Large Aperture Telescope Technology

towards large active primary mirrors for space telescopes

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The LATT Team

CGS S.p.A.: coordinator

A.D.S. International: opto-mech. system
electr.+control, systems+testing

Italian Optics Inst.: shell

Italian Astrophysics Inst.: AO expertise+optical testing

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LATT is a response to an ESA TRP call for:
active mirror for space telescopes
  – Study
  – Prototyping

• Requirements
  • Large format
  • Possibly deployable/segmented
  • Lightweighted

• Scientific cases
  • Astronomical space telescopes
    – IR? UV?
  • LIDAR
  • Earth monitoring
  • Telecommunications

Active mirror?
The optical surface is controlled against thermo-mechanical bendings

Preliminary study:
* ALC project in 2007

LATT prototyping:
* ESTEC/Contract No. 22321/09/NL/RA
The team:
• has 15 years **expertise** in **ground based adaptive optics** (AO).
• developed the **adaptive secondary mirror** concept.
• implemented it into AO facilities at **8m class telescopes** (LBT, Magellan, VLT)
• now contracted by **Extremely Large Telescope** projects (E-ELT, GMT) for their large deformable mirrors

**OBJECTIVES**
• To **advance** the technologies of the ground based telescopes adaptive mirrors and implement/tailor them into an active space primary mirrors;
• To **assess** the technology and **demonstrate** it in relevant test/environment;
• To **answer** key-question for space active optics:
  • lightweight system
  • optical controllability vs power consumption
  • fragile optics safety

Three areas shall be considered and investigated in detail during the review and development of novel technologies:
- Lightweight mirror technologies for a deployable primary mirror telescope;
- Deployable mechanisms and systems;
- Subsystems and methods for safe launch and operation of large aperture deployable telescopes in space.
Real goal: to fine-align the ESA logo!!

LATT can handle it!
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The activity has been carried out in 2 phases - 6 tasks

- **PHASE 1: Study (competitive parallel contracts)**
  - (Task1) Review of requirements and technologies
  - (Task2) Preliminary design and Demonstration of novel Technologies

**LATT TECHNOLOGY SELECTED**

- **PHASE 2: Prototyping**
  - (Task 3) Detailed design of the BreadBoard
  - (Task 4) Manufacturing of the BB
  - (Task 5) Testing of the BB
  - (Task 6) Performance assessment

This activity shall be executed in two phases. Phase 1 shall include Tasks 1 and 2, while Phase 2 shall contain Task 3 to Task 6. The contractor shall not start Phase 2 until he has received a formal authorization to proceed (ATP) from the Agency.

The work shall be organised in six tasks:
- Task 1 – Review of requirements and technologies (phase 1)
- Task 2 – Preliminary design and demonstration of novel technologies (phase 1)
- Task 3 – Detailed design of the breadboard (phase 2)
- Task 4 – Manufacturing of the breadboard (phase 2)
- Task 5 – Testing of the breadboard (phase 2)
- Task 6 – Performance assessment and critical appraisal (phase 2)
**Actuators:**

**Contactless**, voice coil motors + magnet glued on the back of the shell:
- low print-through (nm)
- no hard point in case of failure (fail safe)
- very large range (hundreds of um)

**Internal metrology:**
Actuators are commanded in local close loop, fed by the capacitive position sensors.

Contactless sensing: the TS is detached from the RB.
**Mind the gap!**

The optical element (Zerodur TS) is ~ 0.5mm far from the support (RB):

- **Mechanics decoupled from optics**
- Mech. support relaxed shape tolerances (thermal): may be ultra-low weight
- Mech. bending of support is propagated to glass as actuator influence functions
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CHALLENGES

• How lightweight can we go? New materials?

