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VERY LARGE TELESCOPE

MACAO -VLTI
System Overview

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1 Scope

This document describes the system architecture of the MACAO-VLTI (Multiple Application Curvature Adaptive Optics) system at ESO and its implementation as a subsystem of the VLTI. It presents an overview of the system and its subsystems, their mechanical, optical, electrical, electronic and software interfaces, describes the operational concepts and the external interfaces of the system.

1.1 Applicable Documents

The following documents are referred to as AD# in this document:

AD 1	*Top Level Requirements for MACAO-VLTI*	VLT-SPE-ESO-15600-2082

1.2 Reference documents

The following documents are referred to as RD# in this document:

RD 1	*MACAO-VLTI Technical Specification*	VLT-SPE-ESO-15600-2245
RD 2	*MACAO-VLTI System Design Analysis*	VLT-TRE-ESO-15600-2067
RD 3	*MACAO-VLTI Preliminary Mechanical design and analysis report of the Coudé AO facilities*	VLT-TRE-ESO-15600-2274
RD 4	*MACAO-VLTI Optical Design*	VLT-TRE-ESO-15600-2273
RD 5	*MACAO-VLTI Interface Control Document*	VLT-ICD-ESO-15600-2057
RD 6	*MACAO-VLTI Electronics-Overview*	VLT-TRE-ESO-15600-2268
RD 6a	*MACAO-VLTI Electronics-APD*	VLT-TRE-ESO-15600-2269
RD 6b	*MACAO-VLTI Electronics-LCU*	VLT-TRE-ESO-15600-2270
RD 6c	*MACAO-VLTI Electronics-DM Control*	VLT-TRE-ESO-15600-2271
RD 7a	*MACAO-VLTI Software Design OS*	VLT-SPE-ESO-15600-2439
RD 7b	*MACAO-VLTI Software Functional Specs RTC*	VLT-SPE-ESO-15600-2062
RD 7c	*MACAO-VLTI Software Design RTC*	VLT-SPE-ESO-11640-2353
RD 7d	*MACAO-VLTI Software Design ICS*	VLT-SPE-ESO-15600-2440
RD 8	*Technical Specification and Statement of work for*	VLT-SPE-ESO-11640-2460

	the two micro lenslet arrays	
RD 9	*MACAO-VLTI Deformable Mirror Technical Specification*	VLT-SPE-ESO-15600-2064
RD 10	*MACAO-VLTI Deformable Mirror Design Report*	VLT-SPE-CIL-15600-XXX
RD 11	*Technical Specification ESO Adaptive Optics System Deformable Mirror Control*	VLT-SOW-ESO-11640-1943
RD 12	*VLT TCS Tracking Design Description*	VLT-SPE-ESO-17230-0755
RD 13	*NAOS Simulator Unit Design Report*	VLT-TRE-NAO-11650-1-400000-0001
RD 14	*VLTI Fast Link Technical Report*	VLT-TRE-ESO-15400-1373
RD 15	*MACAO – VLTI Tip Tilt Mount Final Design Report*	VLT-TRE-ODP-11640-0002
RD16	*MACAO-VLTI AIT Plan*	VLT-PLA-ESO-15600-2241
RD17	*MACAO-VLTI Technical Specification X-Y Table*	VLT-SPE-ESO-15600-2126
RD18	*MACAO Wavefront Sensor Unit: Technical Specification and statement of work*	VLT-SPE-ESO-11640-2189
RD19	*Requirements for the UT Nasmyth beacons*	VLT-VIF-00/088
RD20	*Analysis of Melepal Field Stabilisation Test Data*	VLT-TRE-ESO-10200-2125
RD21	*Technical Specification: MACAO APD Counter Module*	VLT-SPE-ESO-11640-2262
RD22	*Effect of DM Dynamics on MACAO Performance*	VLT-TRE-ESO-11640-2429

1.3 Applicable drawings

1.4 Acronyms

RD	Reference Document
AIT	Assembly, Integration and Tests
AO	Adaptive Optics
APD	Avalanche Photo Diode
ASM	Atmospherical Site Monitor
BOB	Broker of Observation Blocks
CCS	Central Control Software
CWFS	Curvature Wavefront Sensor
CFT	Call for tender
DM	Deformable Mirror
ESO	European Southern Observatory
FITS	Flexible Image Transport System
FOV	Field of View
HO	High Order
HW	Hardware
ICS	Instrument Control Software
ICD	Interface Control Document
IR	Infrared (1.0-2.2μm)
ISS	Interferometer Supervisor Software
LCU	Local Control Unit
LOS	Line of Sight, the seeing in the direction that the scope is looking
MACAO	Multiple Applications Curvature Adaptive Optics
Mas	Milli arcsec on the sky
MLA	Micro Lens Assembly
ND	Neutral Density filter
NGS	Natural Guide Star (a point source < 0.2” in size)
OB	Observation Block
OLDB	Online Database
OS	Observing Software
PSF	Point Spread Function
STRAP	System for Tip-tilt Removal with Avalanche Photodiodes
SW	Software
TBC	To Be Confirmed
TBD	To be determined
TRS	Time Reference System
UT	Unit Telescope (8.2-m diameter)
VLT	Very Large Telescope
VLTI	VLT Interferometer
WFE	Wavefront Error
WFS	wavefront Sensor
WFSA	wavefront sensor assembly
WRT	with respect to
WS	Workstation
WFSA	Wavefront Sensor Assembly

2 INTRODUCTION

The MACAO-VLTI system is a 60 element curvature AO system operating at the Coudé focus of one of the VLT UTs delivering a corrected wavefront to the VLTI delay lines after reflection off the dichroic M9. The corrective optics consists of a deformable mirror with 60 actuators mounted on a tip/tilt stage situated at M8 in the Coudé train. The Curvature Wavefront Sensor is based on a 60 element lenslet array located in a pupil plane feeding fibers connected to 60 APD modules; the CWFS is hosted in the wavefront sensor assembly (WFSA) mounted on an X-Y table standing on the Coudé floor below M9. MACAO-VLTI is designed to operate only with natural guide stars.

For bright sources (m_v 8^{th} mag) MACAO is specified to deliver at least 50% Strehl ratio @2.2µm on axis under median seeing conditions (0.65”) and for faint sources (m_V 15.5^{th} mag) at least 25% Strehl ratio @2.2µm under the same seeing conditions. An IR output beam stability of 10mas ignoring residual refraction and star position errors is guaranteed, an interface is provided to allow feedback from an IR tip/tilt camera located in the interferometric lab under the control of the VLTI to compensate for these errors. Strict limits are placed on the piston introduced by the AO system.

MACAO can close the AO loop on point sources and extended objects with a size < 2.5”, up to a maximum of seeing 1.0” @0.5µm. The MACAO system can operate with the NGS on-axis or, by tracking the X-Y table on which the WFSA sits, up to 1’ off-axis.

MACAO includes a TCCD viewing camera within the WFSA, which allows the performance of the system to be monitored during daytime operations using an artificial source and may also be used as a 10” diameter FOV acquisition camera for the VLTI. The WFSA also hosts a STRAP unit whose operation is outside the scope of MACAO-VLTI.

The MACAO software provides automatic guide star acquisition and AO loop optimisation procedures. During closed loop operation it provides low frequency diagnostics via the OLDB and high frequency diagnostics via the VLTI reflective memory network. At the end of an observation a FITS file containing time tagged data characterising the AO correction during the observation is made available to the VLTI.

For the VLTI, up to four Coudé foci will be equipped with MACAO systems which are coordinated with the other subsystems of the VLTI and the TCS by the VLT interferometer supervisor software (VLT ISS).

3 System Architecture

The subsystems comprising MACAO are:

For each equipped UT

- Corrective Optics Assembly
  - A deformable mirror mounted in a gimbal Tip/Tilt stage located at M8 in the Coudé tube, driven by HV electronics located on the azimuth platform with a small electronics conditioning box located close to the Tip/Tilt stage
- Wavefront Sensor Assembly
  - A CWFS "box" containing the membrane, relay optics and lenslet array connected by a fiber guide to a cooled rack containing the APD modules.

    The CWFS box is mounted below M9 and telecentricity lens with the membrane located at the Coudé focus. The box is supported on an X-Y stage for off axis operation.
- Instrument Control Electronics
  - Two VLT standard PowerPC based LCUs located in cooled cabinets on the Coudé floor. One ICS LCU controlling the X/Y stage and other motor functions, one Real Time Computer LCU containing two PowerPCs performing the real-time adaptive optics control.
- APD Electronics
  - The APD modules are mounted in their own cooled rack located close to the WFSA, the APD modules are connected electrically to the APD counter boards located within one of the instrument electronics racks.
- Monitoring X-Terminal
  - Located in the VLTI control room, displaying the diagnostic and monitoring GUIs, the software is hosted on the MACAO instrument workstation.

