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# VST Project: the Adapter Rotator (M1 cell)

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## ABSTRACT

The VLT Survey Telescope (VST) is a cooperative program between the European Southern Observatory (ESO) and the INAF Capodimonte Astronomical Observatory (OAC), Naples, for the study, design, and realization of a 2.6-m wide-field optical imaging telescope to be operated at the Paranal Observatory, Chile. The VST has been specifically designed to carry out stand-alone observations in the UV to I spectral range and to supply target databases for the ESO Very Large Telescope (VLT). The telescope design, manufacturing and integration are responsibility of OAC. The telescope is in Cassegrain configuration and for this reason the primary mirror cell represents one of the most complex telescope subsystems, designed to host a large amount of auxiliary sub-systems and to support a wide field camera. The paper describes the solutions adopted as a result of an integrated optimized optical and mechanical design.

**Keywords:** primary mirror cell, adapter/rotator, Atmospheric Dispersion Compensator, Shack Hartmann wave front sensor

## 1. INTRODUCTION

The VLT Survey Telescope (VST) is a cooperative program between the European Southern Observatory (ESO) and the INAF Capodimonte Astronomical Observatory (OAC), Naples, for the study, design, and realization of a wide-field optical imaging facility to be operated at the ESO Paranal Observatory in Chile. The telescope, expected to be installed at Paranal within the year 2003, has been designed, manufactured and integrated by the Technology Working Group of the Astronomical Observatory of Capodimonte, Italy. The enclosure and civil work at the VLT environment at Paranal are responsibility of ESO. The VST camera, a CCD mosaic named OmegaCAM, is being built by a European consortium which includes the Netherlands, Germany, Italy, and the European Southern Observatory. The data reduction pipeline is under construction by the OmegacCAM Consortium and by OAC. The VST telescope features are: modified Ritchey-Chretien optical layout, 2.6 m aperture, f/5.5 focal ratio, three lenses wide-field corrector with optional atmospheric dispersion compensation, active primary mirror, hexapod driven secondary mirror, and alt-azimuth mounting. The design is optimized for high quality, seeing limited wide-field astronomical imaging on a 1 degree x 1 degree corrected field of view, mapped by a 16k x 16k pixel CCD mosaic with 0.21 arcsecond/pixel scale, in the wavelength range from 320nm/365nm to 1014 nm. High image quality performance is guaranteed by an active control of the optics, acting on both primary and secondary mirror. Due to its mounting configuration and active optical control requirements, a careful attention has been paid to the Adapter/Rotator (AD/ROT) combined subsystems contained in the primary mirror cell, that represents one of the most complex telescope subsystems. The VST AD/ROT includes facilities for the fine telescope positioning (autoguiding system), for the optical quality optimization (sensing and atmospheric dispersion correction) and for the interface and field rotation correction of the scientific instrument (rotator axis) that will be described as they are positioned in the primary mirror cell and with reference to opto-mechanical implications.

## 2. ADAPTER

The VST M1 cell is provided with dedicated interfaces to support two switching optical correctors. Two rotating flanges allow to support the guide probe (adapter) and the scientific instrumentation (rotator). The adapter provides functions for the fine position control of the telescope and for image quality optimization. A section of the M1 cell where is possible to identify these parts is represented in Fig.1a.

