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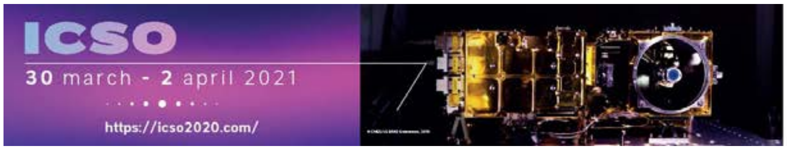

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Full scale active telescope engineering model

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ABSTRACT

Thales Alenia Space has designed and developed space high performance observation instruments for more than 40 years.

The future missions will have to deal with better performance, better optical quality while from affordability point of view, the total mass, the development schedule and the final cost have to be reduced. These constraints induce an innovative generation of solutions based on larger entrance optics associated to high lightweight ratio. In these conditions, the enhancement of the final performance can only be guaranteed by using active optics in flight.

In this context, Thales Alenia Space has been selected by French National Space Agency (CNES) to develop an active optics full scale telescope to path the way for the new class of Extremely high resolution telescopes. The whole building blocks have been already tested and qualified over the last 4 years.

So, a deformable mirror is implemented in the future large telescopes in order to correct manufacturing residues, ground/flight evolution including gravity. Moreover, low mass and high agility satellites require more compact designs which implies telescope solutions more sensitive to misalignments. An active positioning mechanism is then also needed in order to correct the telescope alignment during flight conditions. A wavefront sensor is implemented in the mission focal plane and the global active loop validated.

This paper presents the validation of active optic telescope on a full scale Engineering Model of 1500mm of entrance pupil diameter. All the active optic building blocks already qualified are mounted on this demonstrator. This Engineering model has followed a complete integration and alignment process that confirms the breakthrough simplification expected. The test plan validates on a full scale model the wave-front correction algorithms on-ground and in flight conditions, ensuring the best performance achievable with the telescope all along the lifetime.

Keywords: telescope, active optics, deformable mirror, wave front sensor, positioning mechanism, lightweighted mirror, alignment, active loop.

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 or medium resolution at geostationary orbit, the entrance pupil size of the telescope becomes larger and larger. For several years, Thales Alenia Space France has been preparing the next generation telescopes with internal fundings and Space Agencies supports.

TANGO is one of the most important technology program for active optics development for space based large telescope. TANGO has been funded by CNES with Thales Alenia Space co-fundings.

The first part of the TANGO program has designed, developed and qualified the key technologies through the following building block [6]:

- The large lighweighted Zerodur® Primary Mirror
- The deformable mirror, called MADRAS,
- Five degrees of freedom M2 positioning mechanism, called MM2,
- The wave front sensor with its control loop.

For the second part of the TANGO project, Thales Alenia Space France has been selected as sole contractor by CNES to integrate and test a full-size Engineering Model of 1500mm of entrance pupil diameter. All the active optics building blocks already developed and qualified are mounted on this demonstrator. This Engineering model, a mandatory step in the active telescope program securisation, has followed a complete integration and alignment process. Then, the test plan has validated the wave-front correction algorithms on-ground and in-flight conditions on the full scale model.

Thales Alenia Space France has developed an end-to-end design philosophy, combining the choice of the most suited technology for the Primary Mirror, the active components (MM2 and Madras), the wave-front sensing element, together with an end-to-end software taking into account all parameters.

The active telescope design rationales for Extremely High Resolution in Earth observation have been developed in [1]. The variations of attitude during the orbit lead to thermal flux variations. The induced temperature fluctuations in entrance pupil generate thermal gradient variations typically around 1°C. The large pupil primary mirror shows very high lightweighted ratio, leading to cancel the benefit of conductivity property to homogenize the thermal gradients.

Thus the Coefficient of Thermal Expansion (CTE) dominates and becomes the metric for thermal stability. By choosing the Zerodur™ for the primary mirror with a CTE lower than 0,01ppm/K, the WFE is stable along the orbit and the control loop frequency is very low with few corrections per day. The 2 mechanisms being OFF between corrections, thus the solution shows an excellent mission availability and reliability.

