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RESULTS OF A SYSTEM STUDY FOR THE ESO VERY LARGE TELESCOPE ADAPTIVE OPTICS

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Abstract

This paper outlines the key results of the Very Large Telescope (VLT) Adaptive Optics System Study performed by MMS/UTOS under an ESO contract. A conceptual design was developed based entirely on available and demonstrated technologies. Key subsystems included a 250 actuator continuous facesheet Deformable Mirror, an intensified Shack-Hartmann wavefront sensor and a DSP-based fast processor utilizing a parallel architecture. The control algorithm is modal and adapted to the atmospheric phase disturbance and to the observing conditions. The system performance was assessed by simulating the atmospheric phase perturbations and the adaptive optics compensation. The simulation results are presented over a range of observing conditions with variations in seeing, wind speed profile, reference star magnitude and isoplanatic angle.

1- Introduction

Adaptive Optics is one of the main feature of the Very Large Telescope of the European Southern Observatory (ESO). Use of the large telescopes for imaging, spectroscopy and astronomical spatial interferometry depends substantially on the availability of adaptive optics, which allows diffraction limited imaging for each individual telescope in the near infrared wavelength range (2.2 to 5 microns) and partial correction of atmospheric distortions towards the visible wavelength range.

Based on these considerations, a long term strategy was followed at ESO to evaluate and demonstrate the feasibility of such a system for 8-meter class telescopes. A first prototype called Come-On was installed at the ESO 3.6-meter telescope where significant scientific results were obtained [1,2,3]. Then, a second generation of this prototype [4], called Come-On-Plus, was developed and tested at La Silla [5]. It is now the only system of its kind offered as a standard "instrument" to the European astronomical community. The next phase in the Come-On program has now been launched with a view to obtaining user-friendly adaptive optics for the 3.6-meter telescope [6] and, from this experience, to optimize the operation of the VLT adaptive optics.

Before the Call For Tenders for the design and construction of turn-key adaptive optics, ESO decided to support a system study to assess the available technology and to evaluate the feasibility within a certain budget of a built-in adaptive optics system for the VLT. This study was done by Matra-Marconi Space (MMS) and United Technologies Optical Systems (UTOS). The main study results are presented here. The first objective of this study was to perform a Component Review in order to assess the available technology at component level in terms of performance, schedule information, expected lifetime and cost. Then, a system conceptual design was performed followed by a parametric performance analysis versus the observing conditions (seeing, wind speed, isoplanatism etc) and the system parameters.

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The functional requirements for the VLT adaptive optics were to reach the diffraction limit (Strehl ratio = 0.8) for wavelengths larger than 2.2 micrometers under 0.8 arcsec seeing conditions and 10.5 m/s average wind speed for a reference star visible magnitude of 13. The image motion stabilization was required to be better than 10 milliarcsec rms on the sky. The study of the infrared wavefront sensor was also required.

2- Component Review

From ESO top level requirements, MMS/UTOS derived a Request For Information (RFI) on the basis of a preliminary system design for the adaptive optics subsystems, namely the deformable mirror, the wavefront sensor and the fast processor. The RFIs and the list of potential suppliers were approved by ESO. About 60 companies in the world were contacted. The supplier responses varied in level of completeness from simple statements of capability to fully detailed resports. The Component Review exercise was very useful since it allowed the collection of interesting technical and cost information and provided ESO with an overview of the state-of-art in the field of adaptive optics. A detailed description of the Component Review results is out of the scope of this paper. The key conclusion of the review is that the VLT adaptive optics system is achievable with available or demonstrated technologies.