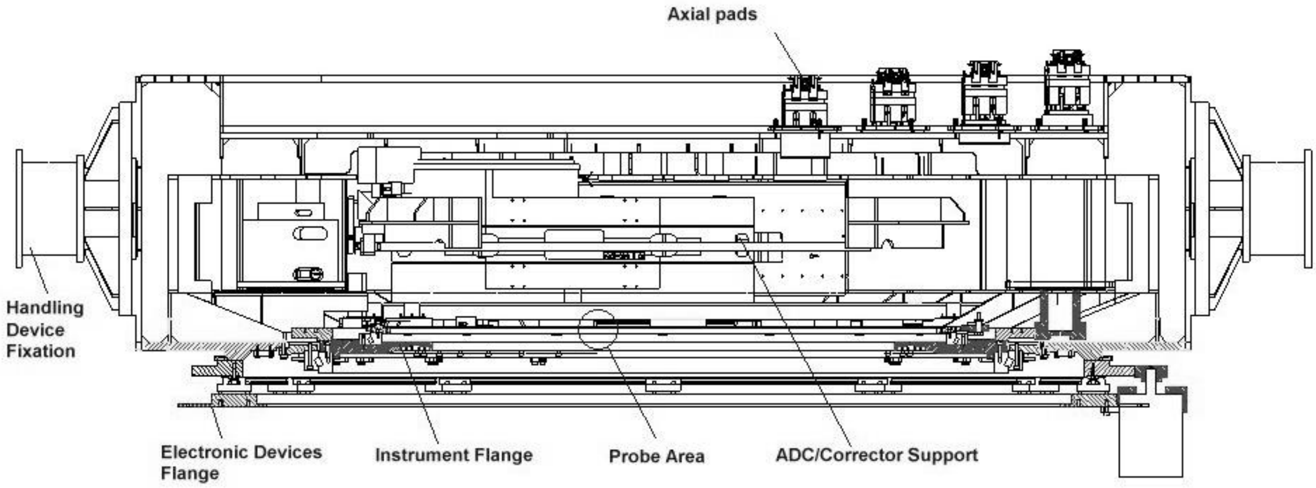


**Fig. 1.a – Identification of the main components in the M1 cell**

## 3. CORRECTOR'S CAMERA OPTOMECHANICAL DESIGN STRATEGY

The VST adapter is provided with two different corrector's camera with refracting and dispersing elements. One corrector (hereinafter the "Two-Lens" corrector) is composed by two lenses and operates from U to I bands (0.320 ÷1.014 μm) at 0° zenith angle (Fig. 3); the other (hereinafter the "ADC" - Atmospheric Dispersion Corrector) is composed by two rotating double prisms and one different lens to observe from B to I bands (0.365 ÷ 1.014 μm) at different angles until 60° from zenith (Fig. 4). In order to cover the wide field of view with a high image quality, the telescope is not a pure Ritchey-Chretien, but it is optimized together with the two corrector's camera and the dewar window, which is a lens with a correcting power (Fig. 1b-2). The overall assembly has been designed as an integrated system, using FEA analysis to evaluate the effects of gravitational deformations on the image quality degradation. The main project guide-line has been to consider telescope and camera as a unique system. The optical design of the VST correctors has been optimized together with that of the mirrors and of the detector dewar window of OmegaCAM camera. Both optical configurations have been optimized in order to satisfy the project main scientific, dimensional and mechanical requirements. The telescope covers a very large field of view (1.47° diagonal), with a high resolution (0.21"/pixel) and a high image quality (80% of EE enclosed in two pixel). In particular, the solution found for two-lens corrector configuration shows an optical quality, which is close to the goal. The complete optical system (telescope, camera and dewar window) maintains the same f/number and image scale of the telescope. It represents a compromise between the maximum achievable distance of last corrector element from the dewar window, and the maximum acceptable percent distortion on the image plane. The optics design has been optimized also in order to have two compacts interchangeable correcting systems. Another guideline has been to minimize the number of elements in order to increase the telescope transmittance and keeping a good image quality at the same time. The thickness of optical correctors lenses has been chosen to limit absorption losses without loosing the necessary handling safety. The two - lens corrector and the dewar window are made of Silica, which transmits well in the VST wavelength range. In order to reduce the lens manufacturing cost, all curvatures of the two correctors are spherical and normalized to manufacturer standard radii. The mechanics has been designed on the base of the requirements coming from the optics, with an interactive optimization process. The two correctors (ADC plus 1 lens and 2 lenses corrector) are placed inside a corrector switching support. It allows to switch the correctors and to carefully position them in the optical path (Fig.5 - 6). The zero positions are obtained by very precise (1 μm) switches. The rotation of the two prisms of the ADC is obtained by stepper motors. In Fig. 7 the two correctors barrels solution is shown. It takes into account the relative thermal expansion between lenses and barrels. The optomechanical solution has been optimized on the base of optomechanical tolerances analysis, guiding / sensing optics arms and the tight mechanical requirements coming from OmegaCAM camera interface position, placed between last corrector element and the filter. The ADC corrector is made of two double prisms, with curve entrance and exit surfaces, separated form a thin layer of air (Fig. 4).

The external surfaces are not flat, since the ADC design is integrated in the corrector wide field camera design, so it has a correcting power. The two cemented prisms must be suitably counter rotated, to correct the atmospherical dispersion at the different observation angles, respect to zenith. In Fig.8 and Fig. 9 spot diagrams with ADC in its neutral position and in its correcting position at 60° are respectively shown.

