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Active Optics in Deployable Systems for Future EO and Science Missions

ESR - Executive Summary Report

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Approval evidence is kept within the documentation management system.

CHANGE RECORDS

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1. INTRODUCTION

1.1. SCOPE AND PURPOSE

Increasingly demanding space-based applications require a large primary mirror diameter, on which depends the optical instrument resolution. However, mass and volume of a monolithic primary mirror would dramatically increase along with its size, which, in addition to cost and technical issues, is also limited by the launch vehicle fairing available volume. Thus, to reach large primary mirror diameters, development of instrument that will include a deployable, segmented primary mirror and an active correction loop to optimize its optical performance will be of utmost interest. Such technologies will allow to address highly demanding space-based applications such as high-contrast imaging for Earth-like exoplanets direct detection or high resolution Earth observation from the geostationary orbit.

This study aimed at defining a technological roadmap of such an active optics correction loop, which will include sensing devices and active correction components. This technological roadmap has been supported by the design of two active correction loops implemented in two preliminary instrument designs dedicated to two different missions:

- A Science mission case, the goal of which is the imaging and characterization of Earth-like exoplanets;
- An Earth observation mission at high-resolution case, from the geostationary orbit.

For both cases, the active optics loop design was performed through trade-off analysis of correction strategies and technologies, based on the requested performances evaluation at system level. Such an evaluation allowed to identify the active optics correction chain technical challenges and led to a development roadmap

This Executive Summary Report provides a synthetic description of all the work done during the study.

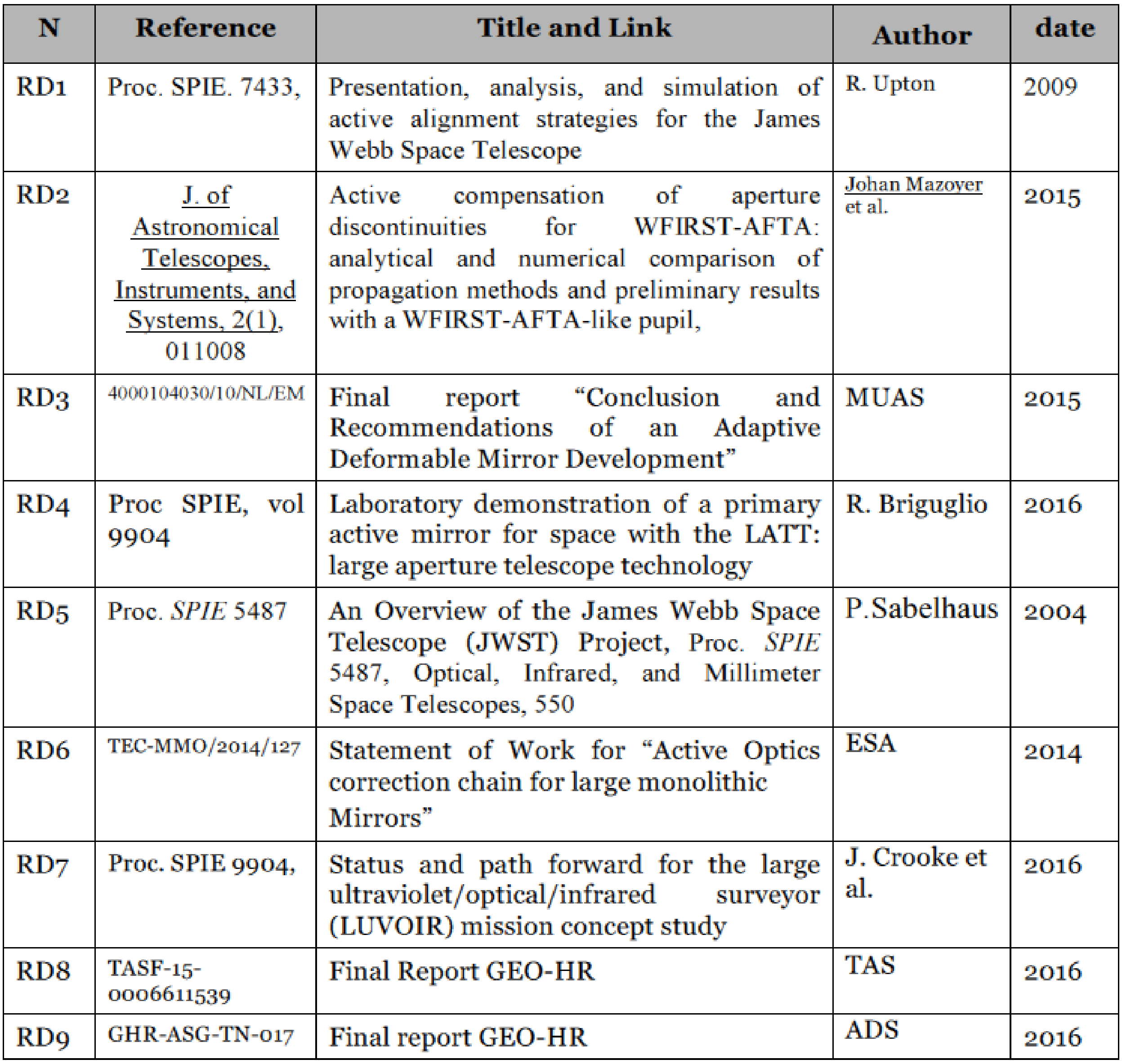
1.2. APPLICABLE DOCUMENTS

[AD 1] Contract « Active Optics in Deployable Systems for Future Earth Observation and Science Missions »

ESA Contract No. 4000125154/18/NL/AR/ig

1.3. REFERENCE DOCUMENTS

References from the Statement of Work:



N	Reference	Title and Link	Author	date
RD1	Proc. SPIE. 7433,	Presentation, analysis, and simulation of active alignment strategies for the James Webb Space Telescope	R. Upton	2009
RD2	J. of Astronomical Telescopes, Instruments, and Systems, 2(1), 011008	Active compensation of aperture discontinuities for WFIRST-AFTA: analytical and numerical comparison of propagation methods and preliminary results with a WFIRST-AFTA-like pupil,	Johan Mazoyer et al.	2015
RD3	4000104030/10/NL/EM	Final report "Conclusion and Recommendations of an Adaptive Deformable Mirror Development"	MUAS	2015
RD4	Proc SPIE, vol 9904	Laboratory demonstration of a primary active mirror for space with the LATT: large aperture telescope technology	R. Briguglio	2016
RD5	Proc. *SPIE* 5487	An Overview of the James Webb Space Telescope (JWST) Project, Proc. *SPIE* 5487, Optical, Infrared, and Millimeter Space Telescopes, 550	P.Sabelhaus	2004
RD6	TEC-MMO/2014/127	Statement of Work for "Active Optics correction chain for large monolithic Mirrors"	ESA	2014
RD7	Proc. SPIE 9904,	Status and path forward for the large ultraviolet/optical/infrared surveyor (LUVOIR) mission concept study	J. Crooke et al.	2016
RD8	TASF-15-0006611539	Final Report GEO-HR	TAS	2016
RD9	GHR-ASG-TN-017	Final report GEO-HR	ADS	2016

RD10	Proc. SPIE. 9904	Status and path forward for the large ultraviolet/optical/infrared surveyor (LUVOIR) mission concept study	s. Domagal-Goldman	2016
RD11	Proc. SPIE. 9602	A future large-aperture UVOIR space observatory: reference designs	N. Rioux	2015

Technical notes previously issued in the framework of this study:

[RD 12] TN1 - State of the Art in Active and deployable optics technologies for space applications

0005-0010166292, issue 01, dated 22nd Nov. 2018

[RD 13] TN2 - Requirements of an Active Optics correction system for large deployable optical instruments in Earth Observation and Science missions

0005-0010177767, issue 01, dated 27nd Nov. 2018

[RD 14] TN3 – Active optics in deployable systems for Science: trade-off analysis and preliminary design

0005-0012288581, issue 01, dated 24/09/2020

[RD 15] TN4 - Active optics in deployable systems for Earth Observation: trade-off analysis and preliminary design

0005-0011662251, issue 01, dated 23nd January 2020

[RD 16] TN5 – Technological roadmap for active optics implementation in large deployable systems

GeoHR: 0005-0011876020, Issue 01, dated 07/05/2020

Science case: 0005-0012288627, Issue 01, date24/09/2020

[RD 17] FR – Final Report

0005-0012288815, issue 01, dated 24th September 2020

Literature references:

[RD 18] L. Pueyo et al., “The LUVOIR Architecture A: coronagraph instrument,” UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VIII, Proc. SPIE, Aug. 2017.

[RD 19] M. R. Bolcar et al., “Technology gap assessment for a future large-aperture ultraviolet-optical-infrared space telescope,” J. Astron. Telesc. Instrum. Syst., Oct.-Dec. 2016.

