientation towards the pupil)**
  - From the GTC point of view: Relative position of the pupil image in AG and Science Instruments fields (affecting wave-front sensing and corresponding optics correction)
  - From the GC-Set supplier point of view: errors in relative orientation of AG and Science Instruments (given by their corresponding coordinate systems at the focal plane) because of manufacturing and mounting deviations and gravity deformations.

- **Absolute Pupil error (Science Instrument orientation towards the Pupil)**
  - From the GTC point of view: Pupil image position error on the instrument (affecting mainly the optics sizing margins for the Science Instrument)
  - From the GC-Set supplier point of view: The error in orientation of the Science Instrument towards the pupil (given by its coordinate system orientation) because of manufacturing and mounting deviations and gravity deformations.

- **Lateral positioning error (AG Instrument relative to Science Instrument)**
  - From the GTC point of view: AG Instrument pointing relative to Science Instrument pointing (affecting the pointing with the Telescope axes, to place the image at the expected pixel in the Science Instrument, in circumstances which differ from those of the relative pointing calibration)
  - From the GC-Set supplier point of view: lateral positioning error of AG Instrument relative to Science Instrument (given by their corresponding coordinate systems at the focal plane) after a point to point movement, or after remounting the POM or the Linear Stage, and under any temperature or gravity orientation conditions

- **Lateral position stability (AG Instrument relative to Science Instrument)**
  - From the GTC point of view: AG Instrument lateral position stability relative to Science Instrument (limit the image movement during the observation)
  - From the GC-Set supplier point of view: AG Instrument lateral position stability relative to Science Instrument (given by their corresponding coordinate systems at the focal plane) while the Rotator is rotating and the Probe Arm and Turn Table have been stopped, allowing for any temperature or gravity orientation variations

- **Axial positioning error (AG Instrument relative to Science Instrument)**
- **Axial position stability (AG Instrument relative to Science Instrument)**
  - From the GTC point of view: AG instrument focus stability relative to Science Instrument (maintain image invariability during the observation).
  - From the GC-Set supplier point of view: AG Instrument axial position stability relative to Science Instrument (given by their corresponding coordinate systems at the focal plane) while the Rotator is rotating and the Probe Arm and Turn Table have been stopped, allowing for any temperature or gravity orientation variations.

Tolerances for these errors are found in document A1 (Performance Requirements), except for the Absolute Pupil error. It is not placed as such in the requirements since there are only 2 terms affecting this error within scope of the Tender (Instrument flange wobble and bending). Specific requirements for those terms are placed rather than constraining the total pupil error, which is anyhow useful to calculate from the GTC point of view.

In the budget results hereafter is stated for each term whether it is within scope of the Tender “contractor” or out of scope “GTC”.

### 9.1.1 Relative Pupil Error (Science and AG-Instrument relative orientation towards the pupil)

#### 9.1.1.1 Relative orientation Error due to Gravity

To determine the relative pupil displacement due to gravity, the point of observation is put one time onto the focal plane of the AG-Instrument and another time onto the focal plane of the Science Instrument, looking in both cases towards M2. The deformations of the rotator structure, pick-off mirror and optical bench will make see M2 in another position.

The orientation error is determined by the normal vectors of the focal planes which are altered by displacements and rotations due to gravitational deformations (i.e. the point where the normal vector hits the pupil is determined). The normal vector of the focal plane of the AG-Instrument first is reflected over the pick-off mirror which itself experiences movements due to gravity, looking afterwards the orientation error (see Fig. 100).
The Excel-Sheet “CG-Set-Error-Budget.xls”, Gravity (case 1 to 4) contains the equations for calculating the orientation errors. The results from the FE-Analysis are inserted in the green marked cells, the resulting orientation errors are shown in the orange marked cells.