- Calibration unit (implemented by the VLTI)
  - Located at M4 bent Nasmyth focus, containing reference sources for interaction matrix generation, system calibration and alignment.
- Test IR Camera (during installation & commissioning)
  - Capable of sampling the PSF, installed at the reflected Coudé focus during MACAO system AIT. The test camera will be moved from UT to UT as each MACAO system is commissioned.

Shared Between up to 4 UTs

- Instrument Workstation
  - An HP J5000 workstation located in VLTI computer room adjacent to the control room hosting the workstation components of the MACAO SW supporting the MACAO systems installed in up to 4 UTs.

3.1 Corrective Optics Assembly

The MACAO corrective optics consists of a curvature bimorph mirror with 60 actuators mounted in a tip/tilt stage.

The curvature mirror is based on bimorph piezoelectric technology. The mirrors for MACAO-VLTI have a 105mm clear aperture diameter, with an outer diameter of 150 mm, are ~2mm thick and have 60 actuators. These mirrors are being procured from CILAS.

Bimorph mirrors consist of two piezoelectric ceramic wafers bonded together and oppositely polarised, sandwiched between the two wafers the electrode pattern (matching that of the CWFS lenslet) is deposited. The mirrors supplied by CILAS have 0,2mm thick glass plates attached to the front and rear PZT plates, the front glass plate is polished to achieve the desired surface quality and a protected silver coating applied.

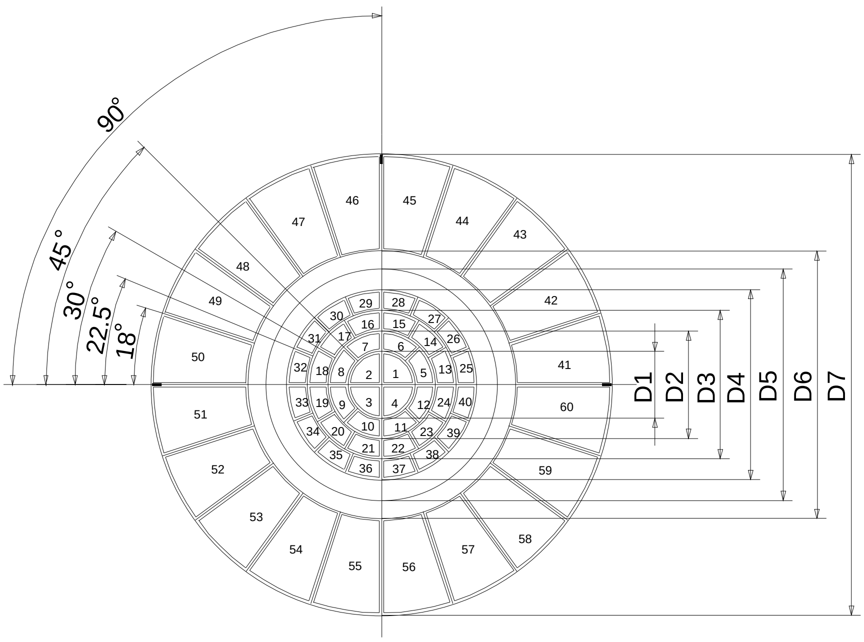

Figure 1 Deformable mirror actuator pattern

The mirrors are specified to provide reflectivity of 97-98% at wavelengths between 450nm and 13000nm, however the design report from CILAS indicates that reflectivity should be > 98% up to 50000nm.

High Voltage amplifiers capable of supplying voltages from –400 to + 400V with 14 bits of resolution are connected to the electrodes controlling the local curvature of the mirror. The voltages applied provide a maximum stroke capable of correcting up to 1.0” seeing on one of the VLT UTs. The high voltage amplifier specification is given in RD11.

The design of the mirrors for VLTI has been undertaken by CILAS and a design report is available [RD10] based on technical specifications provided by ESO [RD9]. The effect of DM resonant properties has been analysed and the results can be found in [RD22].

To preserve stroke on the DM, it is mounted in a tip/tilt stage. It is mounted such that the centre of rotation and centre of gravity is on the surface of the DM to avoid introduction of piston errors during operation. The tip/tilt stage is used to offload high stroke tip and tilt with an effective update frequency of ~5Hz and a range of +/- 3”.

The following diagram shows a design for the Tip/Tilt mount as presented in RD15.

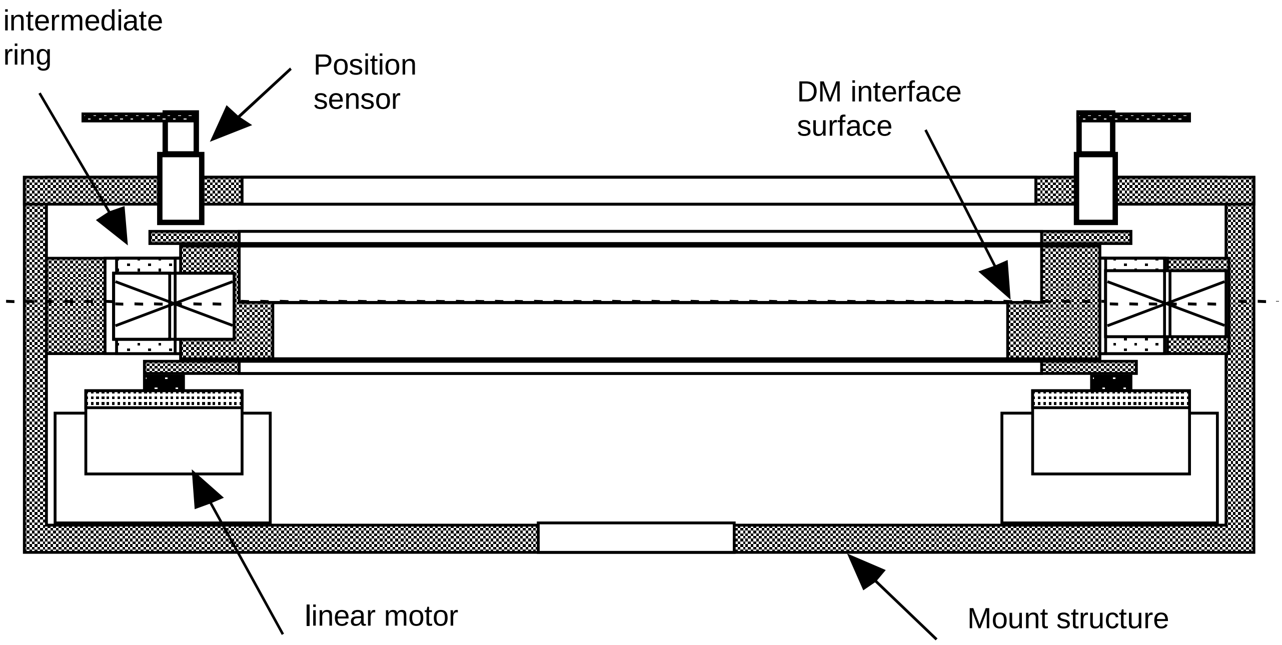

Figure 2 Tip/Tilt mount concept

An analysis has been undertaken to ensure that there is no electrical influence between the DM actuators and the operation of the Tip/Tilt mount, this can be found in RD22.