[RD 20] Pueyo & Norman ApJ 2013: https://iopscience.iop.org/article/10.1088/0004-637X/769/2/102

[RD 21] Guyon et al. ApJ 2014: https://iopscience.iop.org/article/10.1088/0004-637X/780/2/171

[RD 22] N’Diaye et al. ApJ 2016: https://iopscience.iop.org/article/10.3847/0004-637X/818/2/163

[RD 23] Ruane et al. JATIS 2018: https://ui.adsabs.harvard.edu/link_gateway/2018JATIS...4a5004R/doi:10.1117/1.JATIS.4.1.015004

[RD 24] ZImmerman et al. SPIE 2016: https://ui.adsabs.harvard.edu/link_gateway/2016SPIE.9904E..1YZ/doi:10.1117/12.2233205

[RD 25] Mazoyer et al. 2018a: https://iopscience.iop.org/article/10.3847/1538-3881/aa91cf

[RD 26] Mazoyer et al. 2018b: https://iopscience.iop.org/article/10.3847/1538-3881/aa91d7

[RD 27] Iva Laginja 2019 : Trade-Off analysis and Preliminay Design of the Active Optics System for the Science mision case

[RD 28] Coyle 2019 : Large ultra-stable telescope system study

[RD 29] Leboulleux, Sauvage, A. Pueyo, etc. : Pair-based Analytical model for Segmented Telescopes Imaging from Space for sensitivity analysis

[RD 30] LUVOIR Final Report_2019-08-26

[RD 31] System Level Segmented Telescope Design (SLSTD) Final Report Rev B_2019-04-24_Lockkeed Martin Advanced Technology Center – Collins Aerospace – Harris Corporation - Coherent

GeoHR:

[RD 32] GEO – HR : Mission Assumptions and preliminary Technical Requirements (MATER)

EOP-SF/2013-09-1757, Issue 01

1.4. DEFINITIONS AND ACRONYMS

CoWFS	Cophasing Wave-Front Sensor
DhWFS	Dark hole Wave-Front Sensor
DM	Deformable Mirror
EO	Earth Observation
FSM	Fast Steering Mirror
ITT	Invitation To Tender
IWA	Inner Working Angle
JWST	James Webb Space Telescope
LoS	Line of Sight
LUVOIR	Large UV/Optical/IR Surveyor
M1	Primary mirror
M2	Secondary mirror
M2M	Secondary mirror mechanism
MTF	Modulation Transfert Function
OWA	Outer Working Angle
PSF	Point Spread Function
RMS	Root Mean Square
SoW	Statement of Work
StabWFS	Stabilization Wave-Front Sensor
UKATC	United Kingdom Astronomical Technical Center
WFE	Wave-Front Error
WFIRST-AFTA	Wide Field Infrared Survey Telescope
WFS	Wave-Front Sensor

1.5. DOCUMENT OUTLINE

Section 2 describes the context in which the project was done.
Section 3 describes the programme of work.
Section 4 reports the activities as they have been performed and the main results up to the definition of technological roadmaps (Section 4.4).

2. CONTEXT

2.1. BACKGROUND

Active Optics (AO) is a technique that can be applied in optical systems on-board spacecraft in order to correct errors resulting from inaccuracies in the initial deployment of the optical system and/or thermal and mechanical variations occurring during the nominal operations of the spacecraft (changes in the attitude of the platform, varying thermal loads). The wavefront errors in large or segmented optics can be produced by gravity release or by thermo-elastic deformations of the elements that make up the system.

The AO technique has been in use for decades in ground-based observatories; without it the operation of ground telescopes of apertures of more than 8 m would be impossible. European Southern Observatory (ESO) engineers developed the concept in which a deformable primary mirror is controlled by an active support system applying the necessary force to correct for slow gravitation- and thermal-induced deformations as the telescope changes its orientation.

For space applications, due to increasing demands for higher resolution and contrast, the technique is also being considered. For future large missions or missions requiring extreme contrast imaging, Active Optics will actually be an enabling technology. Currently in the final stages of its development, the James Webb Space Telescope (JWST) will include active optics in order to adjust phasing of its large segmented deployable primary mirror and correct for line of sight variations [RD1], while future mission WFIRST will include deformable mirrors in its coronagraph to correct for wavefront error instabilities [RD2].

At ESA, the interest in AO has mostly been so far on its application to correction of optical systems with monolithic primary mirrors. After 2 successful technological developments of deformable mirrors (see [RD3] and [RD4]), two TRP activities are currently being conducted on AO correction loop concepts for monolithic primary mirrors, with apertures of up to 3.5 m which - alike Herschel´s primary mirror- are compatible with current A5 and planned A6 fairing sizes. Domains of application include Earth Observation (e.g. Geoculus, GEO HR,…), and science.

The use of deployable, segmented optics could be more practical in space beyond certain aperture sizes, to be able to fit the elements within the fairing of the launch vehicle. This is indeed already the case for design of the James Webb Space Telescope´s (JWST) 6-m segmented primary mirror [RD 5]. In fact, AO will need to be applied to all future large astronomy telescopes where e.g. the individual elements of a deployable primary mirror need to be deployed and co-phased once in orbit (e.g. NASA mission study LUVOIR regarding a large space observatory incl. deployable primary mirror with diameter of the 12m-16m class – see [RD7]).

Future high-resolution Geostationary Earth Observation mission concepts have recently been studied by ESA (i.e. GEO-HR) as part of a preliminary mission study, and involve a very large monolithic primary mirror (see [RD8], [RD9]) which would represent a significant technological leap w.r.t. current mirror sizes and manufacturing capabilities for space optics. Therefore, it would be extremely valuable to explore the possibility to use a deployable segmented primary mirror in the frame of GEO-HR and to investigate in detail the approaches enabling the active correction of errors linked to the optics segmentation and deployment, and also the constraints that such system will pose to the nominal operations, as a function of e.g. aperture size and number of segments, and the on-ground and in-space verification approaches that would be required.

2.2. OBJECTIVES OF THE ACTIVITY

The goal of this study was to assess the feasibility of the use of Active Optics for correction of large deployable systems for Earth Observation, e.g. high-resolution GEO, and Science, e.g. space telescope for Earth-sized exoplanet imaging and characterisation).
This translated into the following objectives, respectively for EO and for L2-based science missions:
- To identify the technical challenges at trade-offs at system level,
- To perform the preliminary design of an active correction loop for large deployable telescopes,
- To define a technological roadmap towards for the development of the active correction loop for the selected design.

Note: in this document, the terms “active correction loop” or “active correction chain” refers to an image and line of sight correction system consisting of:
- active correction component(s) (e.g. deformable mirror),
- image quality sensing device(s) (e.g. wavefront sensor),
- algorithms for correction determination and correction components control
- calibration strategy and implementation in the instrument to be corrected

In order to reach this objective, an important effort was put on the design of the telescopes for both application cases, as this is the basis for the active optics system.

