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ACTIVE OPTICS FOR NEXT GENERATION SPACE TELESCOPES

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I. INTRODUCTION

High resolution observation systems need bigger and bigger telescopes. The design of such telescopes is a key element for the satellite design. In order to improve the imaging resolution with minimum impact on the satellite, a big effort must be made to improve the compactness of the telescope. Compactness is also important for the agility of the satellite and for the size and cost of the launcher.

Moreover, the capability to compensate shape defaults of the primary mirror is the way to simplify the mirror manufacture, to mitigate the development risks and to minimize the cost. The larger the primary mirror is, the more interesting it is to implement active optics for shape compensations .

CNES is preparing next generation of earth observation satellites in the frame of OTOS (Observation de la Terre Optique Super-Résolue; High resolution Earth observing optical system). OTOS is a technology program. In particular optical technological developments and breadboards dedicated to active optics are on-going.

II. OPTICAL DESIGN

A. Optical requirement

The telescope characteristics are determined by the angular resolution goal, the image sensor parameters and the image requirements. The OTOS concept is a push-broom system. The mission consists in covering a 1.2° field of view with 30 cm ground pixels. The satellite altitude is 700 km. The angular resolution is 0.43µrad.

Alternative image sensors have been studied. In particular a two-dimensional array associated with a fast telescope (F-number from 5.4 to 8.5) can be an interesting solution. We only describe in this paper the classical Korsch design.

The optical MTF requirement is to guarantee a 0.25 optical MTF at frequency corresponding to 30 cm on ground.

B. Optical design

A comparative study has been led at CNES. Several compact optical designs (TMA, catadioptric and Korsch concepts) with different apertures, from F/5.4 to F/20, have been studied and compared [1]. For long focal length telescopes, the Korsch concept is the most common and is chosen for its compactness and for several optical key advantages: it allows an easy to design of a diffraction limited system, little occultation, easy baffling thanks to an intermediate image and a real exit pupil.

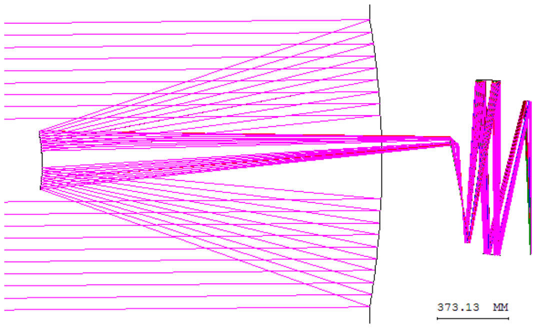


Fig. 1. Korsch F/20 design

The axial dimension is more than eleven times smaller than the focal length. The fore optics (primary and secondary mirrors) is the very sensitive part. The aft part, kept behind the primary mirror, is much more tolerant. Table 1 gives the main characteristics of our optical design.

Table 1. Optical main characteristics of Korsch design

Optical characteristic	Korsch F/20 design
Telescope Focal length	30 m
Primary mirror f-number	1.5
Secondary mirror f-number	1.8
Tertiary mirror f-number	5.8
Axial Primary mirror magnification	165
Axial Secondary mirror magnification	170
Axial Tertiary mirror magnification	6.5

C. Optical performances

The optical MTF requirement is 0.25 at the frequency of interest. Its value of 1.17 10^6 rad^{-1} corresponds to an instantaneous field of view of 30 cm at 700 km altitude.

The opto-mechanical sensitive terms are the focus, the decentering and the tilt amplitude of the fore optics. Table 2 gives the budget corresponding to an optical MTF of 0.25. The optical distortion is also an important performance regarding the use of a time delay and integration sensor.

Table 2. Main optical performances

Optical performance	Korsch F/20
Optical Theoretical MTF	0.34
Focus tolerance	1.35 µm
Decentering tolerance	13.5 µm
Tilt tolerance	13.5 µrad
X distorsion	0.9%
Y distorsion	0.3%

These opto-mechanical tolerances are challenging. A sensitivity study is detailed in the following chapter. The optical distortion is acceptable.