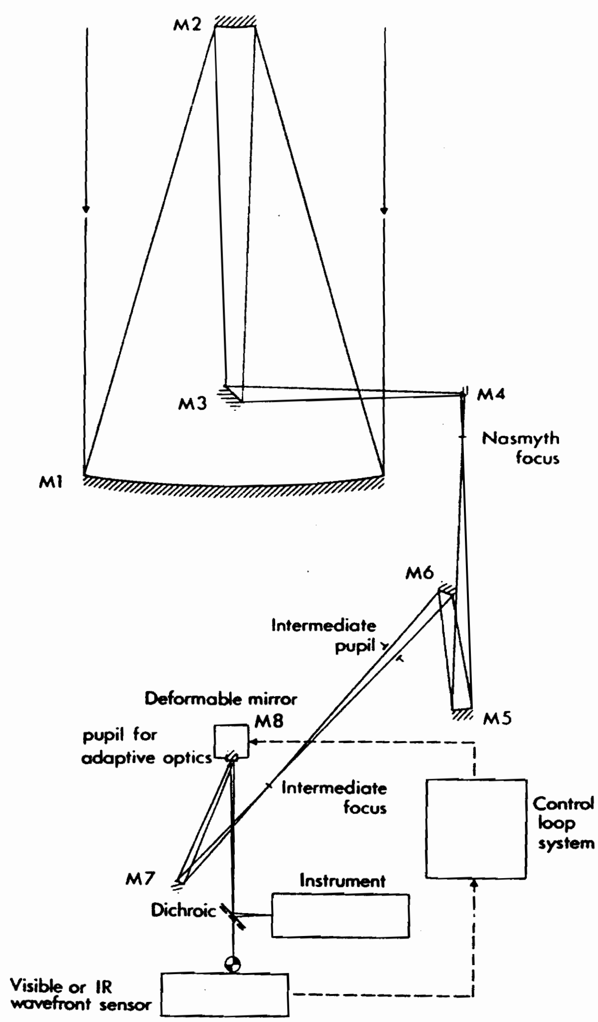

Figure 1: Coudé beam configuration and adaptive optics location

3- System Conceptual Design

The VLT adaptive optics will be integrated in the Coudé train of the 8-meter unit telescopes as a "standard guiding system" (see fig. 1). The deformable mirror is one of the Coudé mirrors (M8) and is located at a telescope exit pupil of diameter 110 mm. The wavefront sensor unit is located at the Coudé focus in the so-called Coudé station, and consists of a visible wavefront sensor, an infrared wavefront sensor and a guiding camera which is used when the adaptive optics are not operating. The infrared wavefront sensor is used when no convenient visible counterpart of the observed object is available. A dichroic (M9) separates the light for the science instrument or interferometric beam combination and for the wavefront sensor. This dichroic will be exchangeable to offer the best throughput towards the instrument and the best correction efficiency depending on the observing conditions. When adaptive optics are not in operation, there are two options: either switching to a flat low frequency mirror located at M8, or keeping the deformable mirror, which will provide a DC wavefront correction for all constant residual aberrations of the Coudé path.

The adaptive optics conceptual design performed in the study is based entirely on available or demonstrated technology. The subsystem top-level requirements are provided in table 1.

The deformable mirror is a continuous facesheet mirror with 250 actuators in the clear aperture and is supported by an active mount for the tip-tilt compensation. The deformable mirror is based on an existing UTOS design and is currently manufactured at UTOS.

The wavefront sensor is of Shack-Hartmann type, intensified in the visible range in order to reach the photon noise limit. The number of subapertures is matched to the number of actuators. The wavefront sensor detector is nominally a 256x256 array detector. In fact, the selection of detector size results from a trade-off between the gain in field-of-view per subaperture and the increase of the closed-loop delay time due to the detector read-out.

The fast processor is based on existing Matra DSP boards and uses parallel architecture for meeting the computation time requirement.

Subsystem	Parameter	Requirement
Deformable Mirror	Diameter (clear aperture)	110 mm
	Number of actuators	250
	Actuator stroke	10 μm
Wavefront Sensor	Operating wavelength	0.5-0.9 μm (visible wavefront sensor) H-K bands (IR wavefront sensor)
	Frame rate	500 Hz (max)
	Noise	Photon noise limited
Control System	Control algorithm	Modal
	Delay time (detector read-out and actuator commands)	< 1.5 ms (goal 0.5 ms)
	Number of corrected modes	Adapted to the observing conditions (seeing, isoplanatism angle, etc.)

Table 1: Subsystem top level requirements.

The total closed-loop delay time induced by the adaptive optics - including the detector read-out, the computation time and the actuator command - is less than 1.5 ms with the 256x256 array detector. It is dominated by the detector read-out time and would be less than 0.5 ms with a 128x128 array detector. However, there is a reasonable probability that the 0.5 ms delay time goal for the detector read-out and data processing will be reached with a 256x256 array detector at the beginning of the VLT adaptive optics development.

