Design of a calibration system for the Q and W band receivers for the Aries XXI 40m Radiotelescope

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Contents

Abstract

Keywords: Nanocosmos project, RT 40m, Calibration Load, Noise Temperature, Cryogenic receiver.

The new Q and W cryogenic receiver have been installed in the 40 meter radio telescope of Yebes Observatory. These receivers are located in the M4 branch of the radio telescope and a new Calibration Load is necessary to calibrate the noise temperature of the receiver prior to an observation. This report explains how this calibration load has been designed, built and installed in the radio telescope. The system consists on a linear motion system controlled with a stepper motor for the positioning of a microwave absorbent and a elliptical mirror, and a module to control the stepper motor.

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Chapter 1

Introduction

Two new receivers have been installed in the 40 meters radio-telescope Aries XXI at Yebes Observatory. These receivers cover the Q (31.5-50 GHz) and W (72-90.5 GHz) frequency bands. As at these frequencies the calibration of the receivers can not be performed with noise diodes, it is necessary to install a calibration system that calculates their noise temperature with the Y-Factor method. To use this method it is necessary to use a system that switches between a hot load and a cold load, T_{cold} and T_{hot}.These temperatures are known and stable during the calibration time. Equation 1.1 and Equation 1.2 show how to calculate the receiver noise temperature from the received power with the hot and cold loads.

$$Y = \frac{P_{hot}}{P_{cold}} = \frac{T_{hot} + T_{rx}}{T_{cold} + T_{rx}} \tag{1.1}$$

$$T_{rx} = \frac{T_{hot} - Y \cdot T_{cold}}{Y - 1} \tag{1.2}$$

In addition, this system can also be used to calculate the atmosphere opacity (τ_{atm}).

To achieve T_{hot}, a microwave absorber at room temperature is used, and to achieve T_{cold}, a load inside a cryostat at known cryogenic temperature.

To be able to use these hot and cold loads, it is necessary to use system that switches between them automatically, and that it can be controlled by the radio-telescope software.

This technical report details the design, construction and integration of the calibration system in the receivers cabin of the radio-telescope.

Chapter 2

System requirements

2.1 General description

To implement this calibration system, a linear motion system based on a ball screw moved by a stepper motor has been chosen. The stepper motor connected to the ball screw slide along two rails an structure with an elliptic mirror and a microwave absorber panel mounted over four rollers.

The system is divided in four parts: An aluminum plate that holds the cryostat with the cold load and the linear motion system, a structure that leans over two steal beams of the receivers cabin of the radio-telescope, the cryostat with the cold load, and the power supply and control module located in a 19 inch 2U rack mounted under the aluminum plate hanging off the structure.

2.2 Linear motion system positions

The calibration system has three positions:

- **Sky:** The receiver is receiving radiation from the source of observation.
- **Cold load:** The elliptic mirror is moved over the Cold Load Cryostat so the receivers see the cold load.
- **Hot load:** The microwave absorber is moved to the center of the beam so the receiver sees the hot load.

Figure 2.1 shows the different positions and the width of the mirror and the microwave absorber as well as the margins for the electric and mechanical limits of the linear motion system.

The position of the mirror that redirect the beam of the cold load to through the receivers is fixed by design, of the mirrors and the main beam of the radio-telescope.

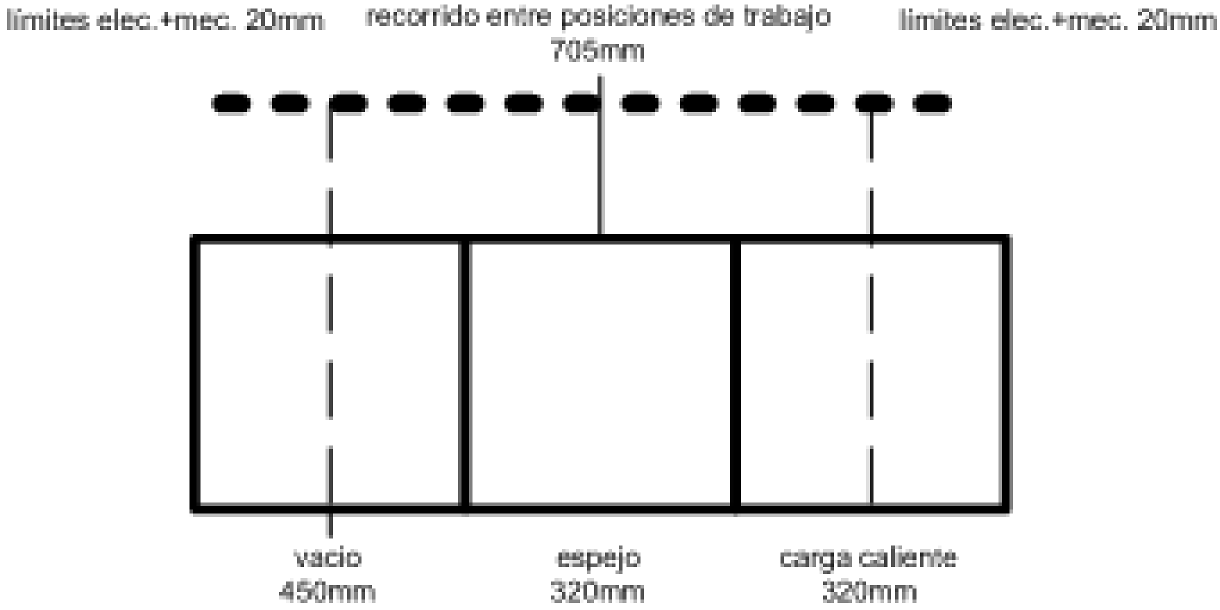


Figure 2.1: System positions

Therefore, the position of the table with the linear motion system had to be adjusted accordingly. It is also important to take into consideration that when the radio-telescope is scanning a source the main beam cannot be blocked by anything.

Chapter 3

System design

3.1 Mechanical design

The complete 3D model assembly is shown in Figure 3.1.

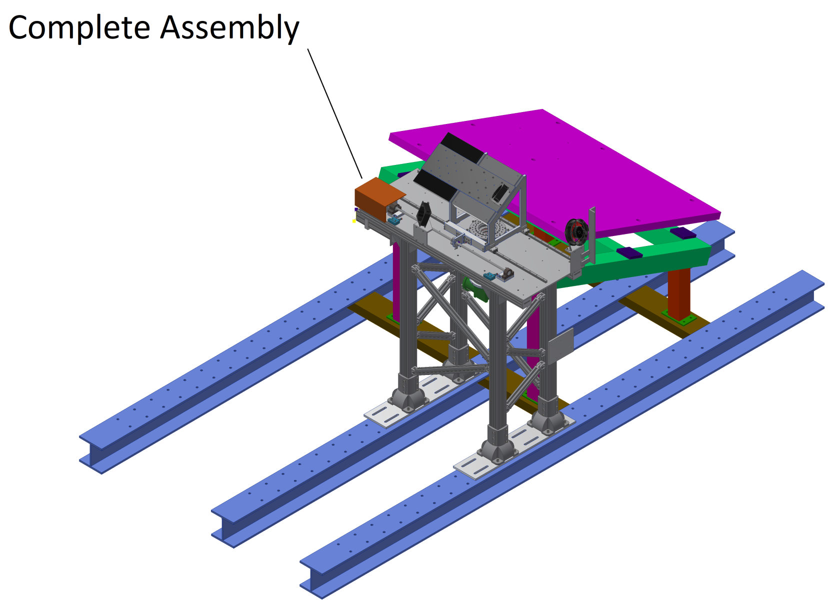


Figure 3.1: Complete assembly in the receivers cabin of the radio-telescope

The system is separated in four parts or sub assemblies:

- Load: The table (aluminum plate) that holds the linear motion system with the elliptic mirror, the microwave absorber and the cold load cryostat.
- Structure (Est): Extruded aluminum profiles to hold the aluminum plate with the linear motion system. This structure can be adjust along the Y axis (along the receivers cabin steel beams) with groves in the fixing plate to the steel beams, and the Z axis (height) with M16 threaded foot in each leg.
- Cryostat (Cryo): The cold load cryostat.
- Power Supply and Control Unit: 19 inch 2U *Rack* with the motor and logic power supplies, and the communication and control system. This unit is mounted hanging off the structure under the table.

3.1.1 Load (Linear motion system)

The first part of the design is the linear motion system to be able to switch between the three positions mentioned in section 2.2. The subassebly is shown in Figure 3.2.

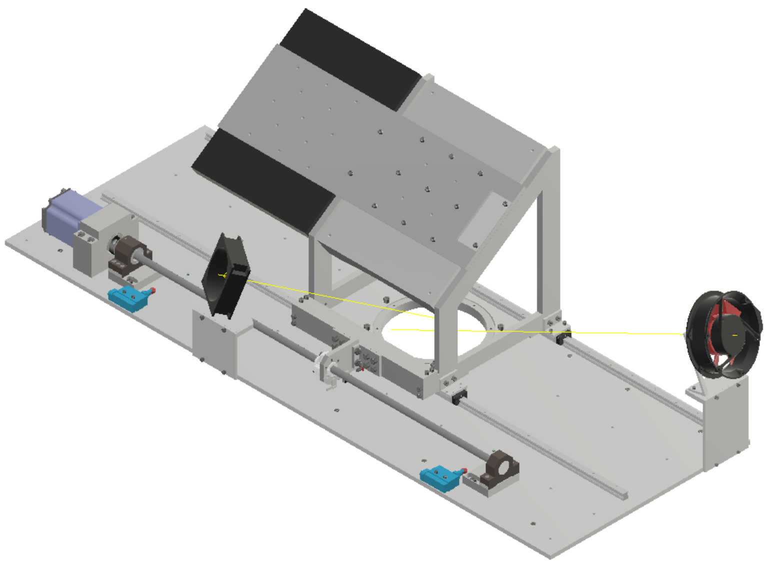


Figure 3.2: Load Subassembly

Next follows the description of the most important groups of parts which their design peculiarities.