3.2 MACAO Wavefront Sensor Assembly

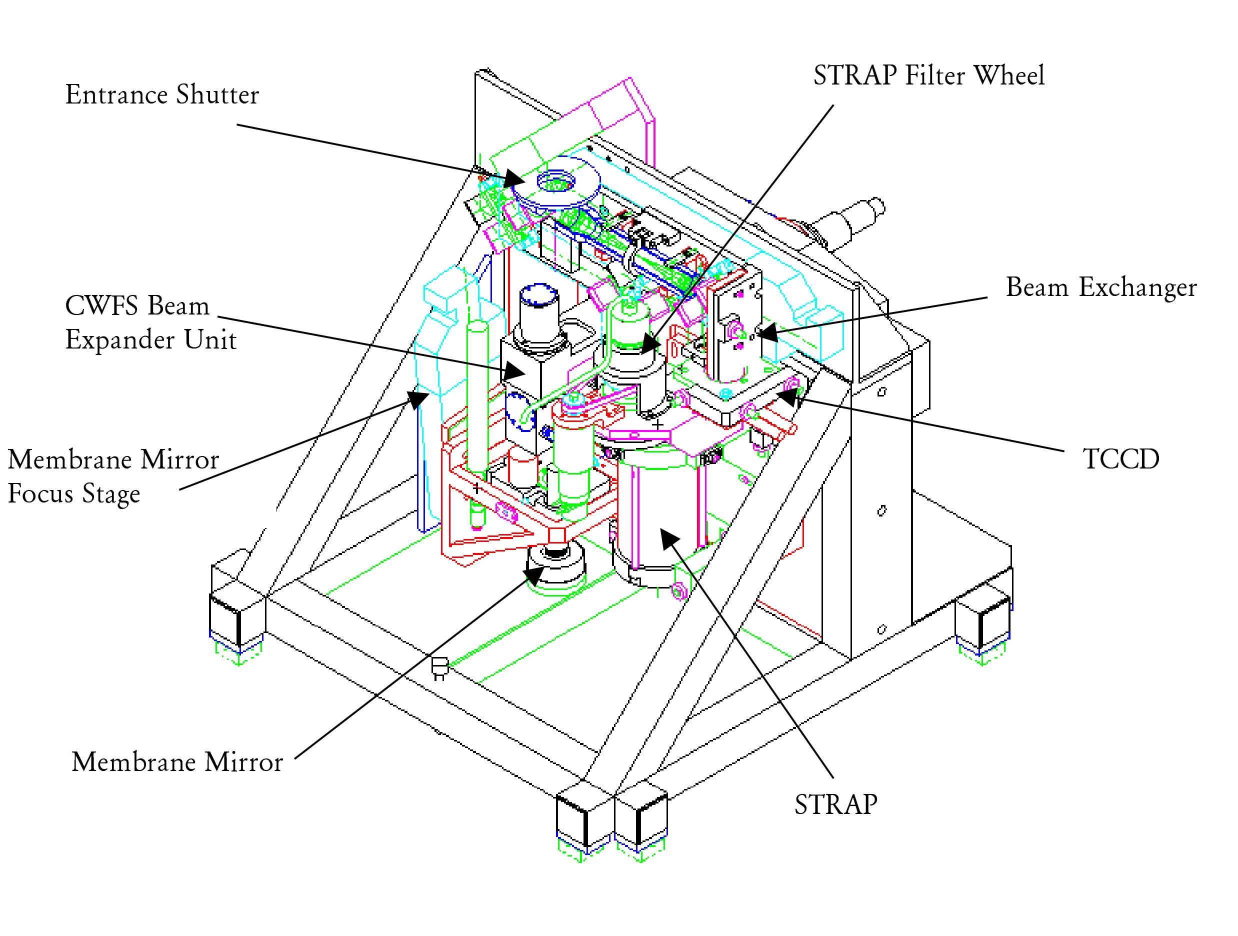

Figure 3 MACAO Wavefront Sensor Assembly

The Wavefront Sensor Assembly (WFSA) contains:

- The curvature wavefront sensor (CWFS) comprising a variable curvature membrane, relay optics and the CWFS lenslet array connected by fibers to the APD rack (See section 3.3).
- A Neutral Density wheel with 11 positions (one blocking, one free, one glass and 8 NDs) situated before the CWFS lenslet array allowing the APDs to operate in their nominal range of < 2Mcounts/sec up to the maximum GS magnitude M_v-1.
- A motorised optical derotator to compensate for the differential rotation between DM and lenslet.

- A TCCD viewing camera provided by the VLTI allowing the performance of the AO system to be monitored during daytime using the artificial source and during night-time for bright guide stars. This camera can also operate as a VLTI acquisition camera.

  The viewing camera is a VLT standard small technical CCD (TCCD), the TCCD has a format of 290x386 22μm pixels giving a plate scale of ~11mas/pixel and a naked FOV of 3.1"x4.2".

  When used as an acquisition camera an objective can be placed in front of the TCCD providing a 10" FOV.
- A STRAP unit provided by VLTI. Although the STRAP unit does not form part of the MACAO system, hosting the STRAP unit in the WFS box allows easy switching between STRAP and MACAO operation modes by selecting the appropriate beam path with optics mounted on a linear stage.
- A Beam Exchanger Unit with 5 positions selecting the beam path within the WFS
  - Open, passing the beam to the CWFS
  - 50/50 beam splitter, sharing the beam between the TCCD with and the CWFS
  - Folding flat, feeding the STRAP unit
  - Folding flat, feeding the STRAP unit with a dichroic feeding 50% of the light to the TCCD
  - Folding flat, feeding the TCCD via an objective giving a 10" FOV on the TCCD
- A protective shutter at the WFS box entrance

The WFSA is mounted on an X-Y stage, which is capable of centring the CWFS on an NGS anywhere within the 2' diameter FOV. The X-Y Table is described in more detail in section 3.3.3.

The WFSA is described in detail in RD3, the Optical design is given in RD4, and the technical specifications of the WFS unit are given in RD18.

3.3 Curvature Wavefront Sensor

A 10mm variable curvature membrane mirror transferring a 5" FOV is situated directly at the Coudé focus, the CWFS optics form an image of the telescope pupil on the Micro Lens Assembly (MLA) when the membrane mirror is flat. The membrane mirror is made to oscillate at ~2.1kHz forming alternately intra and extra focal images.

The membrane is mounted with three remotely controlled motions, tip and tilt are used to control pupil alignment and a Z motion along the optical axis provides the ability to offset in focus ±15mm. Mounted before the membrane is a diaphragm, which can be stopped down to 1 mm (0.5" on sky), for use in high sky background and good seeing regimes.

3.3.1 Micro Lens Assembly

The MLA comprises two lenslet arrays. The first array (see Fig 4) is 21mm diameter with a pupil diameter of 14mm, it extracts 60 keystone shaped subapertures. The second array reimages these subapertures onto 100μm fibers forming micro pupils, each fiber feeds an APD module from PerkinElmer. The specifications for the MLA are given in [RD8].

Situated in front of the MLA is a Neutral Density allowing the APDs to operate in their nominal range (500k-2M counts per second) with NGS magnitudes up to a maximum of M_v -1. Each ND filter forms a light tight seal with the front of the MLA.

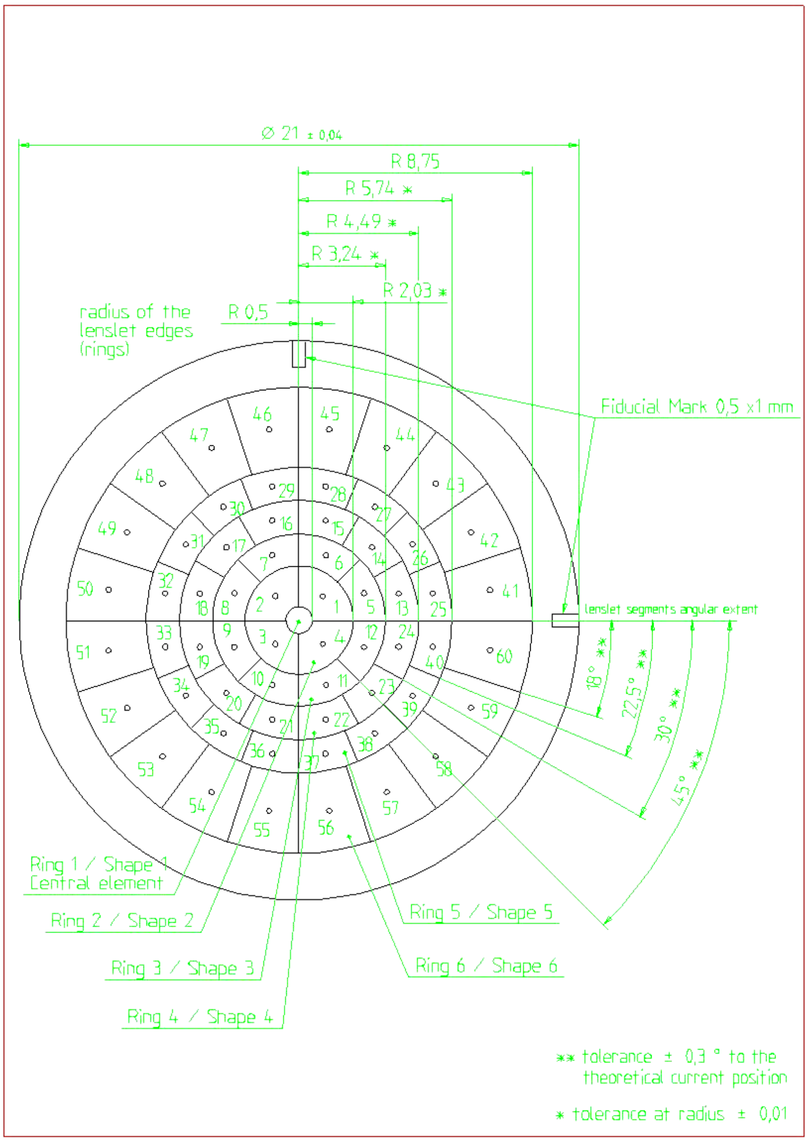

Figure 4 Lenslet Geometry

This lenslet geometry was selected after simulation to minimise noise propagation and to reduce closed loop residual variance (See RD2).