D. Compactness impact

We compare different configurations in order to quantify the impact of compactness on the opto-mechanical tolerances requirements. For this comparison, the parameter is the aperture number of the primary mirror. Compactness of the telescope is directly coupled with low aperture number.

The following F/2, F/1.5 and F/1 primary mirror Korsch configurations have been designed.

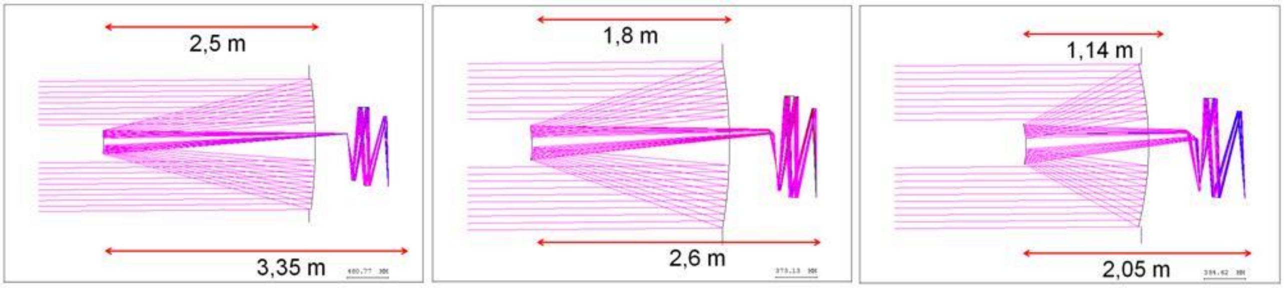


Fig. 2. Korsch design with resp. F/2, F/1.5 and F/1 primary mirror

For these configurations, the aft part is very similar. The main change is the axial dimension of the fore optics. The comparison of the main optical characteristics and performances is summarized in Table 3.

Table 3. Design trade-off Optical characteristics and performances

Primary mirror	F/2	F/1.5	F/1
M1 f-number	2.0	1.5	1.0
M2 f-number	2.5	1.8	1.2
M3 f-number	6.8	5.8	4.6
Axial M2 magnification	96	170	381
Axial M3 magnification	5	6.5	12
Focus tolerance (µm)	2.2	1.3	0.5
Decentering tolerance (µm)	22.5	13.5	5.0
Tilt tolerance (µrad)	22.5	13.5	5.0
X distorsion	1.2%	0.9%	0.7%
Y distorsion	0.4%	0.3%	0.26%

This sensitivity study points out how important the fore optics axial dimension is for the compromise between compactness and opto-mechanical tolerances. Compactness is associated with very sharp opto-mechanical tolerances. Starting with a F/2 primary mirror design, a gain of a factor of two makes the opto-mechanical tolerances being 4.5 times more difficult.

The gain in the telescope size must be balanced with the increase of both tolerance requirements and manufacturing complexity. Considering all these parameters, in the frame of OTOS, we made the choice of a F/1.2 primary mirror design. The associated opto-mechanical stabilities will be afforded thanks to active optics.

III. ACTIVE OPTICS

A. Principle

Two types of defaults contribute to the wave front error degradation: alignment and shape errors of the optics.

In the Korsch telescope, a positioning mechanism is implemented behind the secondary mirror in order to compensate total or partial alignments defaults of the fore optics. The first step for this approach is very well known: it consists in adjusting the focus term of the optical system. The challenge is now to generalize this compensation to alignment aberrations. This mechanism is implemented in the fore optics, because it is the most sensitive part. It can be a 3 or 5 degree of freedom mechanism depending on the performance capacities of the mechanism and depending on the WFE performance objectives. This approach enables us to cope with the stringent opto-mechanical requirements.

A deformable mirror is implemented at the pupil stop in order to compensate mirror shape errors. The deformable mirror is in the aft part thanks to the real Korsch exit pupil. This approach enables us to simplify the primary mirror requirements.