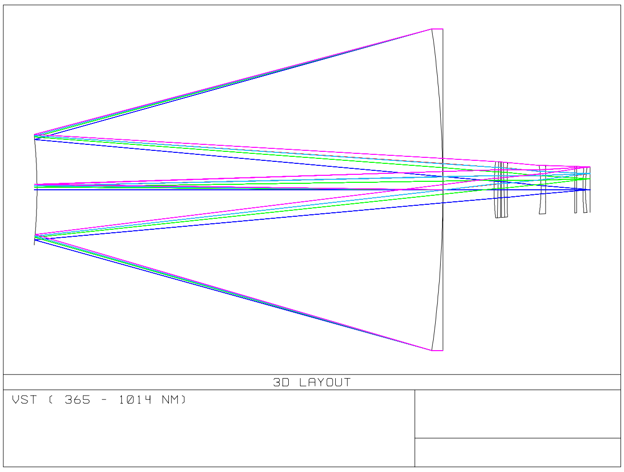


**Fig. 2b - Complete optical layout of telescope with one - lens and ADC, with a curve dewar window**

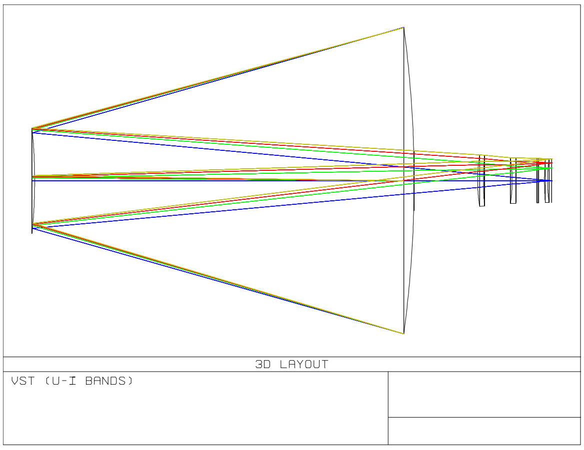


**Fig. 3 - Optical layout of telescope with two - lens corrector (U ÷ I bands) with a curve dewar window**

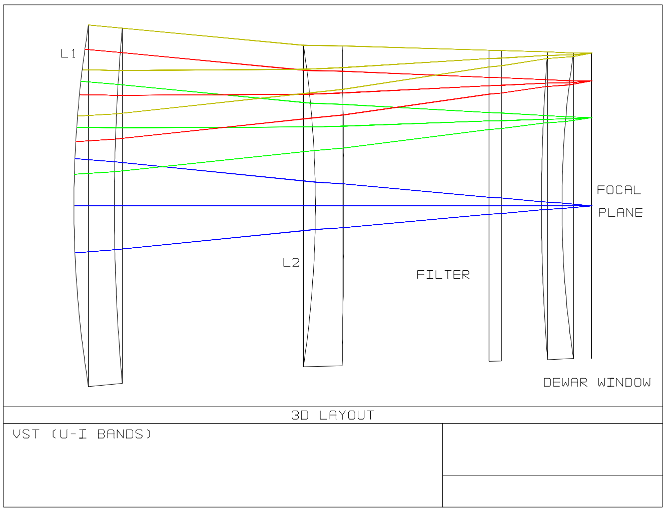


**Fig. 4 – Two-lens corrector optical layout**

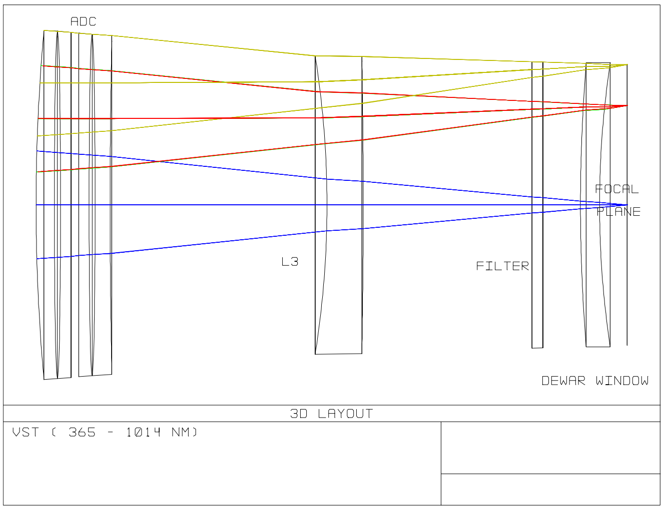


**Fig. 5 - ADC and one-lens corrector optical layout**

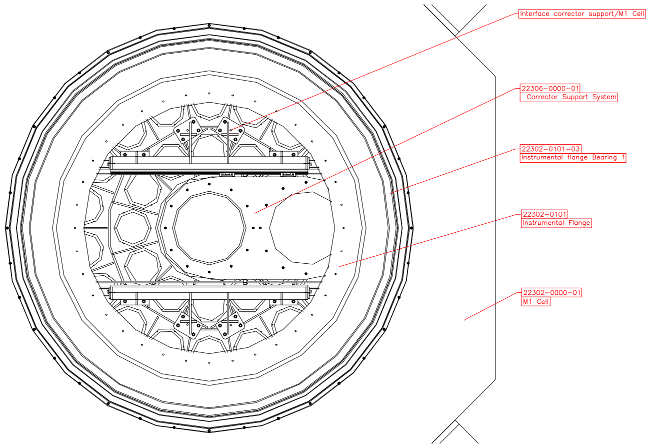


**Fig. 6 – Corrector Support view from instrument flange side**

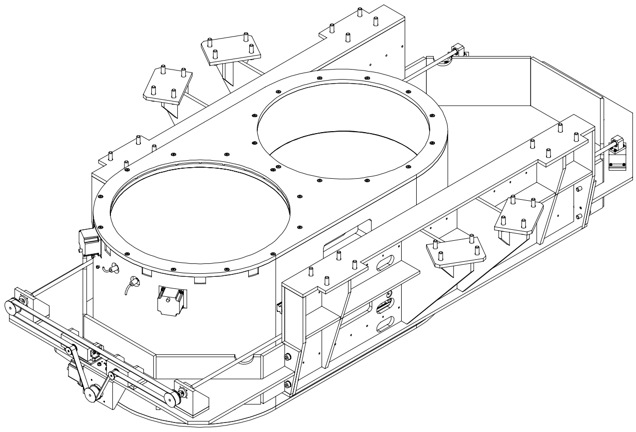

**Fig. 7 – Corrector Support 3D view**

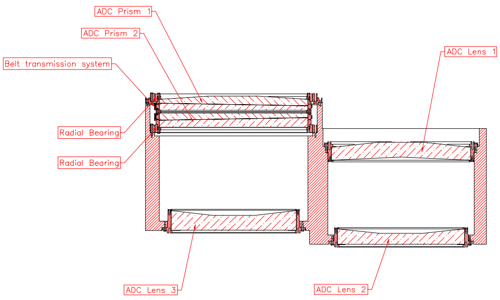


**Fig.8 – Correctors Support section**

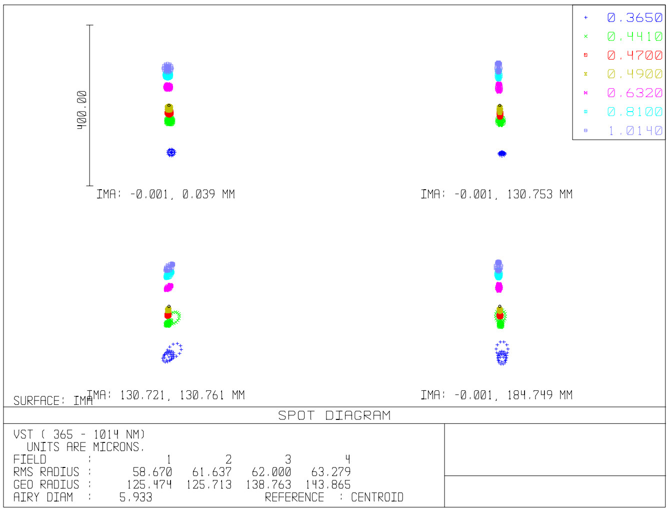


**Fig.9 – Spot without ADC correction at 60° z angle**

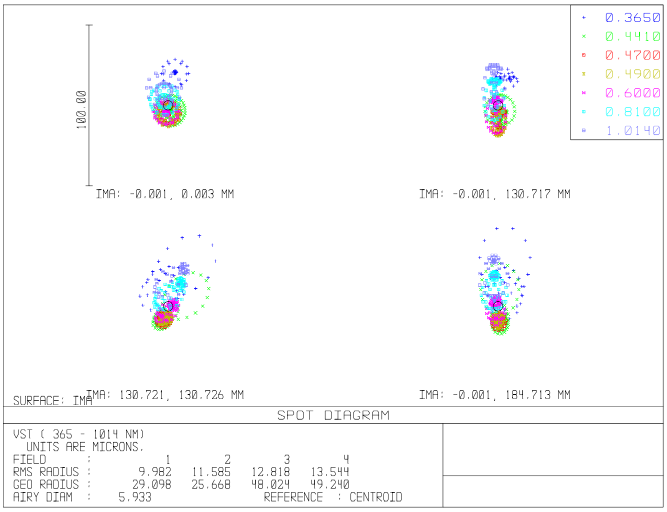


**Fig.10 – Spot with ADC correction at 60° z angle**

## 4. THE GUIDING - SENSOR ARM OPTOMECHANICS

The VST optical performance is optimized by an active optics system, making use of a Shack Hartmann (SH) wavefront sensor to measure the optical system aberrations which are then corrected in a closed-loop by changing M2 positions and M1 support forces. At the same time, the telescope tracking is helped by an autoguiding system to correct for image drifts. For both tasks of wavefront sensing and guiding, a SH/guiding combined probe (guiding - sensor arm) has been designed, placed in the adapter. The probe is composed of:

- a probe rotating gear
- a sensing/guiding carriage
- a supporting arm
- a focusing device
- a reference system
- optical system
- CCD Sensors

### 4.1 Guiding - sensor arm supports

The VST guiding - sensor - arm has a pick-up mirror mounted at the end of the supporting arm which can be rotated in the telescope field of view. The center of the pick-up mirror field of view can be positioned on the optical axis of the telescope. The probe, in turn, is mounted on a gear rotating around the optical axis of the telescope, independent on the rotation of the instrument rotator. The probe rotation along the gear and the radial translation of the pick-up mirror constitute a polar coordinate system which allow to place the mirror anywhere in the telescope field, in order to select