Thales Alenia Space active optic telescope solution developed through TANGO brings:

- The ability to use a shorter and lighter telescope, by relaxing the integration and alignment constraints that become very hazardous for comparable passive telescope due to optical lay-out compactness and inherent sensibility (on-ground alignment, gravity effect, ageing, stability ...) [3][6].
- Top performance and the guaranty to keep the best MTF performance all along the flight lifetime.

2. THE QUALIFIED BUILDING BLOCKS

2.1 Large lighweighted Zerodur® Primary Mirror

A joint team Thales Alenia Space France & 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. Zerodur® material, aside the best in flight performances provided, shows unrivalled properties of stability and polishability giving industrial advantages. Several innovative technical solutions have been implemented on this primary mirror to optimize the mass, the stiffness and the volume. A high lightweighting rate with a surfacic mass of 25 kg/m² is reached while conserving high stability properties and high stiffness to sustain launch environments. Important lead time reduction is also gained by this solution and by several process improvements implemented during the manufacturing by Thales SESO. This solution is well adapted to large size mirrors, typically TANGO's pupil diameter and above.
To meet the stringent mass requirement, the mirror fixation devices are made of brazed Silicon Nitride parts featuring a flight design.
Final polishing has been successfully achieved meeting the required WFE performance. The optical coating has been applied implementing the last improvements made in the frame of TANGO program by Thales SESO.

The coated mirror equipped with its brazed Silicon Nitride fixation devices has been integrated on a Silicon Nitride ceramic frame and the complete performance has been successfully verified before environmental testing.

Figure 1. Fully equipped M1 Mirror (optical coating and flight Silicon Nitride isostatic mounts) during vacuum thermal cycling configuration set-up. This 1,5 m Zerodur equipped mirror has a total surfacic mass of 25 kg/m².

The equipped primary mirror has undergone successfully a full qualification campaign:

- Thermal-optical testing under vacuum, demonstrating the stability under space environments. The excellent WFE thermal stability of 1nm per °C has been confirmed under vacuum in line with mirror material trade-off conclusion: stability to mission scenario and mission availability.
- Mechanical vibration testing (sine and acoustic) at qualification levels demonstrating the capacity to sustain launch environments.

The large primary mirror technology has been declared qualified for Space applications (TRL7) in 2019.

2.2 Deformable Mirror

MADRAS (deformable mirror developed by Thales Alenia Space France with a Thales SESO mirror) is based on an original concept from the Laboratoire d'Astrophysique de Marseille (LAM developed to a TRL 4 level in a pathfinder collaborative study [4]).
The deformable mirror maintains the WFE correction stable during a long period without any voltage applied. 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.

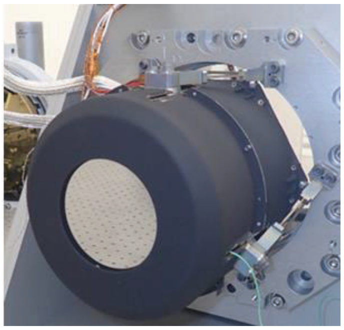
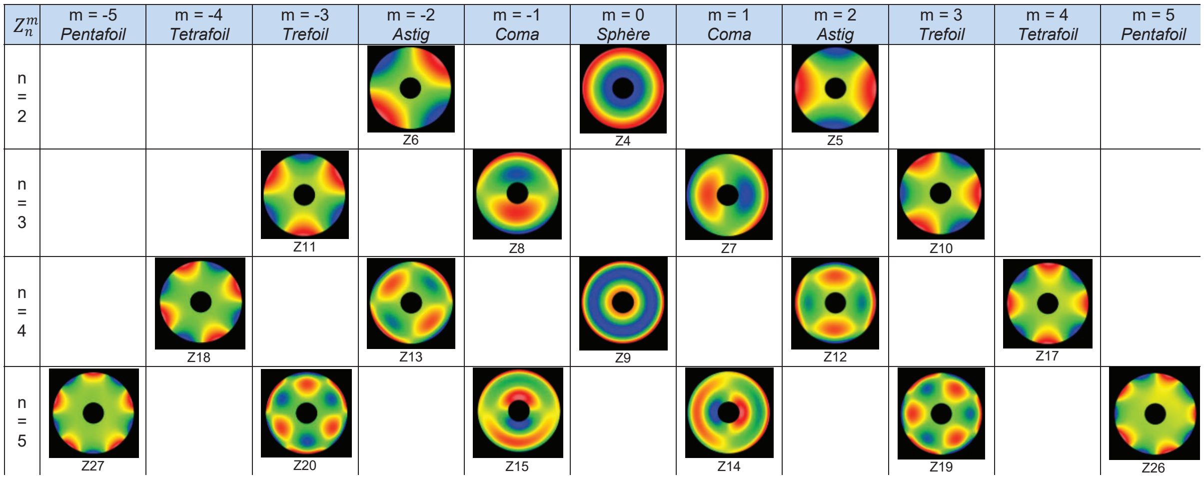


