International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 1118008 · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2535927

ACTIVE OPTICS FOR NEXT GENERATION OF SPACE OBSERVATION INSTRUMENTS

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ABSTRACT

Thales Alenia Space has been involved in the design and the development of space observation instruments for over 40 years. This paper will explain why active optics is needed for next generation of instruments for Earth observation. We will also describe what kind of solution is preferred and why. We will give an overview of the development status on the associated technologies. Indeed, the future missions will have to deal with better performance, better optical quality while from manufacturing point of view, the total mass, the development schedule and the final cost have to be reduced. These constraints induce a new generation of solutions based on large entrance optics associated to high lightweight ratio which naturally provide solutions sensitive to gravity deformation. In these conditions, the enhancement of the final performance can only be guaranteed by using active optics in flight. A deformable mirror is therefore foreseen to be implemented in future large telescopes in order to correct manufacturing residues, ground/flight evolution including gravity. Moreover, low mass and low cost require more compact designs which entail solutions more sensitive to misalignment. An active positioning mechanism is then also needed in order to correct the telescope alignment during operation conditions. Thales Alenia Space has been selected by CNES to develop and qualify active optics building blocks and then to test and demonstrate the improvement that new active technologies can bring in a full size instrument representative of the next generation of observation instruments. An overview of the current development status and the achievable performances is given.

Keywords: telescope, active optics, deformable mirror, wave front sensor, positioning mechanism, lightweight mirror

1. INTRODUCTION

Thales Alenia Space France has a great experience in the design and production of large space telescopes, for both Earth Observation and Science applications. In future Earth observation programs, either for very high resolution at low Earth orbit for MOD or medium resolution at geostationary orbit for civilian applications, the entrance pupil size of the telescope becomes larger and larger. For now several years, Thales Alenia Space has been preparing the next generation telescopes with internal funding and space agencies supports.

TANGO is one of the most important project currently under progress dealing with active optics. TANGO is a CNES funded technology program for active optics technologies development for space based large monolithic telescope as part of CNES OTOS program. The benefits of active optics technologies for TANGO are the ability to use a shorter and lighter telescope for which the driver constraints are relaxed (on ground alignment, gravity effect, ageing, stability ...). The first part of the TANGO project aims at developing the key technologies for active optics system up to a TRL 5/6. For the second part of the TANGO project, Thales Alenia Space has been selected as sole contractor by CNES to integrate a full size active optics telescope that include the active optics loop components developed during the first part of the project.

In parallel to these technological developments, Thales Alenia Space has also been developing a unique expertise in the conception of efficient algorithms for image correction, image stabilization, image coding or telescope phase retrieval which allow to drastically simplify the hardware.

2. CHALLENGES FOR NEXT GENERATION OF INSTRUMENTS

2.1 Dimensions and mass of optics

The entrance pupil dimension is one of the most important drivers for the instrument performance: SNR and MTF (spatial resolution) are fully derived from this dimension. For a given performance, if the pupil size varies linearly with the altitude of the satellite, it is not the case with the ground sampling distance. For a given orbit, an improvement by a factor 2 of the spatial resolution induces more than a factor 2 on the pupil dimension (for a given MTF)

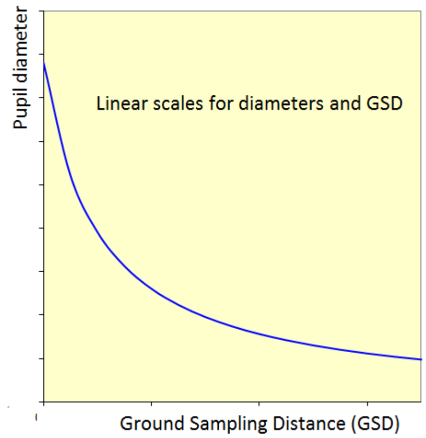

Figure 1. Entrance pupil evolution with respect to the ground sampling distance for a given orbit and for a given MTF performance. Improvement in GSD can affect significantly the entrance pupil size.