the star light to feed the guiding camera and/or the SH wavefront sensor. The VST probe is composed by a main support, which is the interface with the instrumental flange and holds all the probe system steady in its relative position inside the telescope. It is interfaced with the telescope by means of a dedicated flange, which rotates relatively to the instrumental flange. The probe is positioned between the correctors system and the OmegaCAM camera (Fig. 12). The probe system is guided inside the optical field by the pick-up mirror support which slides towards the optical field of the VST on two linear rails. The optical train stands on the lens support interfaced with the main support by linear slides which allow a longitudinal regulation. Two pinholes are provided within the optical train of the probe. One is coupled with a diode led which can be positioned by an electro-magnet. Both the pinholes are mounted on a support which is interfaced with the lens support by means of two linear slides, allowing a longitudinal displacement. All other optical components and other assemblies (CCDs, focusing device and reference system) are fixed to the supporting arm structure.

### 4.2 Guiding- sensing arm optical system

A general view of the optical design for the sensing and guiding arms is shown in Fig. 11. Light from the pick up mirror is split using a dichroic beam-splitter, to feed two separate CCD sensors. One sensor is used for acquisition and guiding, the other for the active optics wavefront sensing. Without the dewar window and filters of the scientific camera, the relative aperture difference between the Two-Lens Corrector and the ADC and one-lens corrector is small (F/5.54 compared to F/5.50). The design has been optimized for the sensing arm positioned outside the scientific CCD (field of view greater than 1°). Other fields or configuration can be optimized by means of a dedicated focusing mechanism. In Fig. 12 the pick up mirror for the two-lens corrector configuration is represented by ray tracing. Guide star is on the scientific CCD corner. When the pick up mirror is placed in the center of telescope field of view, there is a great vignetting of the pick-up itself, of the dichroic and of the SH optics. So the SH is used OFF-LINE on axis, and ON-LINE off -axis.

