The VLT Deformable secondary is planned to be installed on the VLT UT#4 as part of the telescope conversion into the Adaptive Optics test Facility (AOF). The adaptive unit is based on the well proven contactless, voice coil motor technology that has been already successfully implemented in the MMT, LBT and Magellan adaptive secondaries, and is considered a promising technical choice for the forthcoming ELT-generation adaptive correctors, like the E-ELT M4 and the GMT ASM. The VLT adaptive unit has been recently assembled after the completion of the manufacturing and modular test phases. In this paper, we present the most relevant aspects of the system integration and report the preliminary results of the electromechanical tests performed on the unit. This test campaign is a typical major step foreseen in all similar systems built so far: thanks to the metrology embedded in the system, that allows generating time-dependent stimuli and recording in real time the position of the controlled mirror on all actuators, typical dynamic response quality parameters like modal settling time, overshoot and following error can be acquired without employing optical measurements. In this way the system dynamic and some aspect of its thermal and long term stability can be fully characterized before starting the optical tests and calibrations.

Keywords: VLT DSM, VLT AOF, adaptive optics, adaptive mirrors, deformable mirrors, adaptive secondary, voice-coil, massive control

1 INTRODUCTION

The VLT Deformable Secondary Mirror (VLT DSM) is the third generation (Gen 3) of adaptive secondary mirrors, after the MMT336 unit (Gen 1) and the two LBT672 and MAG585 units (Gen 2). The final design and manufacturing, integration assembly and test contract has been awarded by ESO to Microgate (acting as prime contractor) and ADS in February 2008. The unit is designed to become one of the key elements of the Adaptive Optics Facility (AOF) that will transform the VLT UT#4 in an adaptive telescope. It will provide atmospheric tip-tilt correction, field stabilization and high order seeing correction up to R-band; besides, it provides also chopping capability for IR observation.

The VLT DSM is based on the voice-coil based, contactless adaptive mirror technology originally conceived by Piero Salinari in 1993 [1], but several improvements have been introduced to meet the design specification on this 1170 actuators, 1.12m diameter unit.
In this paper we describe the main characteristics of the unit and describe the most relevant aspects of the system integration, focusing on the preliminary results of the electromechanical tests performed on the unit.

2 VLT DSM SYSTEM DESCRIPTION

The VLT DSM will replace the current Dornier M2-unit of the VLT UT#4. Therefore, the mechanical interface and optical prescriptions are identical to the current unit, with a diameter of 1.12m, a central hole hosting the membrane with 96mm diameter and a convex aspheric surface with 4.55m radius of curvature. The 2mm thick continuous facesheet Zerodur mirror [4] is sustained and deformed by 1170 contactless force actuators, with magnets glued on the mirror rear face and coils on the tip of the 190mm long actuators, see Figure 1. The bottom side of the actuators is rigidly connected to the cold plate, acting as actuator support and heat sink for the coils. Position feedback is obtained by means of capacitive sensors that measure the gap between the reference body and the thin shell rear face. Control is ensured by a very powerful on-board control unit, based on 78 dedicated DSP control board, with a total computational throughput of 152 GMACs/s. Each board controls 16 coils by means of high efficiency switching drives. Fine positioning is obtained by means of a hexapod directly linked to the cold plate where the actuators are installed.

Figure 1 – VLT DSM fully assembled on the tilting test stand.
Several improvements have been introduced with respect to the previous generation LBT and Magellan units as summarized in Table 1.

Table 1 – Technology improvements from the LBT Adaptive secondaries to the VLT DSM.

<table>
<thead>
<tr>
<th>LBT672</th>
<th>VLT DSM</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>672 actuators, 0.91m diameter</td>
<td>1170 actuators, 1.12m diameter</td>
<td>Actuator spacing projected on entrance pupil:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LBT: 0.28m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VLT: 0.21m (Nasmyth focus)</td>
</tr>
<tr>
<td>Hexapod above the crate support</td>
<td>Coldplate directly fixed to the hexapod</td>
<td>Improve mechanical stiffness</td>
</tr>
<tr>
<td>Solid Zerodur reference body</td>
<td>Highly light-weighted Zerodur reference body</td>
<td>Weight, mechanical stiffness</td>
</tr>
<tr>
<td>Power consumption reduction</td>
<td>Switching voice coil driving circuitry (Gen3 electronics)</td>
<td>Power from 2.4 to 1.2 W/act</td>
</tr>
<tr>
<td>8 channel DSP control boards, 80 GMac/s, anal. link to capacitive sensors</td>
<td>16 channel DSP control boards, 152GMac/s, digital link to capacitive sensors</td>
<td>More computational demand, more compact electronics</td>
</tr>
<tr>
<td>Externally triggered Thin Shell Safety System</td>
<td>Fully autonomous Thin shell Safety System + battery backup</td>
<td>Earthquake + wind safety</td>
</tr>
</tbody>
</table>