3.1.1.1 Table (Aluminum plate)

Aluminum plate where the stepper motor, rails ball screw mounting set, limit switches and the cryostat. The plate also has H7 tolerance holes to mount the prism to align the system inside the receivers cabin. Figure 3.3 shows an upper view of the table.

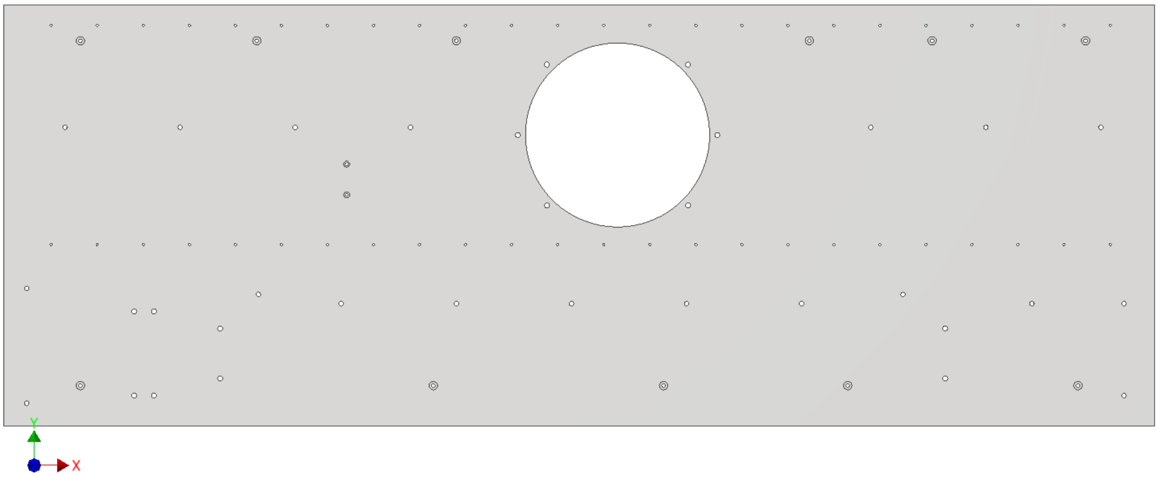


Figure 3.3: Table

3.1.1.2 Stepper motor, linear motion system and limits

This subassembly contains the stepper motor with its driver, the linear motion system with the ball screw, nut and mounts, the rails, the rollers and the mechanical and electrical limits.

The linear motion system consists of a stepper motor (Trinamic TMCM-1180 PD86-1180) and a ball screw linear guide with rails.

The stepper motor has a built in driver attached to it and it is controlled with a RS232 bus. The motor has also inputs for the electric limit switches.

Finally the electric and mechanical limits. The mechanical limits are two parts mounted in the flange that holds the sliding structure to the ball screw nut with two rubber pieces. The movement of the optic system is then limited by the precision switches **Precision_Switch_L and Precision_Switch_R** (also used for the motor referencing), and the security limits **Security_Switch_L and Security_Switch_R** as shown in

Figure 3.4. The nominal positions for the optic system are **Sky**, **Cold Load**) and **Hot Load** referred to the left precision switch (used by default to reference the motor).

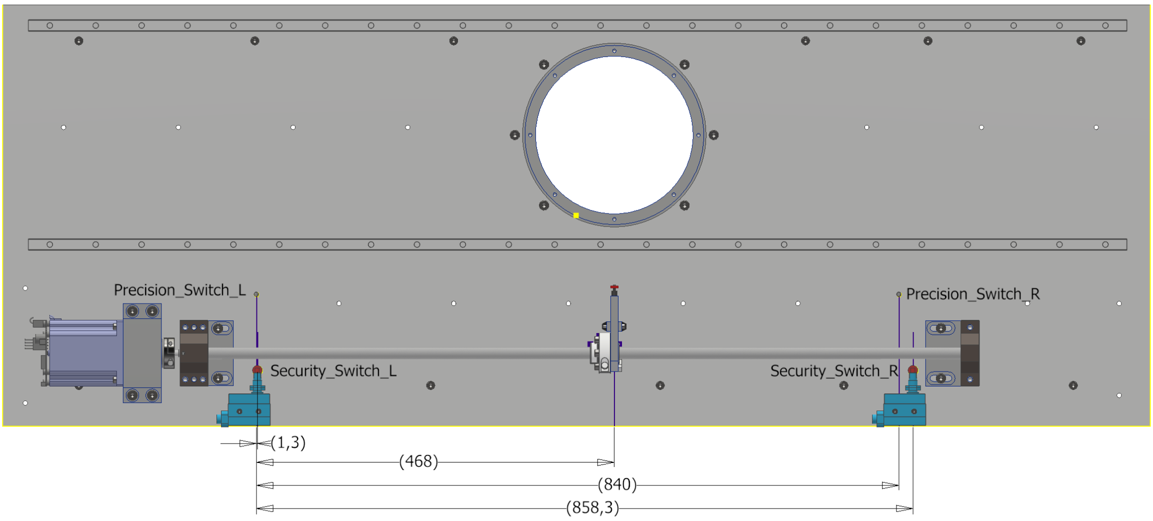


Figure 3.4: Switch position schematic

Optic Positions (mm)				
Precision_Switch_L	**Sky**	**Cold Load**	**Hot Load**	**Precision_Switch_R**
0 (Reference)	10	468	813	840

Table 3.1: Nominal optic positions

In addition to the parts detailed above, there are several other aluminum parts that are part of the structure that holds the elliptic mirror and the absorber, and the levers that press the limit switches.

3.1.2 Structure

The structure is design with extruded aluminum profiles. The structure, as mentioned before, holds the table (Figure 3.3) and is also used to align the system along the Y axis (receivers cabin steel beam direction) and Z axis (height of the table). The alignment on the X axis is done when mounting the table over the structure.

3.1.3 Cryostat

The cold load cryostat, as stated before, is mounted hanging off the table with a flange. The cryostat is shown in Figure 3.5.

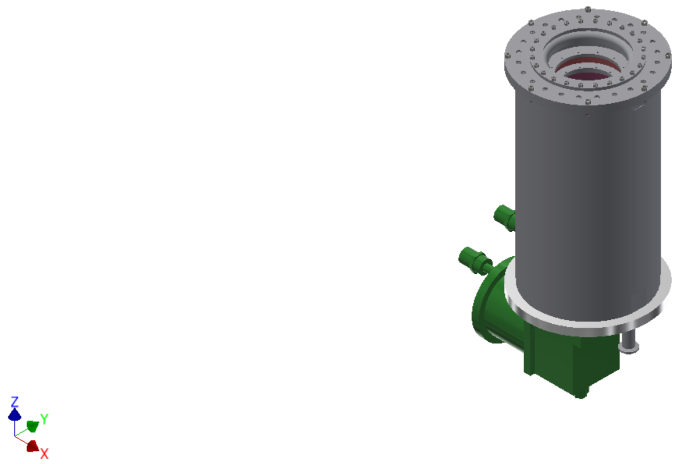


Figure 3.5: Cryostat

3.2 Alignment in the receivers cabin

The alignment is performed with a total station using the global coordinate system of the receivers cabin. All the coordinates of the pin holes for the alignment are referred to this system.

Figure 3.6 shows all the reference positions where the prism (corner cube) used together with the total station can be mounted on.

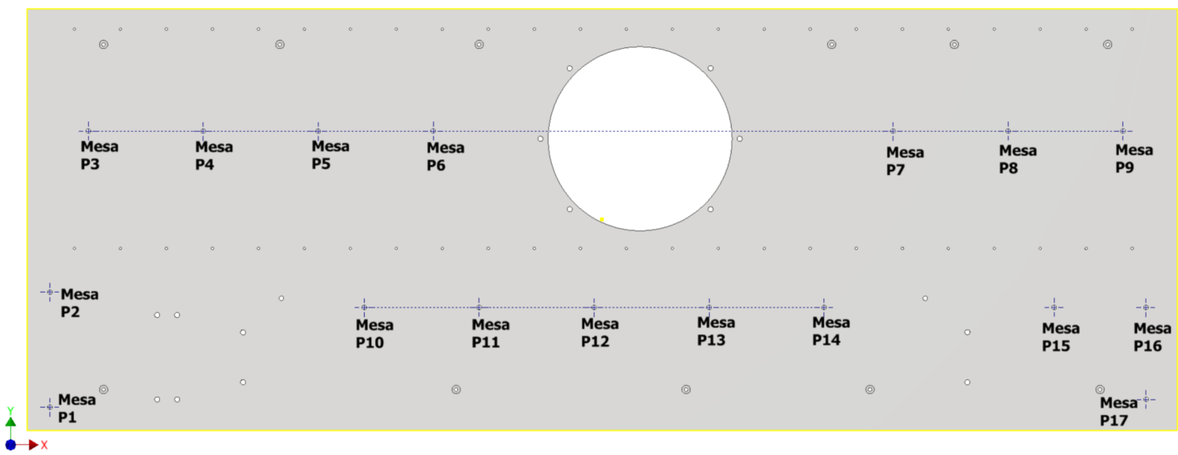


Figure 3.6: Holes in the table

The holes in the elliptic mirror mounting plate are shown in Figure 3.7.