• Power consumption vs optical controllability
  – controllability in vacuum (no air damping)

• Fragile thin shell vs launch vibrations!
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ACHIEVEMENTS

LATT OBB (Optical BreadBoard)

- F/6 spherical mirror
- 40 cm diameter
- 19 actuators
- shell: 1mm thick Zerodur
- RefBody: Alum. Honeycomb + CFRP

17 kg/m²
TRL 5
Actuator frame: carbon fiber + Zerodur

Actuator embedded electronics

Ref Body (front) with actuators installed

Ref Body:
aluminum honeycomb + Carbon fiber

Surface accuracy 30 μm PV
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SHELL MANUFACTURING

Coordinated Final Presentation Days (CFPDs)
21st–22nd Nov. 2016 - ESTEC

ESTEC/Contract No. 22321/09/NL/RA 12

TS polishing

TS thinning to 1 mm

Made in Italy by INO

TS ready with magnets on the back side
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OBB INTEGRATED

- CFRP+Al honeycomb Reference Body (<6 kg/m²)
- Co-located control electronics embedded in Smart Actuator
  - Position capacitive sensors (nm precision)
  - Voice-coil motors (<55mW, 1mm stroke)
- Low print-through glued magnet, pitch 100 mm
- 1mm thin glass shell

- 2 cables, 2 small electronics boxes
  (providing local control loop and launch safety mechanism for the thin shell)
OBB \(^{(1)}\) measured areal density: 18 kg/m\(^2\)  
[excluding laboratory mount interfaces]

- Areal density as active primary mirror: \(15 \,(^{(2)}\) kg/m\(^2\)
  - thin shell: 13 % total mass
  - Ultra low weight Ref Body: no optical specs

- **Current approach:** stiff (thick) optical surface
- **LATT way:** low mass, stiffness increased with actuators

\(^{(1)}\) computed on 440mm DIA  
\(^{(2)}\) before RB reworking
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OPTICAL QUALITY

WITH LOW POWER BUDGET/ACT DENSITY

LATT OBB

Diam: 20 cm
WFE: 26 nm RMS

LBT TS#4

Diam: 6 cm
WFE: 20 nm RMS

100 act/m²
55mW/act

1500 act/m²
2W/act

- Shell controlled successfully
- Stability checked
- Optical performances comparable with AO: 20 nm RMS WFE

Thanks to:
- Low BandWidth
- Smart actuators

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DYNAMIC RESPONSE

Reduce power \(\Rightarrow\) Reduce control freq.

No air damping

- settling time < 0.72s = 1 Hz large motion BW
- 10 s demanded operational (vacuum) settling time
  - OK for lowest 11 modes
  - FFWD not implemented (yet)
The shell is ‘glued’ on the RefBody by means of an electrical field: *electrostatic locking*

- **Adhesion pressure:**
  \[ 600\text{N/m}^2 \text{ @ } 100 \text{V} \]

- **Tested on vibration bench:**
  launch loads

<table>
<thead>
<tr>
<th>Excitation axis</th>
<th>Full level random test [g RMS]</th>
<th>Mid level random test [g RMS]</th>
<th>Low level random test [g RMS]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>[ 7.22 &lt; a &lt; 7.99 ]</td>
<td>[ 3.61 &lt; a &lt; 3.99 ]</td>
<td>[ 1.80 &lt; a &lt; 1.99 ]</td>
</tr>
<tr>
<td>Y</td>
<td>[ 6.33 &lt; a &lt; 7.9 ]</td>
<td>[ 3.16 &lt; a &lt; 3.5 ]</td>
<td>[ 1.58 &lt; a &lt; 1.75 ]</td>
</tr>
<tr>
<td>Z</td>
<td>[ 9.93 &lt; a &lt; 10.98 ]</td>
<td>[ 4.96 &lt; a &lt; 5.49 ]</td>
<td>[ 2.48 &lt; a &lt; 2.74 ]</td>
</tr>
</tbody>
</table>
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**Laboratory test campaign**

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**ENVIRONMENTAL TESTS**

**Thermal test**
- Temp: -25°C → 55°C

**Thermo-vacuum test**
- Tested @ 1e-5mbar

**Optical test**
- WFE comparable with AO after removing the membranes deformation (λ/6 @UV)

**Electrostatic lock test**
- Lock pressure: 600 N/m²

**Vibration test**
- Max acceleration: 11g

**plus vacuum funct. test**

**DONE**
How may the LATT mark the way toward large space telescopes?

or:

Our recipe to

“..Make use of light-weight mirrors and structures through active control, translating into overall savings.”