Figure 2. Deformable mirror (MADRAS) fully integrated with its cover and interface filtering devices.

The deformable mirror has been fully integrated and complete performance has been successfully verified. The system demonstrated its capability to correct accurately Zernike's polynomials up to Z29 with an accuracy of a few nanometers (figure 3). The stability of the correction and performance in vacuum have been verified as well.



Z_n^m	m = -5 *Pentafoil*	m = -4 *Tetrafoil*	m = -3 *Trefoil*	m = -2 *Astig*	m = -1 *Coma*	m = 0 *Sphère*	m = 1 *Coma*	m = 2 *Astig*	m = 3 *Trefoil*	m = 4 *Tetrafoil*	m = 5 *Pentafoil*
n = 2				Z6		Z4		Z5			
n = 3			Z11		Z8		Z7		Z10		
n = 4		Z18		Z13		Z9		Z12		Z17	
n = 5	Z27		Z20		Z15		Z14		Z19		Z26

Figure 3. Deformable mirror (MADRAS) WFE correction performance measurements: Zernike modes are very close to theoretical shapes, as per predictions.

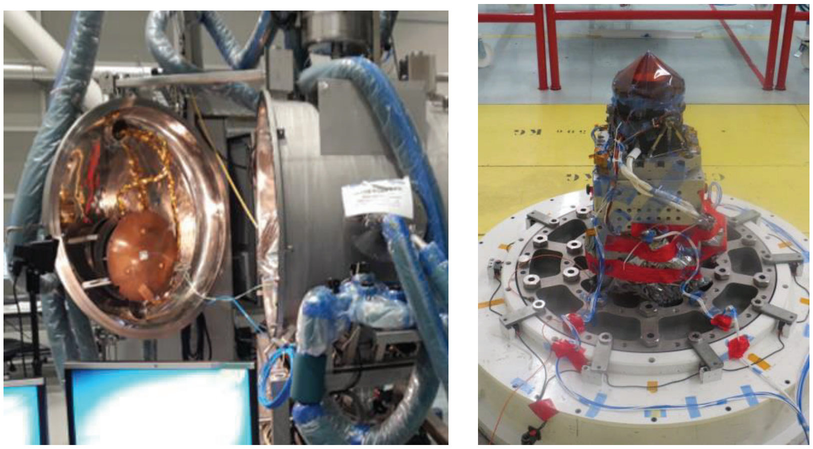


Figure 4. Deformable mirror (MADRAS) in vacuum chamber for performance validation and vibration test set-up.

The MADRAS deformable mirror has undergone successfully a full qualification campaign:

- at actuator level including lifetime testing under ultra-vacuum
- at MADRAS level with sine & random vibration environment and thermal vacuum environments.

The performance under vacuum have been validated.

The MADRAS technology has been declared qualified for Space applications (TRL7) by the end of 2018 and MADRAS supply chain is ready for future programs.

2.3 Five degrees of freedom M2 positioning mechanism

This mechanism is placed at the secondary mirror (M2) level as in a Korsch telescope, M2 is the most critical element in the alignment.

The main advantage of this mechanism is to offer the possibility to fully re-align the M2 after launch and during the lifetime. Thus, the integration of the M2 on-ground and the alignment sequence accuracy are relaxed, but also the mechanical design of the telescope (no need to keep alignment between ground and flight). The objective is to give the capability to move the M2 mirror by combining the 3 translations and 2 relevant rotations (five degrees of freedom). The hexapod structure of this mechanism features 6 degrees of freedom. Therefore, by design, the mission is still achieved with full performance even in case of failure of one actuator. Furthermore, all actuators are redounded to secure the capability of inflight correction.