So, for the more demanding performance in the future telescope requirements on GSD and image quality, the next generation of Earth observation telescopes will have significant larger entrance pupil than today. The risk is that this enlargement on one hand will be certainly associated to reductions on the other hand (mass, schedule, cost). The next primary mirrors generation will certainly suffer from gravity effect (on ground mirror deformation under gravity) due to the association of large dimension and low mass whatever the material selected will be.

2.2 Volume constraints

The volume of the instrument is a cost driver since the less volume we have, the smaller launcher we can have or a multi payloads launch can be envisaged. Therefore, there is a high constraint today on the instrument volume that will certainly increase in the next years. The problem is that for a given mission (entrance pupil and focal length fixed), the more compact the telescope is, the more sensitive to misalignment it will be. This can be illustrated by the following exercise in which we have designed 4 telescopes associated to the same mission parameters (entrance pupil, focal length) but different envelops. For these designs we have applied the same misalignment errors on the mirrors and computed the WFE deviation for all telescopes.

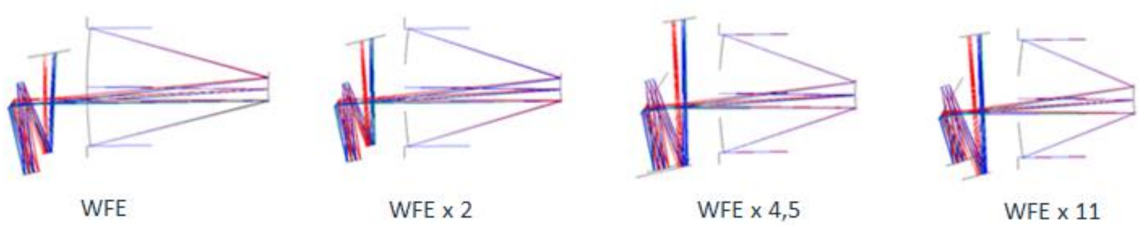

Figure 2. Effect of the instrument volume on its performance: the more compact, the more degradation appears due to any misalignment

2.3 Development constraints

The time dedicated to the telescope development is also a cost driver. It is assumed that tomorrow the allocated time for mirror manufacturing schedule, telescope alignment and tests will decrease significantly. That means that the next generation telescopes will be more difficult to master (increase of pupil size, smaller volume) and we will have less time to deal with it. This can constitute a major risk of delay or bad performance if nothing is anticipated from now.

2.4 Earth observation environment

Once in orbit, the instrument is subject to high thermal flux variations. Typically, for low Earth orbit observation the Earth albedo is changing along the orbit with a period around 100 min. But it can be also required to change the pointing position of the satellite for addressing different observable areas inducing some important variations of solar flux on the instrument.

In geostationary orbit, very high thermal flux variations are induced by the Sun itself which can enter inside the instrument each day around midnight (Earth and Sun are then in the same direction of observation for the instrument).