The control algorithm is modal: the measured phase disturbance is expanded over a set of orthogonal spatial modes, such as Zernike polynomials. Actually, the selected modes consist of a discrete Kahrünen-Loeve expansion and are optimized with respect to the phase disturbance spectrum and to the deformable mirror influence function. Modal control is optimum for astronomical observations since it introduces the flexibility to easily control the level of correction both in the spatial domain, by adjusting the number of modes to be corrected, and in the temporal domain by adapting the control law for each mode with respect to the observing conditions. In that way, the adaptive optics system performs the optimum compensation versus the observing conditions: seeing, reference star magnitude, wind speed and reference star shift (isoplanatism effect).

4- Performance Analysis

The adaptive optics performance was assessed by MMS with a full time simulation software. The performance analysis consists of generating the atmospheric phase disturbance (using Born-von Karman spectrum) and simulating the closed-loop compensation in the time domain. The deformable mirror spatial response (actuator influence function) was generated by UTOS with a NASTRAN model. The simulations take into account the wavefront reconstruction from slope measurements and the wavefront sensor noise.

Since a lot of parameters can be varied, such as the seeing profile, the wind speed profile, the reference star magnitude etc., MMS has generated, in accordance with ESO, five atmospheric models with variation in seeing from 2 arcsec to 0.4 arcsec and in wind speed from 18 m/s to 5 m/s. Each atmospheric model consists of five independent turbulent layers of height between 0 km and 13 km. The wind speed and the refractive index structure constant C_n^2 profiles were determined from measurements performed by ESO at Paranal. In total, 12 simulation cases were performed for various reference star magnitudes. For each case, the control laws and the number of corrected modes were optimized versus the observing conditions. The results are given on table 2 and figure 2. One can see that for magnitude 13, seeing 0.8 arcsec, and wind speed 10.5 m/s, which can be considered as average observing conditions, the Strehl ratio is 0.74 at 2.2 μm wavelengths, which is very close to the 0.8 Strehl ratio goal. Moreover, the compensation remains acceptable for magnitudes as high as 15. Further investigations show that there is a strong drop in the system performance above magnitude 16. These results are valid for the visible wavefront sensor. For the infrared wavefront sensor, the limiting magnitude is about 10.

The isoplanatism effect was assessed by shifting the reference star with respect to the observed object with an angle varying from 0 arcseconds to 2 arcminutes. This was done for two C_n^2 profiles: for the profile n°1 63% of the seeing was generated by the ground turbulent layer while for the profile n°2, the contribution of the turbulent layer was reduced to 36%. As expected, profile n°2 leads to a faster drop of the Strehl ratio versus the isoplanatism angle (figure 3)

Seeing (arcsec)	Average wind speed (m/s)	Ref. star magnitude (visible)	WFE rms no correction (µm)	WFE rms residual (µm)	Strehl ratio	Image stabilization (marcsec)
2	18	6	5.35	0.3	0.3	14
2	18	13	5.35	0.39	0.18	16
1.2	12	13	3.49	0.25	0.49	11.5
0.8	10.5	6	2.49	0.12	0.8	3.4
0.8	10.5	10	2.49	0.12	0.8	3.5
0.8	10.5	13	2.49	0.16	0.74	4.2
0.8	10.5	14	2.49	0.18	0.69	5.1
0.8	10.5	15	2.49	0.22	0.6	7.3
0.8	7.5	13	2.49	0.16	0.74	4.5
0.8	7.5	15	2.49	0.21	0.63	5.2
0.4	5	13	1.4	0.09	0.91	2.8
0.4	5	15	1.4	0.14	0.82	6.3

Table 2: Summary of the closed-loop simulations (250 actuators, Strehl ratio including tilt and calculated at λ = 2.2 µm)