Because the WFS box is mounted on the fixed Coudé floor, and the DM is mounted on the rotating telescope structure there is a relative rotation between the two. If this is not compensated, the correspondence between CWFS lenslet subapertures and DM actuators would constantly change depending upon the telescope azimuthal location requiring continuous updates of the interaction matrices. To avoid this an optical derotator is installed before the CWFS lenslet array, this is driven to match the lenslet to the DM by the instrument control software. The alternative of updating the interaction matrix in S/W has been investigated and rejected due to the degradation in performance which would be caused.

3.3.2 APD Electronics

The APD modules produced by PerkinElmer (formerly EG&G) are single photon detectors containing silicon avalanche photo diodes with a peak quantum efficiency of 70% (the specified QE curve is given in Figure 5). Modules are available with different specifications of dark current ranging from 25 to 250 counts per second (cps), after simulation (See RD2) the 250 cps modules have been selected for MACAO-VLTI. These APD modules are thermoelectrically cooled and have a maximum specified count rate of 10 million counts per second, however due to nonlinearity effects the nominal count rate will be limited to 2M cps by use of an ND filter.

The APDs are connected by optical fibers <3m long to the rear of the MLA. The maximum length of the fibers is defined by the "dead" time of the module after each photon detection event, which is ~40ns. As each photon is detected, an avalanche is produced in the APD and light is emitted, if the fibers are too long then the APD module will detect this emitted light after reflection at the lenslet array.

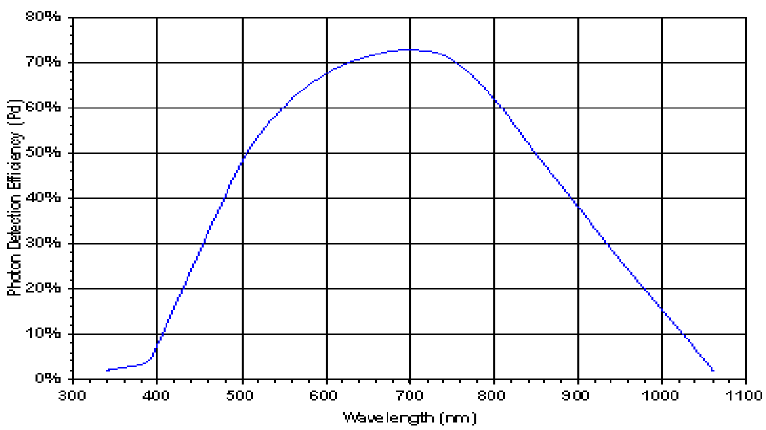

Figure 5 APD QE

There is a slight risk of physical damage to the APDs if exposed to excessive illumination, although this risk has been significantly reduced in the latest PerkinElmer APD modules. To avoid this risk there are safety features at software and hardware level. In software the current count rate is constantly monitored by the RTC and the protective shutter closed and ND placed at its darkest position when the APD counts exceed a safety threshold. A hardware interlock is implemented in the APD counters; the counters detect when the count rate goes above a safety threshold and power to the APD modules is shut off.

The APD modules generate a 25ns TTL pulse for each photon detected, the TTL pulses are fed by coax cables to counter boards. The counters boards are synchronised with the membrane driver accumulating the counts on either side of focus for each subaperture and sending the total counts to the realtime computer over a fiber link at the end of each intra/extra focal cycle.

The APD modules are housed in a cooled APD rack located close to the WFS box, the APD counters are housed in the ICS electronics cabinets.

The APD module rack is described in RD6a and the APD counters are described in RD21.

3.3.3 X-Y Tables

The WFS box is mounted on an X-Y table, which is used to centre the WFS on an NGS anywhere within the 2’ diameter FOV in the Coudé. The location of the WFS defines the reference position for the AO system. Any error in position or vibration will impact directly on the position of the output science beam; therefore high accuracy and stability are required.

The basic specifications of the X-Y stage are listed below:

Range of motion in both axes:	250mm
Absolute positioning accuracy :	±100µm (50mas on sky)
Relative positioning accuracy :	±(8-12)µm (4-6mas on sky), depending on location

To compensate for the field rotation in the Coudé lab, the position of the X-Y table is driven with a guide star tracking algorithm implemented by the instrument control software (See 6.2.2) which compensates both for field rotation and for transversal atmospheric dispersion.

Fine offsets to the tracking trajectory can be passed to MACAO at 1Hz; these offsets could be generated from an IR Tip/Tilt sensor, implemented by the VLTI, measuring residual tip/tilt in the interferometric laboratory, this would compensate for any residual atmospheric dispersion correction or flexure induced errors.

Detailed specification of the X-Y tables are given in RD17.

3.3.4 M9 Dichroic and Telecentricity Lens

The M9 Dichroic and Telecentricity lens are provided by VLTI. The Dichroic is designed to transmit light between 450-990nm and to reflect between 1000-13000nm. It is important to note that any aberrations introduced by these components will be non common-path and will therefore impact directly on the quality of the output science beam.

See RD2 for more detail of the analysis and error budget.

3.4 Calibration and Alignment Unit

MACAO requires a white light (0.5-2.2μm) source forming diffraction limited spot in the visible for generation of system interaction matrixes.

This calibration source is hosted in the VLTI calibration unit located at the bent Nasmyth focus under control of one of the VLT LCUs and is described in RD5, MACAO controls this calibration source through commands sent to the Telescope Control Software (TCS).

4 Real Time Control

Figure 6 shows the overall control architecture of MACAO and its interaction with the TCS and Instrument during closed loop operations.

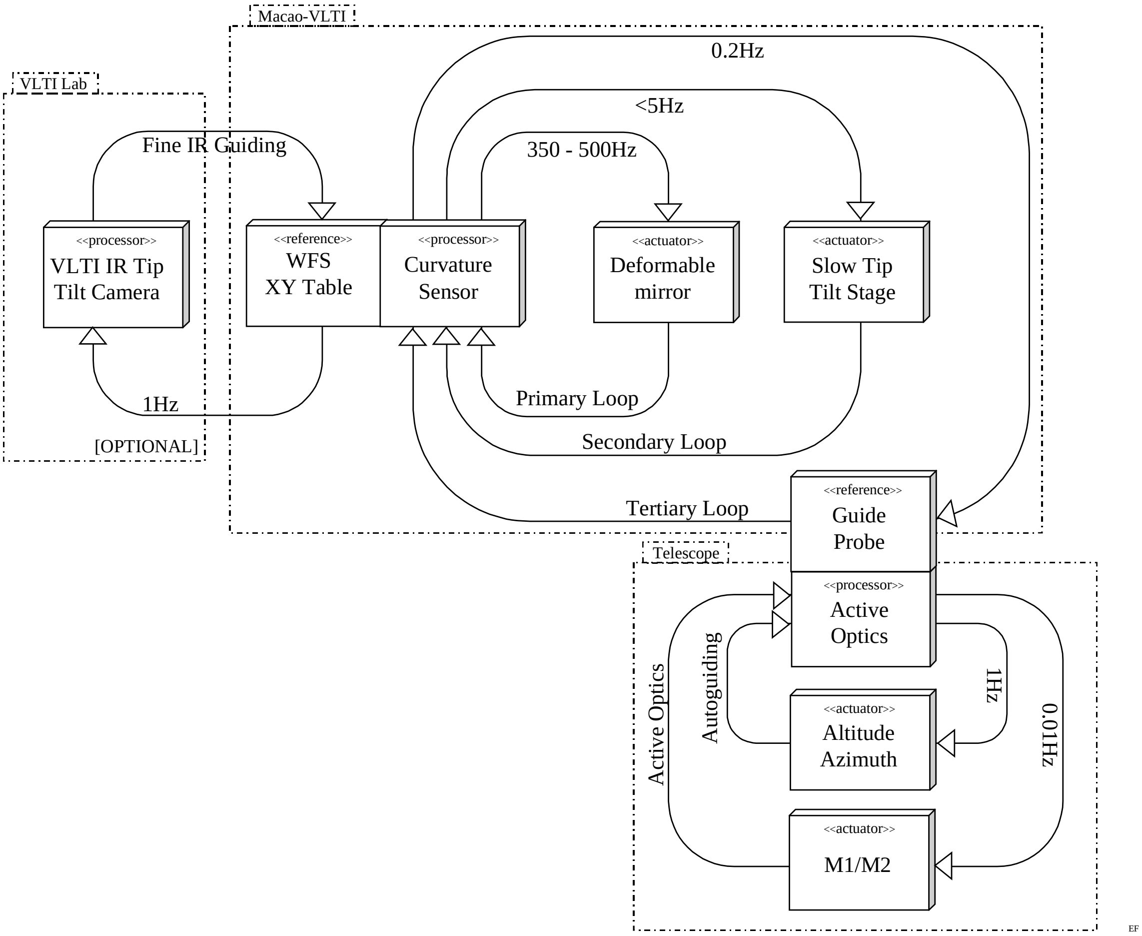

Figure 6 MACAO Overall Control Concept

There are three subsystems implementing servo loops in the diagram above. The MACAO adaptive optics system, the telescope control system (TCS), and the VLTI.