Feinberg et al. 2012

System needs: Functional req.s:

- Segmented apertures $\leftrightarrow$ Phasing control
- Lightweighth mirrors $\leftrightarrow$ Active stability
- Diff. limited optics $\leftrightarrow$ WF control

3 functionalities built-in in the LATT, derived from adaptive mirrors

Current strategy:

rigid body control, set-forget + passive stability $\rightarrow$ L2 ‘quite’ orbit

LATT way:

high orders, continous control + active stability $\rightarrow$ low ‘harsh’ orbit?
“..Make use of light-weight mirrors and structures through active control, translating into overall savings.”

LATT Feature:

- Contacless actuation
- 1mm stroke with nm accuracy
- kHz control
- Act. internal metrology
- Contactless optical surface
- Correction @M1
- DoF distribution
- Modal control/subaps. control

Technical response to:

- Fail-safeness
- Relaxed deployment tolerances
- Built-in figure + phasing device
- Lightweight
- Support structure with no optical REQ
- Areal density independent wrt size
- Segments managing
- Improved WF error
- Virtually stiffer and more stable

next generation Space Telescope requirements
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Dead actuators may be SW disabled with **negligible static foot-print**.
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Act. Stroke may take care of initial coarse phasing/alignment. Phase tracking may be allocated to suitable WFS (Pyramid WFS?)

All-in-one shape and segment phasing control, as will be implemented in 40m telescopes (GMT, E-ELT)

Agapito et al. 2015
Esposito et al. 2013
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**Current areal density:**
active control system+metrology + support + mirror = **15 kg/m²**

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---

**OBB Mass budget [kg]**

<table>
<thead>
<tr>
<th></th>
<th>Mechanical assembly</th>
<th>VCM assembly</th>
<th>Capsens assembly</th>
<th>Thin Shell</th>
<th>Reference Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight [kg]</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
<td>1</td>
</tr>
</tbody>
</table>

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**ESTEC/Contract No. 22321/09/NL/RA**
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WF is restored where the aberration is created:

- Simpler design: no pupil relay optics (for pupil DM)
- Better WF correction
LATT Feature:

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The current baseline:

- few DoF and rely on the M1 stiffness (passive stability)

Our approach:

- **actuators to increase stiffness and stability**
  (acts don’t affect mass and power budget)
• Assess the case of the entire active telescope, including:
  – WFS and control loop (co-phasing)
  – Space qualified electronics
  – Segments support (deployment accuracy, mech.&therm. stability, …)
  – Shell lateral constraint (as final system)

• Improve the control strategy to fully exploit the contactless actuation
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A BRICK FOR MORE COMPLEX SYSTEMS

LATT OBB: 40 cm, 19 acts

1m, 7 segments

Addressing segmentation and co-phasing

1m, monolithic

Addressing larger apertures

3-5m, segmented

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THAT’S ALL

QUESTIONS?

THANK YOU
Backup slides
LATT Feature:

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The Ref Body deformations are propagated by the internal position loop. Can be corrected with **0% fitting error** with:

- WFS (low freq)
- Filtering the metrology (high freq)
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INTERNAL METROLOGY & CLOSED LOOP?

- You can command the final position and the loop will keep it
- If you command a single act., the others keep their position
- Co-located position feedback
- E-ELT case: internal metrology of M4 serves the entire telescope
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## OBB REQUIREMENTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement / Characteristic description</th>
<th>Expected Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ACTUATORS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>±500μm</td>
<td></td>
<td>Covers mirror alignment to recover deployment errors and shape correction due to thermal deformation</td>
</tr>
<tr>
<td>Positioning accuracy</td>
<td>&lt; 117nm rms</td>
<td></td>
<td>λ/8 (goal spec for M1)</td>
</tr>
<tr>
<td>Positioning resolution</td>
<td>&lt;50 nm</td>
<td></td>
<td>Expected</td>
</tr>
<tr>
<td>Force capability</td>
<td>&lt; ± 0.13 N</td>
<td></td>
<td>On the base of the experimental data available on LBT, the total force is expected equal to 83mN (28mN for Mirror flattening and 55mN for 1g testing. Within the requirement also considering a safety factor of 1.5</td>
</tr>
<tr>
<td>Closed loop bandwidth</td>
<td>50 Hz</td>
<td></td>
<td>Refers to the global system (frequency of first undamped mirror mode)</td>
</tr>
<tr>
<td>Open loop bandwidth</td>
<td>3 kHz</td>
<td></td>
<td>A large margin is needed on top of the CL bandwidth in order to damp uncontrolled modes. The value applies to both actuator and capacitive sensor subsystems. System controllability suggests to keep a large margin on this aspect.</td>
</tr>
<tr>
<td>Power consumption</td>
<td>1 W on the mirror + 15 W central processing</td>
<td></td>
<td>We allocate 15W for the power supply and centralized control system. Considering the 19 actuators (55 mW dissipation each), we obtain the reported dissipation figure. At M1 level the expected overall power is 92W (55mW/act x 1400act + 15W cpu) w.r.t. the requirement of 40W. The increase of power has a limited impact at satellite level &lt;5%.</td>
</tr>
<tr>
<td>Lateral stiffness</td>
<td>N/A</td>
<td></td>
<td>Lateral stiffness is not provided by the actuators</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;10 g each actuator</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Large Aperture Telescope Technology

