GTC adaptive optics hardware electronics

M. Núñez Cagigal*a, O. Tubio Araujoa, R. Vilelab, N. Martinez Rey*a, J. C. López-Ruiz*a, L. F. Rodríguez Ramos*a, C. Martín Díaz*a
*aInstituto de Astrofísica de Canarias (IAC), La Laguna, Spain.
*bGran Telescopio Canarias (GTC), La Laguna, Spain.

ABSTRACT

The Adaptive optics for GTC is a single conjugated post focal AO system placed in the Nasmyth platform over a static optical table. It has been designed initially for natural guide star and in the later project phase adapted to one laser guide star. The AO system is composed of the following subsystems: wavefront corrector, wavefront sensor, structure, calibration system and test camera. This paper presents the hardware electronics to support all these subsystems including a real time control introduction.

Keywords: Adaptive optics, electronics, GTC

1. INTRODUCTION

The Adaptive optics (AO) for Gran Telescopio Canarias (GTC)1,2,3 is a single conjugated post focal AO system placed in the GTC Nasmyth platform over a static optical table. GTCAO follows the classic design of an AO system with the use of two identical off-axis parabolas, maintaining the effective focal distance of the telescope. It has been designed initially for Natural Guide Star (NGS) and in a later project phase adapted to one Laser Guide Star (LGS). After the AO system, the FRIDA4 science instrument will be installed, which is a near infrared spectrograph that will offer broad and narrow band imaging and integral field spectroscopy capabilities with low (1000), intermediate (4500) and high (30000) spectral resolutions to operate in the wavelength range 0.9 – 2.5 μm. Main high level specifications are in table 1.

Figure 1. GTCAO optical bench with all subsystems and cable conduits.

*migueln@iac.es
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Wavelength</td>
<td>1.0-2.5 micron, with a goal of 0.8-5 micron</td>
</tr>
<tr>
<td>Strehl Ratio</td>
<td>SR&gt;=0.65 at 2.2 micron for a bright NGS on axis</td>
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<tr>
<td></td>
<td>SR&gt;=0.1 at 2.2 micron for a faint NGS (m_R=14.5)</td>
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<tr>
<td>Range of operation</td>
<td>Seeing better than 1.5 arcsec FWHM at 500 nm</td>
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<tr>
<td>Field of View (FoV)</td>
<td>1.5 arcmin available to the science instrument</td>
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<td></td>
<td>2.0 arcmin accessible for wavefront sensing</td>
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<tr>
<td>Observation time</td>
<td>At least 1 h exposure time on the science instrument</td>
</tr>
<tr>
<td>Dithering</td>
<td>Offsets of 0.25 arcsec (goal 1.0 arcsec) without interrupting operation</td>
</tr>
<tr>
<td>Nodding</td>
<td>Ability to keep the loop closed while nodding the telescope at 1 arcsec per second (TBC)</td>
</tr>
<tr>
<td>Throughput</td>
<td>Throughput of wavefront corrector shall be at least 70% in the wavelength range from 1.0 to 2.5 micron with a goal of 70% in the range 0.8 to 5 micron</td>
</tr>
<tr>
<td>Emissivity</td>
<td>&lt; 20% at 3.8 micron</td>
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<tr>
<td>Ghost images</td>
<td>Defocused ghosts: &lt;1e-5 (except dichroic 1e-4)</td>
</tr>
<tr>
<td></td>
<td>Focused ghosts: &lt;1e-3 and located within 0.2 arcsec</td>
</tr>
<tr>
<td>Upgrades</td>
<td>First upgrade for the use of a single Laser Guide Star</td>
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</table>

Table 1. GTCAO main high level requirements.