3. PROGRAMME OF WORK

3.1. WORK LOGIC

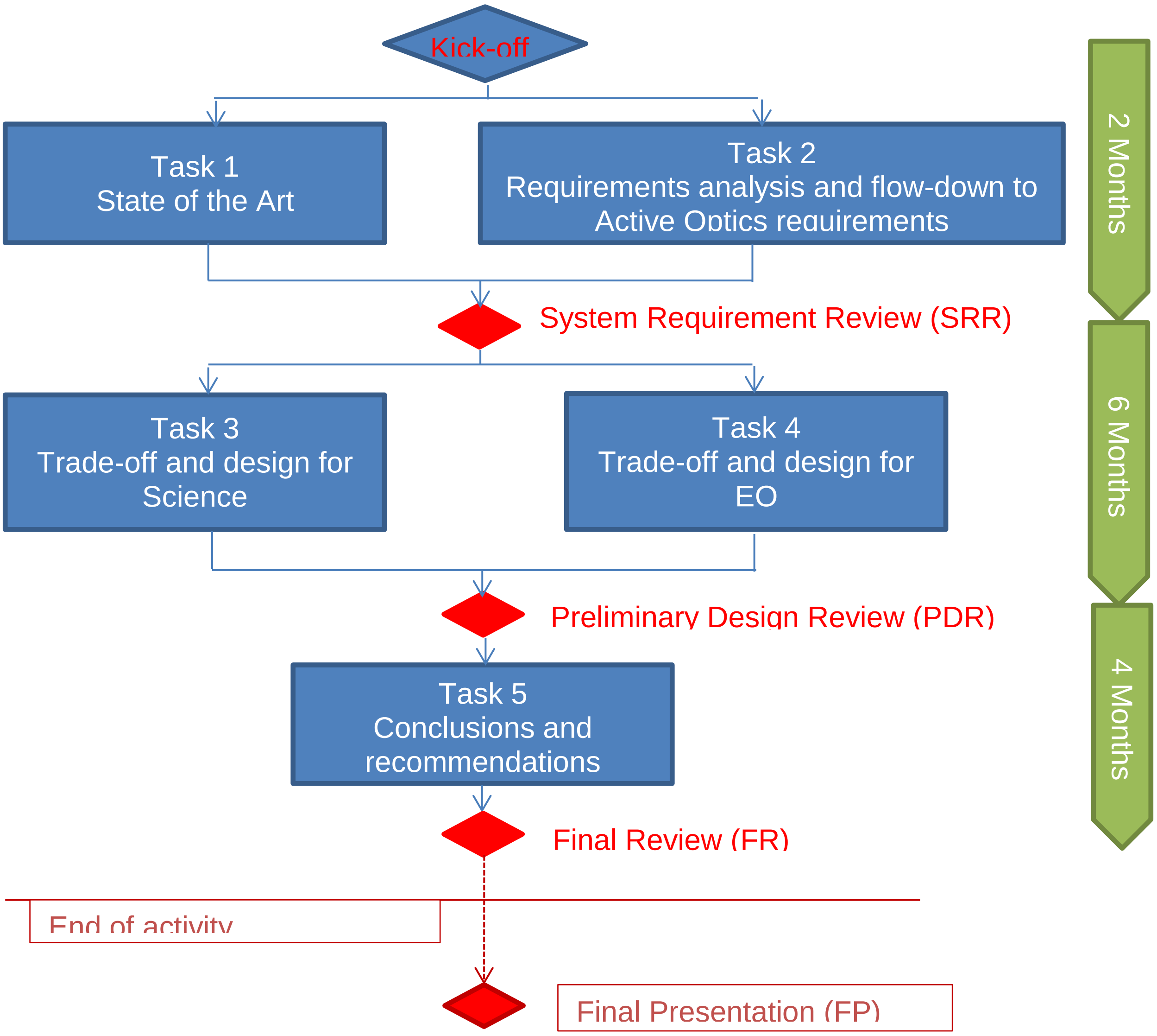
The work was organised as follows:
Task 1: State-of-the-art survey of the developments in Active Optics and techniques relevant to EO and Science deployable optic systems,

Task 2: Mission requirements analysis and flow-down to Active Optics requirements, supported by an instrument conceptual design for resp. EO and Science cases.

Task 3: Trade-off analysis and Preliminary Design for the Science mission case

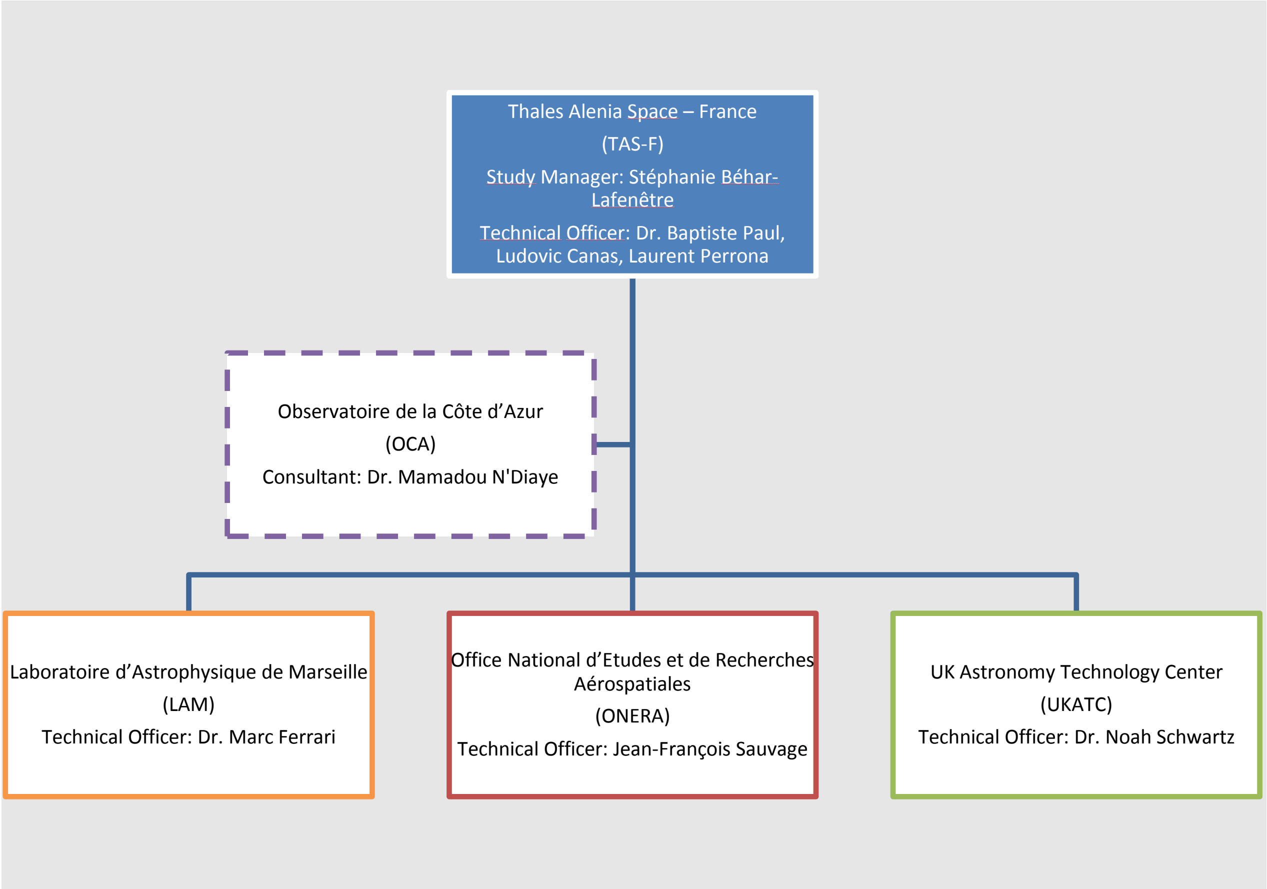
Task 4: Trade-off analysis and Preliminary Design for the EO mission case

Task 5: Conclusions and recommendations, including feasibility assessment and definition of a roadmap for the development of the active optics correction chains designed in tasks 3 and 4.



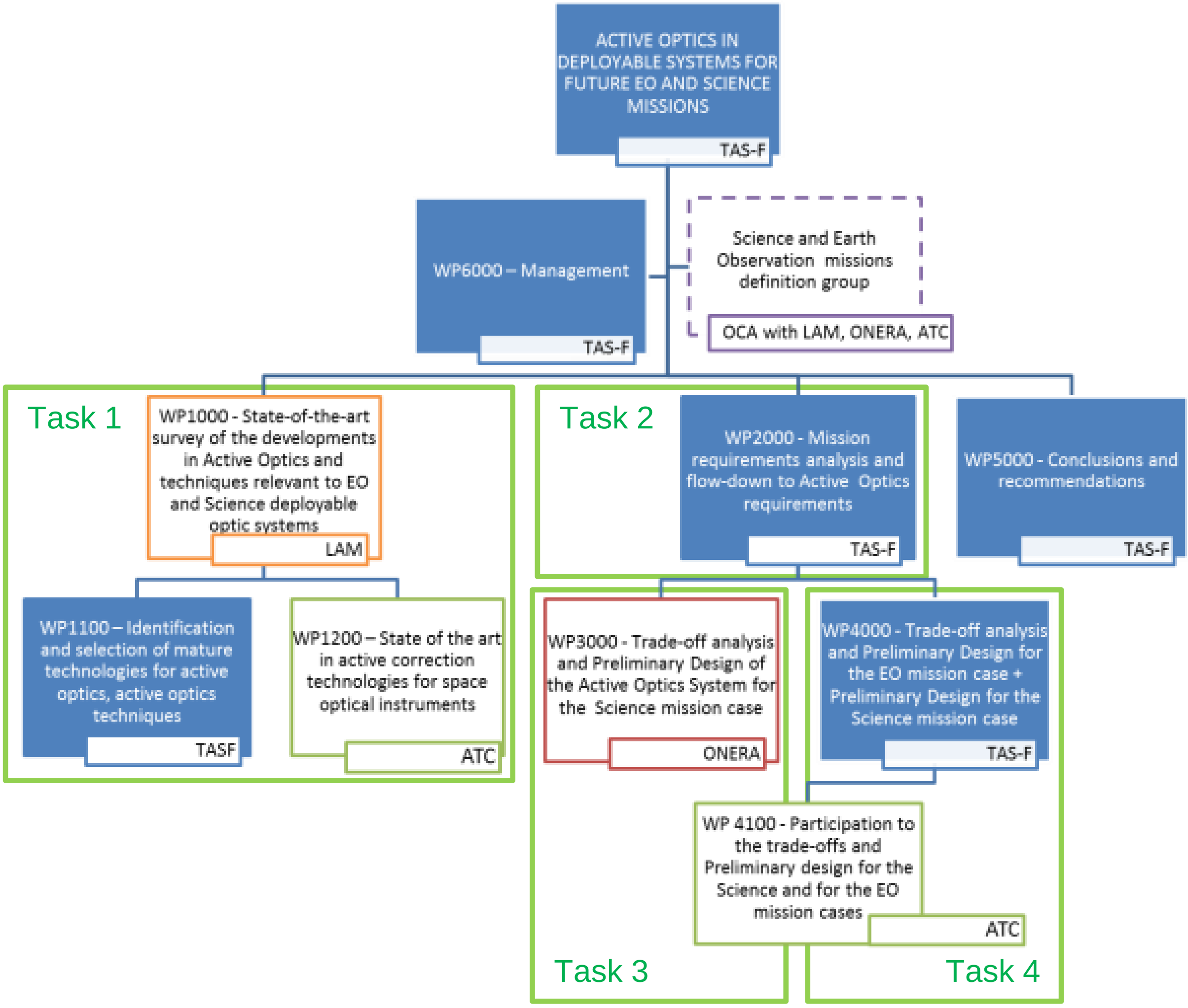
3.2. INDUSTRIAL ORGANIZATION

The Organization Breakdown Structure for the Study is described below. The identified Key Personnel is indicated in each box corresponding to a member of the Team.