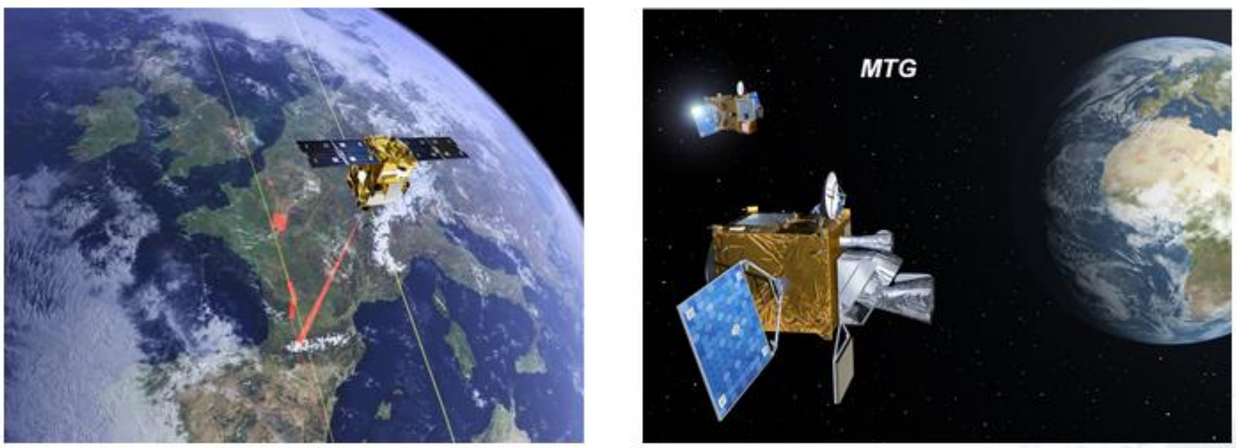

Figure 3. Instruments for Earth observation shall withstand high thermal flux variations without or with limited impact on the performance either for LEO applications (on the left) or GEO applications (on the right).

These thermal variations will, of course, affect more or less severely the inflight alignment (consequently the inflight performance) depending on the material selected for the optics and their structure.

2.5 Risks to be mitigated

From the above analysis, two major risks can be identified for the next generation telescopes. The first one is linked to the large primary mirror which shall have a low mass, therefore a limited stiffness, and a very good performance (WFE). With current conventional technics, optical quality of large optics (due to gravity, polishing time …) is an issue. To mitigate the risk, a deformable mirror can be put in an exit pupil to correct this defect during on ground operations and can be used on flight to correct the gravity release residual error plus any mirror deformations due to ageing or thermal environment.

A second risk is linked to the alignment of the optical parts (in classical telescope, mostly M1 and M2 mirrors). Indeed, if we cumulate the time constraints with the compactness of the next solutions, the risk to not achieve during the allocated time the good performance is high. To mitigate this risk, the use of a 5 degree of freedom mechanism for telescope alignment can relax the on ground constraints, the design sizing margins and can allow to converge efficiently towards the ultimate performance in flight environment.

3. ACTIVE CORRECTION PHILOSOPHY

3.1 Design and material selection

Since a control loop of the instrument is implemented, 2 kinds of philosophy could be considered:

- Use of stable materials (very low CTE) associated to a low frequency correction loop: thermal orbital effect induces low impact (only focus) on performance, long term effect (aging, thermal drift) and bias coming from ground to space effects have to be corrected.
- Use of less stable materials (medium or high CTE) associated to a high frequency correction loop: thermal orbital effect have to be corrected more stringently depending on the CTE of the selected materials.

Whatever the solution is, for a given in flight performance, the WFE degradation between 2 corrections will be the same. The following curve gives the relationship between the acceptable axial thermal gradient (ΔT) and the material CTE. For a given primary mirror geometry, the WFE is proportional to the product CTE x ΔT .

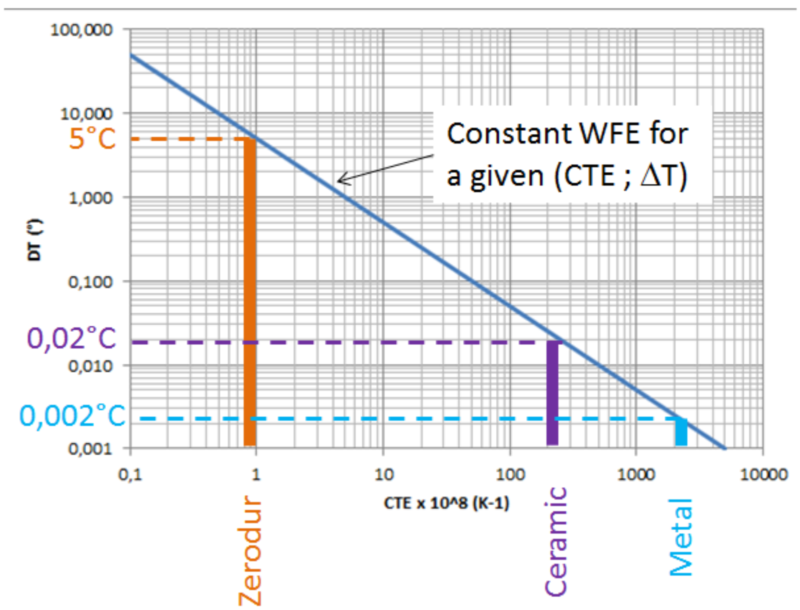

Figure 4. Trade-off for primary mirror material selection. For a given acceptable WFE degradation, different amplitude on thermal gradients can be accepted. Due to thermal orbital fluctuations, the higher is the acceptable thermal gradient the lower is the correction loop frequency.