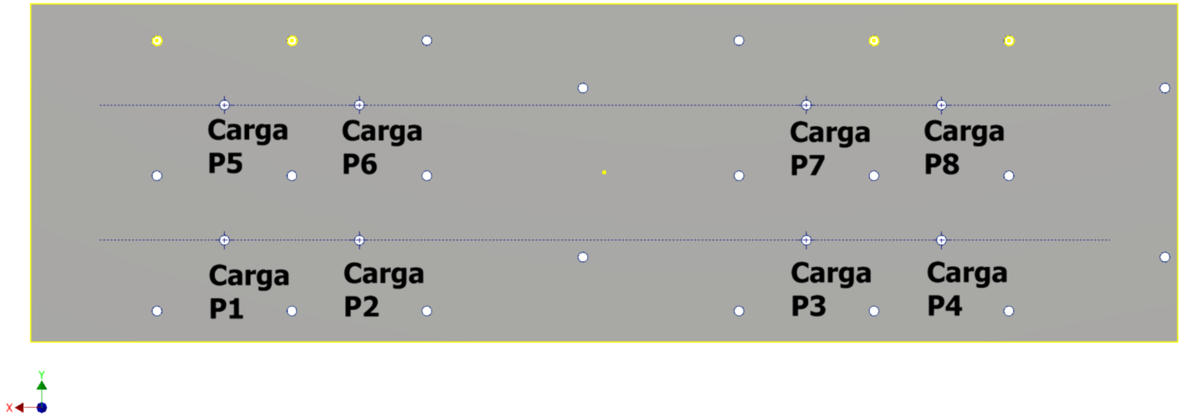


Figure 3.7: Elliptic mirror mounting place holes placement

3.3 Electric design (Control module)

The electric part of the system consists of a power supply and control unit for the stepper motor with its limit switches and emergency stop system. This unit consists of a 19 inch 2U rack where the power supply for the motor, the power supply for the precision limit switches and the security switches, a Raspberry Pi 3B+ with its power supply which is a gateway between the RS232 bus of the motor and the Ethernet connection to the radio-telescope control system (ACS), as well as control the relays that switches between the precision switches for referencing and security limits for normal operation.

For the motor, a switching power supply has been chosen: 48V output and 15.7A. Another power supply with 24V output and 2.2A is used to power the precision switches and the security limit switches. As stated before two relay circuits are used to switch between the precision switches and security switches so only a set of them is connected to the motor at a time. The relay control signals are produced and controlled by the Raspberry Pi with a control software.

The communication with the motor is established through the Raspberry Pi 3B+ using Raspbian. This is used as a gateway from RS232 (motor) to Ethernet (Radio-telescope control software). In addition, the Raspberry Pi controls the switching between the two sets of limit switches (precision switches and security switches) using an external circuit with a relay controlled by a GPIO port from the Raspberry Pi. The power supply for the Raspberry Pi is a AC/DC converter 230Vac to 5Vdc. The conversion between the USB in the Raspberry Pi and RS232 bus is made with the FTDI USB-RS232 cable soldered to a DB9 connector in the panel of the 19 inch rack.

The connection of the precision limit switches to the motor is made through opto-couplers mounted on a PCB (schematics can be found in Appendix A).

As explained before, the system has two electric security switches, and two precision switches. The precision switches are used for the motor reference search and are activated by the control software from ACS sending a control signal to switch the relay so they are connected to the motor. Once the motor has been referenced, with another signal from ACS the relay goes to its default state in which the security switches are connected to the motor. The Normally Closed (NC) circuit of the relay is connected to the security switches and the Normally Open (NO) circuit to the precision switches. Figure 3.8 shows the control module.

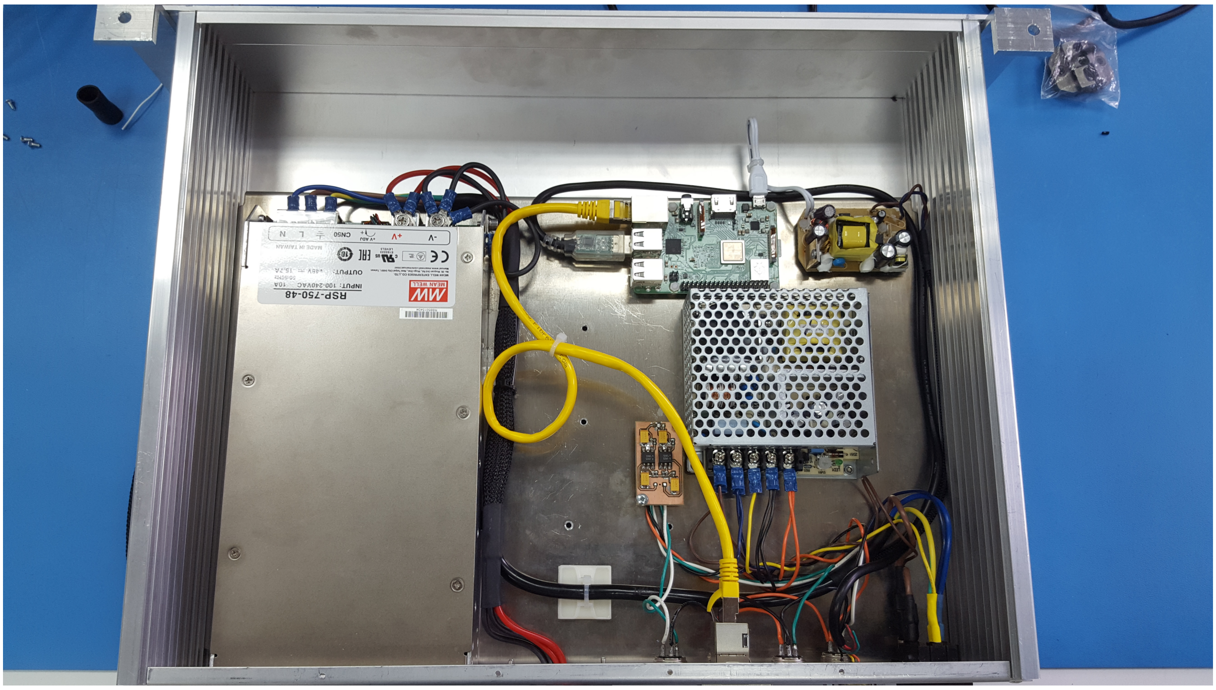


Figure 3.8: Power supply and control module

Chapter 4

Control Software and Configuration

4.1 Raspberry Pi set up

Communications between the radio-telescope and the motor go through a **Raspberry Pi 3B+** that implements a service under the OS Raspbian (GNU/Linux distribution based on Debian) that converts between RS232 data and Ethernet packages. The stepper motor uses the serial protocol RS232 with its default configuration, 9600 bauds, 8 data bits and 1 stop bit. To control the motor from any point place the radio-telescope it is necessary to use Ethernet communications.

A memory card with a loaded image with Raspbian with no desktop is inserted into the Raspberry Pi. An IP is assigned to it and the service rs232_gateway.py is launched on power on.

The service configuration saved in **rs232_gateway.service** in the following path: */lib/systemd/system/*.

```
[Unit]
Description=RS232-Ethernet gateway
After=multi-user.target network.target
Requires=network-online.target

[Service]
Type=simple
ExecStart=/usr/bin/python3
/home/oanuser/rs232_gateway_service/rs232_gateway.py
Restart=on-abort

[Install]
WantedBy=multi-user.target
```

Once this is done, from a terminal the service is started:

```
oanuser@cl-40m:~ $ sudo systemctl daemon-reload
oanuser@cl-40m:~ $ sudo systemctl enable rs232_gateway.service
oanuser@cl-40m:~ $ sudo systemctl start rs232_gateway.service
oanuser@cl-40m:~ $ sudo systemctl status rs232_gateway.service
```

The service is now running a server listening on port 5000.

4.2 Motor control software

The motor control software is programmed in C++. It consists of a class structure shown in Figure 4.1. The diagram shows the main parameters and methods of each class.

The class **Comm** takes care of communications: configures the TCP connection with the motor, sends commands, and receives replies.

To generate the motor commands, their checksums and, decoding and validation of the replies and such, the class **StepperCommand** has been implemented.

There is also a file with common functions for the software package: **commonFunctions**.

Finally, the class **MotorFunctions** is used to configured the motor, and give the user the necessary parameters and methods to control the motor. The main methods are listed in the class diagram in Figure 4.1.

This classes are compiled with a main function to generate a test program. To integrate it later in the radio-telescope software (ACS) which uses CORBA standard, a CORBA component is created. This component create instances of the classes Comm, StepperCommand, and MotorFunctions to operate the motor from the radio-telescope control system. This is then used automatically in the observations.