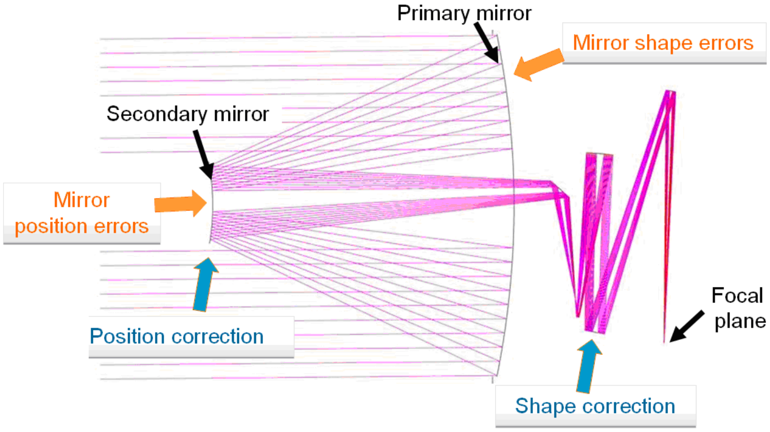


Fig. 3. Active optics principle

B. First CNES experiments

A preliminary optical bench has been developed at CNES in order to validate the expected performances of a closed loop system. This breadbord is constituted of a point source, beam collimating lenses, the deformable mirror and a Shack Hartmann device. Our deformable mirror is a CILAS 63 actuators piezoelectric monomorph mirror. A folding mirror is introduced in the optical path. The breadboard experiment is shown is the following figure.