Thales Alenia Space have selected a Zerodur primary mirror in order to:

- maximize the operational time (low correction loop per year)
- simplify the on board control loop (simple algorithm dedicated to control the focus)
- secure the complex corrections on WFE by operating them on ground (possible because only few corrections expected per year)
- secure the time life of the active mechanisms (only few complex actuations during life)
- secure the mission (in case of control failure, the mission can continue with a degraded performance)

Furthermore, this solution takes benefit from Thales Alenia Space 40 years experience on orbit. Active optics enables a significant technological step forward.

3.2 Active control implementation

The proposed solution to mitigate the risk described in §2.5 is the use of a deformable mirror placed in the exit pupil of a Korsch telescope plus a 5 degree of freedom (5 DoF) mechanism placed at the secondary mirror level. All the defects generated by the M1 mirror (gravity release, bias ground/flight, radiations) are corrected by the deformable mirror and all the defects generated by optics misalignment (moisture release, launch effect, thermal evolution/drift) are corrected by the 5 DoF mechanism.

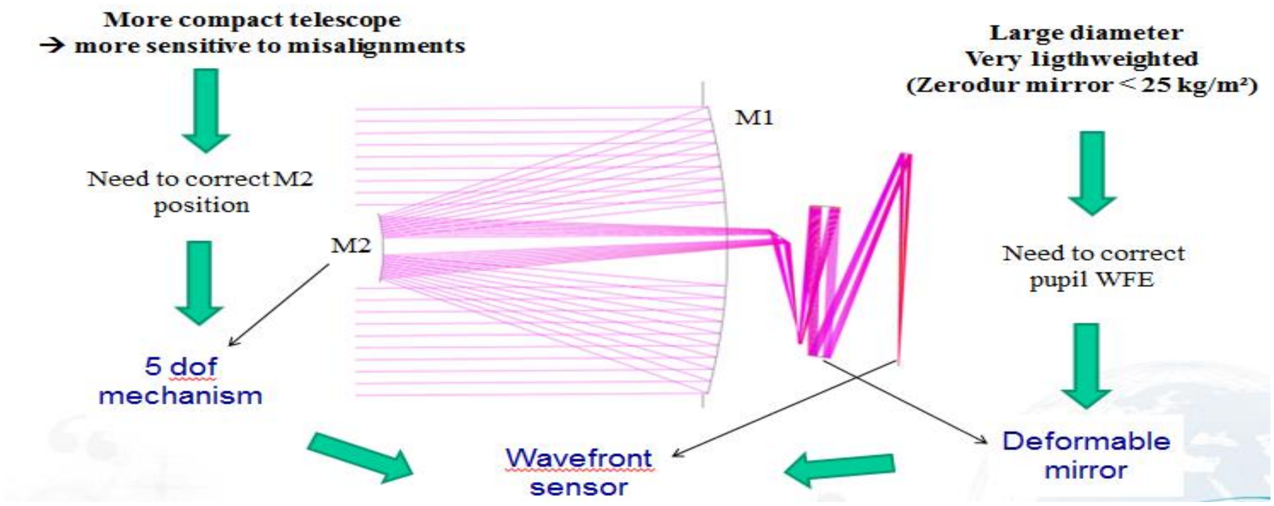

Figure 5. Implementation of active optics proposed in the frame of TANGO project for the next generation of space telescope for Earth observation

It is to be noted that the Thales Alenia Space active control loop is based on mechanisms that maintain their positions without electrical power. Very high reliability can therefore be achieved since the electronics are off most of the time.

3.3 Sensor implementation

The Wave Front Sensor (WFS) shall be able to measure the total WFE of the telescope without disturbing the value. The best place for its implementation is in the telescope focal plane. A tradeoff has been performed during the TANGO project between a classical Shack-Hartman (SH) solution and a solution based on phase retrieval.