The control system of Yebes Observatory radio-telescopes uses the ALMA Common Software (ACS). One of its main advantages is that it allows the programming in three different programming languages (C++, Java and Python) with fully compatibility between them. Another important feature is the component-container distribution, where the developed tools are components and they are managed with containers. This way, to integrate the calibration system software, a new component in C++ has been created. This component uses the functions mentioned above, so other parts of the control system are able to use the calibration system automatically. The available functions of this

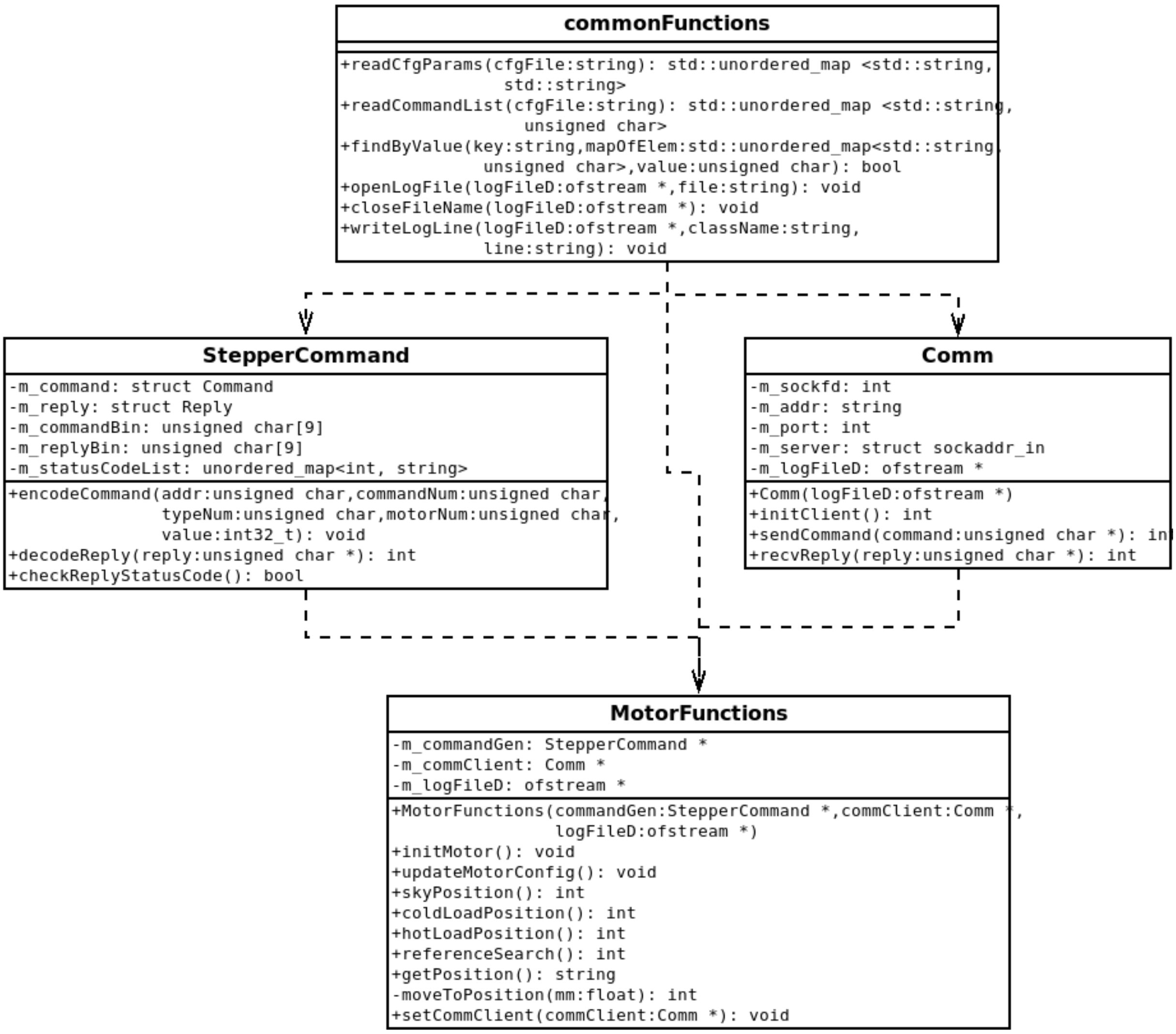


Figure 4.1: Class diagram

component are listed below:

- **setLoadPosition(pos)**: Commands the load to move to the required position. The available options are "SKY", "COLD, and "HOT.
- **getLoadPosition()**: Get the actual position of the load. The returned value can be "SKY", "COLD" and "HOT".
- **referenceSearch()**: Commands the motor to perform a reference search.
- **reloadSocket()**: Closes and opens again a new TCP connection to the motor control module.

Together with the software, and ICD (Interface Control Document) has been generated. In this document the software is thoroughly described.

4.3 Motor validation and verification

A library implemented in C in the file cWrapper.cc which interfaces between C++ and C has been created. The functions in this file are imported from Python with the standard ctypes library. The schematic in Figure 4.2 shows a brief description of the structure of this test software.

In automatedTests.py file a test battery is programmed. This can be used to test various motor features when needed.

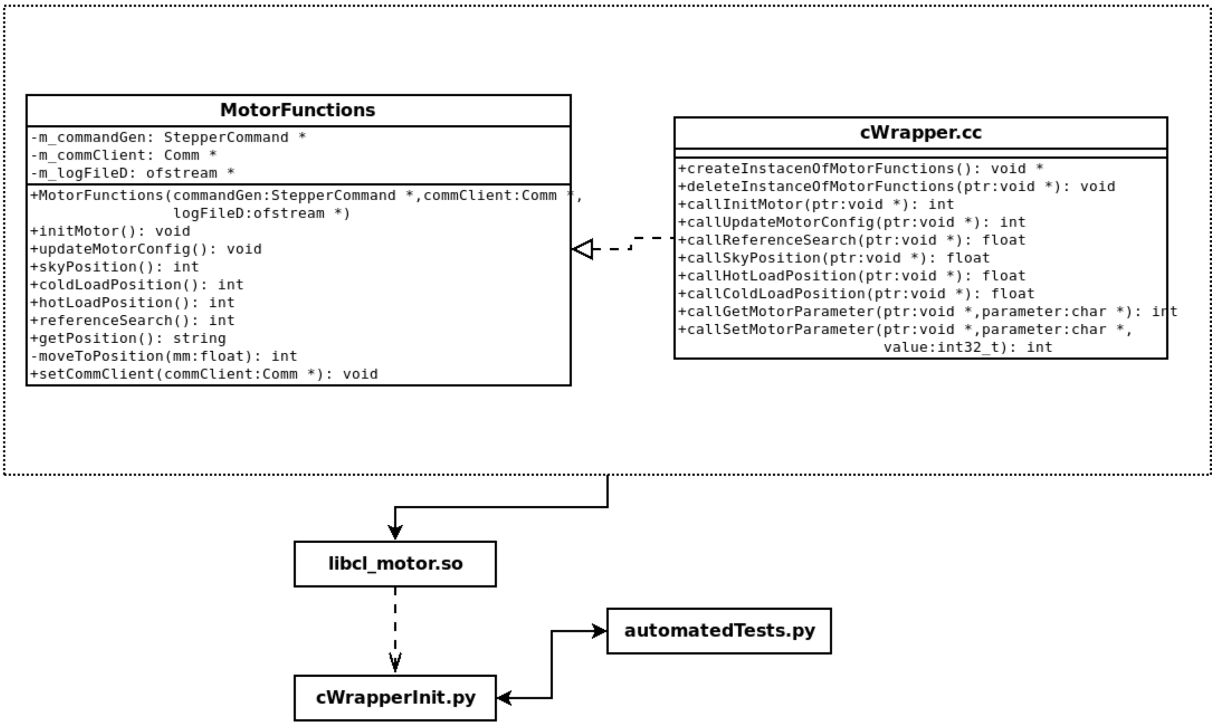


Figure 4.2: Test software structure

Chapter 5

Installation and Alignment

The installation process is carried out in three steps. First, the communications and control module is assembled, then the table with the linear motion system and the limit switches, and finally, in the receivers cabin, the structure that holds the table. Once each part is assembled, they are put together with the Cold Load Cryostat to start the alignment.

5.1 Communications and control module assembly

Prior to the assembly of the communications and control module, the printed circuit board for the Switch Isolator has to be made. This PCB is manufactured in the laboratory numeric mill (LPKF). The PCB is shown in Figure 5.1.

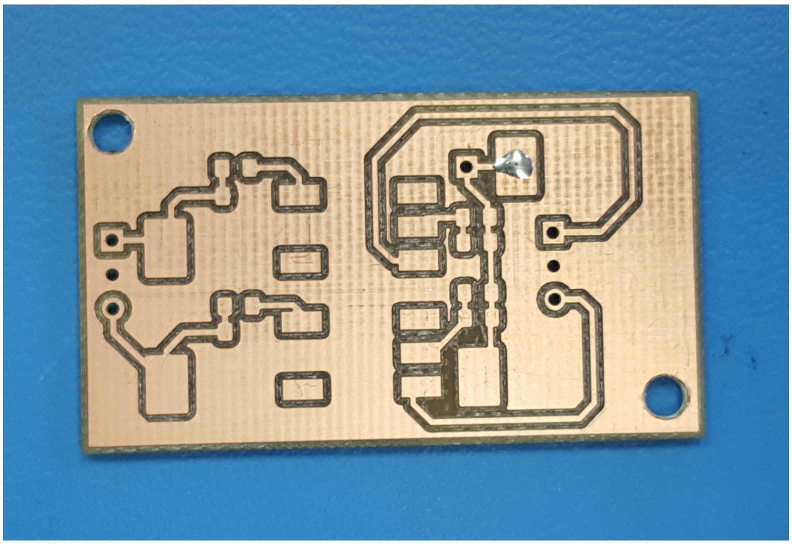


Figure 5.1: Switch Isolator PCB

The PCB with all the components soldered is mounted together with the rest of the power supplies and the raspberry pi in the 19 inch 2U rack as shown in figure Figure 5.2.