**Equations behind the cells**

Exemplary equation for reflection of a point (AG) over a plane (POM):

\[
\overrightarrow{AG}_0^R = \overrightarrow{AG}_0 - 2 \cdot \left( \overrightarrow{n}_{POM} \cdot (\overrightarrow{AG}_0 - POM) \right) \cdot \overrightarrow{n}_{POM}
\]

**Science Instrument**
The normal vector of the focal plane is altered by rotations:

\[ \vec{n}'_{SI} = \vec{n}_{SI} + d\vec{n}_{SI} \]

with

\[ dn_x = n_z \cdot \theta_y - n_y \cdot \theta_z \]
\[ dn_y = -n_z \cdot \theta_x + n_x \cdot \theta_z \]
\[ dn_z = n_y \cdot \theta_x - n_x \cdot \theta_y \]

and

\[ \vec{n}' = \frac{\vec{n} + d\vec{n}}{||\vec{n} + d\vec{n}||} \]

Together with the focal plane displacements \( d_{SI} \), the orientation error is given by

\[ PE_{SI} = d_{SI} + \vec{n}'_{SI} \cdot D_{M2} \]

being \( D_{M2} \) the distance to the telescope pupil.

**AG - Instrument**

In case of the AG - Instrument the focal plane origin \( AG_0 \) is also shifted by displacements.

\[ \vec{AG}'_0 = \vec{AG}_0 + d\vec{AG}_0 \]

Further, a second point is created, defined by focal plane origin and normal, to be able to reflect the focal plane normal.

\[ \vec{AG}'_1 = \vec{AG}'_0 + \vec{n}'_{AG} \]
Both points are reflected over the pick-off mirror obtaining the reflected AG normal

\[ n_{AG}^R = AG_1^R - AG_0^R \]

The orientation error for AG is given by

\[ PE_{AG} = AG_0^R + n_{AG}^R \cdot D_{M2} \]

And the differential or relative orientation error

\[ dPE = PE_{AG} - PE_{SI} \]

The orientation errors or pupil errors are expressed in percent of the pupil radius (590 mm).

### 9.1.1.2 Relative orientation error due to Fabrication and Mounting Errors

Apart from the gravity, fabrication and mounting errors have influence on the pupil displacement. As the error is defined by a relative displacement of the pupil between the Science Instrument and the AG -Instrument, all mechanical interfaces between them are involved, with exception of the errors between the arm rotator axis and the pick-off mirror which can be compensated by the pick-off mirror alignment.

Table 16 shows an estimation for the relative orientation error due to fabrication and mounting errors. The biggest contribution is caused by the mounting surface of the arm rotator, why it is of interest to have a closer look on this interface.

Solutions to reduce the error induced by this surface could be:

- reduce the machining tolerance
- place a spacer under the arm rotator which could be machined according to the dimensional verifications of the assembled rotator
- machine this surface after dimensional verifications of the assembled rotator
### Relative (Pupil) Error AG – SI orientation, due to Fabrication and Mounting Errors