Table 1. Tradeoff between Shack-Hartman and phase retrieval for wave front sensing

	Shack-Hartman	**Phase retrieval**
Main advantages	Well known. Simple exploitation.	Use directly the focal plane information: compact and hardware easy to implement. Full pupil flux exploitation (high SNR). Low mass/volume/cost.
Main drawbacks	Need micro-lenses array. Poor signal on each sub-pupil (low SNR). Dedicated detector array and associated electronics. Need calibration. Need stable alignment between SH and telescope pupil.	Computation power for image processing.

Thales Alenia Space has developed, tested and validated an image processing algorithm for phase retrieval which can be used in real time on board and robust to the diverse observed scenes (point or extended sources) See[4] for more information.

The algorithm has been successfully implemented on a space electronic motherboard currently under qualification demonstrating the readiness of this technology.

3.4 Performance assessment

A end-to-end simulator has been developed by Thales Alenia Space to assess what will be the final performance of a future active telescope. The input of this simulator are the optical sensitivity matrix, the FEM results of the instrument (gravity release, thermo-elastic misalignments, radiation/ageing effects), the thermal model of the instrument under space environment (orbital thermal effect, season effect, thermal drift), parameters of the deformable mirror (Zernike polynomial amplitude, correction, accuracy), parameters of the 5 DoF mechanism (amplitude in rotations and translations, accuracy) and simulated information coming from the WFS (based on real images).

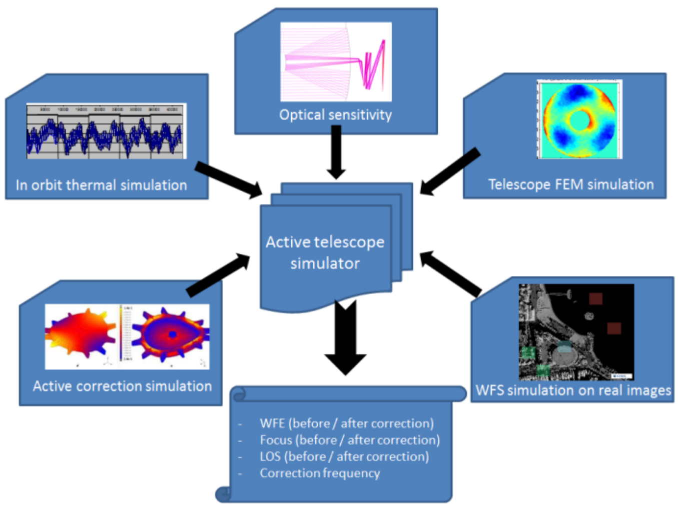

Figure 6. A end-to-end simulator for the active control loop has been proposed to assess the final added value of active optics and specify the needed requirements associated to active components (amplitude, accuracy, working frequency)

The output of this tool gives the probable telescope degradations in WFE, line of sight (LOS) and focus under different situations (beginning of life, around eclipse, at hot case, at cold case, orbital fluctuations, seasonal fluctuations, end of life). For all these situations, the needed correction has been carefully analyzed and a global correction strategy has been proposed in order to maintain the optical quality at an acceptable level during all its orbital life. Thanks to the selected design and the expected performance on each component of the active loop now well advanced in their development, the proposed scenario is:

- **Full correction loop** (deformable mirror + 5 dof mechanism) during commissioning phase. Objective is the correction of all bias, launch and gravity effects.
- **Several full correction loops per years** (only one should be enough after the first year on flight). Objective is the correction of ageing, and drift effects.
- **Simplified autonomous corrections per orbit**. Objective is the correction of short term thermal orbital effects.

Based on this correction strategy, the instrument optical quality is associated to a very good in flight MTF during all its orbit life.

In addition, the use of this active loop enables Thales Alenia Space to simplify and secure the on ground telescope alignment and reduces its development time/cost.

4. TECHNOLOGY MATURITY

4.1 Large primary mirror

A joint team THALES ALENIA SPACE & THALES SESO is in charge of the large primary mirror development.