3 PROCUREMENT AND INTEGRATION STEPS

The procurement, assembly and integration process comprehends the following main steps, for which we also report the responsible entity:

- Procurement, integration and modular test+calibration of subsystems
  - Reference Body – SESO
  - Thin Shell – SAGEM
  - Coldplate – ADS
  - Hexapod including controller – ADS
  - Crates + actuators mechanics – ADS
  - Magnets gluing on thin shell – ADS
  - Control boards – Microgate
  - Actuators – Microgate
  - Auxiliary electronics (Battery, PSU, Master BCU, …) – Microgate
  - MG-LCU and Calibration WS – Microgate
  - Real-time, interface and calibration SW – Microgate
- Mechanical subsystem integration (Coldplate/Reference body) – ADS
- Crates integration and environmental test – Microgate
- System integration w.out Hexapod – Microgate

3.1 Modular testing

Considering the complexity of the system, the large number of components, and the demanded reliability and availability, the screening, testing and calibration of each component are essential phases of the procurement process. These steps need to be managed according to industrial standards and implementing strict quality assurance protocols. In particular for the electronics subsystems, considering the large number of controlled channels, the complexity of the various boards, and the large amount of parameters to be verified and/or calibrated, it is mandatory to conceive and set up dedicated testbenches with automated test procedures. Besides functional testing and calibration, most of the electronic subsystems components went also through a burn-in process including thermally accelerated stress and functional verification beyond the functional operating temperature. We conducted also a complete Electromagnetic Compatibility (EMC) test campaign, including both radiated/conducted immunity and emissivity verification. Instead of
using the complete unit, a risk mitigation approach suggested to use for those tests a reduced size, fully functional unit that was also employed for development and early stage functional verification.

![Figure 2 – Automatic actuators test facility (left) and EMC testing on reduced-size prototype (right).]

### 3.2 System integration

The system integration has followed the same sequence adopted also for the previous systems. The optomechanical subassembly has been integrated at ADS. One critical part of this process is the silver coating of the reference body. With respect to the previous units, this has been particularly difficult because of the highly light-weighted Zerodur structure with a large number of ribs; the isolation between the capacitive sensor armatures on the front surface and the shielding layer on the back surface was difficult and required re-iteration to reach a satisfactory result. Subsequently, the cold plate and reference body were accurately aligned and linked by means of flexures allowing a quasi-kinematic mount, and then integrated with the cooling system ducts. Another important activity at ADS is the thin shell rear-side coating and the accurate gluing of the permanent magnets.

In parallel, the activities at Microgate included the integration and test of the actuators and of the control crates with their electronics. We also focused on the implementation of the large amount of software code required by the VLT DSM control system. We distinguish the hard-real time code embedded on the on-board DSP boards, partially running on the DSPs and partially implemented in hardware on the FPGAs, the middle layer software on the MG-LCU that interfaces the VLT DSM to the ESO control software, and the calibration and test software running on the Calibration Workstation.

![Figure 3 – Calibration workstation typical environment: Matlab processing and monitoring panels according to VLT standards]

The full system integration occurs at Microgate, with the optomechanical subsystem (cold plate and reference body) installed on a tilting integration stand. Actuators are accurately mounted with a tolerance of ±0.05mm. Thanks to the contactless technology, this operation is not particularly critical and can be performed by skilled operators using standard workshop tools and measurement systems. It shall be remarked that the accessibility at some specific locations, e.g. underneath the hexapod mounting plates, is not optimal and this should be considered in the maintenance procedures.
After actuators installation, we integrated the distribution boards, the control crates and completed the installation with hydraulic and electrical harness.

### 4 SYSTEM-LEVEL CALIBRATION AND TEST

#### 4.1 System testing without thin shell

Before proceeding with the shell installation, the fully integrated system undergoes a sequence of tests mainly aimed to verify the overall functionality of each individual actuator and to assess the correct operation of the safety mechanisms embedded in the control system to make sure that the control forces cannot damage the shell. These safety systems include the Wind and Earthquake Shell Protection system that pulls actively the shell against the reference body in case of strong wind or earthquake, and the overcurrent protection that limits by hardware the maximum piston force that can be applied to the thin shell.