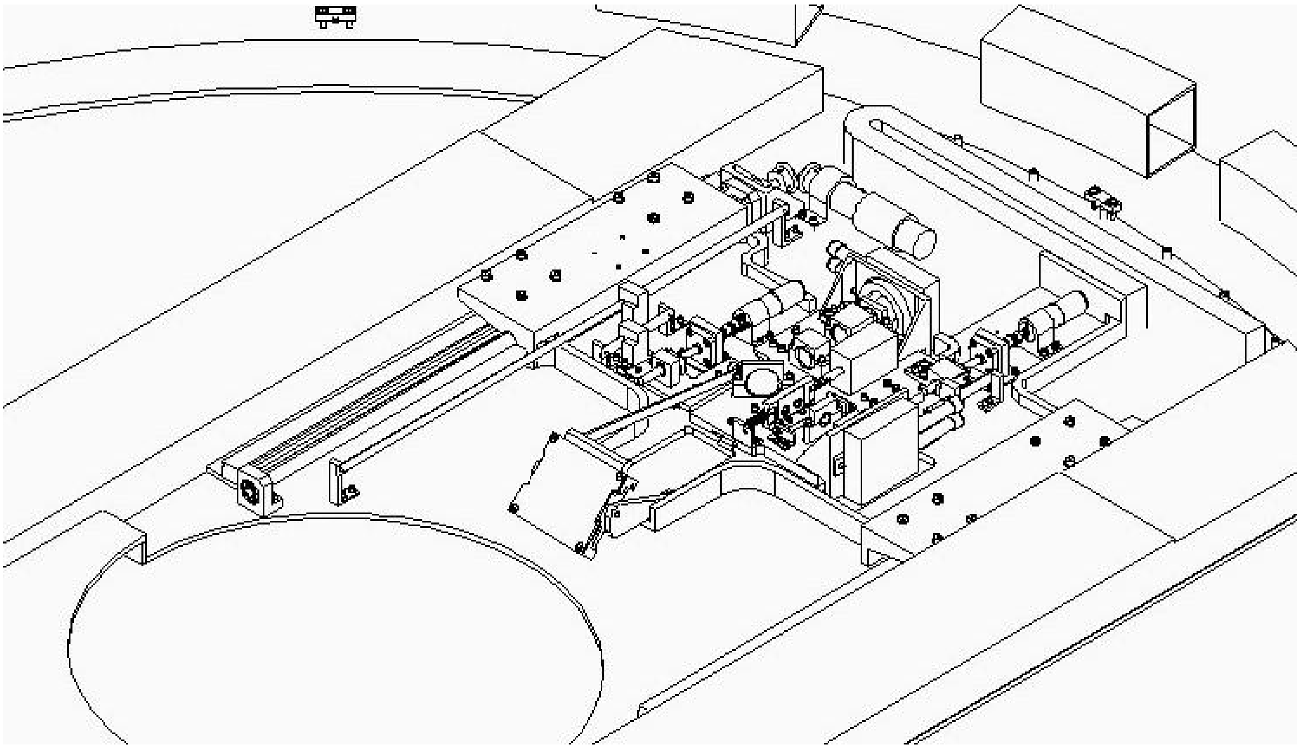

**Fig. 11 – Guiding and sensing probe fixed on the bridge support**

## 4.3 Sensing arm

The wavefront sensing arm optical layout is shown in Fig. 13 - 14. The light reflected by the dichroic goes to a collimator. At the location of the image of the telescope pupil, a lenslet array is used to provide the spots necessary to the Shack-Hartmann analysis. The image aberrations introduced by the system are automatically cancelled in the comparison between reference and star light, except for chromatism which will be interpreted as focus error due to the different wavelength compositions of the reference source and the star. The wavefront analysis system has to be sensitive enough in order to cope guide stars of 14 magnitude. This requires, for integration time of about 30 seconds, subaperture of 250 mm at least. The number of spots across the pupil is therefore at most equivalent to 10. With a 10x10 array it should be easy to find a sufficiently bright star, especially in the large field of VST. A lenslet array with f/45 and $D_l \approx 0.5$ mm fills the area of the technical CCD and fulfills all the requirements. The desired field will be selected by mean of the pin-hole mounted on the focal plane after the reflection due to the dichroic. With the relatively rough sampling of 10x10 only a small number of modes can be measured and corrected. The basic idea is to use the same modes used at ESO NTT telescope. The lenset array has been chosen with F/45 in order to match the spot over 1.5 pixel at least, and optimize the accuracy of the spot centroiding computation. The CCD pixel size is 22 μm. The active optics system compensates for static or slowly varying optical errors such as those caused by manufacturing errors, gravitational and thermal effects, etc. During the observations the wavefront sensor continually provides information on the telescope image quality to the telescope control system for active correction of the primary mirror support forces and of the position of the secondary, using the same reference star as the autoguiding system. The operation of the telescope requires that the active optics system is run in closed loop, even if it can work in open loop using as only input the zenithal distance instead of the SH analysis results.

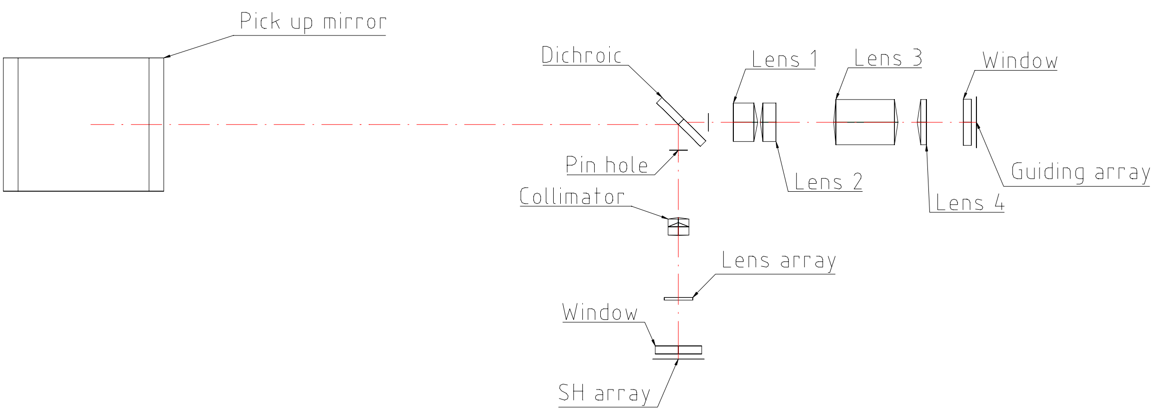


**Fig. 12 - General Layout of the Sensing-Guiding Arm – view from M2 mirror**

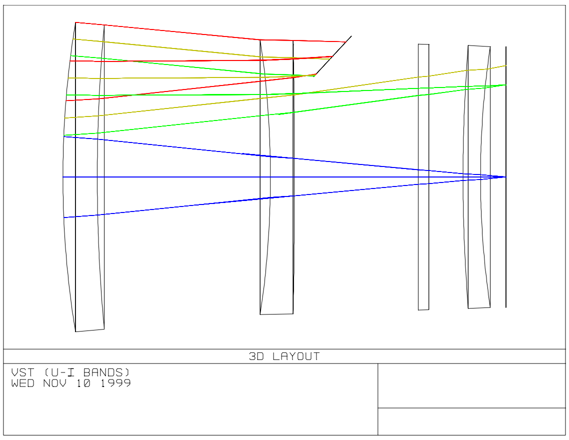


**Fig. 13 - Representation of the pick up mirror for the two-lens corrector configuration by means of ray tracing. Guide star is on the scientific CCD corner**