The AO system for GTC is composed of the following subsystems:

- **Wavefront corrector.** The wavefront corrector is the part of the AO system where the wavefront aberrations caused by the atmosphere are corrected. Its optical design is based on the widely employed design of a collimator-camera formed using a pair of identical off-axis parabolas, with the deformable mirror placed in the collimated beam conjugate to the pupil. It is divided in the following subsystems:
  - **Optical derotator.** It consists of three flat mirrors in a K configuration mounted on a common structure which rotates around the optical axis in order to compensate the rotation of the sky produced by the alt-azimuth telescope mount. The motorized stage is based on a Direct Current (DC) motor with encoder and tachometer feedback which is used within a speed servo-control to achieve a smooth movement.
  - **Deformable mirror.** Manufactured by CILAS, it is a stack array mirror with Ø154mm and 21x21 piezo electric actuators (i.e. 373 useful actuators) spaced ~7mm and with +/-5.5 micron mechanical stroke. It is conjugated to the pupil of the telescope.
  - **Atmospheric Dispersion Corrector (ADC).** The ADC is composed of a pair of prisms with Ø155mm which are anti-symmetrically rotated to compensate the atmospheric dispersion as a function of the zenith angle and, as a whole, to orientate the introduced dispersion with the parallactic angle. It has two mechanisms: insertion, based on one stepper motor, and rotation of the prisms based on two stepper motors.
  - **Dichroic.** Transmits the infrared radiation to the scientific instrument, while it reflects the visible radiation to feed the wavefront sensor. Cut-off wavelength 0.9µm-2.5µm.
  - **Off-axis parabolas and fold mirror.**

- **Wavefront sensor (WFS).** It is a Shack-Hartmann sensor designed to operate in a high order wavefront sensor mode with 20x20 sub-apertures (lenslet array) in a Fried geometry arrangement, and in a low order wavefront sensor mode with 2x2 sub-apertures. The latter will be employed when operating with LGS as a tip-tilt and defocus sensor on NGS. The WFS system includes two optical stages, a camera and a global positioning mechanism:
  - **The first stage,** a collimator-camera achromatic lenses relay, is employed to place an ADC at a pupil image, not to produce significant chromatic effects at the lenslet array plane. It includes:
    - **Filter wheel.** Based on a stepper motor.
    - **Pupil positioner.** A tip-tilt mechanism based on two stepper motors.
    - **ADC to correct chromatic effects in the WFS.** It has two mechanical stages based on stepper motors.
- **The second stage** is a collimator consisting in two doublets that conjugates the pupil plane onto the lenslet arrays. Its only mechanism is a **Lenslet array wheel** so that pupil can be sampled for high order modes 20x20 or for low order modes 2x2.

- **The Camera** is an Ocam2 by First Light based on e2v EMCCD220 detector reading 1500 frames per second with 240x240 pixels, sub-electron read noise and quantum efficiency over 90% between 600nm and 800nm.

- **Global X, Y and Z WFS positioning** to keep the reference star on axis. These mechanical linear stages are based on AC motors which power supply frequency will be managed in a speed closed loop to achieve following the reference star. They have encoder, resolver and limit switches feedback.

- **Aperture wheel.** It includes an aperture, a stop and a LED for WFS calibration. It is based on a stepper motor.

- **Calibration system.** The purpose of the calibration system is to provide a set of illumination sources to introduce light in the adaptive optics system for calibration. It is situated before the optical derotator and it consists of two units: the telescope simulator and the focal plane calibration unit.

  - The focal plane calibration unit is composed of a linear table based on a stepper motor which supports a moving structure that has one position for the field simulator mask and one position for two flat mirrors in a periscope arrangement, allowing feeding the adaptive optics system with the light coming from the telescope simulator, from the field simulator or from the real telescope.

  - The telescope simulator can simulate the telescope and turbulences providing a beam at the entrance focus of the AO system with the same focal ratio as the nominal beam coming from GTC. it is divided in the following mechanisms:
    - Phase screens insertion. Based on one stepper motor.
    - Phase screens rotation. Based on two stepper motors.
    - LGS simulator focus. Based on one stepper motor.

- **Test camera.** The test camera will be used to test and verify the AO system both at the laboratory and at the telescope in the absence of a science instrument. The camera is a Xenics Xeva with 256x320, 30 micron pixels working between 0.9 and 1.7 micron wavelength. The design comprises off-the-shelf optical components and a filter wheel.