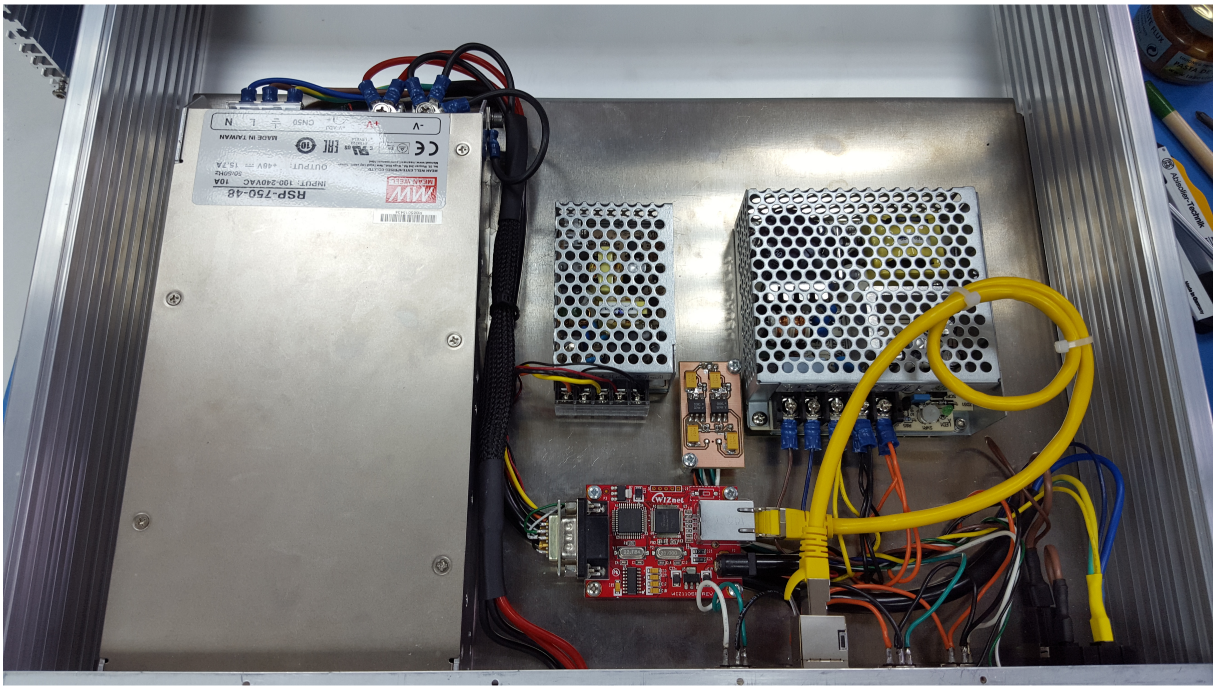


Figure 5.2: Communications and Control Module

5.2 Mechanical part assembly

Figure 5.3, Figure 5.4, Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8 show parts of the assembly process.