We measured accurately also the thermal time constants of the system. Both the cold plate and the reference body have a thermal time constant of approximately one hour - see Figure 4. This is useful information for system operation that might lead to the practical consequence of keeping always the system powered, as it currently done in all systems already installed on the telescopes.

The power consumption of the unit has been measured applying in open loop to the actuators different force patterns corresponding to different realizations of turbulence phase-screens, finding a good correspondence between the simulations performed in the design phase and the experimental data. The GRAAL test case with 400 corrected modes leads to a power consumption on the unit of 1369W, compared with 1293W predicted by simulation.

Figure 4 – Coldplate thermal time constant.

#### 4.2 Tests with the slumped shell

The original project plan foresaw the manufacturing of two additional thin shells, besides the scientific shell for optical use: a slumped shell, aimed to be used only for practicing the shell handling and verifying the transport and flipping tools, and an engineering shell manufactured with the same rear face and thickness specifications of the scientific shell, but being spherical and without optical prescriptions for the front face. The manufacturing of this shell failed and, because of time limitation, it was decided to stop this program and to use the slumped shell as limited backup for the initial tests. Unfortunately, the slumped shell shows a huge curvature error with respect to the reference body curvature of ~1.5mm at the edge. The operation is dramatically limited with this large gap: the capacitive sensors have poor sensitivity and high noise, the voice coil motors efficiency is lowered by almost a factor of two, and the stabilizing air damping generated by the air between the reference body and the shell is completely ineffective. Therefore, it is unrealistic to obtain any relevant dynamic performance with this shell. Nevertheless, we could perform a very useful sequence of tests and activities with this unit, including control at moderate gain, repetition of the safety tests, and installation of the central membrane. The central membrane is a mechanical flexure with high in-plane stiffness and low piston and tip-tilt rigidity, holding the shell in the center when the telescope points away from Zenith. Without it, it is still possible to operate the shell but only at Zenith. The gluing process is performed keeping the shell in closed loop and
continuously monitoring the forces during the curing phase. The operation was successfully completed and we could also perform slewing tests from Zenith to 20 deg pointing while keeping the shell controlled in closed loop.

### 4.3 System calibration with the scientific shell

The scientific shell manufactured by Safran-Sagem [4] was delivered to Microgate at the beginning of June.

After the very first steps aimed to perform the first cleaning and installation of the shell and to control it in closed loop at moderate gain, the initial activities comprehend the electromechanical calibration of the capacitive sensors [6]. This is obtained by calibrating first a very limited number of sensors using reference plastic shims. The calibration curve obtained in this way is used as reference for the following step, in which we command stepwise in piston the shell and acquire the capacitive sensors of all actuators at each step; then, we fit a specific calibration curve for each channel, according to the 'physical' response curve of the sensors. The convergence of such process is based on the assumption that the shell keeps its shape during the motion. Considering the very low stiffness of the shell, in particular for the large spatial order modes, we implemented a shell relaxation at each step based on the cancellation, by means of modal filtering, of all forces that might induce an elastic deformation of the mirror. In Figure 5 we report the results of such process. The fitting error, defined as rms between fitted model and acquired data, is in the range of 10~20nm. It shall be noticed that this calibration will be used just for the electromechanical tests and will be later superseded by the calibration performed as preparation of the optical tests, using the interferometer.

![Figure 5 – Capacitive sensor fitting examples (left) and fitting error (right).](image)

The calibrated capacitive sensors allowed estimating with good accuracy the gap variation between reference body and thin shell rear surface. This depends on the manufacturing error of the reference body surface and on the thickness inaccuracy of the thin shell. The error amounts to 36µm ptv, while the LBT Adaptive Secondary shells had a typical error of 22µm. The values are quite comparable considering that the error is expected to scale with area of the mirror. It shall be noticed that the reported value might vary slightly once the optical flat will be calibrated.
The following important calibration step is the acquisition of the feed-forward matrix, i.e. the interaction matrix between actuators forces and capacitive sensor reading. This matrix is representative of the shell stiffness, considering the actuators and the co-located capacitive sensors as control points, therefore it allows computing in real time the static forces required to achieve the commanded mirror shape; these forces are then applied in open loop to speed up the response of the medium and high order modes. The matrix acquisition is performed first using a zonal approach, i.e. commanding a piston motion on each actuator, then using in a modal way, i.e. applying all modal shapes computed by SVD from the previously acquired matrix. The accurate estimate of such matrix is fundamental to limit the settling error, in particular when the command contains high spatial order components.