- **Mechanical structure.** It is a static system supported directly by the Nasmyth platform and it doesn’t have any mechanical interface with the Nasmyth instrument rotator.

- **Control system.** It is composed of two big cabinets on Nasmyth platform and three small boxes attached to the optical bench:
  - Control cabinet. It includes the DM electronics, OCAM2 electronics, the Real Time Control (RTC) computer where the control loop is closed, the mechanisms computer, Beckoff control modules and electrical AC panel. The two computers where all the system software runs.
  - Power cabinet. It includes electrical AC panel, AC/DC conversion, DC and stepper motors drivers electronics.
  - Auxiliary boxes: they are in charge of specific actions that electrically require to be closer to the components in the optical table. They are described later.
  - Cabling is also a subsystem itself connecting everything and which manufacturing, integration and verification has a non negligible impact on the project.
The GTCAO system was initially developed by the GTC project office\textsuperscript{1,2,3} but it was paused in 2013. The project restarted effectively in 2015 this time leaded by IAC. The project is now in the Laboratory Integration Phase, after closing the design and completing most of the manufacturing. Nevertheless, there are still some components in the manufacturing process, specifically the science ADC and the mechanical parts of the Calibration System. The status of the integration of the different subsystems is published in this congress\textsuperscript{5}.

2. POWER CABINET

It is a 42 U cabinet (2000mmx800mmx800mm) with a back metal plate with all the elements mechanically attached using DIN rails as it can be seen in the following figure. It is composed of:

- DC power supplies for all the motor drivers.
- 16 motor drivers for stepper and DC motors. (WFC, WFS and calibration system)
- Three motor drivers for WFS global positioning.
- AC protection
There are 16 driver electronics for steppers and DC motors because both types of motors are controlled using the same electronics which include both functionalities, which is a great advantage for future maintenance. The chosen electronics is the IDM680 by Techonosoft with serial and CAN bus communication that allows controlling motors in position, speed or torque including S-Curve profiles with an power output stage based on a 10 bit PWM at 20kHz.

On the bottom left corner of the power cabinet there are 3 motors drivers dedicated to AC motors in charge of the X, Y and Z global positioning of the WFS. They have been chosen differently to the DC drivers because they required more power and because they allow controlling the WFS position by merely changing the motors AC power frequency which allows speed control and following a specific trajectory (X, Y), while keeping the reference star in the WFS optical axes. They are Servostar S703 drivers by Kollmorgen that are also used in other GTC telescope subsystems, again for making easier maintenance and spare availability. They required three-phase electrical power supply.

Both types of drivers are commanded using CAN Bus from the mechanism computer in a CAN network schematically represented in following figure. Motor drivers configuration require connecting the electronics to a computer through RS232 serial line which will be available only for changing its nominal configuration.
The future extension to LGS requires a second WFS on the optical table, which space is reserved, to measure high order atmospheric aberrations while the present WFS will be dedicated for measuring tip-tilt. The new WFS positioning will use more electronics drivers which space is reserved in the middle of the power cabinet as seen in figure 3.

3. CONTROL CABINET

It is also a 42 U (2000mmx800mmx800mm) cabinet but in contrast with the power cabinet, it is a rack mount style cabinet that includes a small metal plate in the top for the electrical elements and for remote maintenance control. Within the cabinet it is included:

- Real Time Control computer. Two sockets Intel Xeon e5-2650 with 32GB DDR4 2133(68GB/s) each socket. It includes a Matrox frame grabber connected with the WFS camera using camera-link that allows reading 1500 fps. It also includes the serial fiber optic card SL100 to connect with the deformable mirror controller using SFPDP.

- DM power electronics.
  - High voltage power supplies.
  - Deformable Mirror Drive electronics (DMDE). Communicated with the RTC using SFPDP at 2.5Gb/s.
  - Power management rack. This rack is in charge of delivering the power supplies to the DMDEs and to take in charge the feedback of the interlock line. The rack generates the +24V for the amplifier boards inside the DMDE.

- Mechanisms computer. It includes a CAN bus board as described in figure 4.