<table>
<thead>
<tr>
<th>Surface</th>
<th>Tolerance</th>
<th>Comment</th>
<th>Tolerance [mm, mrad]</th>
<th>Effective Distance [mm]</th>
<th>Displ. on Pupil [mm]</th>
<th>Resp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Instrument (SI)</td>
<td>Flatness</td>
<td>Flange Plane</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>H7/g6 Fit (2025)</td>
<td>Centring with Adapter</td>
<td>0,319</td>
<td>-</td>
<td>0,32</td>
<td>GTC</td>
</tr>
<tr>
<td>Science Instrument Adapter (SI-Side)</td>
<td>Flatness</td>
<td>Flange Plane, SI side</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>Concentricity</td>
<td>SI side to IR side</td>
<td>0,050</td>
<td>-</td>
<td>0,05</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td>SI side to IR side</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>H7/g6 Fit (2080)</td>
<td>Centring with IR</td>
<td>0,319</td>
<td>-</td>
<td>0,32</td>
<td>GTC</td>
</tr>
<tr>
<td>Instrument Rotator, Rotating Ring</td>
<td>Flatness</td>
<td>Flange Plane, Adapter side</td>
<td>0,050</td>
<td>2214</td>
<td>0,41</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Concentricity</td>
<td>Adapter side to AG Structure side</td>
<td>0,050</td>
<td>-</td>
<td>0,05</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td>Adapter side to AG Structure side</td>
<td>0,050</td>
<td>2060</td>
<td>0,44</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>AG Main Structure</td>
<td>Flatness</td>
<td>Flange Plane, Rotator side</td>
<td>0,050</td>
<td>2060</td>
<td>0,87</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>H7/g6 Fit (2060)</td>
<td>Centring with IR</td>
<td>0,319</td>
<td>-</td>
<td>0,32</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td>IR side to AG Bearing side</td>
<td>0,050</td>
<td>978</td>
<td>1,83</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Concentricity</td>
<td>IR side to AG Bearing side</td>
<td>0,050</td>
<td>-</td>
<td>0,05</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>AG Turn Table Bearing</td>
<td>Flatness</td>
<td>Bearing Plane, AG Structure side</td>
<td>0,020</td>
<td>978</td>
<td>0,73</td>
<td>Manufacturer</td>
</tr>
</tbody>
</table>
### Table 16: Estimated Error Budget for relative pupil error due to fabrication and mounting errors.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Error Budget</th>
<th>Measurement</th>
<th>Value</th>
<th>Manufacturer</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>H7/g6 Fit (878)</td>
<td>Centring with AG Structure</td>
<td>0.172</td>
<td></td>
<td>-</td>
<td>0.17</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Radial Oscillation</td>
<td>-</td>
<td>0.020</td>
<td></td>
<td>-</td>
<td>0.02</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Nutation</td>
<td>-</td>
<td>0.015</td>
<td></td>
<td>-</td>
<td>0.27</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>AG Turn Table</td>
<td>Flatness</td>
<td>0.020</td>
<td>1084</td>
<td>0.66</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
<td>H7/g6 Fit (1084)</td>
<td>Centring with AG Bearing</td>
<td>0.199</td>
<td>-</td>
<td>0.20</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
<td>AG Turn Table</td>
<td>Inclined Plane</td>
<td>0.040</td>
<td>192</td>
<td>7.46</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
<td>AG Arm Rotator</td>
<td>H7/g6 Fit (192)</td>
<td>Centring with AG Turn Table</td>
<td>0.090</td>
<td>-</td>
<td>0.09</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Wobble</td>
<td>-</td>
<td>0.020</td>
<td></td>
<td>-</td>
<td>0.36</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>-</td>
<td>0.004</td>
<td></td>
<td>-</td>
<td>0.00</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>AG Linear Stage</td>
<td>Pitch</td>
<td>40 of 100 mm total range</td>
<td>0.030</td>
<td>0.54</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
<td>Yaw</td>
<td>40 of 100 mm total range</td>
<td>0.030</td>
<td></td>
<td>0.54</td>
<td>Manufacturer</td>
<td></td>
</tr>
<tr>
<td>POM alignment</td>
<td>Piston</td>
<td>0.100</td>
<td>-</td>
<td>0.10</td>
<td>GTC</td>
<td></td>
</tr>
<tr>
<td>Tip-Tilt</td>
<td>-</td>
<td>0.100</td>
<td>-</td>
<td>3.54</td>
<td>GTC</td>
<td></td>
</tr>
</tbody>
</table>

Total (RMS) [mm] 8.68
Total (RMS) [%] 1.47
9.1.1.3 Total Relative Pupil Error. Conclusions

The total relative pupil error between Science Instrument and AG -Instrument will result in:

<table>
<thead>
<tr>
<th>Source</th>
<th>Value [mm]</th>
<th>Value [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity (case 3)</td>
<td>0.41</td>
<td>0.07</td>
</tr>
<tr>
<td>Fabrication and Mounting</td>
<td>8.69</td>
<td>1.47</td>
</tr>
<tr>
<td>Total</td>
<td>8.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 17 Estimated Error Budget for the relative pupil error. Values can be found in Excel-Sheet CG-Set- Error-Budget.xls, sheet “Gravity (case 4)” and sheet “Mounting and Fabrication”.

The permissible displacement of 5.9mm (1.0%) is exceeded (even if items out of scope of the Tender are not considered). This is caused mainly by the mounting surface of the arm rotator. However, this value can be reduced following some solutions presented above.

The flexion of the Probe Arm was not considered during the preliminary design but an approximate calculation revealed that the actual Probe Arm design would lead to a rotation of the Probe Arm mirror of about 0.5mm.

9.1.2 Absolute Pupil Error (Science Instrument orientation towards the pupil)

9.1.2.1 Absolute orientation error due to Gravity

In opposite to the Folded Cassegrain Focal Stations, in case of the Cassegrain Focal Station there is not strived to obtain a certain flexibility of the rotator to compensate gravitational deformations of the telescope structure, above all the tertiary mirror tower.

Here the aim is to obtain as much stiffness as necessary to comply with the specified pupil error.