The mechanism sustains launch environment unpowered without launch locking device and M2 position is maintained when the voltage is off.

The challenge is first to have a total envelope 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 lightweighted Zerodur M2 and ultra lightweighted and stable Silicon Nitride ceramic structural parts.

The 5 DoF mechanism has been fully integrated and its performance successfully verified. The system has been demonstrated to be able to correct accurately the three translations in the range of hundreds of µm and rotations in the range of hundreds of µrad with an accuracy of few tens of nanometers and hundreds of nanoradians. Stability in time has been verified.

The five DoF mechanism technology has undergone successfully a full qualification campaign:

- at actuator level including lifetime testing under ultra-vacuum
- at hexapod level with sine & random vibration environment and thermal vacuum environments.

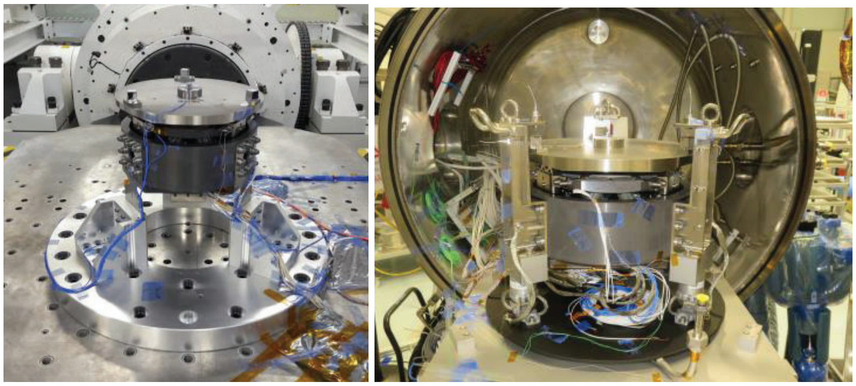


Figure 5. Five DoF mechanism during sine & random vibration environments and thermal vacuum environment tests

The high lightweighted Zerodur M2 featuring a flight design has been integrated on the 5 DoF mechanism in order to confirm the interfacing concept and the mounting procedure. The wave-front error of the M2 mirror mounted onto the 5 DoF mechanism has been characterized and confirms the optical performance of the complete sub-system.

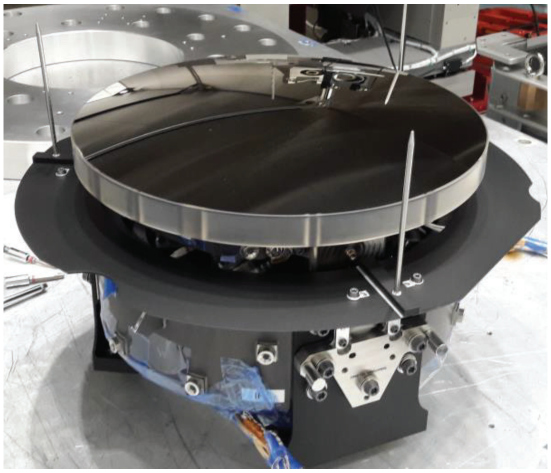


Figure 6. the high lightweighted Zerodur secondary mirror integrated on the Five DoF mechanism has validated the wave front error performance of the complete sub-system.

The five DoF mechanism technology has been declared qualified for Space applications (TRL7) in 2018. The equipped five DoF mechanism equipped with its flight secondary mirror is completely validated and ready for future programs.

2.4 Wave-Front Sensor (WFS) and control loop

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 France Research Team has developed the algorithm over the last decade and tuned it for TANGO. and The algorithm efficiency and robustness has been demonstrated on real images . 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 demonstrating the readiness of this technology. An opto-electronic demonstration bench playing the full sequence has been successfully performed (See [5]).