- Maintenance control electronics by Beckoff. In charge of power on/off and cabinets temperature control.

- AC panel.

- Foldable keyboard and screen connected to both computers for local use.
The interfaces with GTC electronics are:

- Ethernet. The internal GTCAO subnet is a start topology, the real time data sent to GTC control system is:
  - Commands for M2 to correct tip and tilt
  - Monitoring data
  - WFS image downsampling in time for the telescope operator to have a quick feedback on wavefront correction. (TBC)

- CAN bus for switching on/off and cabinets temperature control.

- Two phase and three phase electrical power.

From a thermal point of view the power cabinet and the control cabinet work as only one. They are attached one another and they share a heat exchanger to extract the heat out of the telescope dome using glycol water. A symbolic representation of the air circulation is presented in the following figure. The thermal analysis indicates that the isolating cabinets panels require having a thermal resistance better than 0.12K/W which we find feasible although it has not been measured yet. The Beckoff electronics in the upper part of control cabinet and it is in charge of reading internal cabinets temperature and controlling the flow of glycol water in order to keep the cabinets at a target temperature near 20°C. This Beckoff electronics is also in charge of remotely switching on and off the power of the rest of modules in both cabinets. The interface between the Beckoff electronics and the telescope network will be through a CAN network.

![Figure 5. Power cabinet and control cabinet air flow for cooling. Left: top view. Right: lateral view.](image_url)

### 4. AUXILIARY BOXES AND CABLELING

Additionally to the two big cabinets there are two auxiliary electronic boxes and one interfaces box. They are attached to the optical bench and they include devices that require being near the motors, sensors or calibration lights installed on the optical table. Two of them are shown in figure 6.

![Figure 6. Optical bench with its enclosure. One auxiliary box and the electrical interface box close to the panel of connectors.](image_url)
The auxiliary box A, in figure 7, includes 5 ADAM I/O modules communicated with the mechanism computer through ethernet network. Two of them measure temperatures in the optical table, DM and NGS simulator. The other three ADAM modules controls the calibration light sources: NGS simulator and LGS simulator in the telescope simulator, field simulator, LED for Internal WFS calibration. Finally these modules also control the entrance shutter to the whole AO system and also read some limit switches and an emergency stop. The auxiliary box B includes the power supplys for the ocam2 camera and a glycol water flowmeter. The Electrical interfaces box includes electronics to change some communication protocols to be reliable for long cable lengths.

![Figure 7. Auxiliary box A](image)

Cabling is also an important part of the project considering that there are 80 cables in the optical bench, 57 cables within the electronics cabinets and 36 long cables between the optical table and the cabinets. The cables getting into the optical bench have an intermediate connectors pannel as shown in figure 6 to the left of the interfaces box. The routing within the optical bench includes cable conduits as seen in the 3D representation in figure 1. Concerning manufacturing, it can be said, as an interesting data that it has been roughly counted about 600 soldered connector pins. Cabinets and cables have been manufacturated according to CE marked and safety rules.

5. REAL TIME SYSTEM

The GTCAO real time system carries out some of the more challenging functionality of the AO electronics, particularly the most important tasks are:

- Closing the control loop correcting high order atmospheric aberrations. The classical sequence is: reading the images coming from the WFS camera, pre-processing the images, computing the centroids, calculating the WF error, and updating the DM HV values of the PZT actuators. All these tasks require to be run with a low latency and jitter.
- Sending commands to M2 tip-tilt correction.
- Sending monitoring information at low rate: sub-apertures flux, CCD images, DM actuators commands, centroids slopes etc.

Concerning the first and most challenging task, closing the control loop, the standard seeing scenario proposed is characterized by a set of seeing parameters:

- Fried parameter ($r_0$) is 200 mm at a wavelength of 500 nm.
- Turbulent layer height is 5000 m above the telescope.
- Turbulent layer velocity assumes the frozen turbulence hypothesis. The velocity of the turbulent layer is 10 m/s.
The hardware chosen for the real time control implementation has been mentioned in a previous section and it is now detailed in those aspects relevant for the real time system.