Since the telescope pupil (M2) aligns itself with respect to the primary mirror, only the movements between primary mirror and Cassegrain Focal Station have to be considered, regarding the part of the telescope structure.

Gravitational Deformations of the Telescope Structure

The values for the gravitational deformations of the telescope tube have been taken from the Telescope Structure Stress Report, EXT/SHGH/0099-R. In this report, the Cassegrain focal station was loaded with 5.100 kg plus 200 kg for cabinets, in total 5.300 kg.

According to preliminary estimations the complete Cassegrain Focal Station suffers overweight and probably will reach 6.500 kg. However, the weight attached to the Cassegrain interface flange will be about 5.500 kg at z=7350 mm being more favourable than the modelled 5.100 kg.
at \( z = 7700 \text{ mm} \). The final displacements and rotations are expected to be the same or less as that ones indicated in the Telescope Structure Stress Report.

<table>
<thead>
<tr>
<th>Structure Part</th>
<th>( D_y ) [mm]</th>
<th>( \text{Rot}_x ) [( \mu \text{rad} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Mirror Cell</td>
<td>0.728</td>
<td>-153</td>
</tr>
<tr>
<td>Cassegrain Focal Station</td>
<td>0.565</td>
<td>-87</td>
</tr>
<tr>
<td>Difference</td>
<td>0.163</td>
<td>66</td>
</tr>
</tbody>
</table>

*Table 18: Movements of primary mirror cell and Cassegrain focal station due to gravity in horizontal tube position. These values are the same respect to the vertical tube position (tube coordinate system).*

**Gravitational Deformations of the Instrument Rotator itself**

The pupil error due to the gravitational deformations of the rotator itself is done in analogous way as in case of the relative pupil error. The point of view is set on the Science Instrument focal plane, shifting and rotating it according to the results of the FE-analysis, looking where the focal plane normal hits the telescope pupil. Calculations are done in Excel-sheet in section 11 and results are presented in chapter 9.1.2.3.

**9.1.2.2 Absolute orientation error due to Fabrication and Mounting Errors**

In the case of the absolute pupil error for the Science Instrument, less components of the rotator are involved than in the case of the relative pupil error between AG-Instrument and the Science Instrument, but here the alignment of the CG-Set with the telescope tube axis plays also a role (out of scope of the Tender).

The same alignment tolerances as in case of the Folded Cassegrain Rotators can be established, referred to the Cassegrain coordinate system:

\[
\begin{align*}
  \text{dx, dy} & \quad \pm 1.0 \text{ mm} \\
  \text{dz} & \quad \pm 1.0 \text{ mm} \\
  \text{rotz} & \quad \pm 200 \mu \text{rad}
\end{align*}
\]

The part of the final pupil error caused by gravity could be halved aligning the rotator with an offset corresponding to the half of the total gravitational deformations. However, the gain is not so high as in the Folded Cassegrain Focal Stations where the tertiary mirror comes into play.

In the excel sheet referred in section 11 the effects of the different components of the rotator and the alignment errors of the rotator itself are listed. Since the rotator will be aligned taking as reference the instrument attachment flange, rotating surfaces do not have influence in this count (sheet in section 11).
<table>
<thead>
<tr>
<th>Surface</th>
<th>Tolerance</th>
<th>Value [mm, mrad]</th>
<th>Distance [mm]</th>
<th>Displ. on Pupil [mm]</th>
<th>Resp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Instrument (SI)</td>
<td>Flatness</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>H7/g6 Fit (2025)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centring with Adapter</td>
<td>0,319</td>
<td></td>
<td>0,32</td>
<td>GTC</td>
</tr>
<tr>
<td>Science Instrument Adapter (SI-Side)</td>
<td>Flatness</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>Concentricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SI side to IR side</td>
<td>0,050</td>
<td></td>
<td>0,05</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>Parallelism</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SI side to IR side</td>
<td>0,050</td>
<td>2200</td>
<td>0,41</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>H7/g6 Fit (2080)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centring with IR</td>
<td>0,319</td>
<td></td>
<td>0,32</td>
<td>GTC</td>
</tr>
<tr>
<td>Instrument Rotator, Rotating Ring</td>
<td>Flatness</td>
<td>0,050</td>
<td>2214</td>
<td>0,41</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Radial Oscillation</td>
<td></td>
<td></td>
<td>0,02</td>
<td>Manufacturer</td>
</tr>
<tr>
<td></td>
<td>Wobble</td>
<td>0,015</td>
<td></td>
<td>0,27</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>Rotator Alignment</td>
<td>Concentricity</td>
<td>1,000</td>
<td></td>
<td>1,00</td>
<td>GTC</td>
</tr>
<tr>
<td></td>
<td>Perpendicularity</td>
<td>0,200</td>
<td>2660</td>
<td>1,36</td>
<td>GTC</td>
</tr>
</tbody>
</table>

| Total (RMS)                                  | [mm] 1,95            | [%] 0,33         |               |                      |       |