3.3. TASKS SHARING

The tasks were shared as shown in the Work Breakdown Structure below, based on the skills and background of each partner:



4. ACTIVITIES PERFORMED AND MAIN RESULTS ACHIEVED

4.1. TASK 1 - STATE-OF-THE-ART SURVEY OF THE DEVELOPMENTS IN ACTIVE OPTICS AND TECHNIQUES RELEVANT TO EO AND SCIENCE DEPLOYABLE OPTIC SYSTEMS

In this task, the Team explored the state of the art in active correction for space optical instruments, including deformable components, wavefront/PSF sensing strategies and their implementation, correction and control algorithms, line of sight sensing and stabilisation.
The Team surveyed opto-mechanical deployable systems currently in developments for large space optical instruments, focussing in particular on their implementation, their mechanical and optical stability, and their identified impact on the imaging quality (e.g. WFE, straylight, segment edge diffraction…).

This task resulted in a Technical Note: [RD 12] - TN1 - State of the Art in Active and deployable optics technologies for space applications.

4.2. TASK 2: MISSION REQUIREMENTS ANALYSIS AND FLOW-DOWN TO ACTIVE OPTICS REQUIREMENTS

The Team reviewed and analysed the Science mission cases requirements provided by the Agency as well as the GEO-HR mission requirements provided in [AD 1].
The contractor flowed down those requirements to the Active Optics system level, after identification and assessment of the adverse effects on the instrument optical performance due to the use of a segmented deployable primary mirror. To perform this part of the task, the Team supported its study by an instrument conceptual design for respectively the EO and Science mission cases. For the EO case, the Team used the GeoHR study (final reports listed in [RD8] and [RD9]) as starting point, adapting their instrument design considerations to a deployable primary mirror.

This task resulted in a Technical Note: [RD 13] - TN2 - Requirements of an Active Optics correction system for large deployable optical instruments in Earth Observation and Science missions.

The output of this task was reviewed at the System Requirements Review, which kicked-off the trade-off and preliminary design tasks.

4.3. TRADE-OFF ANALYSES AND PRELIMINARY DESIGNS

Task 3 (Trade-off analysis and Preliminary Design for the Science mission case) and Task 4 (Trade-off analysis and Preliminary Design for the EO mission case) had the same specification, each dedicated to one of the two application cases.
Those two tasks were led in parallel, and appeared much more difficult and longer that initially expected, considering the large amount of information gathered in the state-of-the-art phase, their complexity, and the many design options possible to answer the requirements.
Those two tasks, initially foreseen to last 6 months, required 18 months.

They consisted in 2 parts:

- In a first step, drawing upon the results of task 1 and task 2, the Team performed a detailed trade-off between active correction strategies and technologies identified in TN1 in view of the AO requirements identified in TN2 for each application case case.
- In a second step, the Team updated the instruments conceptual designs of Task 2 for each mission case and performed a preliminary design and a performance analysis of the AO correction system.

Although in principle the same, both tasks quickly appeared to be quite different and needed to be handled in different ways: while the Earth Observation case was based on the GeoHR studies and thus benefited from existing designs on which Thales Alenia Space France had internal background, the Science case was entirely new.
The focus of work was therefore not the same for both cases:

- For the GeoHR, the activity was focused on an adaptation of the existing optical design to a segmented Primary Mirror and Active Optics, and on performance estimation. Only after that phase was mechanical design started, including the introduction of deployable Secondary Mirror (M2). Deployment of Primary Mirror Segments has been considered similar to the one developed for the Science case.
- For the Science case, a lot of bibliography based on the LUVOIR studies in the United States was necessary. The study was therefore more focused on the understanding of the mission and instrument concept (coronograph) and in the synthesis of the outputs from the American studies. Then a conceptual mechanical design of the telescope could be proposed, focusing particularly on the deployment and actuation solutions.

Those tasks resulted in two Technical Notes: [RD 14] - TN3 – Active optics in deployable systems for Science: trade-off analysis and preliminary design and [RD 15] - TN4 - Active optics in deployable systems for Earth Observation: trade-off analysis and preliminary design and several models.

The output of those tasks was reviewed at the Preliminary Design Review and was the basis for the proposed roadmaps.

4.3.1. GeoHR application case

The optical system technical requirements are those of the GEO-HR study [RD 32].

4.3.1.1. CORRECTION PRINCIPLE

The active optics correction loop aims here at guaranteeing the MTF (Modulation Transfer Function) requirements in PAN (panchromatic) and multispectral channels by:

1. Performing the telescope WFE correction during the telescope commissioning, in particular the segmented primary mirror cophasing after deployment;
2. Guaranteeing the telescope image quality for observation through LoS stabilization and WFE compensation, including notably the primary mirror segment cophasing.

The proposed active loop designed to cope with the above objective is presented below:

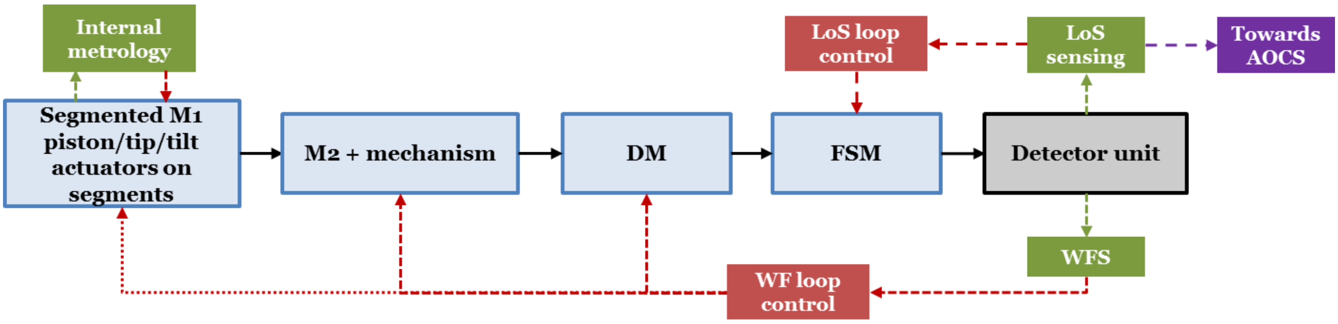


Figure 1 : functional diagram of the active optics loop strategy for the EO mission case.

This active optics loop for the EO mission case relies on the following elements:

- **Correction components**: Actuated primary mirror segments to ensure the primary mirror cophasing, secondary mirror mechanism to relax the mechanical constraints on the secondary mirror positioning, Deformable Mirror (DM) to compensate for the telescope WFE and Fast Steering Mirror (FSM) to ensure the Lind of Sight (LoS) stabilization.

- **Sensing**: Internal metrology technologies may be used to maintain the primary mirror cophasing (after commissioning), while Wave-Front Sensor (WFS) and line-of-sight sensor will be required to assess both WFE and LoS errors. The use of two different sensors originate in the temporal evolution of these two phenomenons: LoS will indeed rapidly vary but requires only the X and Y position estimation on detector, while WFE, whose variation will be much slower, will requires the estimation of several Zernike modes. These both sensors will have to be located as close as possible from the mission focal plane to ensure the most accurate measurement; as such, they shall require the minimum of dedicated hardware to simplify their implementation.

- **Control algorithms**: LoS control will require a dedicated control algorithm that will compute the FSM position from the LoS sensor measurements, while another algorithm will be used to control both M2 mechanism (M2M) and DM to ensure the telescope WFE minimization. A last algorithm will be required to actuate the primary mirror segments from the wavefront sensor position, at least for commissioning operations.