The ocam2 camera by First Light is based on a 240x240 pixels EMCCD220 with 24 µm pixels producing up to 1503 fps with a 14 bit resolution ADC converter. It includes a Peltier cooler to reduce the dark current and it performs a sub-electron readout noise and a quantum efficiency over 90% between 600nm and 800nm. Communication with the RTC is through a camera-link with full configuration which theoretical bandwidth is 255MB/s and we have estimated to need bellow 170MB/s. The images are read by a Matrox frame grabber installed in the Real Time Computer (RTC).

The RTC has two sockets Intel Xeon e5-2650 with 32GB DDR4 2133(68GB/s) each socket, ·PCI E 30*16, 3PCI*8, Dual port GBEIlan, 10*SATA3(&Gps). L1 DATA: 10* 32 Kbytes, L1 INSTRUCTIONS 10*32KBytes, L2 : 10*256 Kbytes, L3: 25 Mbytes. This computer has a theoretical peak performance of 320 GFLOPS (10 cores/package * 16 FP Ops/core/cycle * 2.0 GHz) per socket. Some Linpack benchmark give performances results around 240 GFLOPS. This result is almost 100 times bigger than the GFLOPS demanded initially by our system. The levels of cache (and their size) per core (L1 and L2), and the cache per socket L3 are very important for the performance of the access to data and instructions. This will have an effect on how the algorithms are designed (cache-aware) and the type of optimizations we can expect. Figure 8 shows the current memory-core-socket configuration.

![Figure 8. Current memory-core-socket configuration for the Xeon-e5-2650](image_url)

The DM is a CILAS SAM373, based on the SAM (acronym for “Stacked Array Mirror”) technology. This technology offers stabilized and reliable solutions in DM with large number of actuators at high density. The mirror is made of a 21x21 array of actuators, of which 373 actuators are useful, with 7 mm spacing in horizontal direction and 6.96 mm spacing in vertical direction. In order to obtain the maximum stroke everywhere on the actuation aperture, 24 active actuators have been added to the initial number of actuators, which was 349. It communicates with the RTC through SFPDP (2.5Gbit/s). Concerning the DM transfer function, a basic calculus based on piezo actuator electromechanical properties, produces a theoretical resonance frequency beyond 20KHz, figure 9, which will be avoided by manufacturer electronics bandwidth around 2KHz. The electrical slew rate applied by electronics to the piezos is 100V/ms, this produces a theoretical settling time of 300µs for small stroke.
The software managing the real time tasks with the RTC is DARC\textsuperscript{6,7} It is open software highly configurable and flexible developed by Durham University adaptive optics group. It can work on conventional multicore machines, and it admits the possibility to be extended with hardware accelerators. It has been designed with several performance optimizations in mind. For example, it only uses shared memory to communicate with the real time core. We have extended the DARC in order to adapt it to the GTCAO system with two modules. A camera module for the OCAM2-Matrix Radient and a mirror module for the CILAS-SFPDP deformable mirror controller.

The software managing the real time tasks with the RTC is DARC\textsuperscript{6,7} It is open software highly configurable and flexible developed by Durham University adaptive optics group. It can work on conventional multicore machines (parallelizing tasks on different cores), and it admits the possibility to be extended with hardware accelerators. It has been designed with several performance optimizations in mind. For example, the real time core only uses main memory to run (avoids IO access to disc and avoids operating system pagination) and the interaction with other components is performed through the shared memory to reduce latency. It has also several enhancements in the way access to data is performed, for example, taking into account the continuity of the data for cache optimizations. We have extended the DARC in order to adapt it to the GTCAO system with two modules. A camera module for the OCAM2-Matrix Radient and a mirror module for the CILAS-SFPDP deformable mirror controller.

PRESENT STATUS

Design was closed years ago by the previous GTC team at system level, Optical and Mechanical while electrically has been closed and manufactured recently. The DM and camera has been characterized\textsuperscript{1}, and the project is being integrated at sea level laboratory. The electronics hardware design is closed and available for the first control tests to be carried out in the second half of 2016. Further details about present status are published elsewhere\textsuperscript{5}.

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