This mirror demonstrator is made of assembled Zerodur and has a diameter of 1,5 m. The lightweighting activity has been successfully completed with a mass around 25 Kg/m² taking into account the fixation device. To meet the stringent mass requirement, the mirror fixation devices are made of brazed Si3N4 parts.

The mirror is now assembled on the Si3N4 ceramic telescope frame as part of the full scale TANGO telescope. The critical step of the high lightweight mirror integration versus WFE performance has been validated.

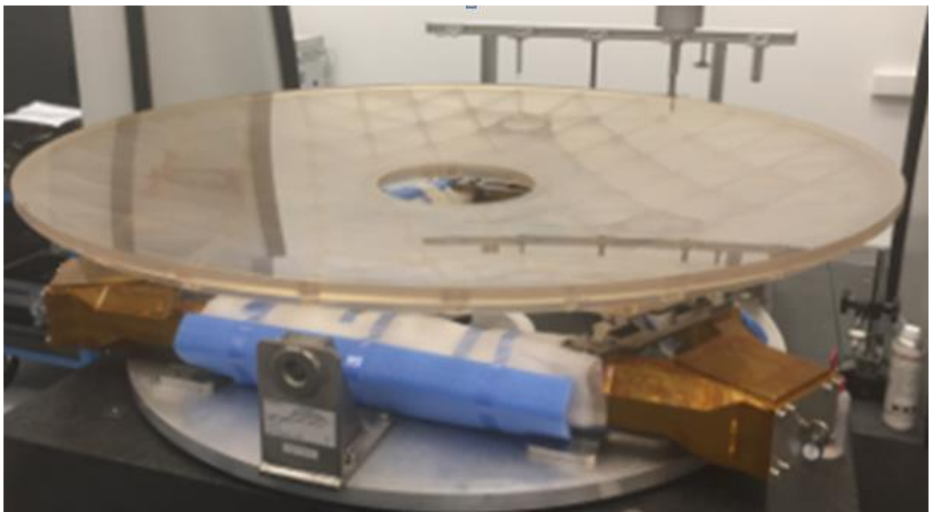

Figure 7. M1 Mirror on instrument Si3N4 main frame. This 1,5 m Zerodur mirror has a total mass around 25 Kg/m².

4.2 Deformable mirror

MADRAS (deformable mirror developed by Thales Alenia Space and THALES SESO for the mirror) is based on an original concept from the Laboratoire d'Astrophysique de Marseille (LAM developed to a TRL 4 level in a previous collaboration [4].

The deformable mirror maintains stable the WFE correction during a long period without any voltage. The principle is based on a Zerodur thin mirror with arms at the edge. By applying forces (push and pull) on these arms, it is possible to deform the mirror and then to correct the low frequency aberrations of the telescope. The actuators are redounded and space qualified. The deformable mirror sustains launch environment without locking device.

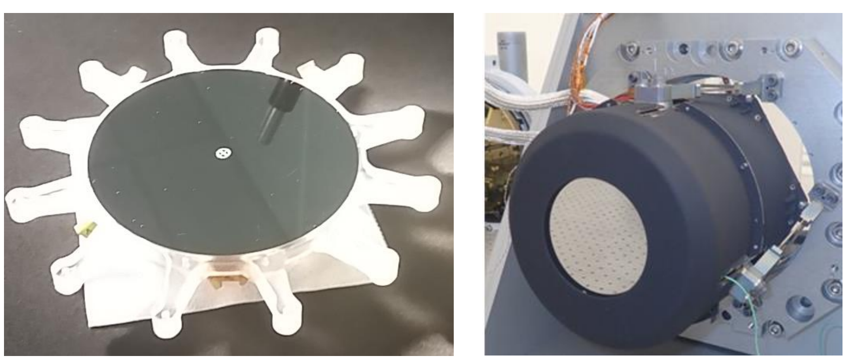

Figure 8. Deformable mirror (MADRAS) integration.

The device has been fully integrated and performance successfully verified. It is now under space qualification before assembly on the full scale active optic instrument demonstrator.