### OBB REQUIREMENTS

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<th>Obtained Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Areal Density</td>
<td>≤ 16 Kg/m² (Ref SOW)</td>
<td>&lt;42 Kg/m² (OBB)</td>
<td>&lt;22Kg/ m²(active M1)</td>
<td>(1)</td>
</tr>
<tr>
<td>Residual Wavefront error</td>
<td>&lt; 156 nm RMS (Ref Sow)</td>
<td>130 nm (considering OD 325 mm)</td>
<td>λ/6 of 935.5 nm</td>
<td></td>
</tr>
</tbody>
</table>

### MIRROR

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement/Characteristic description</th>
<th>Expected Value</th>
<th>Obtained Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Zerodur</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>~ 400 mm</td>
<td>Diameter (400.05±0.05) mm</td>
<td>Thickness (1.012-1.014) mm</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>≤ 1.1 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Axial Symmetric Spherical Mirror</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RoC</td>
<td>= 5000±18mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### BACKPLANE

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement/Characteristic description</th>
<th>Expected Value</th>
<th>Obtained Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CFRP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>~ 440 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>&gt; 400 N/m² ([AD 1 ] )</td>
<td>&gt; 550 N/m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EL shear force</td>
<td>&gt; 530 N/m² ([AD 1 ] )</td>
<td>&gt; 550 N/m²</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ACTUATORS

<table>
<thead>
<tr>
<th>Component</th>
<th>Requirement/Characteristic description</th>
<th>Expected Value</th>
<th>Obtained Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>±500µm ([AD 1 ] )</td>
<td></td>
<td></td>
<td>Not verified because of the too stiff flexures</td>
</tr>
<tr>
<td>Positioning accuracy</td>
<td>117nm r.m.s.</td>
<td></td>
<td></td>
<td>Typical measurement noise is 60nm r.m.s.</td>
</tr>
<tr>
<td>Positioning resolution</td>
<td>&lt;58 nm</td>
<td></td>
<td></td>
<td>Resolution achieved 8nm typical and max. 30nm @ 1.2mm gap</td>
</tr>
<tr>
<td>Force capability</td>
<td>&lt; ± 0.13 N ([AD 1 ] )</td>
<td>± 0.10 N – 1 driver on</td>
<td>± 0.18 N – 2 driver on</td>
<td>± 0.20 N – 3 driver on</td>
</tr>
<tr>
<td>Open loop bandwidth</td>
<td>3 kHz</td>
<td>1.8 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td>72 mW/actuator + 15 W central processing [RD 11 ] and [AD 2 ]</td>
<td>50-58 mW per actuator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;150 g</td>
<td>80g per actuator (cup+CapSens armature+coil+SAB)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The WFE specification (156 nm RMS) is met considering an optical pupil of 325 mm diameter (and correcting for the flexure-induced deformation).

The peak force needed to flatten the mirror is lower than expected 86mN w.r.t. a budget of 250mN.

The low power consumption per actuator 50-58mW gives a power consumption for a 9m^2 deployable active primary mirror with an actuator density of 120 act/m^2 of 78W (including 15W for the power supply and centralized control system).

The Optical test of the OBB demonstrates that the implemented surface actuator density (100-120 act/m^2) is sufficient to fulfil the requirement in terms of surface quality that was not obvious at the begin of the project.

The foreseen areal density for an ACTIVE primary mirror developed using the LATT technology will be <22Kg/m^2 that is competitive also w.r.t. the lightest PASSIVE primary mirror.