4.3.1.2. DESIGN DESCRIPTION

After several trade-offs to choose the most adequate optical combination allowing to accommodate the several correction levels, the selected configuration is made of a segmented hexapod (MLA – Micro-Linear Actuator) on a first pupil and a segmented Deformable Mirror (Nano-Linear Actuator) on a second pupil, with a deployable front cavity.

It represents the following advantages:

- It is efficient to correct the petal positions of the primary mirror,
- It is more reasonable to separate the function “deformable mirror” and the function “positioning by hexapod” (less industrial and technology risks) for active optics,

Thus at the end of Task 4 an architecture for a GeoHR satellite has been retained to be compliant with the main requirement requiring a MTF > 5 pts at Nyquist frequency.

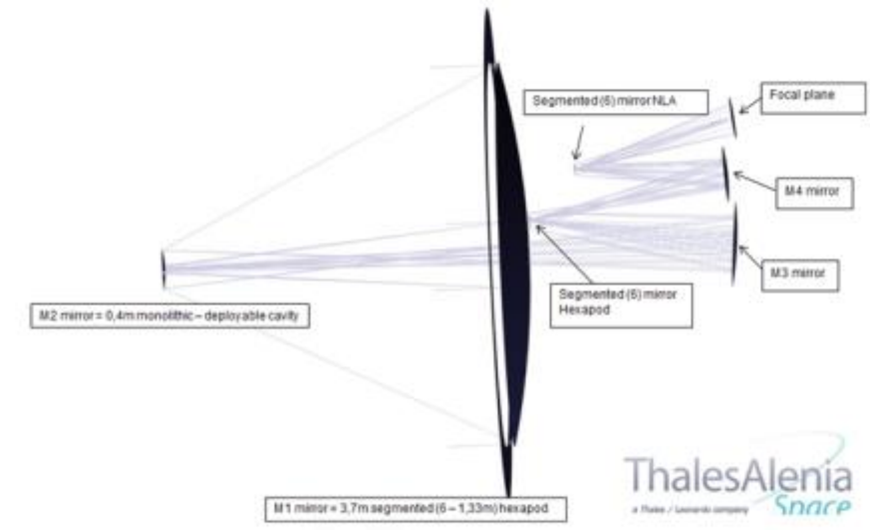


Figure 4-2 – The optical architecture retained by Task4

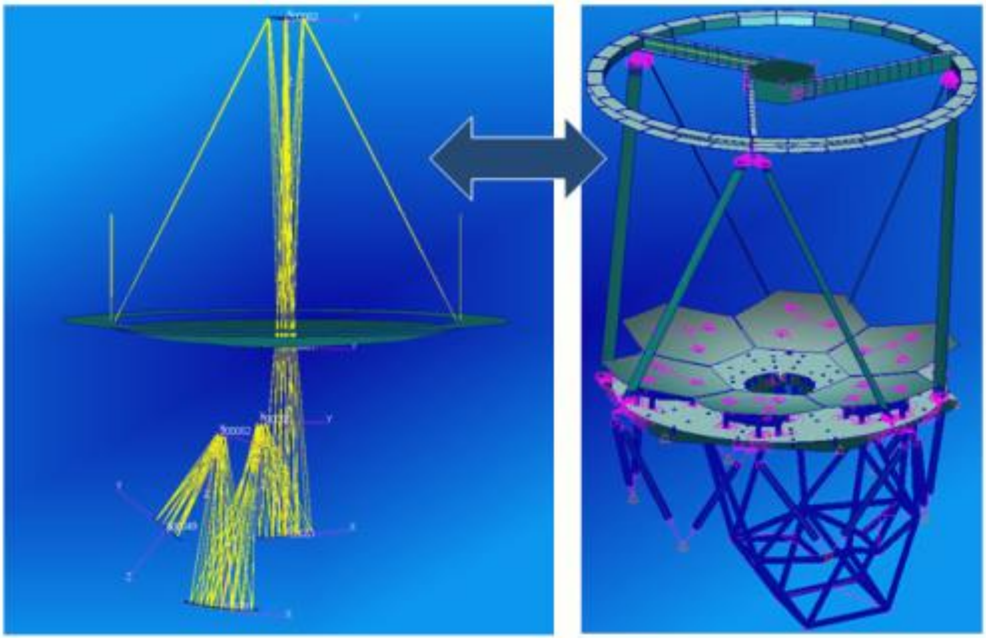


Figure 4-3 – Optical and mechanical models

This architecture consists in:

- A structural concept based on hyper stable materials (carbon, ceramic), with Zerodur® mirrors, to ensure maximum stability and minimize the requirements on complex correction devices.

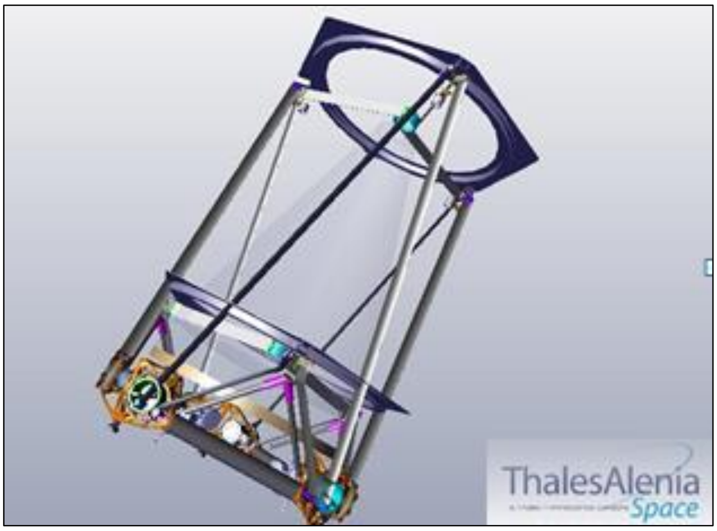
- A six-hexagonal-segment primary mirror. Each segment presents a micrometric movement to allow a fine positioning,

Due to the stroke and the precision required for positioning M1 segments, the technology provided by hexapods is the best.

Piezoelectric actuators have a good resolution and a small size but their principal drawback is their short stroke and the fact that they need to be under voltage all the time. Their holding force is also too small to support and move a primary mirror about one meter in diameter and a mass of several tens of kilos during AIT tests on ground. A UK Research and Innoative study (led by UKATC) on piezoelectric actuators usable for space applications show a potential for improvement of the technology. On the other hand, the mechanical actuators are the technology used on James Webb Space Telescope for aligning primary mirror segment.

The Team has capabilities to develop this type of hexapod due to its legacy on MM2 (M2 Mechanism developed for TANGO) using also 6 mechanical actuators. The stroke and precision are about the same for this application, the difference will be the holding force to move a primary mirror heavier than a secondary mirror (for AIT activities on ground for example).

- A secondary monolithic mirror, together with a deployable front cavity which allows to roll up itself for launch but also allows in space, once unrolled, to adjust the fine positioning of the secondary mirror (thus avoiding the use of an M2 mechanism),

- 

- **Figure 4-4 – Concept of a deployable front cavity**

It is important to consider this new technology for future roadmaps because other gains are possible: reduction of the effects of firing charges on the instrument, mass gains on the structure of the telescope leading to a reduction in inertia and therefore better agility, possibility of multiple launching, etc…

- A correction of the entry pupil in two pupil planes: intermediate pupil and exit pupil. In both cases the correction is done by segmented mirrors. In the intermediate pupil the mirror corrects mainly the line of sight and in the exit pupil the mirror corrects the nanometric defects after being analyzed by a in-flight phase retrieval algorithm processing,
    - in the exit pupil the mirror corrects the nanometric defects after being analyzed by a in-flight phase retrieval algorithm processing. Thales Alenia Space France, following a first demonstrator realized in collaboration with LAM, has developed and qualified a deformable mirror called MADRAS (mirror actively deformed and regulated for applications in space). Based on this experience, for the present application, it will be necessary to develop a deformable mirror compatible with requirements (mainly compatible with a segmented primary mirror), that is to say a deformable mirror consisting of 6 segments, each segment close to 1 mm from each other

    - the metrology is mainly based on “phase diversity” also called “phase retrieval”. It consists in little hardware (a Wave-Front Sensor in the focal plane) associated with the relevant algorithms. This technology is selected due to:
        - Its precision,
        - Its high TRL,
        - Its compacity and ease to be implemented on a focal plane,
        - Its flexibility to calculate the selected Zernike modes.

4.3.1.3. SYNTHESIS

Through the optical and mechanical studies carried out in this document, dealing with a case study of a geostationary instrument for observing the Earth, certain directions to be carried out for the years to come are clear:

- First of all, it seems unthinkable to design such an instrument without using active optics in the broad sense. That is to say as well to have, on board the instrument, a correction of micrometric level mirrors (hexapod allowing an overall correction in piston and tip / tilt) but also at the nanometric level (optimization of the mirror surface).