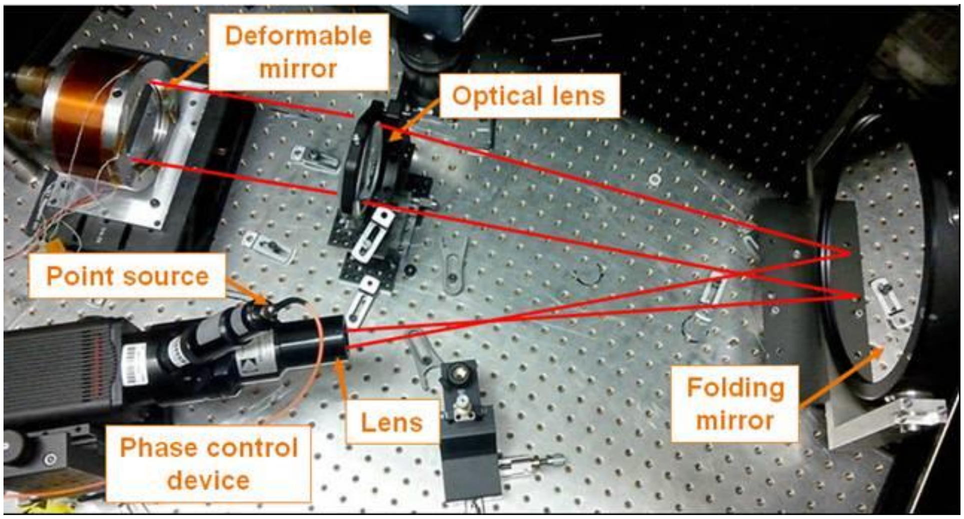


Fig. 4. CNES first breadboard

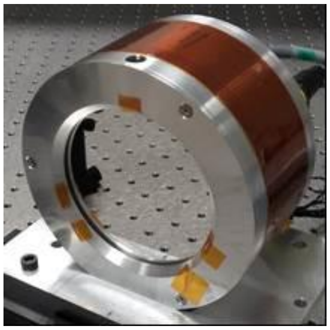
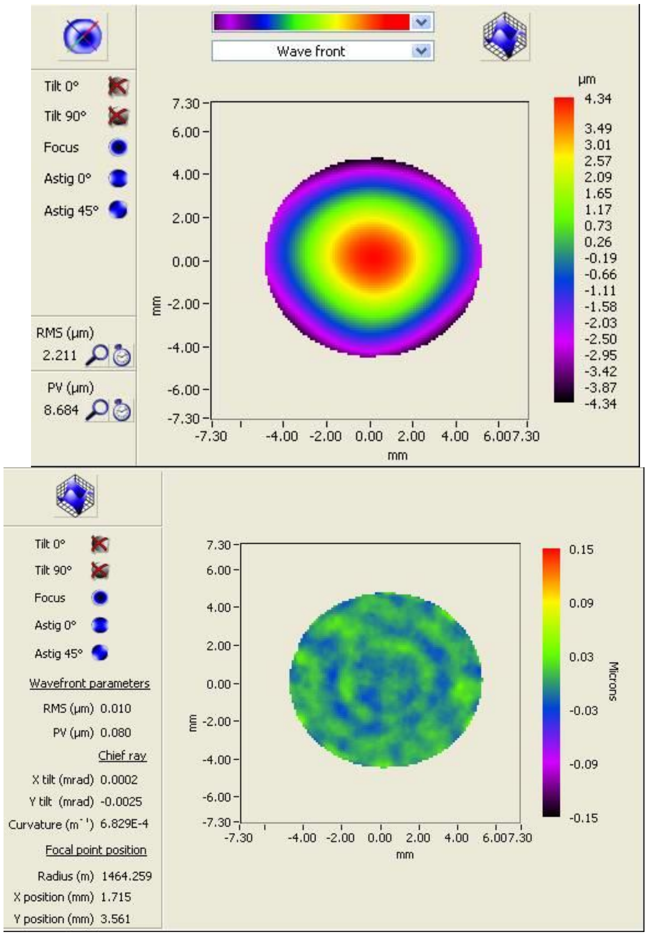


Fig. 5. CILAS piezoelectric deformable mirror

The experimental approach is to define the wavefront measured with a flat reference mirror as the target. So, the goal of our closed loop is to transform the deformable mirror surface close to our reference flat mirror surface. Starting with the deformable mirror switched off, the wavefront error is 2.2 µm RMS. With operating closed loop, the residual performance obtained is 10 nm RMS +/-1 nm.



RMS (µm)
2.211

PV (µm)
8.684

Wavefront parameters
RMS (µm) 0.010
PV (µm) 0.080

Chief ray
X tilt (mrad) 0.0002
Y tilt (mrad) -0.0025
Curvature (m⁻¹) 6.829E-4

Focal point position
Radius (m) 1464.259
X position (mm) 1.715
Y position (mm) 3.561

Fig. 6. Wave front error resp. without and with active optics closed loop

A second configuration has permitted to confirm this very good performance. This alternative configuration separates the source and the metrology. We still work with a CILAS monomorph mirror and a Shack Hartmann. See Figures 7 and 8.