Table 19 Estimated Error Budget for absolute pupil error due to fabrication and mounting errors.
9.1.2.3 Total Absolute Pupil Error. Conclusions

The total absolute pupil error on the Science Instrument will result in:

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity (Telescope Structure)</td>
<td>1.36</td>
<td>0.23</td>
</tr>
<tr>
<td>Gravity (Rotator and Attachment Flange)</td>
<td>0.86</td>
<td>0.14</td>
</tr>
<tr>
<td>Fabrication and Mounting</td>
<td>1.95</td>
<td>0.33</td>
</tr>
<tr>
<td>Total</td>
<td>2.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 20: Estimated Error Budget for the absolute pupil error. Values can be found in Excel-Sheet CG-Set-Error-Budget.xls, sheet “Gravity (case 2-4)” and sheet “Mounting and Fabrication”.

The permissible displacement of 5.9mm (1.0%) is far from exceeded. No critical factors are identified.

9.1.3 Positioning Errors (AG Instrument relative to Science Instrument)

Relative position of AG and Science Instrument shall be calibrated once both Instruments are installed at the GTC. Therefore, fabrication and mounting errors are not involved. Nevertheless, some relative errors will arise when the Arm is placed in positions different from the calibration one or in different temperature conditions, etc.... The same can happen when the POM or the Linear Stage are dismounted and mounted again.

Total positioning error have been calculated in order to be compared with the corresponding requirement. From the total positioning errors, the non-measurable part of the error (or the errors that the encoders cannot read), the uncertainty, has been extracted too. It is interesting from the GTC point of view to quantify the uncertainty to have a reference of how far we can potentially go if measurable errors would be corrected or compensated. This parameter, however, has not been placed as a requirement since it is contained in the total error which, a priori, seems achievable without corrections.

Regarding the position error after a point to point movement it is understood here as the difference between the commanded and the real position.

The relative values are obtained for the Virtual AG coordinate system and the Science Instrument Coordinate System. Lateral movements take place in the X-Y-plane and axial movements along the Z-axis.

Comments:

- This error Budget is based on preliminary calculations and estimations. For the final error budget values from detailed calculations and modelling shall be used, as well as measurements on final components, like run-outs and encoder accuracies.
- The values for gravitational deformations were calculated in the Excel-Sheet CG-Set-
  Error-Budget.xls, sheets Gravity (case 1-4). The final results can be found in sheet “Grav-
  ity (case 4)”, cells G97-109.

Table 21  Pick-off mirror positioning error budget; lateral position uncertainty.

9.1.3.1  Lateral Positioning Error

The total lateral position error of the pick-off mirror is composed above all by gravitational de-
formations, thermal expansion and bearing run-outs. Its maximum value for the two-dimen-
sional error is 82.6μm (0,02arcsec).

The values for the gravitational deformations are taken from the FEM analysis described in
chapter 4.6.3.3.