- These elements must be compatible with segmented mirrors. Indeed, even if in this study the entrance pupil is not necessarily deployable – the size of the M1 being already compatible with the larger fairings - it seems obvious that for a technological, industrial, calendar and reduction of multiple risks compared to a large monolithic primary mirror (diameter 3.6m) that the use of segmented primary mirrors will become widespread. The transition from monolithic active optics to segmented active optics has yet to materialize.

- Besides the design and optimization tools for these new optical architectures will also have to be developed. For this purpose, a new generic tool using codeV was developed. This tool made it possible to provide the needs of such architecture for all the compensation mechanisms in terms of travel and precision expected, which are the inputs necessary for any thermomechanical study.

- Additionally, with the idea also of reducing the volume of the instrument at launch and therefore the mass and loads at launch, it is necessary to continue the studies on the deployment studies of the M1 M2 distance. Thales Alenia Space confirms the interest in a deployable front cavity.

These directions for the coming years are detailed in the way forward section (§ 4.4.1).

4.3.2. Science application case

This application case targets the Science instruments with coronographs.

4.3.2.1. CORRECTION PRINCIPLE

The active optics correction loop will here be used to guarantee the resolution (mandatory to distinguish the planet from its host star) and contrast level in the search area of the science focal plane by:

1. Performing the telescope WFE correction during the telescope commissioning, in particular the segmented primary mirror cophasing after deployment; this is dealt with by corrections inside the telescope itself. This is the focus of our study.
2. Guaranteeing the contrast level in the focal plane search area through LoS stabilization and electric field phase and amplitude control. This is done outside of the telescope itself (either at System level or in the coronograph) and has not been detailed here.

Active optics loop requirements are driven by the required level of contrast in the search area (10^{-10}) during observation, that will notably be ensured by the specified WFE stability (10 pm per wavefront control iteration step) and LoS stabilization (0.4 marcsec on the coronagraphic mask).

After several trade-offs, the preferred solution for correction is to act directly on the Primary mirror segments, as they are by far the main contributor to the WFE.

As for the GeoHR, the active optics loop relies on the following elements:

- **Correction components**: Actuated primary mirror segments to ensure the primary mirror cophasing and to compensate for the telescope WFE, secondary mirror mechanism to relax the mechanical constraints on the secondary mirror positioning.
- **Sensing**: Internal metrology technologies may be used to maintain the primary mirror cophasing (after commissioning), while Wave-Front Sensor (WFS) and line-of-sight sensor will be required to assess both WFE and LoS errors.
- **Control algorithms**.

4.3.2.2. DESIGN DESCRIPTION

The following topics have been identified as critical for the performance of the telescope:

- Deployment of Primary Mirror:
- Deployment of Secondary Mirror:
- Active Optics at Telescope level
- Supporting structure

4.3.2.2.1. Deployment of mirrors

In stowed position, for the size of half the Primary Mirror diameter fitting in a launcher fairing we can fit all the instrument and minimize the number of deployment and associated risks.
The M2 is first deployed, then the central baffle, holding the Fast Steering Mirror (FSM). Finally the two parts of the M1 are deployed and locked.

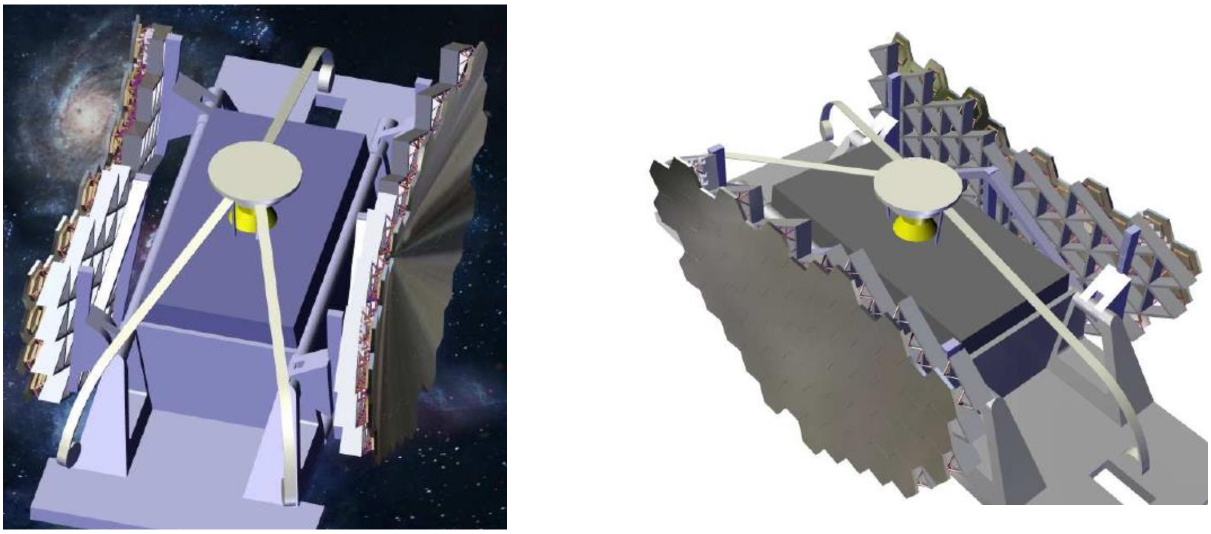


Figure 5: TAS 2-parts Telescope in stowed configuration

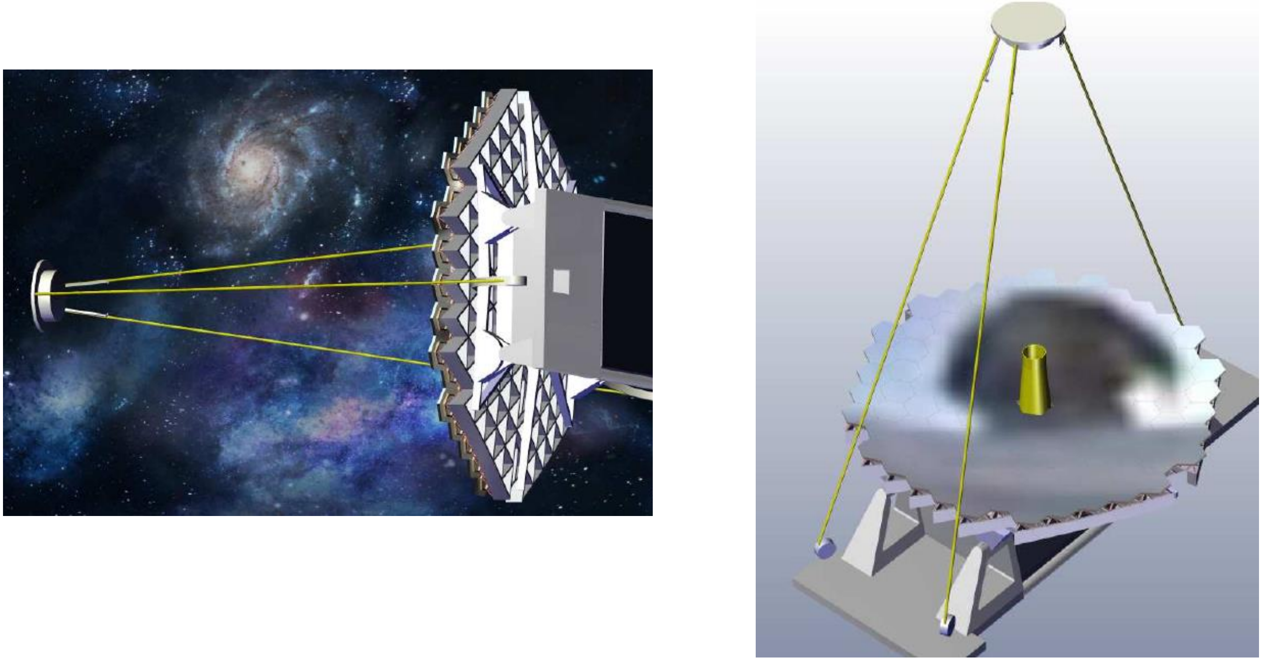


Figure 6: TAS 2-parts Telescope in deployed configuration

The proposed solution is here based on the Tape Spring Deployment technology developed since many years by Thales Alenia Space (stemming from an ESA ITI) with the following advantages:

- Stowed configuration: Simplified, the M2 will be directly stowed on the central structure

- Deployement:
    - Less risks of blocking and seizure than articulated beams
    - Smooth and controled deployment
- Active Piston/Tip/Tilt correction when deployed

For the regarded application, the deployment, the stability and the needed correction (only 3 axes, Piton/Tip/Tilt) require only 3 deployable tapes.
The diameter of the Tape when deployed is 12cm (thus compliant with the <15cm width).
The adjustment capability has to be about 1µm after deployment .
Such a system avoids any Secondary Mirror Mechanism as it allows to tune the position of the M2 directly with the same actuators used for deployment.