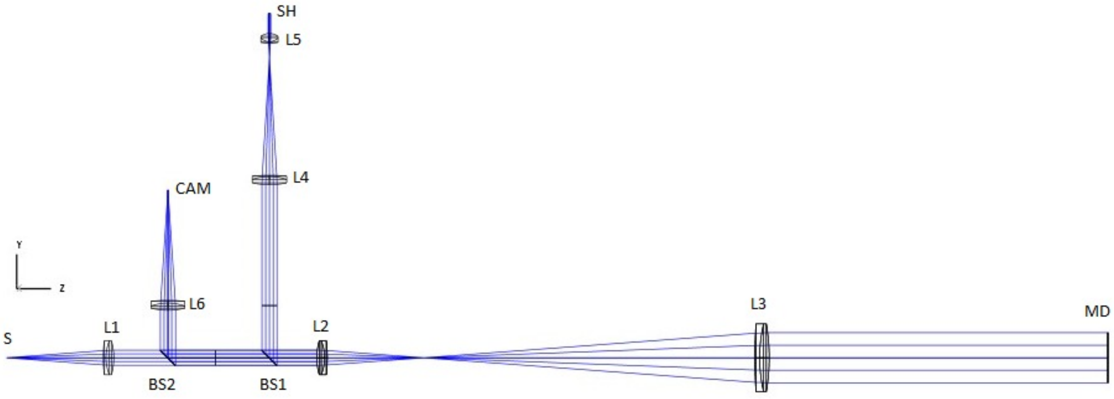


Fig. 7. Second configuration design

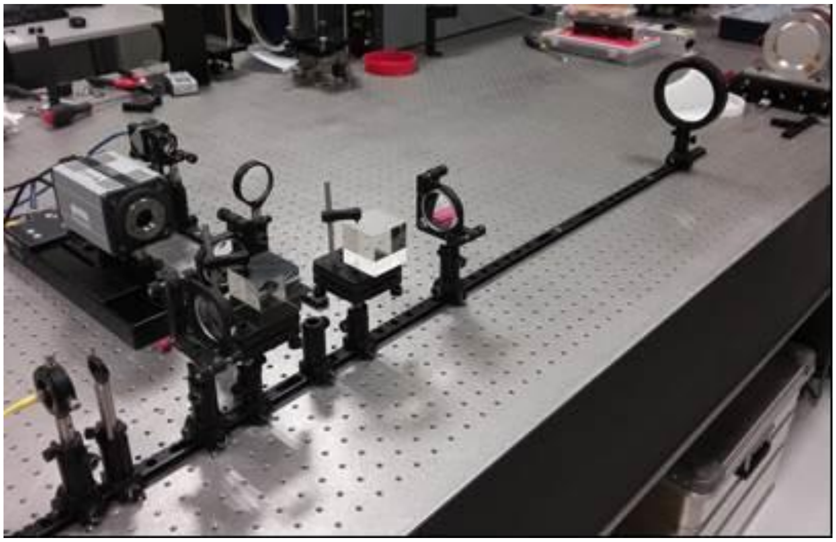
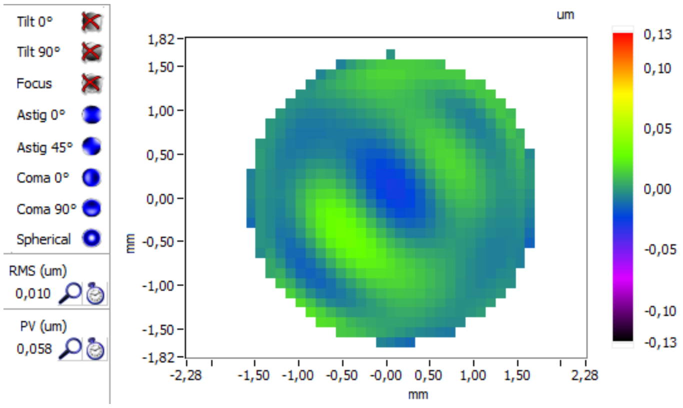


Fig. 8. Optical bench view

The WFE performance is confirmed to be 10 nm RMS +/-1 nm. In this configuration the optical aperture on the deformable mirror is limited to 65 mm instead of 85 mm for full aperture.



RMS (um)
0,010

PV (um)
0,058

Fig. 9. Residual wave front error obtained with the active optics closed loop

IV. ON-GOING DEVELOPMENTS

OTOS is a technology program preparing next generation earth observation satellite. Different developments are on-going with the aim to achieve TRL 5 to TRL 6. For the optical part of OTOS, we have started the development of active optics devices and of very large lightweight primary mirrors. These developments are led by CNES with Thales Alenia Space and Airbus Defence and Space.

A. New concepts of extremely lightweight mirrors

The capability to compensate shape defaults of the primary mirror is the way to simplify the mirror manufacture, to mitigate its development risks and to minimize the cost. The validation of very new primary mirror design is a big issue to handle. It is important to couple and to optimize the global performance of the closed loop system with the release of the primary mirror requirements.

OTOS primary mirror requirements are challenging : 1.5m diameter, 1.2 F-number and mass target of 25kg/m2.