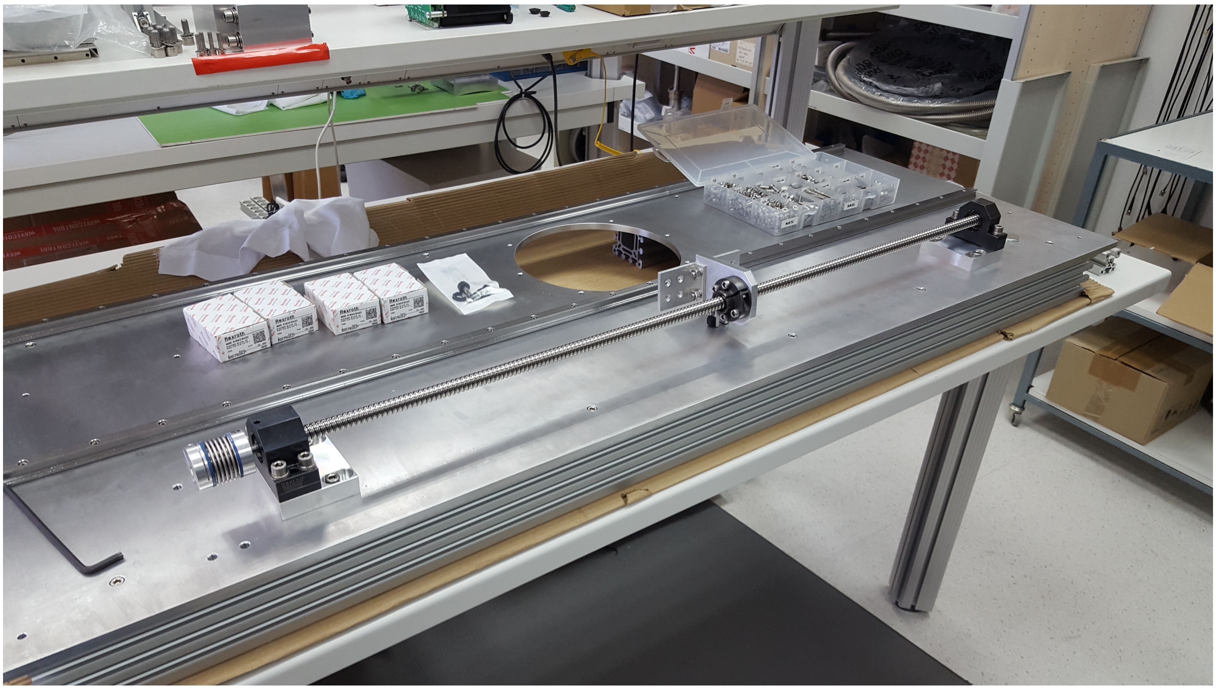


Figure 5.3: Partial assembly of the linear motion system

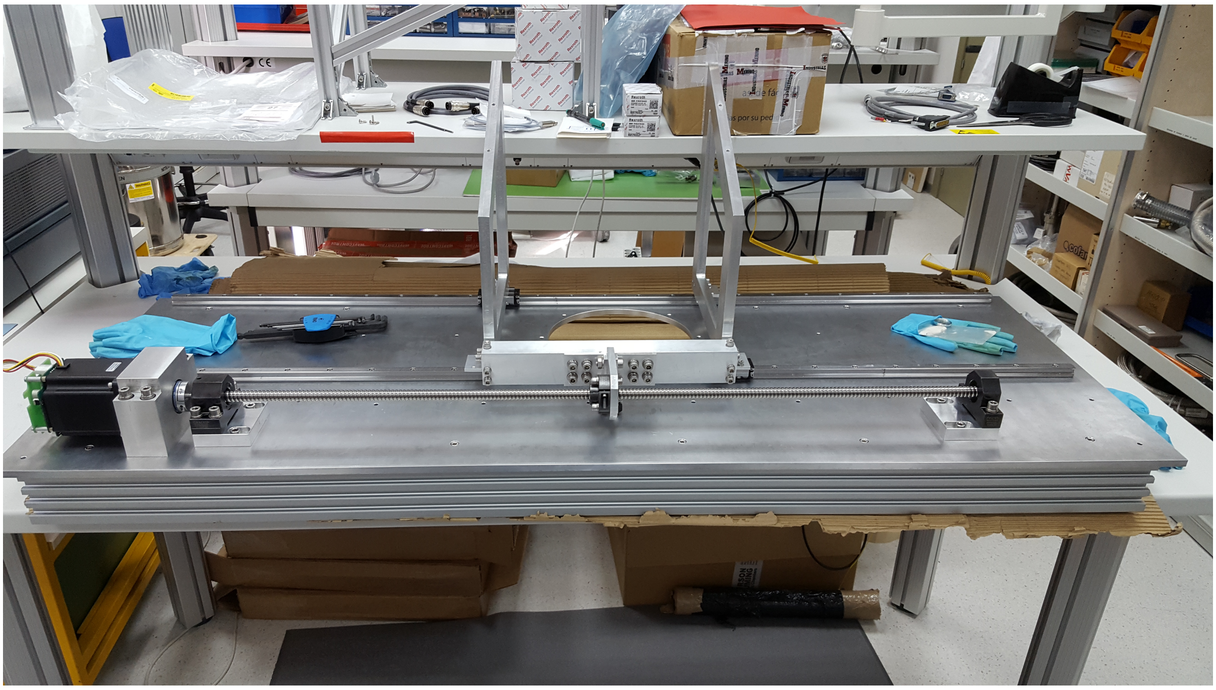


Figure 5.4: Partial assembly of the linear motion system with the load

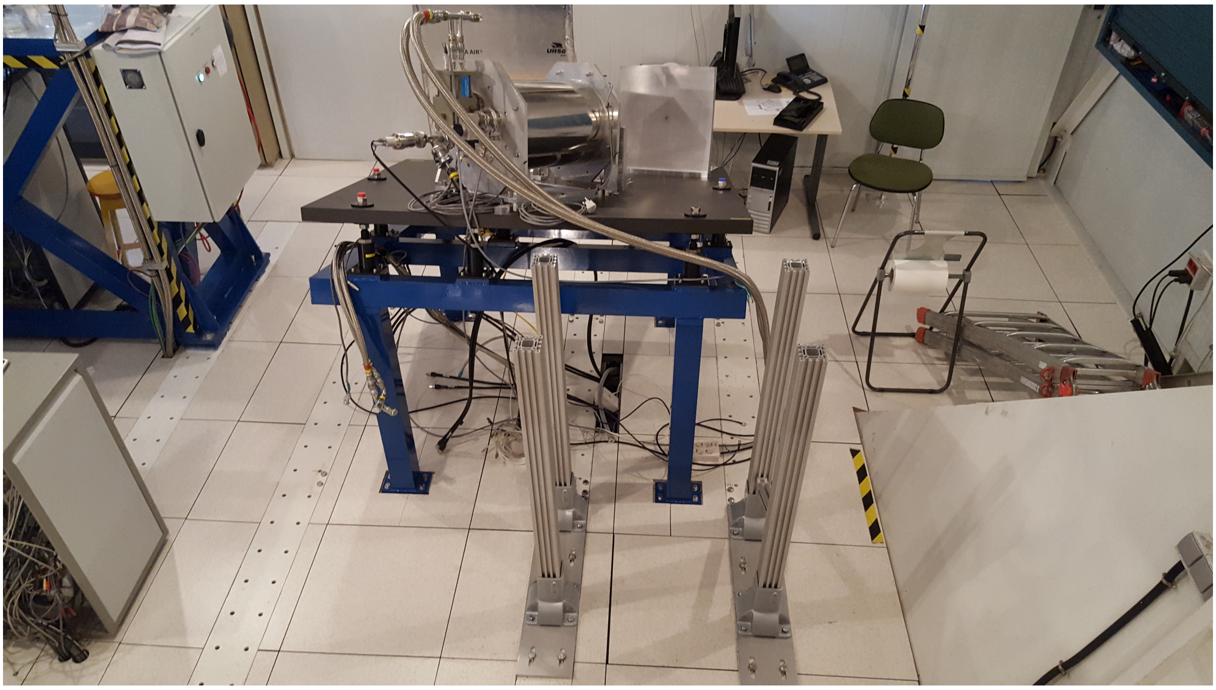


Figure 5.5: Structure partial assembly

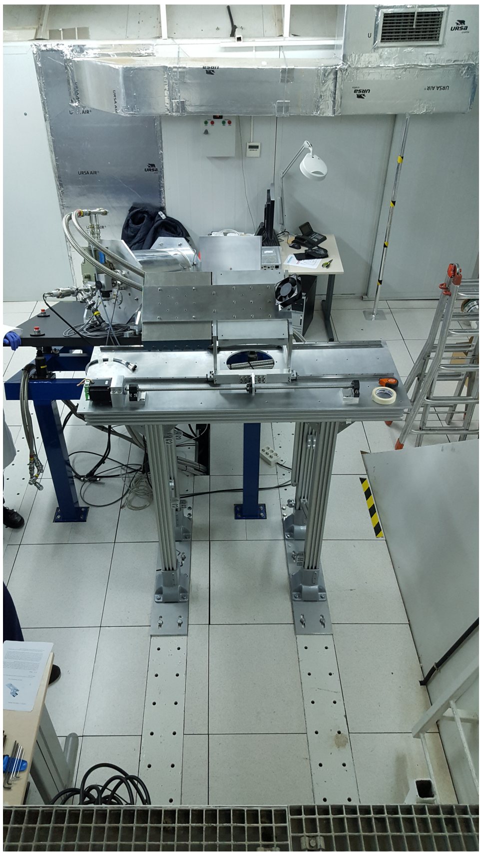


Figure 5.6: Table assembly over the structure

Figure 5.7: Front view of the system

Figure 5.8: Side view of the system

5.3 Alignment in the receivers cabin

Once assembled, it is necessary to align the system inside the receivers cabin. This is carried out with the total station. Figure 5.9 shows the total station mounted over the receivers cabin steel beams.

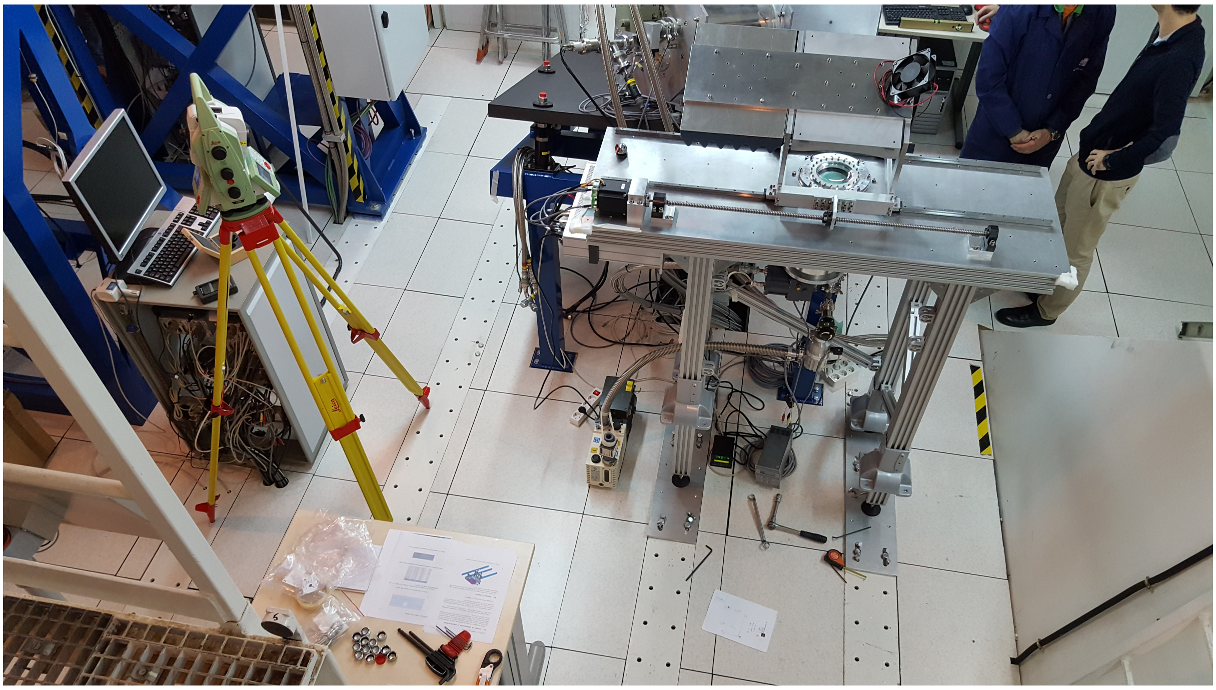


Figure 5.9: Alignment process with the total station

There are two parts to align, the table, and the mirror (in cold load position, with the mirror on top of the cold load cryostat). The first part to align is the table: the height (Z axis) is adjusted, then the Y axis parallel to the cabin floor steel beams and finally the X axis, orthogonal to the other two axis.

Once the table is aligned, the mirror is moved on top of the cold load cryostat and the corner cube is used to align it. This is done to correct the manufacturing tolerances. It is also important to check the correct position of the mirror over the cold load cryostat along the X axis.

The global precision achieved with the total station is $\pm 1mm$.

Chapter 6

System parameter adjustment and measurements

6.1 Preliminary tests

Once the system is fully assembled, with the test software, the motor has been tested, as well as the electric security switches and the precision switches. The emergency stop button has also been tested.

To check the precision switch, a reference search on each side has been performed. It has also been checked that when the motor turn right, the right security switch stops the motor, and the same on the left side.

The emergency stop button has been tested commanding the motor to move whit the button pressed, and also pushing it in the middle of a motor positioning. The motor was stopped right away.

6.1.1 System physical parameters adjustment

Prior to start using the system, the physical parameters which define it (**parameters.cfg** file) have to be defined: the motor speed, the acceleration, the maximum current, number of micro-steps, sky, cold, and hot load positions, etc.

The most critical parameters are the speed, acceleration, maximum current and micro-step number because they are directly related with the motor torque (Figure 6.1).

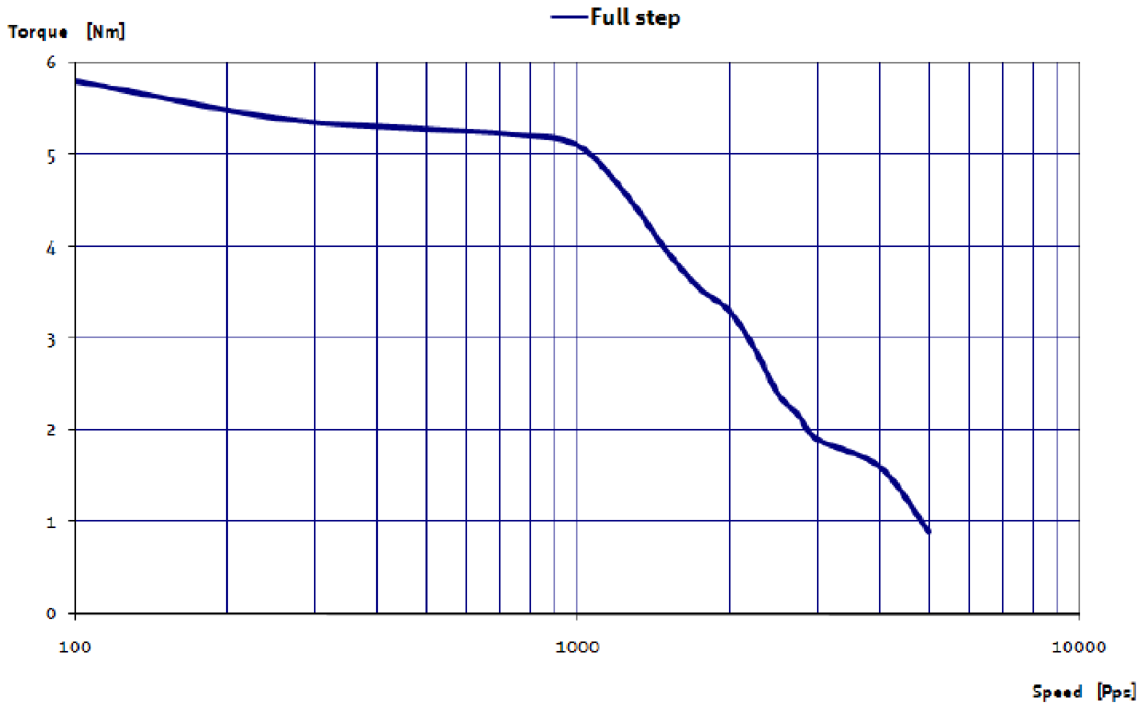


Figure 6.1: Speed vs Torque (micro-step per second)

In this system the switching time between positions (Sky, Cold Load, Hot Load) is desired to be the minimum possible. Therefore the motor has to run at high speeds, then the motor torque is going to decrease.