<table>
<thead>
<tr>
<th>Lateral Positioning Error</th>
<th>Comment</th>
<th>Half P-P [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravitational Displacements</strong></td>
<td>2400 kg Science Instrument, horizontal tube position</td>
<td>9</td>
</tr>
<tr>
<td><strong>Turn Table Bearing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial run-out</td>
<td>Assumption: AG-CSYS and POM have the same displacement.</td>
<td>10</td>
</tr>
<tr>
<td>Precession</td>
<td>3° (x2) assuming that the indicated value is the half cone angle; turn table moving as rigid body.</td>
<td>7</td>
</tr>
<tr>
<td><strong>Turn Table Encoder Accuracy</strong></td>
<td>6,5°, R(FOV)=371 mm.</td>
<td>11</td>
</tr>
<tr>
<td><strong>Arm Rotator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eccentricity</td>
<td>2 μm, (x1) due to small rotation range of 120°</td>
<td>1</td>
</tr>
<tr>
<td>Wobble</td>
<td>10 μrad (half cone), (x1) due to small rotation range of 120°; arm as rigid body</td>
<td>2,25</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/-0,0025° absolute accuracy, R(Arm)=525 mm.</td>
<td>23</td>
</tr>
<tr>
<td>Mounting Repeatability</td>
<td>+/-0,005 mm at R=87 mm</td>
<td>26</td>
</tr>
<tr>
<td><strong>Linear Positioner</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral Deviation</td>
<td>(due to integration)</td>
<td>10</td>
</tr>
<tr>
<td>Rolling Stiffness</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>Mounting Repeatability</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Thermal displacements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotator Structure</td>
<td>Global effects, total operation range -2/+19°C, R(FOV)=371 mm.</td>
<td>46,5</td>
</tr>
</tbody>
</table>
Arm

Local effects due to fast changing temperature, medium value 1.8°C in 1h, D(AG)=450 mm, (x2). 10

Brakes

Backlash 0.5° estimated, i=1000, R(FOV)=371 mm, (x2) 3

Clamping Motion 0.5° estimated, i=1000, R(FOV)=371 mm, (x2) 3

Pick-off Mirror

Mounting Repeatability 9 2 x 10 µrad in two directions 13

Total RMS 59

---

Table 22  Lateral positioning error budget.

---

The lateral position uncertainty is practically determined by the accuracy of the encoders and the gravitational deformations. The encoder accuracy is one of the main sources for the lateral uncertainty why a calibration should be taken into account.

<table>
<thead>
<tr>
<th>Lateral position Uncertainty</th>
<th>Comment</th>
<th>Half P-P [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Displacements</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Turn Table Bearing</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Radial run-out</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Precession (rotation as effect)</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Turn Table Encoder Accuracy</td>
<td>6.5°, R(FOV)=371 mm.</td>
<td>11</td>
</tr>
<tr>
<td>Arm Rotator</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Eccentricity</td>
<td></td>
<td>2,25</td>
</tr>
<tr>
<td>Wobble (rotation as effect)</td>
<td></td>
<td>2,25</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/-0.0025° absolute accuracy, R(Arm)=525 mm.</td>
<td>23</td>
</tr>
<tr>
<td>Mounting Repeatability</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>Linear Positioner</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Lateral Deviation</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Rolling Stiffness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mounting Repeatability</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td><strong>Thermal displacements</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9 Responsibility has GTC.
9.1.3.2 Axial Positioning Error

See also lateral position error, chapter 9.1.3.1.

The maximum value for the axial error is 55μm, established in the document A1.

<table>
<thead>
<tr>
<th>Source</th>
<th>Comment</th>
<th>Half P-P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Displacements</td>
<td>2400 kg Science Instrument at Z=-425 mm, horizontal tube position</td>
<td>22</td>
</tr>
<tr>
<td>Turn Table Bearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial run-out</td>
<td>Assumption: AG-CSYS and POM have the same displacement.</td>
<td>10</td>
</tr>
<tr>
<td>Arm Rotator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wobble (displacement as effect)</td>
<td>10 μrad (half cone), D(AG)=450 mm. (x1) due to small rotation range of 120°</td>
<td>2,6</td>
</tr>
<tr>
<td>Linear Positioner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/-1 μm reference, +/-1 μm repeatability + 2 μm Backlash (TBC)</td>
<td>3</td>
</tr>
<tr>
<td>Axial Stiffness</td>
<td>3 N/μm, 1,5 kg AG -Instrument</td>
<td>2,5</td>
</tr>
<tr>
<td>Thermal displacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotator Structure</td>
<td>Global effects, total operation range - 2/+19°C, R(FOV)=371 mm.</td>
<td>46,5</td>
</tr>
<tr>
<td>Arm</td>
<td>Local effects due to fast changing temperature, medium value 1,8°C in 1h, D(AG)=450 mm, (x2).</td>
<td>10</td>
</tr>
<tr>
<td>Brakes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backlash</td>
<td>0,5° estimated, i=1000, R(FOV)=371 mm, (x2)</td>
<td>3</td>
</tr>
</tbody>
</table>

10 Responsibility has GTC.
9.1.3.3 Conclusions

The lateral and axial errors are dominated by thermal deformations of the Rotator structure, although arm flexibility has not been considered and might be significant in the final result. New analysis must be performed taking this factor into account.