4.4 Preliminary electromechanical tests with the scientific shell

Given the short time available until now to calibrate and test the unit with the scientific shell, we report hereafter the preliminary results of the electromechanical tests that will be shortly refined and completed. All tests have been executed without central membrane, so with the shell in 'pure' magnetic levitation, and therefore at Zenith pointing.
4.4.1 Modal step response

For the modal response test reported hereafter we used the right singular vectors of the feed-forward matrix SVD, ordered in increasing stiffness. According to contractual specification, the unit shall reach a settling time to 90% of the commanded step within 1.5ms (goal: 1ms). The performance shall be obtained with a global tilt within ±6 arcsec, while the operational specification demands up to ±12 arcsec tilt to compensate for field stabilization. For reported test cases, we present the results with no tilt (thin shell parallel to the reference body) and with 12 arcsec tilt, i.e. at the limit of the functional specification. Figure 8 reports the results for modes 0, 20, 100 and 600, while Figure 9 summarizes the results for all modes in terms of settling time and overshoot. All results have been obtained with the same setup both in terms of gains and commands pre-shaping. The very low order modes are almost critically damped with very limited overshoot. The modes up to ~100 show an increase of the overshoot, with few modes being marginally out of specification. This range is critical because of the cumulative effect of the feed-forward forces and of the control proportional gain that is still higher than or comparable with the modal stiffness. Moving to the higher orders, the system response is dominated by the feed-forward forces and appears to be almost purely elastic. Concerning the very high order modes, the overshoot reported in Figure 9 is mainly an artifact due to the very small amplitude of the modal steps, where the sensor noise starts to play a significant role. Concerning the settling time, all modes are substantially within the goal specification of 1ms. The general behavior is coherent with the results of similar tests on the LBT system, showing a benchmark of the correct overall functionality of the VLT DSM unit [5].

![Modal step response](image)

Figure 8 – Modal step response. Dashed lines: ±10% of command. Bottom traces: amplitudes of other modes.

![Modal step response](image)

Figure 9 – Modal step response. Settling time to 90% (left) and overshoot (right) of all modes.
4.4.2 Following error

The following error test is performed by commanding the shell to follow a simulated wavefront. Thanks to the accurate embedded metrology, the mirror can be effectively commanded without any optical closed loop, and the error can be computed as rms error of the difference between command and capacitive sensor reading; two rms operations are necessary, the first being spatial, i.e. computed on all actuators at each temporal step, the second being temporal, i.e. computing the rms of the spatial rms at each step. The error computation is done on the acquisition performed at the internal control frequency of 61kHz, and taking into account 130µs time delay due to the data transfer from the Real Time Computer, global computation of the feed-forward forces and safety checks on the applied force and position commands; all this is performed before the commands can be safely applied to the shell. The results shall be considered as very preliminary, in fact the input time history has been derived by interpolation from a different system and without fitting the command on the shell shape to minimize the fitting error; in the final system, this is covered automatically by the interaction matrix. This said, adjusting the input time history to the GRAAL case with 400 corrected modes, we obtained a typical error of 64nm rms WFE, to be compared with a specification of 80nm rms WFE ($r_0 = 0.132m$ at 0.5 µm).

![Figure 10](image1.png)

4.4.3 Chopping

The chopping specification requires ±20arcsec of mirror mechanical motion with 10ms settling time and 5Hz maximum chopping frequency; optical performance and adaptive correction is required only during the on-star phase, while there is no optical quality prescription during the off-star phase. This allows controlling the mirror in the off-star position without feed-forward control; this relieves slightly our internal requirements in terms of calibration accuracy. Figure 11 reports the test results, showing that the system is in specification also concerning the chopping performance.

![Figure 11](image2.png)
5 CONCLUSIONS

The integration of the VLT DSM has been successfully completed, and a preliminary screening of the electromechanical performances indicates that the unit meets the specification, performing close to goal specification on several aspects. Given these results, we can consider most of the major potentially critical issues to be behind us. The short term planning foresees the completion of the electromechanical performance test, focusing on the fine tuning of the system to further optimize the dynamic behavior. In this frame we will test new control features and automatic gain tuning, but always with the final aim to gain in robustness rather than pursuing the ultimate dynamic performance. In fact, the reliability of system operation is a key aspect that cannot by traded in favor of pure performance. During this optimization phase we will also install the central membrane, after this it will be clearly necessary to partially re-calibrate the system and to repeat the performance tests. The test campaign will be completed by system-level verification over the whole functional temperature range. Following this phase, the unit will be shipped to ADS for final integration with the hexapod and with the hub, 'official' repetition of the electromechanical tests and coating of the shell optical side. The shipment to ESO to start the optical tests on ASSIST [3] is foreseen for November 2012.

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