In addition, it is important to take into account that stepper motors has a several speed points at which the motor starts oscillating which produces resonances and the torque decreases abruptly. Tests have to be carried out to avoid these resonance areas, and if possible install a system that damp or reduces these resonances.

It is also important to mention that it is necessary to used relatively high accelerations, so the programmed speed is reached as soon as possible and then skip the possible resonance areas as quickly as possible (manufacturer recommendation). This has been tested adjusting the value of acceleration.

To adjust the speed and acceleration ranges it is necessary to use three more motor parameters: the micro-step number, the *Pulse Divisor* and the *Ramp Divisor*. The micro-step number (16 micro-steps), has been chosen according to the manufacturer advice to use more than 8 micro-step so the motor run smoothly at high speed. The other two parameters are used in the unit conversion formulas for speed and acceleration to adjust the value range from the motor parameter value (1 to 2047) to physical units.

The selected parameters are:

- **Maximum positioning speed** = 160 mm/s
- **Maximum acceleration** = 100 mm/s^2
- **Pulse Divisor** = 1
- **Ramp Divisor** = 8
- **Microstep resolution** = 16

With the equations listed below, to perform the unit conversion, it is possible to calculate the pps (micro-step per second) from the speed value 160mm/s.

$$\begin{cases} v_{pps} = \frac{16 \cdot 10^6 \cdot val}{2^{pulse\_div} \cdot 2048 \cdot 32} & \text{(ustep/s)} \\ v_{rps} = \frac{v_{pps}}{F \cdot uF} & \text{(rev/s)} \\ v_{mms} = v_{rps} \cdot L & \text{(mm/s)} \\ val = \frac{v_{mms} \cdot 2^{pulse\_div} \cdot 2048 \cdot 32 \cdot F \cdot uF}{16 \cdot 10^6 \cdot L} \end{cases}$$

Where *val* is the speed value in motor units, *pulse_ div* is the *Pulse Divisor* parameter, F the number of motor steps [1], uF number of micro-step selected (ustep/revolution), and L is the ball screw lead (5mm/revolution).

The calculations are shown in Equation 6.1 y la Equation 6.2.

$$val = \frac{160 \cdot 2^1 \cdot 2048 \cdot 32 \cdot 200 \cdot 16}{16 \cdot 10^6 \cdot 5} = 838 \tag{6.1}$$

$$v_{pps} = \frac{16 \cdot 10^6 \cdot 838}{2^1 \cdot 2048 \cdot 32} = 102294.92\text{(pps)} \tag{6.2}$$

Due to the fact that the plot in Figure 6.1 is for the 0 micro-step configuration, the value pf Equation 6.2 has to be divided by 16 (number of micro-steps selected), resulting in $v_{pps\_fullstep} = 6393.43$. As it can be observed in Figure 6.1, at the selected speed, the motor torque is reduced approximately $1N \cdot m$.

On top of the already selected parameters, it is necessary to define the values of the Sky, Hot Load and Cold Load positions, the **Maximum current=232** to allow the selected high speed, and the reference search speed, slower than the one used for positioning

[1] The number of steps of the motor (F) is 200

in normal operation. This speed has been optimized with tests to avoid resonance areas.

With this parameters the motor works correctly. Nevertheless, the parameters will be adjusted if necessary to achieve a better and more optimal behaviour.

Other options to improve the behaviour of the motor were installing a vibration damper to mitigate the cold head from the cryostat vibrations. The damper was design and build but after testing, the behaviour was similar so it was decided not to keep it.

6.2 Load positioning tests

Once the main motor parameters have been adjusted, several tests to check the repeatability in the positioning has been conducted. These test have been performed for the different positions (Sky, Hot Load and Cold Load). A reference search test with both precision switches, right and left have been performed.

The final positions (defined in the parameters.cfg file) *Sky*, *Hot Load* and *Cold Load* are **10mm**, **811.9mm** and **466.9mm**, respectively. All referenced to the left limit in absolute coordinates. These positions have been adjusted with the total station. Table 6.1 shows the nominal positions and the final positions, adjusted with the total station.

The distance between the left and right reference switches has been measured with the motor encoder by doing a reference search with the right switch and then the left switch and measuring the distance between them with the END_SWITCH_DISTANCE motor parameter. Four measures have been taken with an average of 836.51 mm and a standard deviation of $9.45\dot{1}0^{-}3$ mm.

Optical Positions (mm)					
	Precision_Switch_L	**Sky**	**Cold Load**	**Hot Load**	**Precision_Switch_R**
Nominal	0 (Reference)	10	468	813	840
Measured	0 (Reference)	10	466.9	811.9	836.51

Table 6.1: Optical positions from left switch reference

In the case of a breakdown of the left reference switch, it is possible to use the right switch for reference or to replace the left switch and re-calibrate the whole system again. In this case, Table 6.2 shows the optical positions from the right reference switch. In the configuration file (parameters.cfg) it is possible to select the reference switch side (left or right) and the optical positions depending of the chosen reference switch according to

Table 6.1 or Table 6.2.

Optical Positions (mm)					
	Precision_Switch_L	**Sky**	**Cold Load**	**Hot Load**	**Precision_Switch_R**
Measured	-836.51	-826.51	-369.61	-24.61	0 (Reference)

Table 6.2: Optical positions from right switch reference

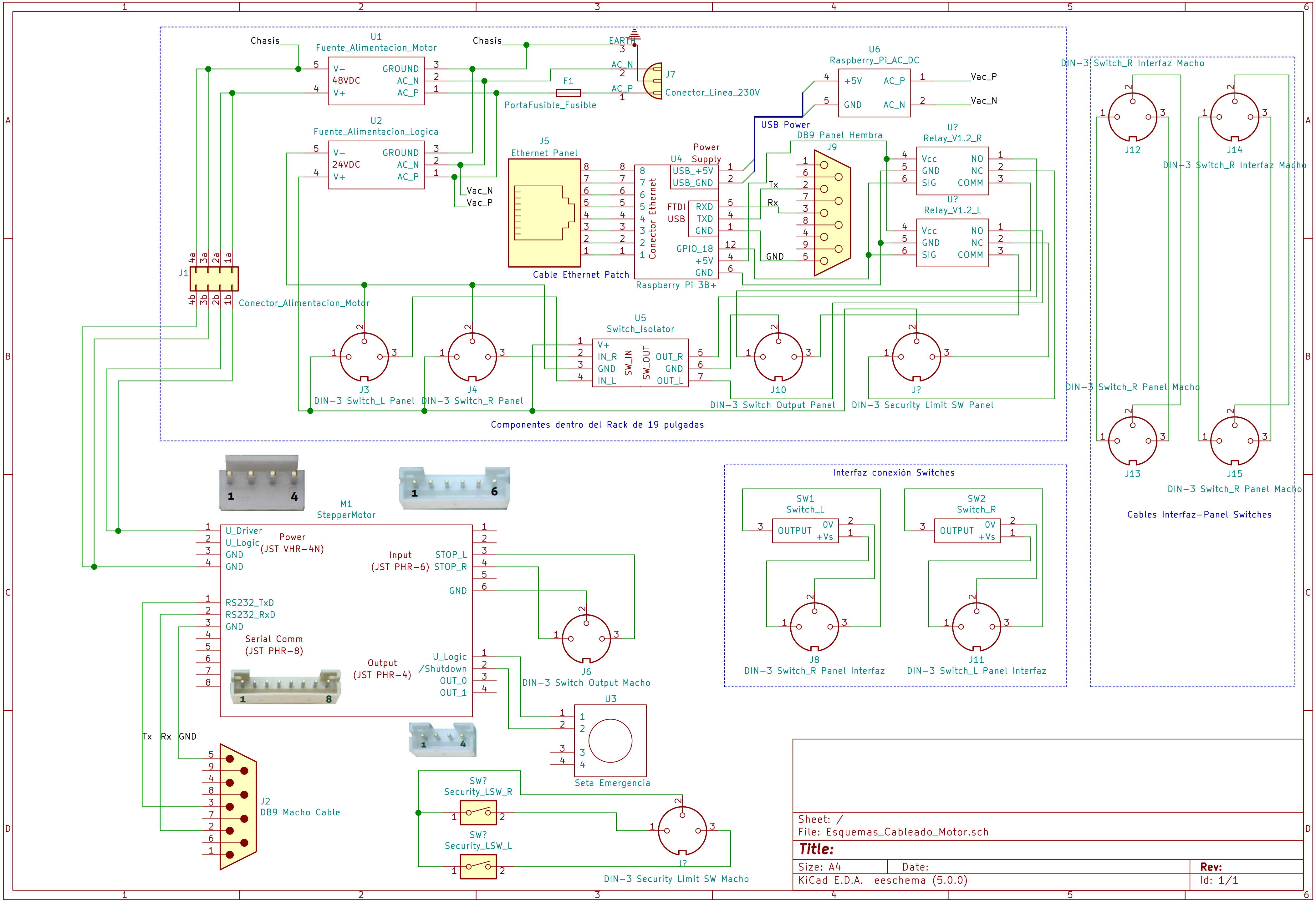
Another important parameter in the configuration is the **maximum allowed deviation** when positioning the load. The maximum allowed deviation selected is 0.05mm. This deviation is measured as the difference between the selected position and the position value measured with the internal motor encoder. The logger, implemented in the software, records that deviation in a file. An example of some measured deviations is listed below. All values fall within the maximum allowed deviation.