In both, lateral and axial errors, the only errors that might be known by the encoder are the brakes effects but this are so small that the encoder accuracy is not enough to measure it reliably and therefore there is no place for telescope pointing corrections based on the errors measured by the encoders.

9.1.4 Position stability (AG Instrument relative to Science Instrument)

9.1.4.1 Lateral Position Stability

In the count for the stability enters the complete gravitational deformation, that means the peak-to-peak value instead of the half peak-to-peak value, since the rotator is moving around its axis. Further the brake backlash is counted and global and local thermal displacements. For the global thermal gradient, the complete nominal temperature range has been considered for thermal variation.
The maximum value for the two-dimensional stability is 82.6μm (0.1arcsec), established in the document A1.

<table>
<thead>
<tr>
<th>Lateral position Stability</th>
<th>Comment</th>
<th>P-P [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Displacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Positioner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rolling Stiffness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal displacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotator Structure</td>
<td></td>
<td>46.5</td>
</tr>
<tr>
<td>Arm</td>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>Brakes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backlash</td>
<td></td>
<td>6.0</td>
</tr>
</tbody>
</table>

Table 25 Lateral position stability error budget.

9.1.4.2 Axial Position Stability

<table>
<thead>
<tr>
<th>Axial position Stability</th>
<th>Comment</th>
<th>P-P [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Displacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Positioner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backlash</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial Stiffness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal displacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotator Structure</td>
<td></td>
<td>46.5</td>
</tr>
<tr>
<td>Arm</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Brakes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Backlash</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Table 26 Axial position stability error budget.
9.1.4.3 Conclusions

Thermal deformations are again the most significant factor. Requirements are met although, again for this error, the Probe Arm flexibility must be considered.

There is not a specific Axial position stability requirement for practical reasons. Although this requirement is important conceptually, it terms in the budget are constrained already by other requirements.

9.2 Mass Budget

The most meaningful terms of the System Mass Budget are shown hereafter.

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotator Mechanics assembly</td>
<td>1537</td>
</tr>
<tr>
<td>Rotator Main Assembly</td>
<td>1467</td>
</tr>
<tr>
<td>Main Rotator Bearing</td>
<td>1095</td>
</tr>
<tr>
<td>Others</td>
<td>371</td>
</tr>
<tr>
<td>Others</td>
<td>70</td>
</tr>
<tr>
<td>AG Mechanics Assembly</td>
<td>978</td>
</tr>
<tr>
<td>AG TurnTable Main Assembly</td>
<td>801</td>
</tr>
<tr>
<td>A&amp;G Main Structure</td>
<td>402</td>
</tr>
<tr>
<td>TurnTable Bearing</td>
<td>169</td>
</tr>
<tr>
<td>TurnTable Structure</td>
<td>103</td>
</tr>
<tr>
<td>A&amp;G Arm Structure</td>
<td>8</td>
</tr>
<tr>
<td>Others</td>
<td>117</td>
</tr>
<tr>
<td>Others</td>
<td>177</td>
</tr>
<tr>
<td>TOTAL (Rotator + AG Mechanics)</td>
<td>2515</td>
</tr>
</tbody>
</table>

9.3 Electrical power

TBD

Open design issue

- Elaborate a power budget, divided into both types of electrical supply, UPS and 3-phase “clean” and compare with the available power at the GTC specified in document A1.

9.4 Thermal dissipation

TBD

Open design issue
- Elaborate a thermal dissipation budget, both inside the cabinet and at the Rotator assembly in order to compare with dissipation requirements in document A1, and to proceed with the cabinet cooling system calculations and assess feasibility of the cooling system
10 COMMERCIAL COMPONENTS LIST

The commercial components listed below are for guidance only. The definitive components shall be selected during the detailed design. Small parts like spring plungers, index bolts or special adjustment screws are not listed.