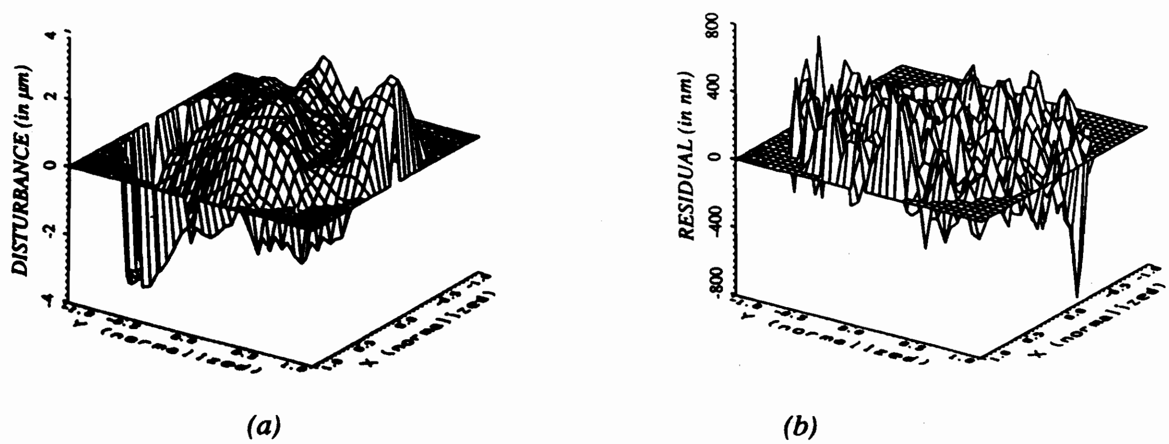

Figure 2: Example of wavefront error maps: (a) no compensation, (b) with adaptive optics compensation

Finally, the evolution of the system performance versus the number of actuators was investigated. The results are shown in table 3. The 250 actuator mirror appears to be the reasonable choice for the VLT since increasing significantly the number of actuators (say above 400) would lead to a considerable increase in cost with a marginal performance improvement in the near infrared, while reducing the number of actuators to about 100 would lead to a worse performance especially for wavelengths below 2.2 µm.

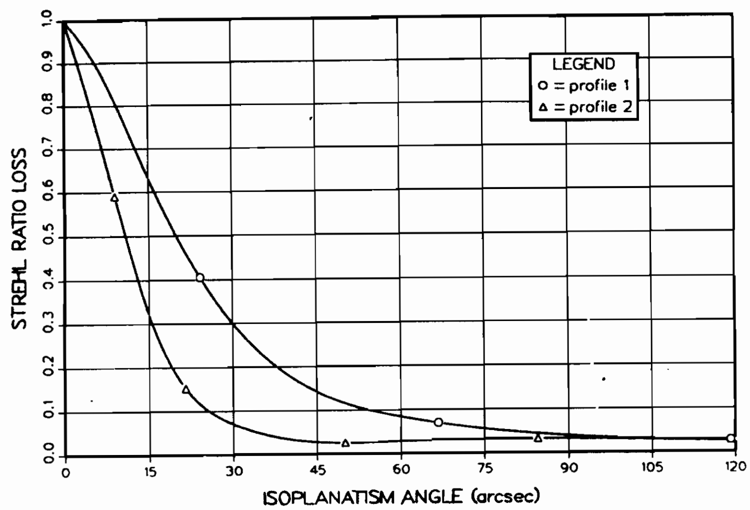

Figure 3: Strehl ratio loss at 2.2 μm wavelength versus isoplanatism angle. Atmospheric conditions: seeing 0.8 arcesc, average wind speed 10.5 m/s.

Number of actuators	114	250	415
Observing conditions seeing 1.2 arcsec, magn. 13, wind speed 12.5 m/s	Residual WFE = 0.36 µm Strehl ratio = 0.35	Residual WFE = 0.3 µm Strehl ratio = 0.49	Residual WFE = 0.25 µm Strehl ratio = 0.61
Observing conditions seeing 0.8 arcsec, magn. 13, wind speed 10.5 m/s	Residual WFE = 0.24 µm Strehl ratio = 0.63	Residual WFE = 0.19 µm Strehl ratio = 0.74	Residual WFE = 0.17 µm Strehl ratio = 0.79

Table 3: Performance evolution with the number of actuators. Strehl ratio calculated at λ = 2.2 μm.

5- Conclusion

The work performed in this study shows that the VLT adaptive optics system is achievable with 250 actuators in the clear aperture and with available technologies. The Component Review confirmed this conclusion at component level. The system Conceptual Design and the performance analysis reinforced this conclusion at VLT system level. The simulation results show that the designed system almost allows recovery of the diffration limit for VLT 8-meter telescopes, even for reference star magnitudes as high as 15, allowing a considerable breakthrough for groundbased astronomical observations.

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