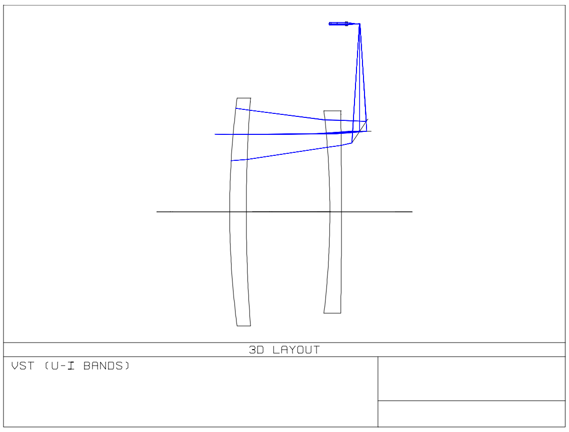


**Fig. 14 - Optical Layout of the Sensing- Arm**

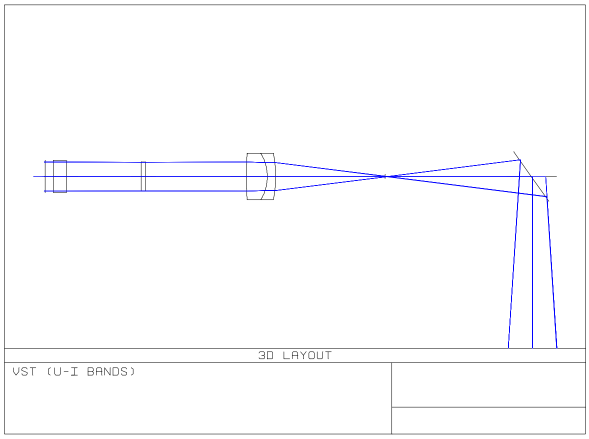


**Fig. 15 - Zoom of Optical Layout of the Sensing- Arm**

### 4.4 Guiding optics

In Fig.15 and 16 the optical layout of the guide arm and its zoom are respectively shown. In Tab.1 the characteristics of the guide train are shown..

| | |
|---|---|
| VST Configuration | Two Lenses |
| Input F/N | 5.54 |
| Output F/N | 8.6271 |
| Magnification | 0.6422 |
| Pixel size | 22 μm |
| Pixel number | 290 x 386 |
| Detector size | 6.34 x 8.45 $mm^2$ |
| Maximum field (sky) | 58.078 x 77.406 $arcsec^2$ |
| Scale (arcsec/pixel) | 0.201 arcsec/pix |

**Tab. 1 Characteristics of the Acquisition/Guiding train**

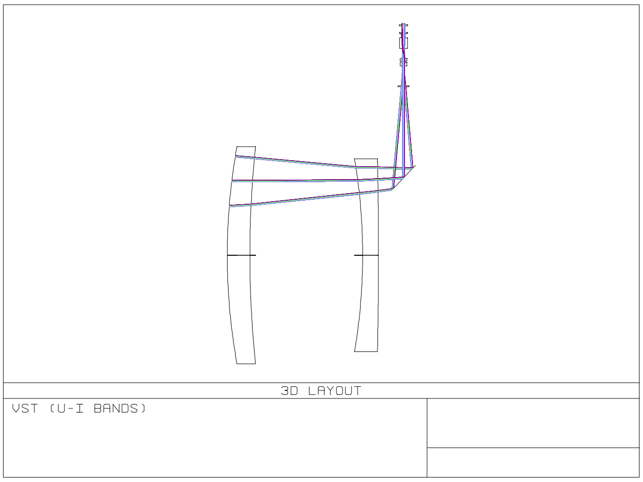


**Fig. 16 - Optical Layout of the Guiding- Arm after corrector last lens**

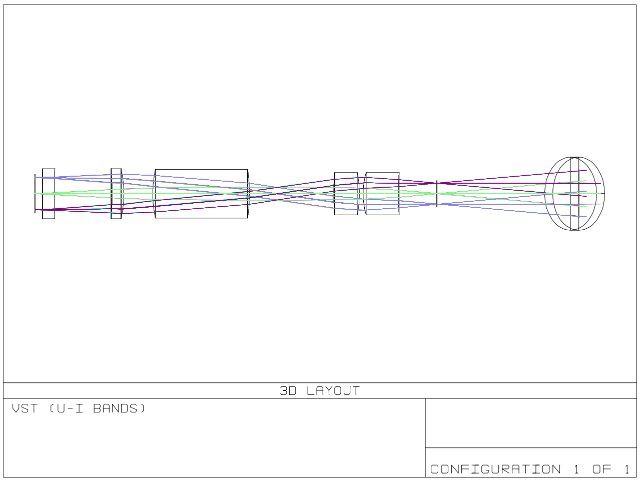


**Fig. 17 - Zoom of Optical Layout of the Guiding- Arm**

### 4.5 Guiding / Sensing image quality and efficiency requirements

The guiding optical system must be tested at 633 nm and it is identical (but for focusing) for both VST configurations. The optical quality of the system is shown in Fig. 17, where the spot diagram on the guiding focal plane is reported. In Fig.18 the SH spot diagram before the dichroic is reported.

The guiding image quality specifications are the following (Two Lenses Configuration) :

- on axis, the spot size must be better than 80 μm diameter (80 % Encircled Energy)
- at the CCD corner, the spot size must be better than 100 μm diameter (80 % Encircled Energy)

The global average efficiency of the acquisition/guiding system must be better than 80 % between 600 and 900 nm (this value do not include the CCD window nor the dichroic).