4.1 MACAO Servo Loops

There are three nested servo loops operating within MACAO

- Primary
  A high order loop using the NGS on the CWFS operating at ~350Hz to calculate mirror commands to control the deformable mirror, correcting high order optical errors and fast tip-tilt

- Secondary
  A slow loop operating at ~5Hz, offloading the low temporal frequency component of the tip-tilt corrected by the DM to the Tip/Tilt stage avoiding the DM running out of stroke
- Tertiary
  A very slow loop operating at ~0.2Hz offloading tip-tilt from the Secondary loop to avoid the Tip/Tilt stage running out of stroke, and optionally low temporal frequency focus terms from the Primary loop to the guide probe by sending OFFSGP (for alpha/delta) and OFFSFAD (for focus) requests to the TCS

4.2 Fine IR Guiding Loop

This loop is optional, its purpose is to correct any residual tip/tilt error detected in the science beam in the VLTI interferometric lab. This loop could be implemented by an IR camera feeding slow (1Hz) OFFSET commands over the normal VLTI AO LAN to the MACAO OS which will forward the command to the software controlling the X-Y table trajectory.

4.3 TCS Servo Loops

Active optics and autoguiding are active at all times when the AO loop is closed. However the field stabilisation loop MUST be disabled to avoid the introduction of high frequency tilt errors by M2 and the introduction of tip/tilt errors due to tilt anisoplanatism (See analysis in RD2).

5 Computer and Control Architecture

The major components of the MACAO control architecture are described in the following sections:

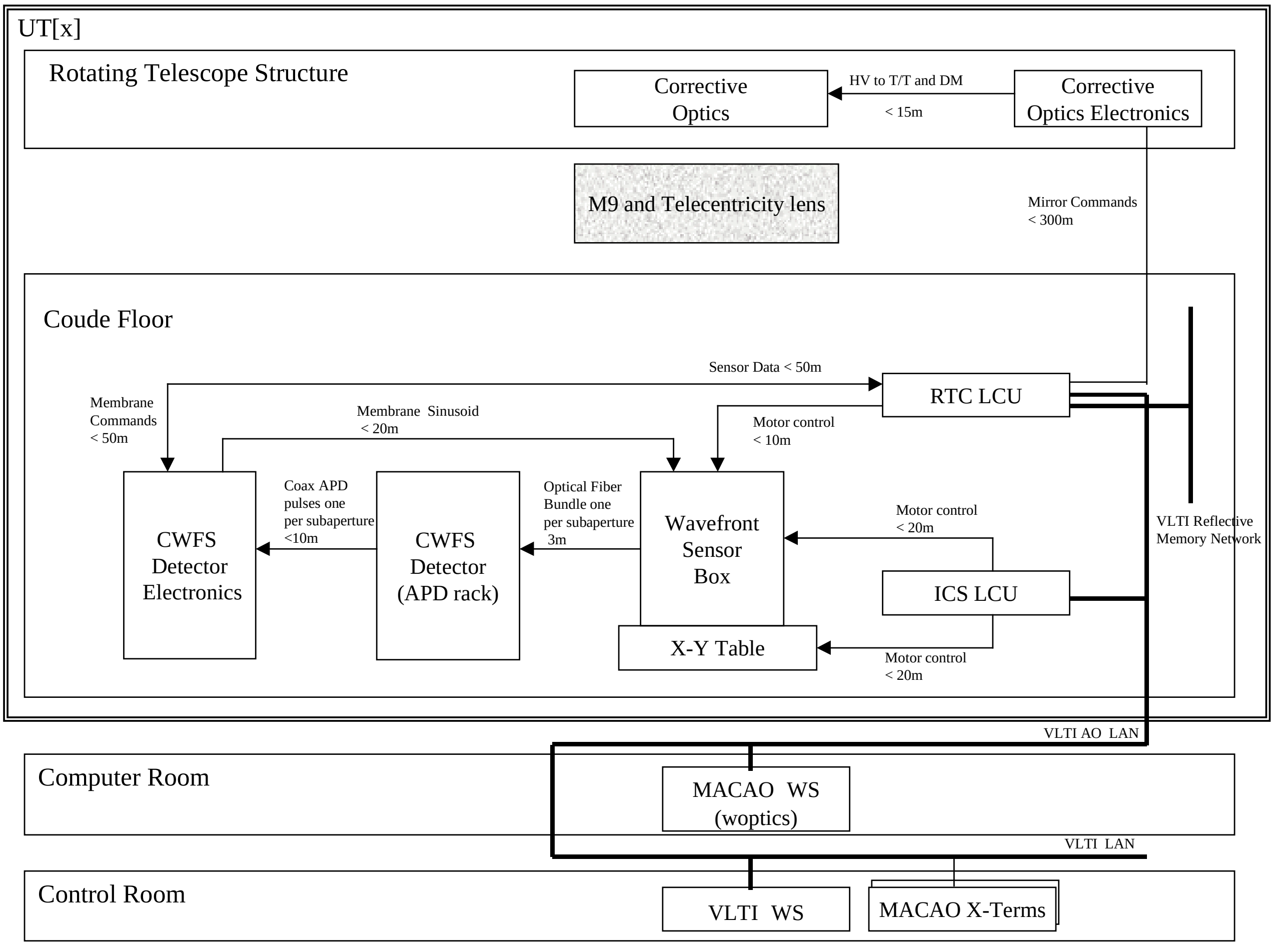

Figure 7 MACAO Overall Control Architecture

The MACAO control architecture is built around two LCUs and the instrument workstation connected by the VLTI AO LAN subnet. Coordination of MACAO with the other VLTI subsystems is performed by software running on the VLTI Supervisor WS which communicates with the MACAO instrument workstation over the VLTI LAN.

The two MACAO LCUs are the RTC (real time computer) LCU and ICS (instrument control) LCU. The RTC LCU is concerned with implementing the AO control loops, interfacing with the CWFS detector and corrective optics, the ICS LCU runs the X/Y table tracking loop and handles the motorised functions which are not directly related to control of the AO loop.

The instrument workstation is a standard VLT instrument workstation hosting the WS components of the MACAO software and providing the external interface to the MACAO system. This workstation supports up to 4 MACAO systems and also runs the WS software for STRAP and TCCD control. Each MACAO system uses an X-Terminal for display of AO diagnostic information.

This control architecture allows a large separation between the DM and the WFS with its associated control electronics, allowing e.g. the WFS to be situated in the Interferometric Lab if required. This would however require a redesign of the WFS optics.

The LCU electronics located at the Coudé floor are housed in two cooled cabinets, one of which has space reserved for the VLTI TCCD & STRAP control. The space allocated being 6HE in a standard 19” rack.

The corrective optics electronics (high voltage amplifiers) are located at the azimuth platform, an additional signal conditioning box is located adjacent to the Tip/Tilt stage mounted close to M8.

The MACAO control electronics is described in detail in RDs 6-6c.

5.1 RTC LCU

The following figure shows the control subsystems that are managed by the RTC LCU.