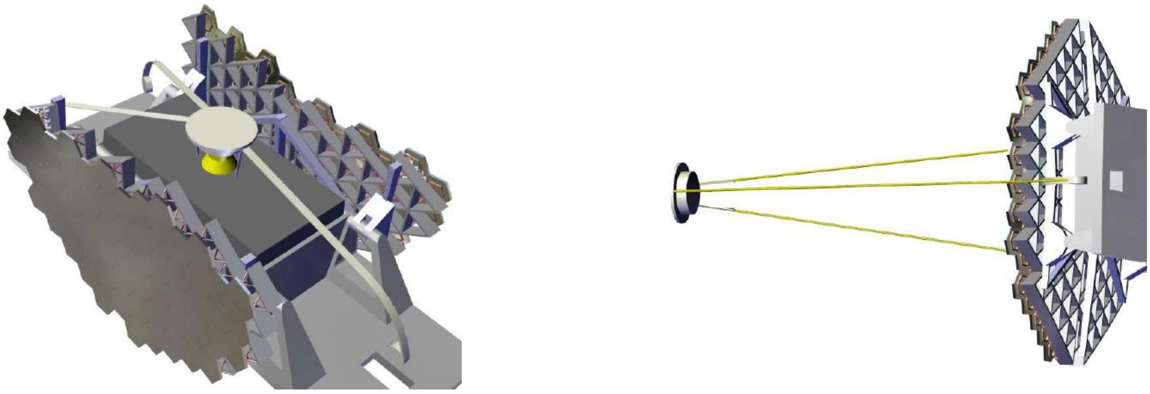


Figure 7: M2 in Stowed and Deployed configuration

The Secondary Mirror (M2) is stowed on the central structure carrying all instruments and the overall observatory.
The Holding devices of the M2 remain hidden from the optical path, being in the shadow of the tape spring after release.
The baffle, carrying the Fast Steering Mirror, may also have a deployable part using “origami” structure (TAS has developed solutions for this, some of which patented).
The 3 Tape Springs are bent to fit the stowed position, which is a big advantage compared to articulated folded bars, and stay behind the two half parts of the Primary Mirror when stowed.

4.3.2.2.2. Active optics technologies : correction at the Primary mirror

The proposed correction system is installed in the back of each hexagonal segment of 1,38m (flat-to-flat) to allow:

- Direct correction of each segment to ensure the global WFE of the instrument < 38nm RMS
- Highly simplified integration and calibration On Ground and In Orbit
- No need of extra Deformable Mirror on the Instrument (except at Coronagraph level) which could avoid to have an intermediate pupil in the telescope optical train, thus reducing the number of mirrors.

Principle: the WFE and picometric positioning corrections are separated into two levels of corrections

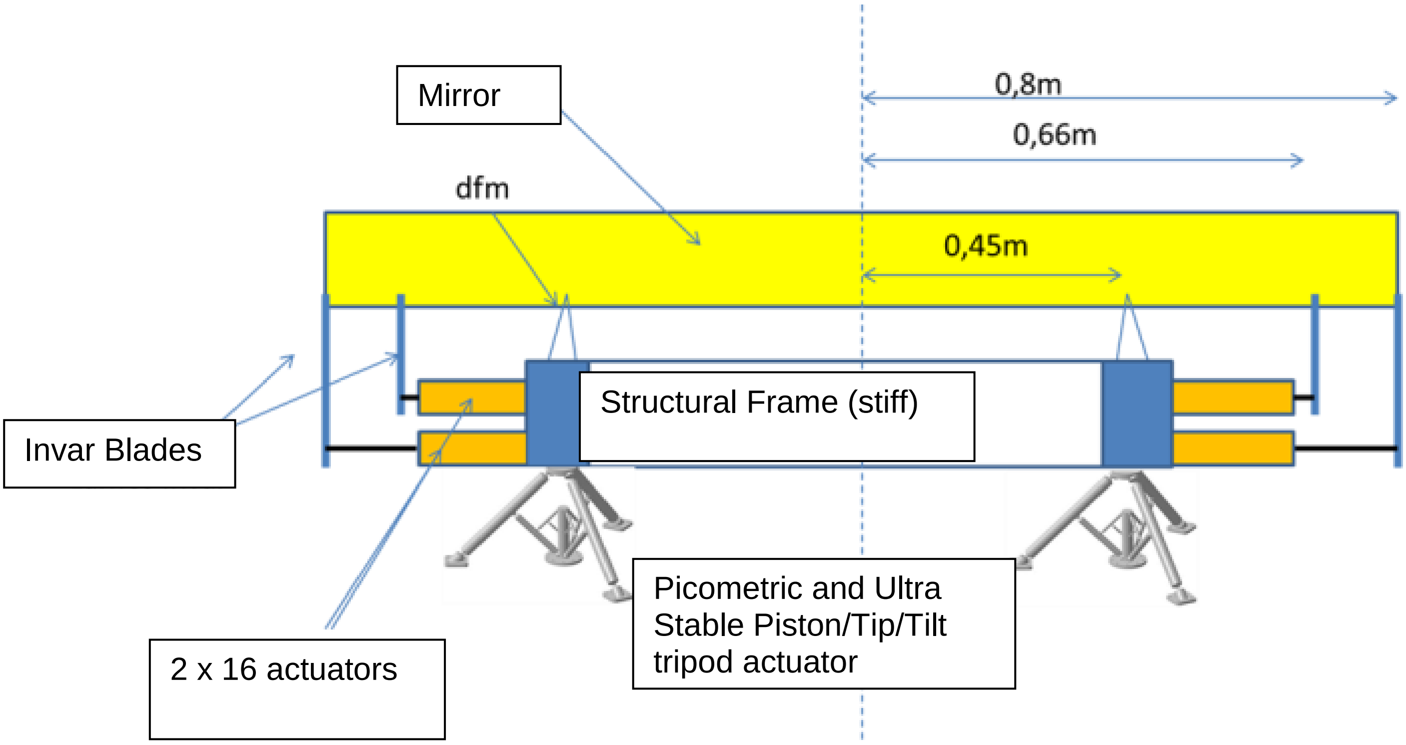


Figure 8: Principle of the Active Segment of the Primary Mirror

The first level (piston/tip/tilt) consists in adjusting the height of a Tipod by thermo-elastic deformation of bars successively one by one.
A first rough setting is obtained at the first level, then the second level modifies this setting with more accuracy, and so on for the following bars:

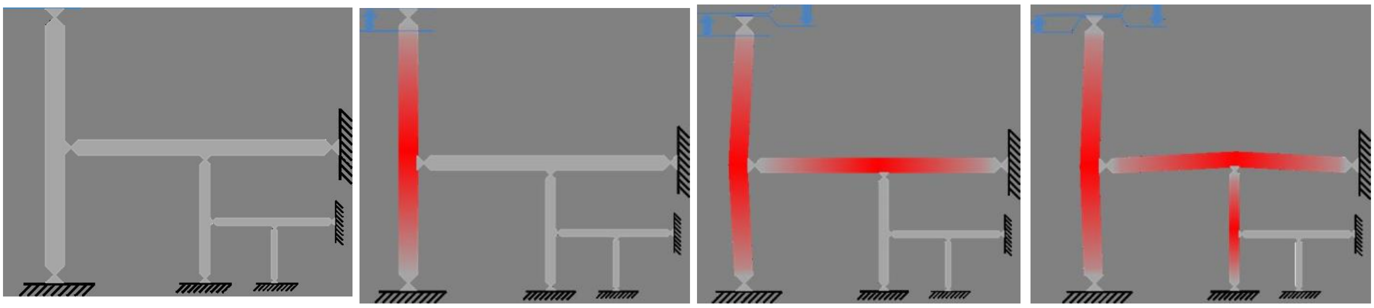


Figure 9: Picometric Thermal actuator tripod principle

The final shape of the actuator can in one part, using multi-material additive manufacturing, and thus avoiding any mechanical link instabilities. This shape can be designed directly as a tripod for stability.

Figure 10: Picometric tripod actuator view of principle

The second level (WFE correction) is derived from the MADRAS, a deformable mirror developed for CNES by LAM and TAS.
TAS, following a first demonstrator realized in collaboration with LAM, developped and qualified the “ Mirror Actively Deformed and Regulated for Applications in Space ” (MADRAS) principle with CNES.
As already mentioned, the MADRAS active concept can be adapted to segments that are close to each other, passing the flexion arms under the mirror surface. This compact configuration, with minimal number of actuators (Lemaitre, Meccanica, 2005), has already been preliminary demonstrated, both theoretically and experimentally by LAM on circular pupils. In the same way, adaptation of the deformation to the hexagonal geometry of the segments can be achieved using angular thickness distributions, mathematically determined, in the mirror support, the mirror itself or both. Thus, by relying on LAM's expertise in segment bending (e. g. LAM/Thales-SESO patent FR 2932897; 2008) and Thales-Alenia-Space's know-how on space systems,

active segments for primary mirrors of future missions could be favorably considered and pre-designed.