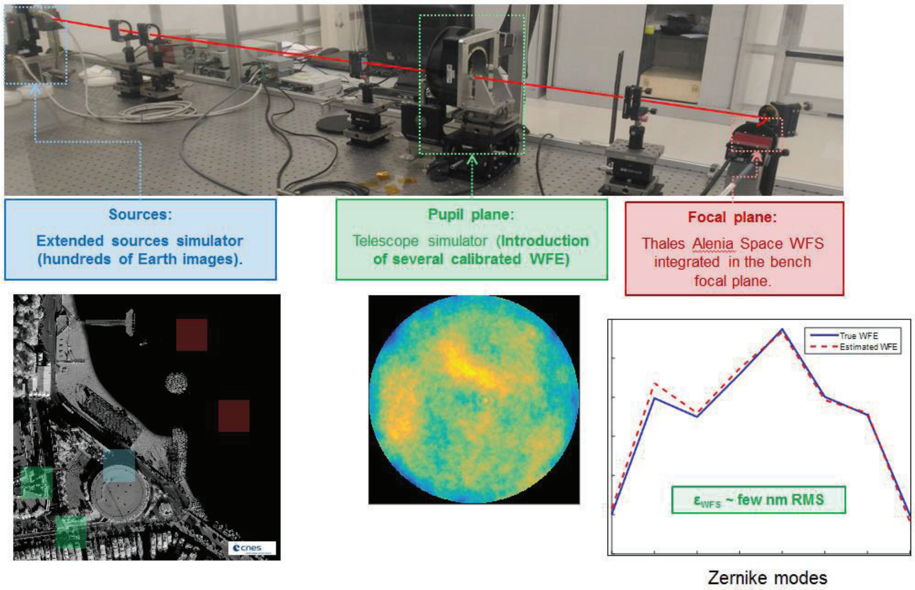


Figure 7. WFS validated on a dedicated bench able to simulate hundreds of Earth images, and tens of telescope WFE. The results show a very good phase retrieval accuracy around few nanometers.

The performance of wave-front sensing and correction algorithm with the MADRAS deformable mirror has been demonstrated on an end-to-end bench on realistic scenes. The Wave Front Sensor and the control loop is further validated as a part of the full scale engineering model test plan as presented in the next chapter.

3. THE FULL SCALE ACTIVE TELESCOPE ENGINEERING MODEL

The qualified building blocks have been assembled in a full scale engineering model providing a flight representative structure in term of thermo-elastic behavior with the use of Si3N4 ceramic truss for the front cavity. The structure parts are designed for ground purpose without mass optimization.

The active telescope concept allows to simplify the assembly and integration phase. Several complex alignment ground support equipment are no more required. For instance, the telescope integration and alignment of the secondary mirror becomes one order of magnitude relaxed and is managed by theodolite means during mechanical integration thanks to the M2 5 Degree of Freedom mechanism.

Figure 8. Active telescope at the end of the integration phase with the secondary mirror already integrated using theodolites.

Once integrated, the full scale engineering model has enabled an extensive optical test campaign at ambient pressure. First the on ground alignment logic has been investigated allowing to validate :

- The active telescope alignment by interferometry,
- A “all in” instrument alignment strategy using the point spread function acquired by the focal plane. The Wave Front Error (WFE) is calculated by phase retrieval.

Figure 9. The “all in” alignment configuration requiring the minimum optical support equipment: an auto-collimating flat mirror (not shown) in front of the telescope equipped with its focal plane.

The alignment principle is the same for the 2 ground alignment methods used, interferometry and « all in » alignment configuration.
First a raw alignment is performed by actuating the MM2 to directly improve the WFE map for interferometry configuration or the PSF in case of « all in » configuration.
Then, a WFE optimization loop is engaged. Each loop is made of the same steps :

1. The WFE acquisition in several points of the field of view,
2. The in-house optimisation algorithm determines the corrections to apply on MM2 and Madras.
3. The MADRAS and MM2 corrections are applied on the telescope
4. The resulting WFE is measured in several points of the field of view.

The active telescope wave front error converges very rapidly during interferometry alignment configuration as for "all in" alignment configuration. Only two optimization loops are necessary to meet the best wave front error performance for the different fields of view as shown in the figure 11.