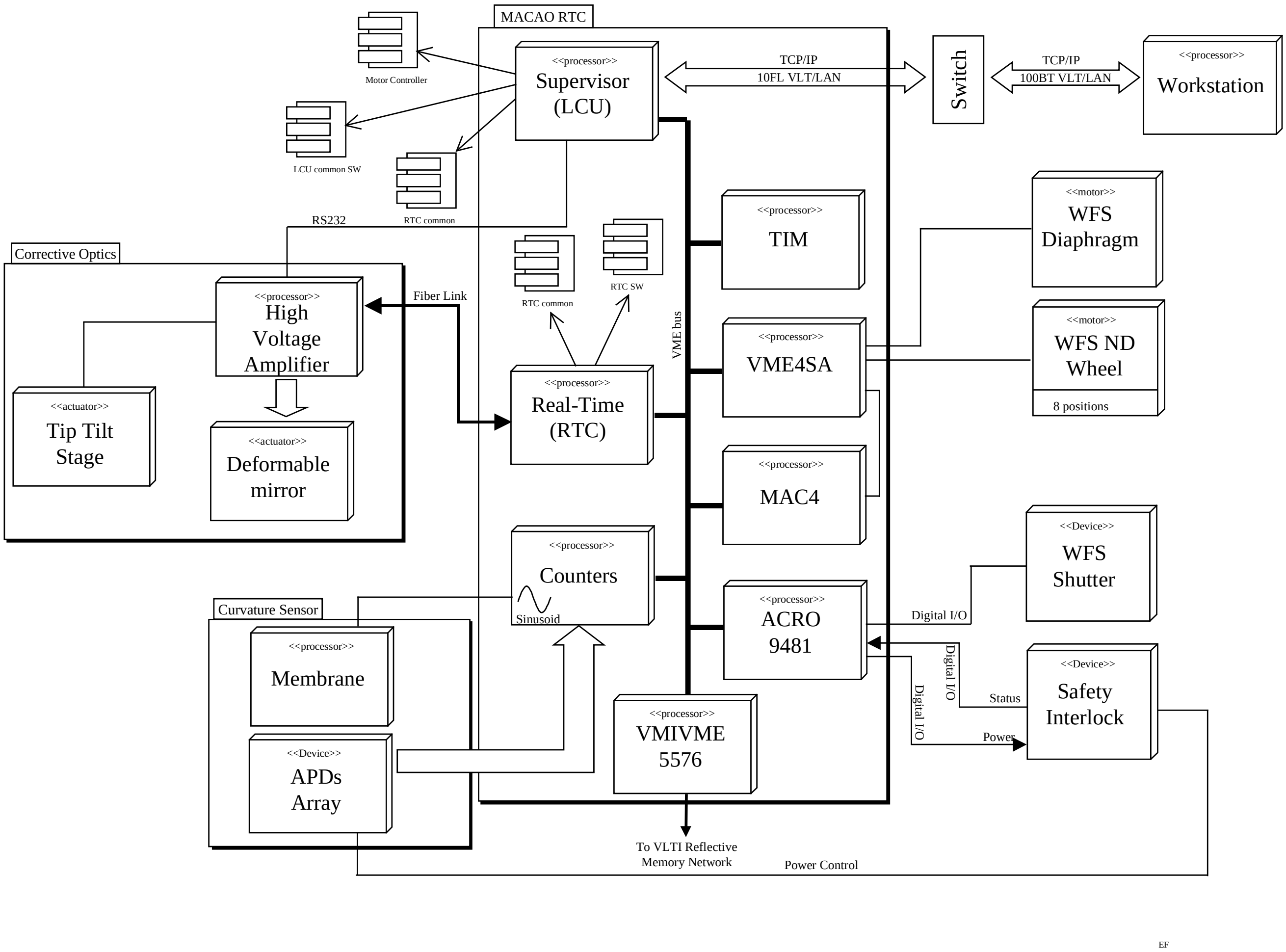

Figure 8 RTC Control Architecture

The RTC LCU uses two PowerPCs, one performing the real time calculations required for the AO loops and one performing supervisery operations.

The RTC controls the motor functions which are directly related to the operation and optimization of the AO loop, the WFS diaphragm , ND wheel and shutter. The RTC monitors the APD count rate and can via an interlock, remove power for the APDs or close the shutter.

The RTC sets the membrane frequency and amplitude depending upon the current NGS and seeing parameters. During normal AO operation it acquires APD counts over the VME bus in a block transfer, performs the loop calculations and outputs the vector of correction values to the Tip/Tilt stage and DM via an optical fiber interface.

The RTC includes a TIM module for access to high accuracy timing information to synchronize chopping cycles with M2.

A reflective memory board is included to allow the RTC to pass low latency real time AO derived data (measured WFE) at the end of each correction cycle to other VLTI sub-systems.

5.2 ICS LCU

The following diagram shows the control subsystems that are managed by the ICS LCU.

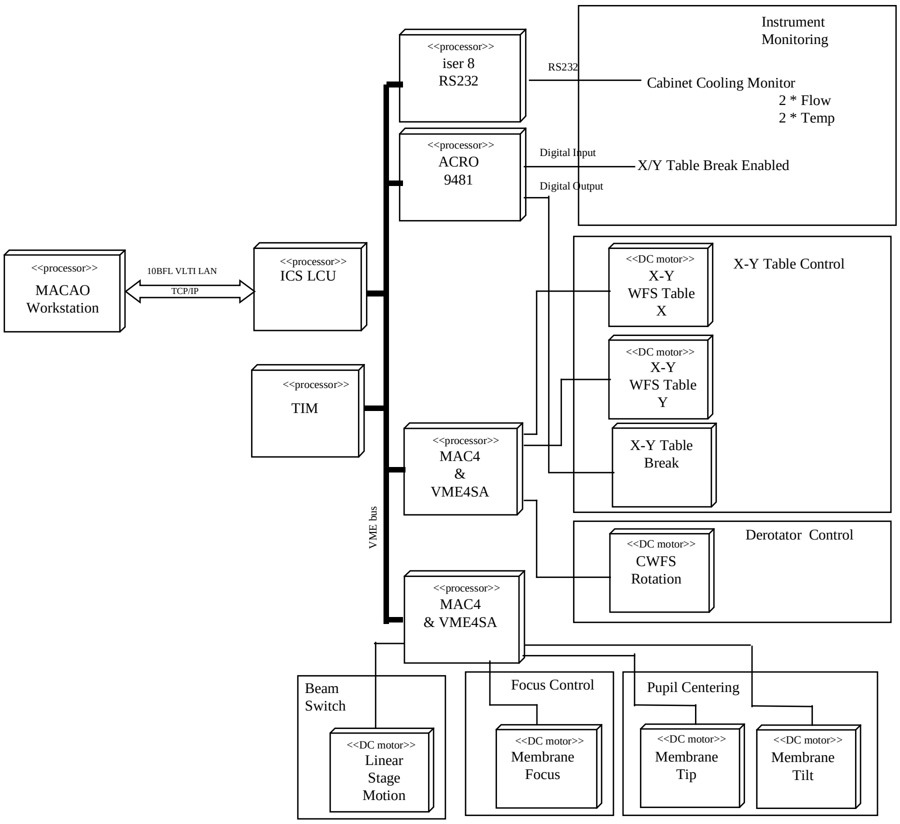

Figure 9 ICS Control Architecture

The ICS LCU is a standard PowerPC with ESO standard motor control boards for controlling the X-Y table, optical derotator, membrane Focus motion and controlling the linear stage selecting the beam path within the WFS box. A TIM board is also required to retrieve the absolute time from the TRS (Time Reference System) for use in calculating the X-Y table trajectory and derotator position.

The ICS LCU implements the instrument monitoring functions via digital I/O signals for the APD power and X/Y table break interlocks and an RS232 connection to the ESO standard cabinet cooling unit.

6 MACAO Software

The following sections give an overview of the architecture and functionality of the MACAO software. RD7A to RD7D describe the MACAO software in detail.

6.1 Software Context

The following figure shows how the MACAO software fits into the overall software architecture of the VLTI.