In the frame of OTOS, two different technologies are developed : a zerodur mirror by Thales Alenia Space (Fig.10) and a brazed SiC mirror by Airbus Defence and Space (Fig.11).

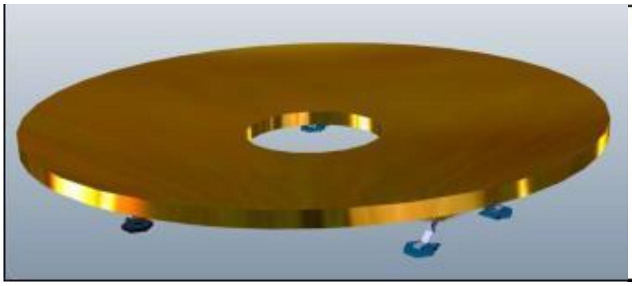


Fig. 10. Design of OTOS zerodur primary mirror

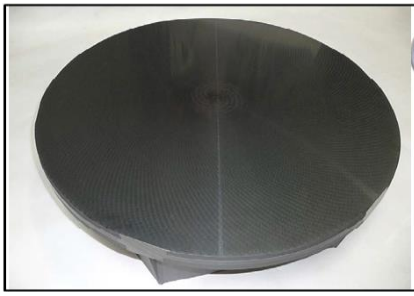


Fig. 11. Preliminary breadboard of OTOS SiC primary mirror

B. Deformable mirrors

Two different deformable mirror technologies are developed.

The development of a zerodur deformable mirror is led by Thales Alenia Space. It benefits from MADRAS heritage. Madras is an innovative solution developed in partnership by Thales, the LAM (Laboratoire d'Astrophysique de Marseille) and Thales SESO [2],[3].

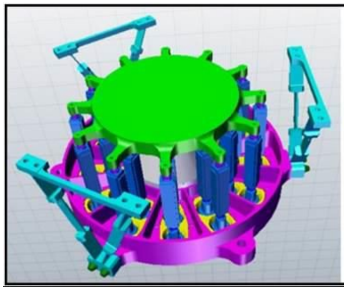


Fig. 12. MADRAS deformable mirror

The development of a monomorph piezoelectric mirror is led by Airbus Defence and Space. This mirror is designed and manufactured by CILAS. CILAS has a great heritage on piezoelectric technology and deformable mirrors [4],[5].

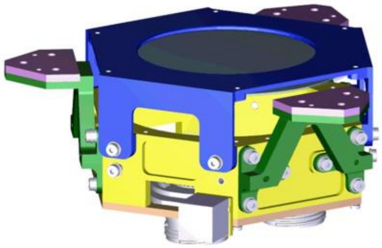


Fig. 13. CILAS monomorph deformable mirror

C. Others

Mirror positioning mechanisms and metrology systems have been studied. Some are developed in the frame of OTOS and will be tested in a first optical bench. This first breadboard will validate the performance of the closed loop system. It will include chosen metrology and developed deformable mirror for each company. The global performance of OTOS closed loop will be measured on 2017.

Complementary to this first step, a full scale telescope demonstrator of a large active instrument is under development. It is led by Thales Alenia Space France. The full scale validation of an active telescope is expected for 2018.

V. CONCLUSION

In the frame of OTOS, a comparative study has been done to choose the best concept for a compact optical telescope.

This paper shows how compact a high resolution telescope can be. A diffraction limited telescope can be less than ten times shorter than its focal length. But the compactness impacts drastically the opto-mechanical sensitivity and the optical performances. The need to implement active optics for positioning requirements raises very quickly and the ability to simplify our primary mirror requirements is shown.

Very interesting work is in progress: two different primary mirrors, two deformable mirrors, performance validation of the closed loop. This work is led by CNES with Thales Alenia Space and Airbus Defence and Space. A first representative validation of the performance of OTOS closed loop is expected in 2017. This validation will include a qualified deformable mirror and representative metrology.

Device deliveries and optical performance results of the closed loop are expected for 2017.

A full scale demonstrator of an active telescope is expected for 2018.

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