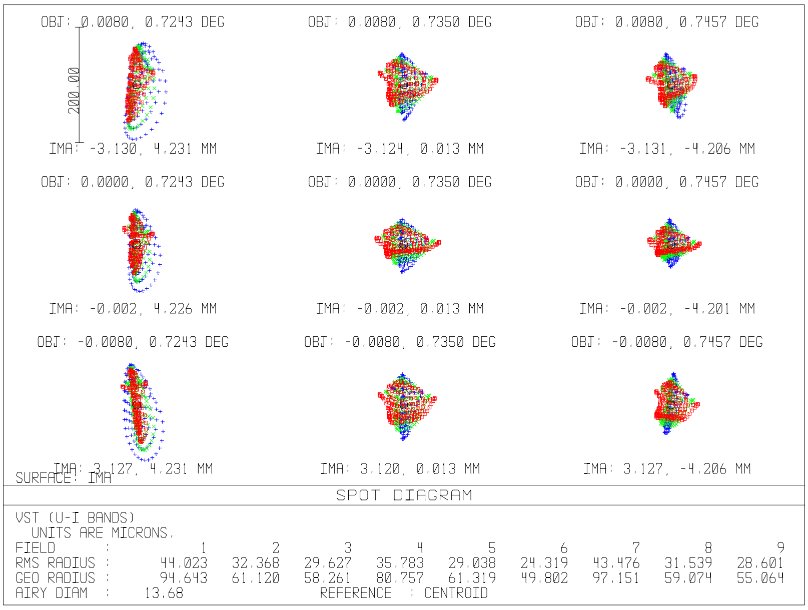


**Fig. 18 - Spot diagram on the the Guiding- Arm image plane**

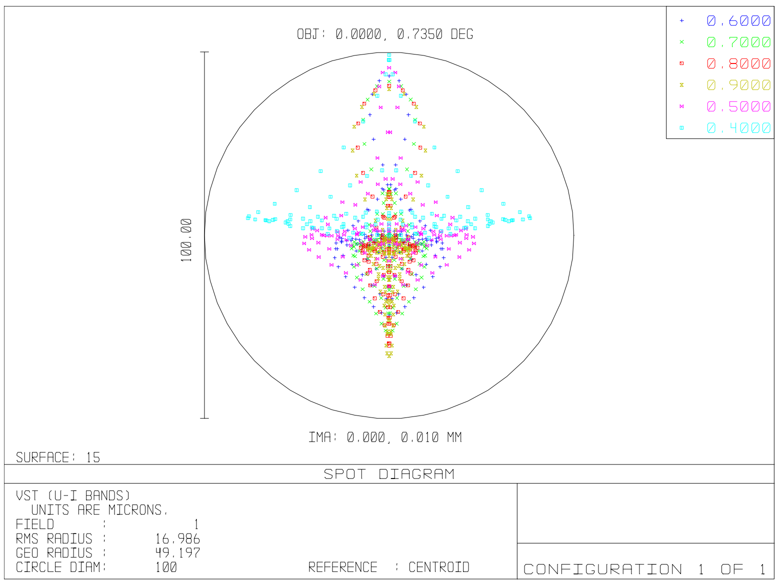


**Fig. 19 - Spot diagram on SH focal plane, before the dichroic**

### 4.6 The focusing device

Telescope focusing is achieved by moving the secondary mirror (M2). The Shack Hartmann wavefront sensor, placed in the sensing arm determines the optimum focus position. The adapter sensor arm contain a separate focusing mechanism along its optical axis, on the supporting arm structure, so it compensates the defocusing error due to:

- the two different VST telescope configurations (Two Lenses and ADC)
- the telescope field curvature and instrument defocusing

The carriage allows adjustment of the separation between the pick up mirror and the other optical components: the dichroic mirror, the camera optics, the SH optics.

### 4.7 The reference system

The system is made of one led with an electro-magnet for positioning and a slit with 2 pin-holes of different diameters moveable with linear slides. The reference system has two purposes:

- It provides a reference grid for the wavefront sensor, obtained by an ideal wavefront. This must be compared with the wavefront coming from the telescope mirrors. Any wavefront aberration introduced by the optics components between the led and the wavefront sensor are automatically eliminated.
- It provides a reference for the center of rotation of the adapter to the acquisition / guide sensor when observing the central field of the telescope. This implies that the led must be placed at the centre of rotation of the adapter.

### 4.8 CCD sensors

There are two identical small CCD heads attached to the focusing device on the Sensor-Guiding Arm. In both cases, the final optical assembly for the two sensors is attached directly to the CCD head. The details about these technical CCD sensors are reported in tab. 2.

| | |
|---|---|
| Small CCD pixel format (image area) | 290x386 |
| Large CCD pixel format (image area) | 578x578 |
| Pre scan pixels | 10 |
| Storage area overscan pixels | 6 |
| Pixel size (small and large CCD) | 22 μm |
| Small CCD sensitive area | 6.34x8.45 $mm^2$ |
| Large CCD sensitive area | 12.67x12.67 $mm^2$ |
| Range of sensitivity | 250-1000 nm |
| RQE at 700 nm | > 50 % |
| RMS Readout noise at 666 kpix/s | ≤ 24 $e^-$ |
| Averaged dark signal at –35°C | < 200 $e^-$/pix/s |
| Full well capacity | 220000 $e^-$ |