### TL-IR-CG-000 Instrument Rotator

<table>
<thead>
<tr>
<th>N°</th>
<th>Component</th>
<th>Model</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Main Rotator Bearing</td>
<td>Rothe Erde Preloaded and sealed customized crossed roller bearing</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Direct Drive Motor</td>
<td>IDAM RI11-3P-2150x175-HD1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Cold Plates</td>
<td>LYTRON CP10GP14</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Encoder</td>
<td>Heidenhain ERA 7480C</td>
<td>2 Heads 1 Tape</td>
</tr>
<tr>
<td>5</td>
<td>Brake</td>
<td>Ringspann DH 10 FPM</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Limit Switches / Absolute Switch</td>
<td>Telemecanique Osiswitch XCMD2116LS</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Telemecanique Osiswitch XCMD2117L1</td>
<td>+1</td>
</tr>
<tr>
<td>7</td>
<td>Hydraulic Damper</td>
<td>Numatics WEB 1.0 M24</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>Swivel ring</td>
<td>Norelem nlm 07710-2030</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>Modular Air Filter, Regulator</td>
<td>SMC AC20B</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pressure and Control Equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3/2 Way spool valve</td>
<td>Asco Numatics S2000213</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Digital Pressure Switch</td>
<td>SMC ISE40A-C6-T</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Compact flow regulator</td>
<td>Legris 7031 06 00</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Direct Drive Controller</td>
<td>Kollmorgen Servo drive S700 series</td>
<td>1</td>
</tr>
</tbody>
</table>

### AG-CR-AG-200 AG Mechanics Assembly

<table>
<thead>
<tr>
<th>N°</th>
<th>Component</th>
<th>Model</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Probe Arm Drive</td>
<td>Newport RV160HAT</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Linear Positioning Stage</td>
<td>PI M-404-42S</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>TurnTable Cable Chain</td>
<td>IGUS 2600.07.063.0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>TurnTable Bearing</td>
<td>Rothe Erde Preloaded customized crossed roller bearing</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Connection Box</td>
<td>RS S173478</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>TurnTable Gear Head</td>
<td>Bayside Stealth RS60</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>TurnTable Motor</td>
<td>Kollmorgen AC Synchronous Servo Motors (AKM Series)</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>TurnTable Encoder</td>
<td>Heidenhain ERA 7480C</td>
<td>2 Heads 1 Tape</td>
</tr>
<tr>
<td>9</td>
<td>TurnTable Limit Switch</td>
<td>Telemecanique Osiswitch XCMD2117L1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Component</td>
<td>Model</td>
<td>Quantity</td>
</tr>
<tr>
<td>---</td>
<td>------------------------------------------</td>
<td>------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>10</td>
<td>Turntable Hydraulic Damper</td>
<td>Numatics WEB 0.15 M24</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Probe Arm Hydraulic Damper</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>Probe Arm Cable Chain</td>
<td>IGUS 1400.050.075.0</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Turntable Drive</td>
<td>Kollmorgen Servo drive S700 series</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Probe Arm Drive</td>
<td>Technosoft</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>Linear Positioning Stage Drive</td>
<td>Technosoft</td>
<td>1</td>
</tr>
</tbody>
</table>

**AG-CR-AG-270 AG Cable Chain Carrier Assembly**

<table>
<thead>
<tr>
<th></th>
<th>Component</th>
<th>Model</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AG Cable Chain</td>
<td>SERIE 2600.09.125</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Small Guiding Wheel</td>
<td>Hepco Motion Dual Vee W2SSX</td>
<td>1</td>
</tr>
</tbody>
</table>


11 ANNEXES

The following data is attached to this document:

<table>
<thead>
<tr>
<th>Data</th>
<th>Folder name</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error Budget</td>
<td>Error Budget</td>
<td></td>
</tr>
<tr>
<td>Component List</td>
<td>Component List</td>
<td></td>
</tr>
<tr>
<td>Cables and Connectors list and drawing</td>
<td>Cables and Connectors</td>
<td></td>
</tr>
<tr>
<td>3D Model</td>
<td>3D Model</td>
<td></td>
</tr>
<tr>
<td>FE Model</td>
<td>FE Model</td>
<td></td>
</tr>
<tr>
<td>Commercial Components</td>
<td>Commercial Data</td>
<td></td>
</tr>
<tr>
<td>Data Sheets &amp; Manuals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Design Compliance Matrix</td>
<td>Compliance Matrix</td>
<td></td>
</tr>
</tbody>
</table>

Either the File names are self-explanatory or there is any kind of README.txt file in the folder. All of them must be kept up to date through the different design phases.