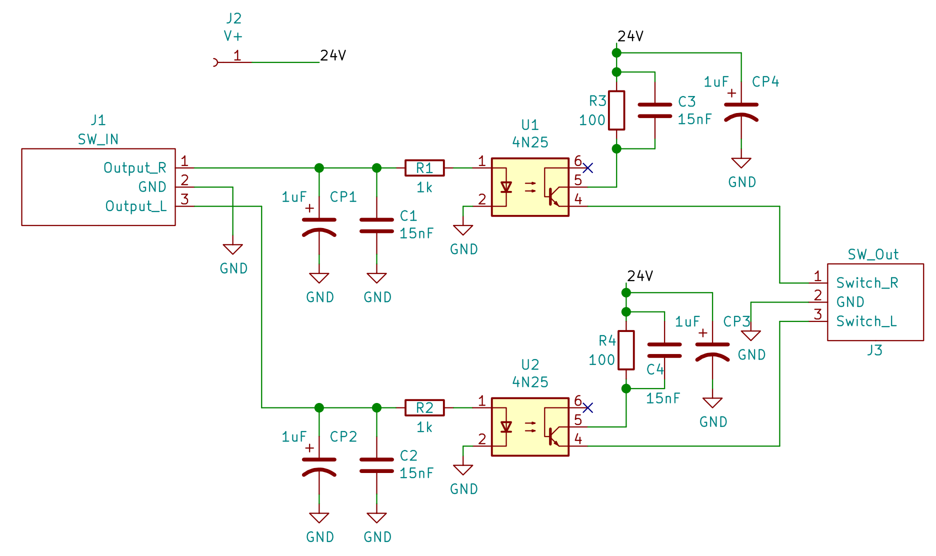
```
Position deviation: 0.014063 millimeters 9 microstep
Position deviation: 0.000000 millimeters 0 microstep
Position deviation: 0.000000 millimeters 0 microstep
Position deviation: −0.006250 millimeters −4 microstep
Position deviation: 0.018750 millimeters 12 microstep
Position deviation: 0.000000 millimeters 0 microstep
Position deviation: 0.000000 millimeters 0 microstep
Position deviation: −0.006250 millimeters −4 microstep
Position deviation: 0.000000 millimeters 0 microstep
Position deviation: 0.014063 millimeters 9 microstep
```

The positioning error average is 5 um with a standard deviation of 7 um.

Appendix A

Electric schematics


Chasis
U1
Fuente_Alimentacion_Motor
V−
48VDC
V+
GROUND
AC_N
AC_P
EARTH
J7
Conector_Linea_230V
F1
PortaFusible_Fusible
U2
Fuente_Alimentacion_Logica
24VDC
Vac_N
Vac_P
U6
Raspberry_Pi_AC_DC
+5V
GND
USB Power
J5
Ethernet Panel
Cable Ethernet Patch
U4
Power Supply
USB_+5V
USB_GND
FTDI USB
RXD
TXD
GPIO_18
Conector Ethernet
Raspberry Pi 3B+
DB9 Panel Hembra
J9
Tx
Rx
U?
Relay_V1.2_R
Relay_V1.2_L
Vcc
SIG
NO
NC
COMM
J1
Conector_Alimentacion_Motor
U5
Switch_Isolator
IN_R
IN_L
SW_IN
SW_OUT
OUT_R
OUT_L
J3
DIN−3 Switch_L Panel
J4
DIN−3 Switch_R Panel
J10
DIN−3 Switch Output Panel
J?
DIN−3 Security Limit SW Panel
Componentes dentro del Rack de 19 pulgadas
DIN−3 Switch_R Interfaz Macho
J12
J14
DIN−3 Switch_R Panel Macho
J13
J15
Cables Interfaz−Panel Switches
M1
StepperMotor
U_Driver
U_Logic
Power
(JST VHR−4N)
Input
(JST PHR−6)
STOP_L
STOP_R
RS232_TxD
RS232_RxD
Serial Comm
(JST PHR−8)
Output
(JST PHR−4)
/Shutdown
OUT_0
OUT_1
J6
DIN−3 Switch Output Macho
U3
Seta Emergencia
J2
DB9 Macho Cable
SW?
Security_LSW_R
Security_LSW_L
DIN−3 Security Limit SW Macho
Interfaz conexión Switches
SW1
Switch_L
SW2
Switch_R
OUTPUT
0V
+Vs
J8
DIN−3 Switch_R Panel Interfaz
J11
DIN−3 Switch_L Panel Interfaz
Sheet: /
File: Esquemas_Cableado_Motor.sch
Title:
Size: A4
Date:
Rev:
KiCad E.D.A. eeschema (5.0.0)
Id: 1/1



Sheet: /	
File: Switch_Isolator.sch	
Title:	
Size: A4 Date:	**Rev:**
KiCad E.D.A. kicad (5.0.0)	Id: 1/1

From	Pin	To	Pin	Color Cable	Longitud Cable
Fuente 48V	L	Fusible	1	Marrón	
	N	Conector Linea	N	Azul	
	Tierra	Conector Linea	Tierra	Amarillo	
	V+	Placa conexiones	1a	Rojo Silicona	
		Placa conexiones	2a	Rojo Silicona	
	V-	Placa conexiones	3a	Rojo Silicona	
		Placa conexiones	4a	Rojo Silicona	
		Chasis Fuente 48V		Negro	
Fuente 24V	L	Fusible	1	Marrón	
	N	Conector Linea	N	Azul	
	Tierra	Conector Linea	Tierra	Amarillo	
	V+	DIN-3 Switch_L Panel	1	Naranja	
		DIN-3 Switch_R Panel	1	Naranja	
	V-	DIN-3 Switch_L Panel	2	Negro	
		DIN-3 Switch_R Panel	2	Negro	
		DIN-3 Switch Output Panel	2	Negro	
Fusible	2	Conector Linea	L	Marrón	
DIN-3 Switch Output Panel	1	Relay_V1.2_R	COMM (3)	Blanco	
	2	Switch_Isolator	GND (6)	Verde	
	3	Relay_V1.2_L	COMM (3)	Negro	
Switch_Isolator	V+ (1)	Fuente 24V	V+	Naranja	
	IN_R (2)	DIN-3 Switch_R Panel	3	Blanco	
	GND (3)	Fuente 24V	V-	Negro	
	IN_L (4)	DIN-3 Switch_L Panel	3	Verde	
Switch_L	1 (+Vs) Cable Marron	DIN-3 Switch_L Panel Interfaz	1	Naranja	
	2 (0V) Cable Azul		2	Negro	
	3 (OUTPUT) Cable Negro		3	Verde	
Switch_R	1 (+Vs) Cable Marron	DIN-3 Switch_R Panel Interfaz	1	Naranja	
	2 (0V) Cable Azul		2	Negro	
	3 (OUTPUT) Cable Negro		3	Blanco	
Cable Macho-Macho DIN-3 (x2 Unidades)			1	Naranja	900 mm
			2	Rojo	
			3	Amarillo	
VHR-4N	1	Placa conexiones	1b	Rojo Silicona	500mm
	1		2b	Rojo Silicona	
	4		3b	Negro Silicona	
	4		4b	Negro Silicona	
PHR-6	3	DIN-3 Switch Output Macho	3	Marrón	500mm
	4		1	Rojo	
	6		2	Naranja	
PHR-8	1	DB9 Macho Cable	3	Marrón	500mm
	2		2	Rojo	
	3		5	Naranja	
Conversor AC/DC Raspberry Pi 3B+	L	Fuente 24V	L	Marrón	
	N		N	Azul	
	5V	Raspberry Pi 3B+ Power Supply	USB	Blanco	
	GND			Blanco	
DB9 Panel Hembra	2	Raspberry Pi 3B+ FTDI USB Cable	4 (TXD)	Naranja	
	3		5 (RXD)	Amarillo	
	5		1 (GND)	Negro	
Security_LSW_R	1	DIN-3 Security Limit SW Macho	2	Blanco	1500mm
	2		1	Rojo	
Security_LSW_L	1		2	Blanco	1500mm
	2		3	Rojo	
Relay_V1.2_R	NO (1)	Switch_Isolator	OUT_R (5)	Blanco	
	NC (2)	DIN-3 Security Limit SW Panel	1	Blanco	
	COMM (3)	DIN-3 Switch Output Panel	1	Violeta	
	Vcc (4)	Raspberry Pi 3B+	5V (4)	Rojo	
	GND (5)		GND (6)	Negro	
	SIG (6)		GPIO_18 (12)	Marrón	
Relay_V1.2_L	NO (1)	Switch_Isolator	OUT_L (7)	Verde	
	NC (2)	DIN-3 Security Limit SW Panel	3	Verde	
	COMM (3)	DIN-3 Switch Output Panel	3	Azul	
	Vcc (4)	Raspberry Pi 3B+	5V (4)	Rojo	
	GND (5)		GND (6)	Negro	
	SIG (6)		GPIO_18 (12)	Marrón	
DIN-3 Security Limit SW Panel	1	Relay_V1.2_R	NC (2)	Violeta	
	2	Fuente 24V	V+	Naranja	
	3	Relay_V1.2_L	NC (2)	Azul	

Table A.1: Lista de conexiones

Bibliography

[1] "Nanocosmos project." https://nanocosmos.iff.csic.es/.

[2] "Motor firmware manual (pd-1180_tmcl_firmware_manual_fw4.48_rev1.13)." https://www.trinamic.com/fileadmin/assets/Products/Drives_Documents/PD-1180_TMCL-firmware_manual_Fw4.48_Rev1.12.pdf.

[3] "Sistemas de movimiento lineal bosch rexroth." https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/index.