**Tab. 2 -Technical CCD Chip Characteristics**

### 4.9 Autoguiding control

The acquisition/guide CCD sensor, located in the carriage sensor arm, can be used to view the central part of the telescope field to provide visual identification of the object to be observed. During the observation, the position of the object in the telescope focal plane must be maintained with an high accuracy. To achieve this, a reference star close to the object being observed (but outside the scientific field) is used as reference point. The Telescope Control System (TCS) uses the acquisition/guide sensor to continually measure the position of the reference star, calculates the x-y position error vector due to the drift, and filters it by a PII controller to provide small tracking corrections. As the telescope field rotates during an observation, the scientific instrument attached to the telescope, and the adapter itself, must be rotated at the same speed to allow the compensation. During this phase the adapter and the rotator are effectively (although not physically) locked together. During the pointing phase, however, the instrument rotator, the adapter and the sensor arm can all be moved independently of each other. In "acquisition mode" the pick-up mirror is positioned on the telescope axis to relay the central part of the field to the autoguiding system. In "guiding mode" the pick-up mirror is centered onto a reference star in the peripheral field of view of the telescope. The star used for guiding is normally used simultaneously also by the wavefront sensor for active optics correction. The selection of the most suitable guide star and the positioning of the pick-up mirror is normally done automatically by the TCS once the object position and relevant instrument parameters have been defined. This selection takes into account a defined unvignetted field of view. Observers may specify in the observation block the guide star they want to use. The telescope control system also corrects the guide star reference position during observations. This is due to the effects of differential atmospheric refraction between the wavelength used for guiding and the central wavelength used by the instrument, as well as of course to the relative changes in the observed positions of the target and the guide star with time. The guiding - sensor arm shadows a part of the telescope field of view. The exact location of the shadow depends on the position of the reference star within the field. It is possible for the instrument software to specify an area in the telescope focal plane, which is to remain unvignetted by the guiding - sensor arm. If such an area is defined, the telescope control system preferentially selects a guide star which does not cause vignetting of this area. In the case where no guide stars are available which do not vignet the field of view, the operator may overrule the control system and demand a particular guide probe setting. The telescope database reflects the fact that the probe is vignetting the field of view and the instrument should notify the user, usually by a check in the observing template, that this is the case. The guide probe is preset in X, Y CCD coordinate system and offset in the same co-ordinate system. The instrument (OmegaCAM camera) may provide its own wavefront sensing (Roddier sensor) and guiding capabilities, compliant with the interfaces to the telescope.

## 5. THE ADAPTER/ROTATOR CONTROL SYSTEM

The heart of the adapter/rotator control system is a VME based Local Control Units (LCU) equipped with a Motorola MVME167 CPU card, hosted in a control cabinet. The operating system is WindRiver VxWorks; the VME crate is equipped with ESO standard boards. The adapter/rotator LCU is managed by an HP-UX workstation, like all the others LCU in the VST control network. All the VME boards and electronic components have been chosen in conformity with ESO VLT standards, in order to ensure compatibility with other ESO applications and simplify maintenance and integration in VLT environment. The LCU has to run many applications for the following tasks:

- Instrument rotator control (brushless motor + encoder)
- Rotator motor cooling
- Adapter rotation control (stepper motor)
- Radial probe control (DC motor + encoder)
- ADC prisms (stepper motors)
- ADC selector (stepper motor)
- Focusing (DC motor + encoder)
- Pick-Up mirror (DC motor + encoder)
- Pin-hole control (electromagnet via I/O line)
- Cabinet cooling controller monitoring

The instrument rotator control follows the main axes strategy: a 500 Hz double position and speed control loop is performed by software, using as feedback the tacho speed measurement (by an A/D VMIC board) and the encoder position value (by Heidenhain interpolator boards). The torque value to drive the two preloaded motors is applied to the driver by a D/A VMIC board. The functions moved by stepper motors are controlled in position mode by a Maccon Mac4-stp controller board + amplifier, while the ones using DC motors use a Maccon Mac4-Inc controller board + amplifier, with encoders to provide the feedback. The cooling of the rotator motor is controlled by a custom microcontroller board equipped with a Microchip PIC microcontroller, connected to a CAN Bus network whose master is the LCU (by a Tews Datentechnick TPMC816 CAN Bus interface mezzanine card). The cooling system of the control cabinets is ensured by an ESO compliant cooling controller, communicating with the LCU via a serial port of a ESD interface board. Fig. 19-20 show two engineering control panels.

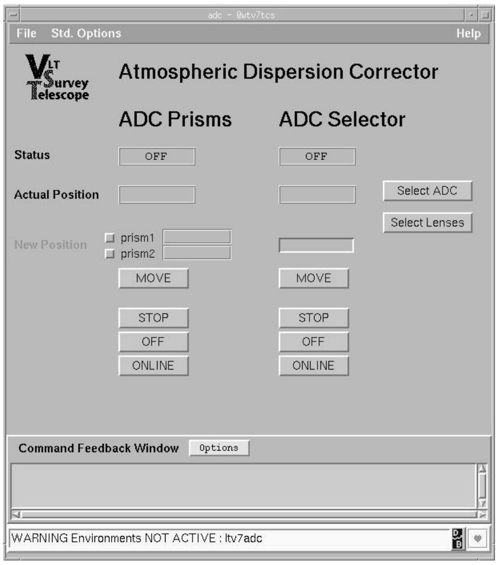


Fig. 20 - TCS: ADC control panel

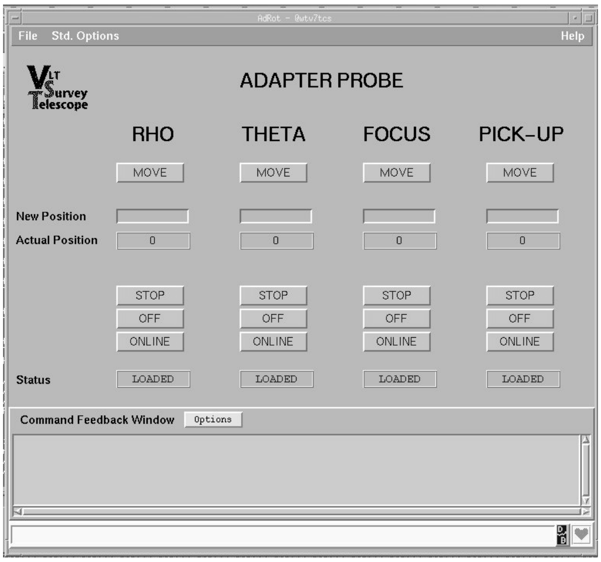


Fig. 21 - TCS: probe control panel

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