4.3 Five DoF M2 positioning mechanism

This mechanism will be placed at the secondary mirror (M2) level. Indeed, in a Korsch telescope, M2 is the most critical part in the alignment.

The main advantage of this mechanism is to simplify, first, the mechanical design of the telescope (no need to keep alignment between ground and flight) and, second, the on ground adjustment of the optics (no need to start a complex manual alignment loop). The objective is to give the capacity to move the M2 mirror by combining the 3 translations and 2 relevant rotations (five degree of freedom).. The hexapod structure of this mechanism features 6 degrees of freedom. Therefore, by design, the mission is still achieved with full performances even in case of failure one actuator. Furthermore, all actuators are redounded to secure the capacity of inflight correction The mechanism sustains launch environment without locking device and M2 position is maintained when the voltage is off.

The challenge is first to have a total envelop smaller than the M2 dimension in order to not increase the telescope obscuration. The second challenge is to minimize the suspended mass thanks to a fully integrated design based on high lightweight Zerodur M2 and ultra lightweight and stable Si3N4 ceramic structural parts.

The assembly is currently under test to reach TRL 6.

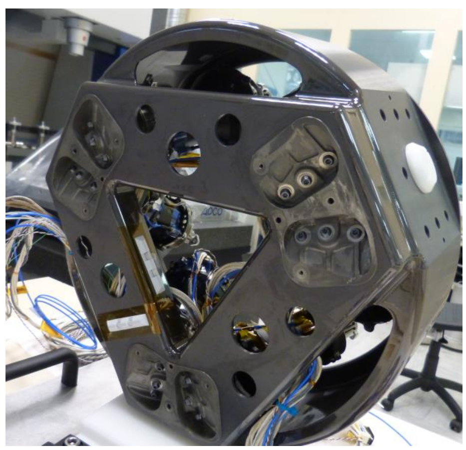

Figure 9. Five DoF mechanism with its 6 actuators and its optimized Si3N4 structure

4.4 Wave Front Sensor (WFS)

The WFS is a key technology to enable in-orbit instrument control. The solution is based on Earth images processing obtained by the telescope focal plan (no dedicated detector). In terms of hardware, it cannot be more simple. The challenge is in the software used to derive the phase information by analyzing in real time the images in the telescope focal plane. Thales Alenia Space has developed an algorithm for this objective and has demonstrated on real images its efficiency. This algorithm is able to favor the most suitable sub-images in an autonomous way and then to retrieve the full telescope WFE by analyzing them in real time.

The algorithm has been successfully implemented on a space electronic motherboard currently under qualification demonstrating the readiness of this technology. An opto electronic demonstration bench playing the full sequence has been successfully performed (See [1]).