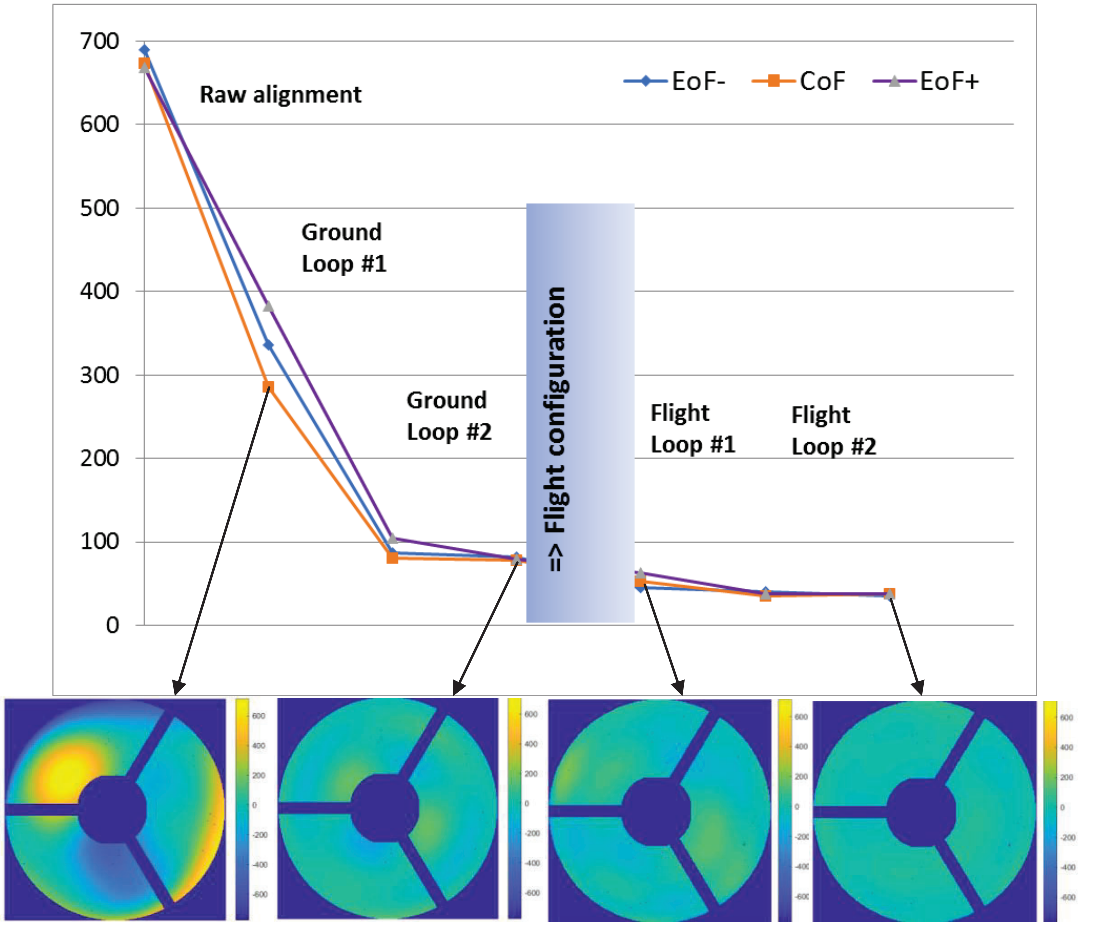


Figure 10. The WFE optimization loops are very effective for the ground alignment and for the flight alignment sequences: the convergence is obtained with two loops in each alignment sequence (End of Field, EoF, Center of Field, CoF). The low frequency WFE optimized by the loops are given for the center of field.

The Madras actuation matrix characterized as sub-system level is perfectly translated in the telescope optical lay-out. This enables an efficient convergence process and is proven by the good correlation between expected values and measurements that have been observed at each step.

The "all in" alignment method implements the phase retrieval to calculate the wave front error from the point spread function, acquired by the focal plane cameras. An important result is that the phase retrieval is able to manage all sorts of WFE dynamics as proven by the several alignment sequences performed on TANGO Engineering Model.