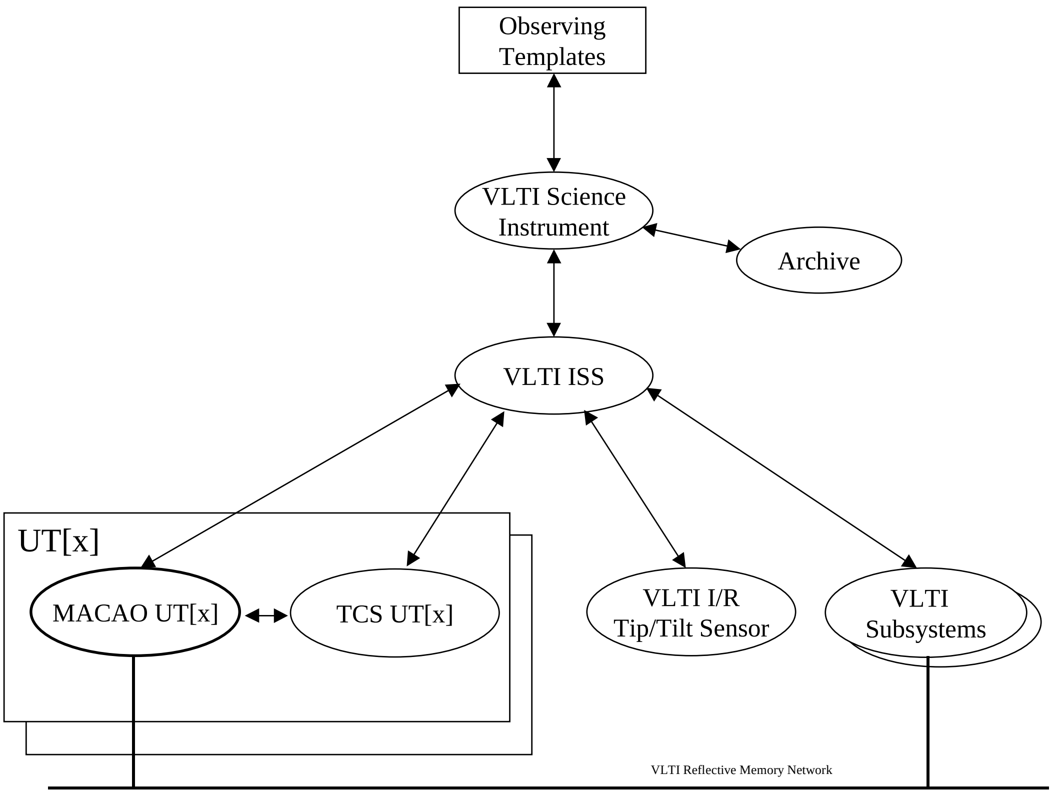

Figure 10 MACAO Software in Context

The VLT Interferometer Supervisor Software (ISS) performs the function of coordinating the MACAO software and the TCS for each UT with the other VLTI subsystems for use by a VLTI science instrument.

MACAO sends commands to the TCS for offloading of Tip and Tilt and for control of the calibration sources.

A VLTI I/R Tip/Tilt sensor subsystem is shown here as a possible source for the IR tip/tilt signals fed to MACAO (via the ISS).

6.2 MACAO Software Architecture

The MACAO Software executes on the MACAO instrument workstation (woptics) and the MACAO LCUs. The external interfaces to the system are hosted on the MACAO WS and take the form of CCS commands sent to the MACAO OS and the MACAO branch of the On-line database (OLDB) which contains the values of the AO loop diagnostic data (updated at ~1Hz).

The MACAO OS optionally produces a FITS file at the end of an observation that contains time tagged data temporaly sampling the atmospheric conditions during the observation; this file is stored on the MACAO instrument workstation hard-disk and may be retrieved by the ISS.

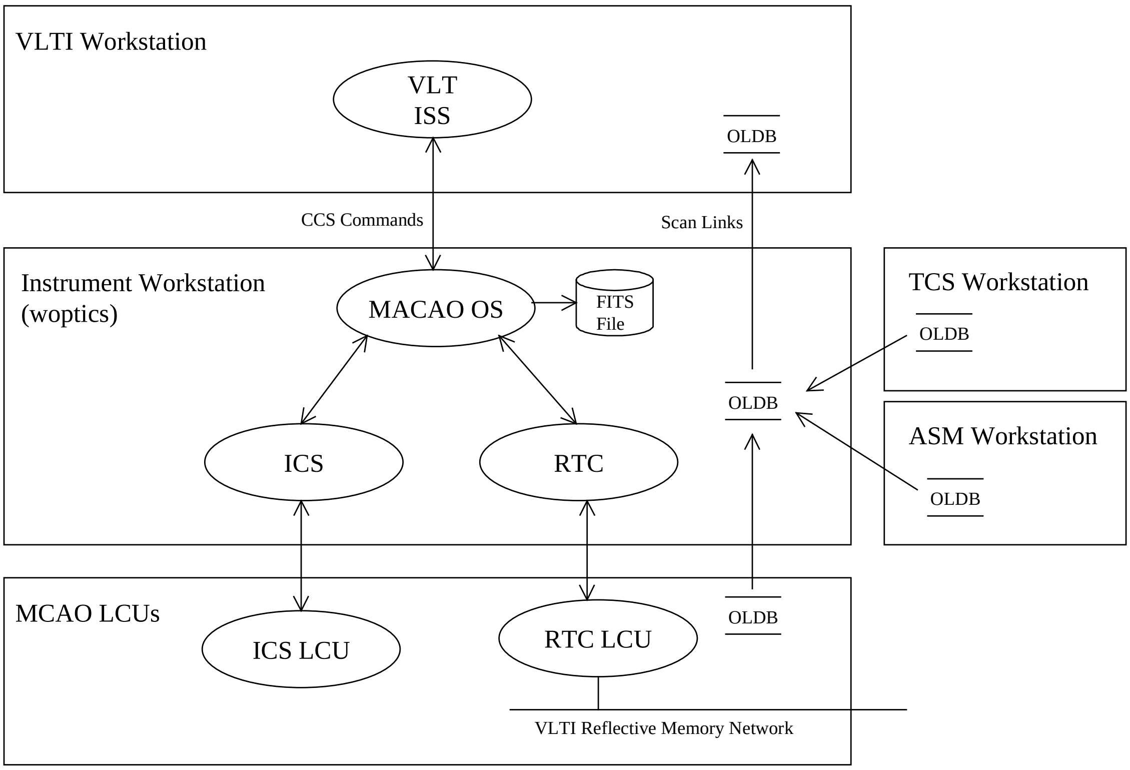

Figure 11 MACAO Software Architecture

The interface to MACAO is defined by the following:

- CCS Commands issued by the VLTI ISS to the MACAO OS

For guide star acquisition, Tip/Tilt and Focus offsetting, High order Zernike offsetting and all normal AO operations

- CCS Commands issued by the MACAO OS to the TCS
  For Tip/Tilt and Focus offloading
- CCS Commands implemented by the telescope interface for control of the calibration sources
  For use by maintenance operations
- Public database points in the on-line DB
  Reflecting current values of AO diagnostic values
- FITS file generated at the end of an exposure
  Containing information acquired during an exposure characterising the AO correction at a user definable sampling frequency
- Data passed in closed loop from the RTC over the VLTI Reflective Memory Network
  Containing measured WFE at each loop cycle

The online database on the instrument workstation is updated with values scanned from the TCS workstation providing telescope parameters (e.g. tracking state) and the ASM workstation providing atmospheric measurements.

The instrument workstation can support up to 4 instances of the MACAO software (one per UT), each operating in its own CCSLite environment.

The MACAO software is decomposed into the following VLT software modules.

6.2.1 OS

The MACAO OS provides the external command interface to the MACAO system and provides high level coordination and monitoring of the MACAO sub-systems. It is also responsible for passing the request to offload tip/tilt or focus to the TCS and for storing the FITS file at the end of observation.

The MACAO OS is described in RD7a.

6.2.2 ICS

The MACAO ICS manages the hardware functions that are not related directly to AO loop optimisation and implements the instrument monitoring functions.

The ICS implements the guide star tracking loop, controlling the X-Y Table position to compensate for field rotation and transversal atmospheric dispersion and the derotator position compensating for telescope azimuthal location.

The MACAO ICS is described in RD7d.

6.2.3 RTC

The MACAO RTC software implements the primary and secondary correction loops, acquiring realtime curvature signals from the CWFS electronics, applying the control matrixes, generating the vector of actuator values required by the DM and tip/tilt stages and outputting them to the corrective optics electronics. At the end of each AO correction cycle diagnostic values estimating the current atmospheric conditions are passed over the VLTI reflective memory network. It performs the calculations required for the tertiary loop (Tip/Tilt and Focus offloads), making the values available to the OS to be offloaded to the TCS.

The MACAO RTC manages the hardware functions which are directly related to optimisation of the AO loop (ND setting, diaphragm setting) and controls the shutter of the CWFS box to provide rapid response to any dangerous increase in flux which might cause damage to the APD array.

The MACAO RTC is described in RDs 7b and 7c.

6.3 Software High Level Capabilities

6.3.1 Open Loop

In Open Loop operation the MACAO system performs no atmospheric correction, the protective shutter protecting the APDs is closed.

On command from the ISS a vector of values previously calculated by MACAO can be applied to the corrective optics making the output wavefront "flat" i.e. the static aberrations of the corrective optics sensed by the WFS are removed. The accuracy of this compensation depends on the time since the flat vector was measured; MACAO provides a procedure by which the ISS can recalibrate this "flat" vector.

6.3.2 Telescope Preset and NGS Tracking

Before the MACAO system is requested to acquire an NGS, the ISS must preset the telescope, enable autoguiding, disable M2 field stabilisation and centre the science target.

In parallel with the telescope preset, the NGS and target locations are passed to MACAO and the X/Y table moved and the derotator are moved to their initial positions and the NGS tracking loop commenced.