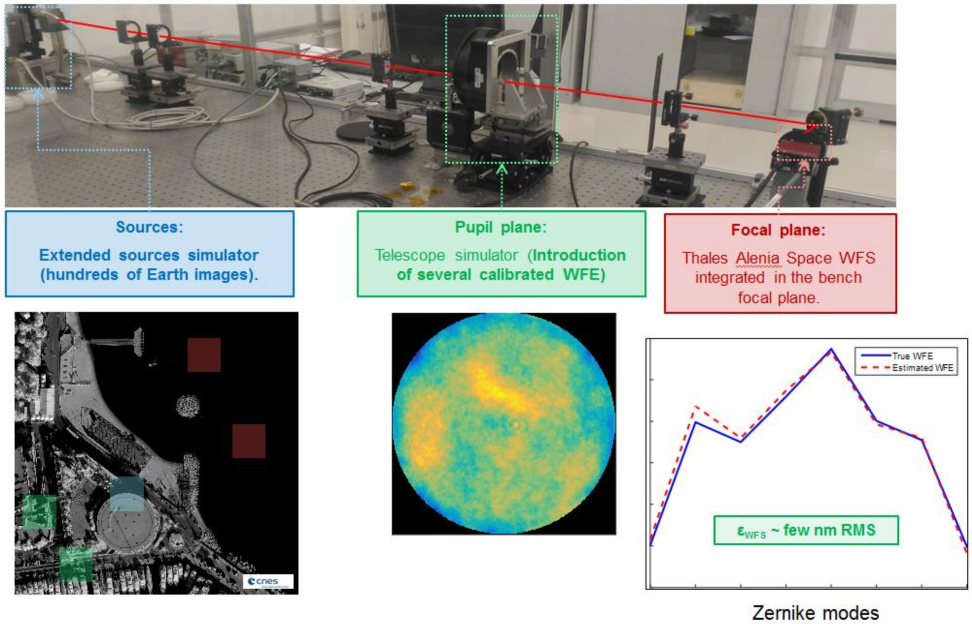

Figure 10. WFS validated on a dedicated bench able to simulate hundreds of Earth images, to simulate tens of telescope WFE. The results show a very good phase retrieval accuracy around few nanometers.

5. CONCLUSION AND WAY FORWARD

Most of the technologies required for future space active telescope are about to reach TRL6 level. These technologies will soon be implemented in a full scale demonstrator by Thales Alenia Space in order to validate and demonstrate the correction loop and the global performance of active correction. The non-active components of this demonstrator are currently well advanced (optics and structure).

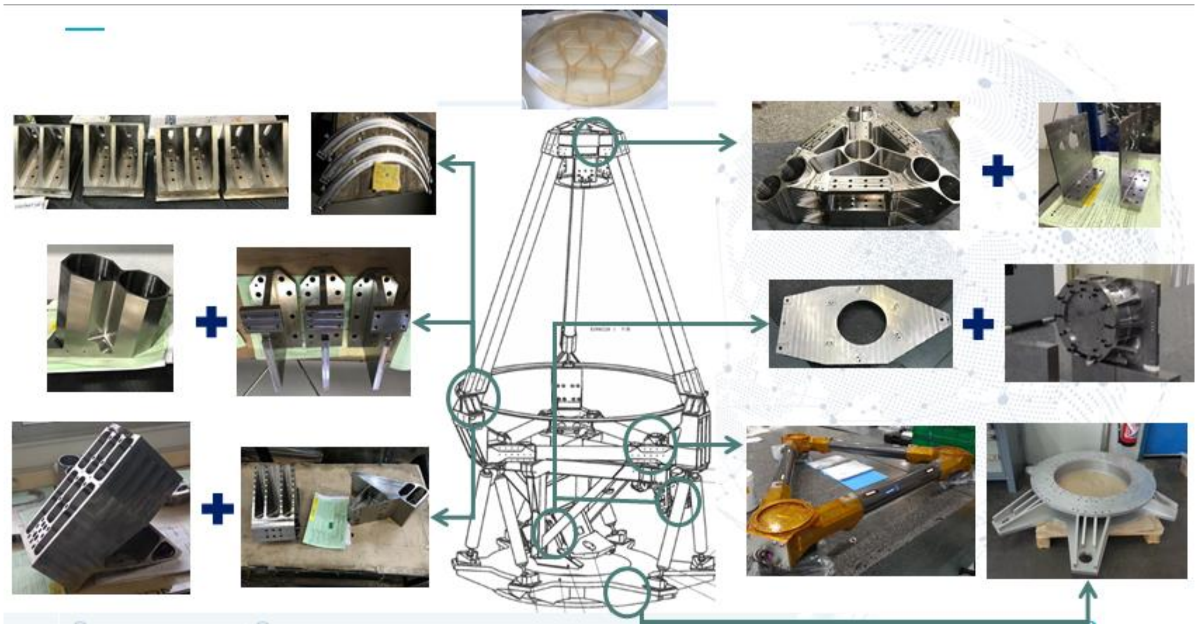

Figure 11. Manufacturing of the active observation instrument full scale demonstrator in progress at Thales Alenia Space. It will allow to demonstrate the performance of the control loop to validate in full scale the efficiency of all developed technologies for active optics.

6. ACKNOWLEDGEMENTS

Thales Alenia Space gratefully acknowledges CNES for confidence placed in our team and for funding most of these TANGO activities. Thales Alenia Space also thanks the French Research Labs for their technical expertise (ONERA, LAM) and the industrial team of partners for TANGO.

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