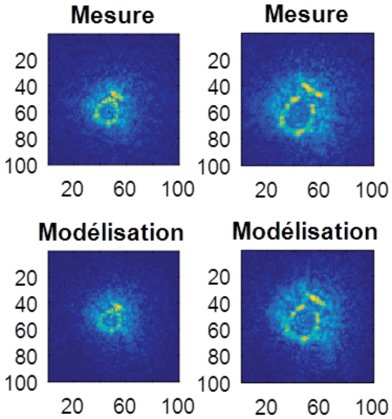


Figure 11: Phase retrieval method has been enhanced to cope with misaligned telescope Point Spread Function (PSF). A robust phase retrieval model is now available as illustrated by the fidelity of the image model compared to the measured PSF. Example for PSF acquired with two different diversity states.

To challenge the alignment process and to show the robustness of the alignment method, different starting point of telescope states at the end of integration have been tested through several alignment sequences. The robustness of the method is proven and we converge each time to the same WFE and focal plane orientation.

The deformable mirror and the M2 mechanism browse their full useful range during alignment sequences. They show at the end comfortable margin with respect to their maximum stroke available. This offers a high potential growth of the active optics bricks.

The full scale telescope is able to reproduce ground and flight configurations with respect to gravity effect. Once the ground alignments have been extensively tested, we move to the flight configuration allowing to run the flight alignment sequence.
The figure 11 shows on the left hand side the fast convergence of the flight alignment in two optimization loops. The WFE is well balanced in the field of view.
The telescope WFE performance is excellent and better than the specification. The WFE measurements match the predictions within 1nm rms accuracy. The success of the flight alignment confirms the logic followed during ground alignment.
The performance of the WFE sensing implemented in full scale telescope is confirmed as well the correction algorithm. The phase retrieval has been tested on both stars and unknown objects as illustrated by the figure 13.

Figure 12: Toulouse raw image acquired by the wavefront sensor implemented on the full scale telescope used by phase diversity algorithm.

4. CONCLUSIONS AND WAY FORWARD

The technologies required for future space active telescope have reached the TRL7 and ready to be embarked on a flight instrument model. All the building blocks of the future active telescope are qualified and ready to be industrialized.

The test results have confirmed on a full scale model:

- the simplified AIT sequence implementing quick and robust alignment method,
- the wave-front correction algorithms and their performance on ground and in-flight conditions.
- The maturity of the qualified sub-systems (high lightweight ratio primary mirror, MADRAS, 5DoF M2 mechanism, Wave front sensor and control loop algorithm) and their performance in the real telescope.

For the flight alignment, we have reached a top level performance. The active telescope maximizes the MTF performance achievable by a large telescope and cancels all the WFE degradation contributors present in passive telescope performance budget.

The optical performance is maintained at the top level all along the lifetime thanks to the in orbit telescope control loop with no impact on mission operations and availability.

The last 4 years of TANGO phase 2 demonstrator activities were key to understand what is required in the design and in the AIT of an active optics telescope. Thales Alenia Space is ready to spacefly this technology that brings major improvements to Earth Observation missions.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Viard T., Blanc J.-F., Bailly B., Falzon F. ‘Active optics for next generation of space observation instruments” , ICSO 2018.

[2] Costes V., Laubier D., Perret L. and Delvit J-M., “Active Optics for next generation space telescopes.” ICSO 2016

[3] Viard, T., Blanc J.-F., Devilliers Ch. Champandard F., Bailly B. Falzon F. Ghibaudo J.-B., Sucher D., Briche G. Costes V., Du Jeu Ch., “Active optics for next generation of Space observation instruments”, Proc. ICSO 2018 (2018)

[4] Laslandes M., Hugot E., Ferrari M., Hourtoule C., Singer C., Devilliers C., Lopez C., Chazallet F., “Mirror actively deformed and regulated for applications in space: design and performance,” *Optical Engineering, Volume 52 issue 09, paper 091803,* September 2013.

[5] Paul B., ‘’High precision wavefront sensing strategy for space based Earth optical observation’’ Innovative Technologies for Space Optics, workshop ESA 2018

[6] Sucher, D. Butel, G. Briche, G. Blanc, J-F. Liotard, A. Bernot, M. Carlavan, M. Suau, A. Louh, L. Galtier, L. Guionie, S. Viard, T. Behar-Lafenetre, S. Champandard, F. Ghibaudo, J-B. Costes, V. “Active optics for space telescopes”, Proc. SPIE. 11116, Astronomical Optics, SPIE 2019