6.3.3 Guide Star Acquisition

When preset operations are complete the NGS acquisition parameters can be passed to MACAO as part of the ACQUIRE command. These parameters include the NGS flux expected, the NGS size (FWHM), and an offset from the NGS where the sky background can be measured.

On receiving the ACQUIRE command the X-Y table is offset first to the sky location to measure the sky background and then back to the NGS coordinates, the NGS magnitude is then checked to ensure that it matches that expected. The AO system then chooses an optimal set of operating parameters (membrane stroke and AO loop gains, ND setting, diaphragm size) and checks that the expected performance meets that requested.

On completion of the acquisition, the AO loop is closed the science beam is ready and the observation may be started.

6.3.4 Closed Loop

During closed loop operation the AO system is correcting the turbulent wavefront and making available in the on-line database performance estimates for R0 and recovered strehl and passing atmospheric diagnostics over the VLTI reflective memory interface at the end of each AO feedback cycle.

Offsets in Tip/Tilt, Focus, and higher order Zernike terms may be requested by the ISS to the OS at a frequency of 1Hz.

Tip/tilt and optionally focus offloading via the TCS is performed at 0.2Hz.

The guide star tracking loop is operating, updating the X-Y table position compensating for field rotation and the derotator position, and accepting tracking Tip/Tilt offsets sent by the ISS.

6.3.5 Start of Observation

When the MACAO system is informed of the start of an observation a FITS file is prepared describing the current configuration of the AO system. During the observation the current atmospheric conditions are logged periodically and acquired and stored at a user defined sampling frequency.

6.3.6 End of Observation

When the MACAO system is informed of the end of an observation, the FITS file prepared during the observation is completed and made available to the ISS.

6.4 MACAO Observation Modes

The MACAO Software supports the following observation modes

- Staring
  A single acquisition where the AO loop remains closed during the entire observation

- Nodding
  An observation where the telescope is used to shift from object to sky and back again repeatedly. The ISS informs the MACAO system at the start of each nod to sky and nod to object cycle, the AO loop is opened during the nod to sky cycles

  The AO loop is re-closed within 1.2 seconds on each nod to object cycle.

- Chopping
  An observation where M2 is used to shift the field from object to sky and back again repeatedly. The RTC is synchronised with the frequency of the M2 chop cycles, via the TRS, and the AO loop is opened during the chop on sky cycles.

  The maximum chopping frequency supported is 1Hz with a duty cycle of 50%.

7 Estimated System Performance

7.1 Closed Loop Analysis

A closed loop analysis has been performed to simulate the performance of the MACAO-VLTI system which is presented in RD2. The analysis has been performed using a matlab simulation, which has been crosschecked with the IDL curvature simulation by F. Rigaut. The simulation uses a three-layer atmosphere model, considers two different seeing conditions (0.65” and 1”) and models bright and dark sky conditions.

The following figure gives a plot of the Strehl ratio @2.2µm versus guide star magnitude for the nominal Paranal seeing conditions (0.65” seeing at 500nm, τ_0 4ms with a 20.5 magnitude sky background). This plot includes the MACAO error budget, i.e. telescope and corrective optics aberrations, alignment tolerances and measurement errors. Also included on this plot are the three provided points defining the VLTI Strehl specification at magnitudes 9, 4.5 and 15.5.

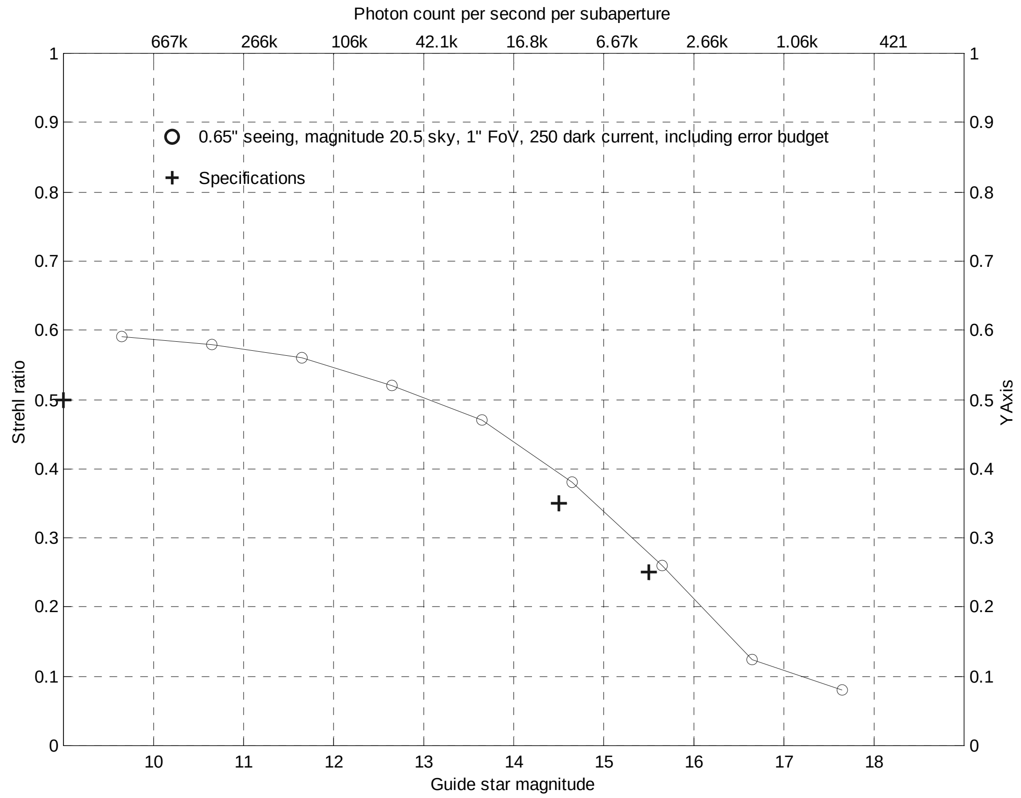

Figure 12 Estimated Strehl versus NGS magnitude including error budget

7.2 Piston Analysis

Of great concern in the operation of the VLTI is the introduction of piston errors. The sources of piston error within the MACAO system have been identified as:

- Imperfect Piston Removal in the control loop
- Hysteresis of the deformable mirror
- Tip/Tilt stage misalignment
- Mirror resonance effects

A detailed analysis of these effects can be found in RD2. The following table gives a summary of the piston error sources.

Piston Error Source	Piston r.m.s (48ms)	Piston r.m.s (290ms)	Piston PTV (10 min)
Imperfect Removal	18 nm	26 nm	76 nm
Hysteresis	1nm	8nm	<700nm
Tip/Tilt misalignment	5.6nm	<5.6nm	<34nm
Mirror resonance	<<1nm	<<1nm	<<1nm
Total Piston Error	**19nm**	**28 nm**	**<810 nm**
VLTI Specification	**25 nm**	**125nm**	**2000nm**

8 System Verification Approach

Verification of the MACAO system performance will be performed using a specially designed test bench environment. Details of the AIT plan for MACAO-VLTI can be found in RD16.

8.1 CWFS Optical Test Bench

This optical test bench will simulate the Coudé pupil and focal planes. The test bench will host the WFS box mounted such that the CWFS membrane is at an f/47.6 focus and the DM and its Tip/Tilt stage mounted in a pupil plane matching that of the M8 in the VLT Coudé train. Care will be taken to ensure that the incident angle and gravitational load on the DM matches that at Coudé.

The bench will be equipped a turbulence generator capable of producing Kolmogorov like turbulence from 0.65" to 1.5". The turbulence generator to be used is based on the design used for NAOS and includes a source module with variable intensity point and extended sources.

PSF measurements will be performed using an IR test camera procured for use in the AIT phases of MACAO .

This bench will allow the characterisation of the CWFS, detector and corrective optics and provide measurements of the **on-axis** closed loop performance of the MACAO system for a range of seeing conditions and NGS magnitudes.

The bench will also allow in-situ measurements of the DM surface quality and the dynamic behaviour of DM and Tip/Tilt stage using an interferometer. A study is underway by ONERA to specify a setup by which closed loop piston measurements can be made on this test bench.

8.2 X-Y Table Tests

The X-Y Table will be tested with the WFS box mounted to ensure that the testing is performed using the correct load.

The X/Y table absolute and relative positioning accuracy, speed and acceleration will be tested a ZLM500 interferometer and a corner cube mounted on the WFS box.

The flatness of travel, and tilt of the WFS box will be measured using an HC250 laser interferometer, autocollimator and a flat mirror mounted on the WFS box.

These setups will allow the X-Y table positioning accuracy and flatness to be measured to a few nm and allow the guide star tracking loops to be fully tested.

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