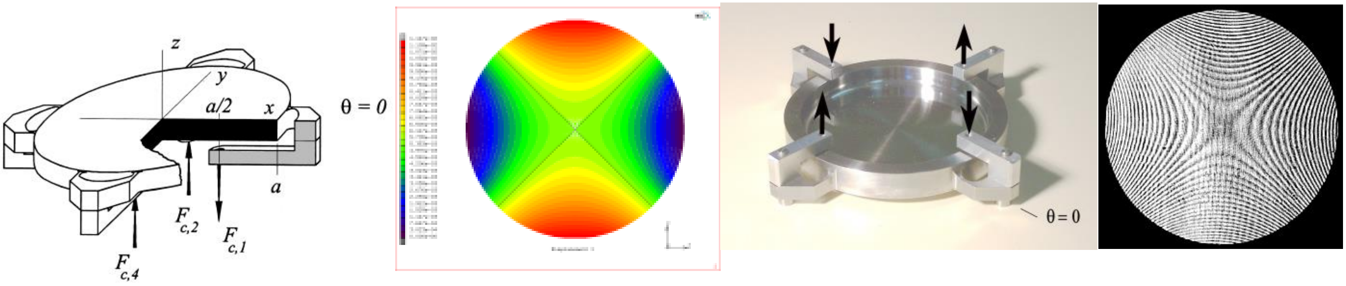


Figure 11: Example of compact configuration for AST3 mode deformable mirror (similar design for 2*n arms) Design, FEA simulation, prototype and real interferogram

As the LAM principle worked perfectly for MADRAS the TAS R&T started to design an adaption of this active optic principle for future big segmented primary mirrors, directly on each segment when the dimension allow it , which is typically our case with hexagonal segment of 1,38m (flat-to-flat). The overall principle of this solution is presented hereafter.

4.3.2.3. SYNTHESIS

Future very big Observatories for High Level Science mission like direct imaging of exo-Earths and search for life depends now mainly on the possibility to build deployable instrument with extreme capacity of correction and extreme stability (a few pm in few minutes).

The high contrast level achieved on ground is already about 10^{-6} using Apodized Pupil Lyot Coronagrah (APLC) with two internal deformable mirrors (DMs).
Using the same technology in space should allow to reach the 10^{-10} needed contrast at the only condition of an extreme stability, both spatial and temporal.

This study has been focused on finding concepts and technologies dedicated to stability adapted to the constraints by the Team, using its expertise and heritage in all Space domains for a large deployable optical instrument.

The first analysis of this design confirms the feasibility of the extreme stabilty expected:

- Thermo-Mechanical Sentivity to **1mK < 600 pm displacement between segments**
    - Picometer Tripod compatible to correct it to pm stable level

- WFE Sensitivity to **1mK < 1,4 nm RMS Total with 2 pm RMS WFE_PTF and 1 pm RMS WFE HF**
    - Active Segment design compatible to correct it to pm stable level

A way forward to develop the necessary techniques and technologies is proposed in section 4.4.2.

4.4. TASK 5: CONCLUSIONS AND RECOMMENDATIONS

The Team identified the shortcomings of the designs and identified a way forward for the designs improvement and related technological development needs.
Drawing from those considerations, the Team provided a technological roadmap of necessary developments in the field of AO for large deployable space instruments for both EO and Science mission cases for the designs implemented.

This task resulted in two Technical Notes (one for each application case): [RD 16] TN5 – Technological roadmap for active optics implementation in large deployable systems.

The output of this task is recalled in the following section, dedicated to the way forward.

4.4.1. Proposed technological roadmaps based on GeoHR

This study highlighted certain design improvements and the associated technological development needs that do not exist today in the commercial market at a high level TRL.
There are four technological products essential to the realization in the near future of the first high resolution instrument for monitoring the Earth in real time:

- Segmented deformable mirror,
- Deployable front cavity,
- Primary mirror micro linear actuators
- And super light and directly polished off-axis segments for the primary mirror

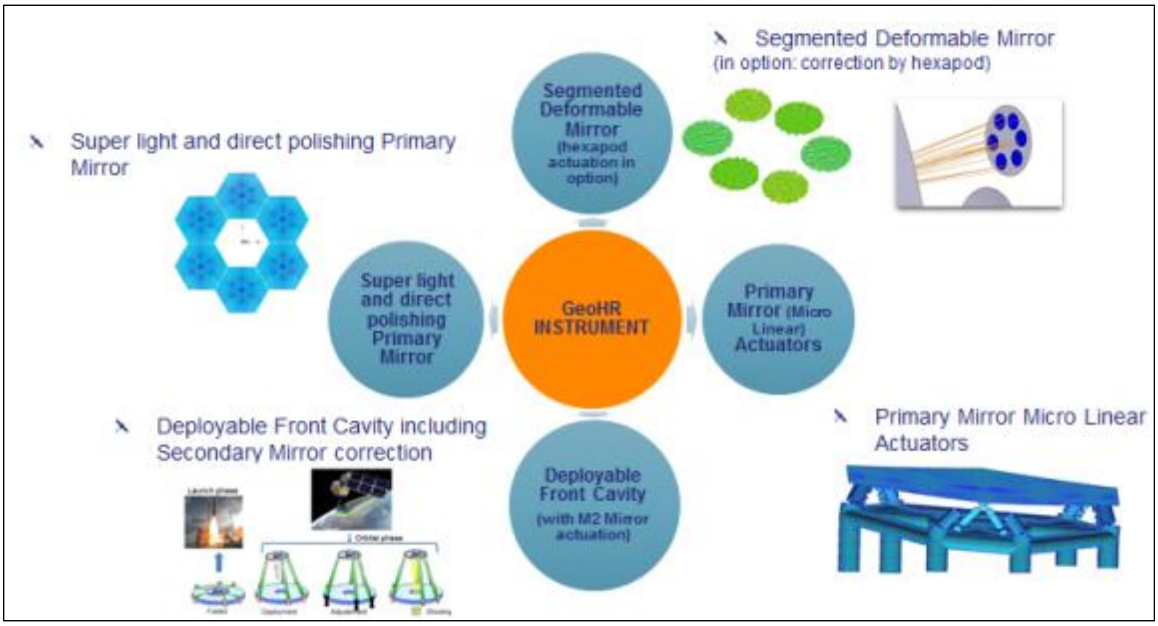
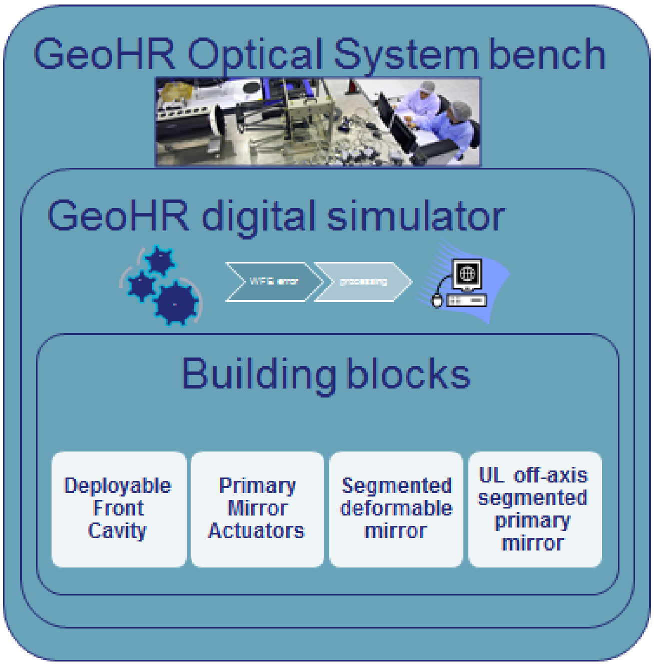


Figure 4-12 – Essential building blocks

These four technological building blocks shall be subjected to dedicated unit validation.



But it is essential to validate their common operation/calibration procedure, i.e. the validity of the adjustment loops (for example one loop for the post-launch and one periodically loop) through:

- Firstly a digital simulator,
- Then by a real test on an optical bench.

An input to this digital simulator will be a metrology system for the telescope. Indeed, in order to fine tune it, we need to know its behavior. It can be a software analysis based on a WFE measurement, for example, or by the installation of metrological devices judiciously placed on the telescope. In the following section, this metrological system to be invented will be indicated as a technological need for improvement.

The system validation will of course be led by the particularity that the optical combination uses segmented optics.
All of these innovations would strengthen the industrial commitment to the production and performance of an active segmented telescope.

These design improvements and the associated technological development needs will be the topic of the next sections.

The following R&D actions are detailed in [RD 16]:

- Segmented deformable mirror
- Deployable front cavity
- Primary mirror (micro linear) actuators
- Super light and direct polishing segmented off-axis primary mirror
- Metrology system
- digital simulator and optical system bench

For the proposed developments the following schedule is suggested:

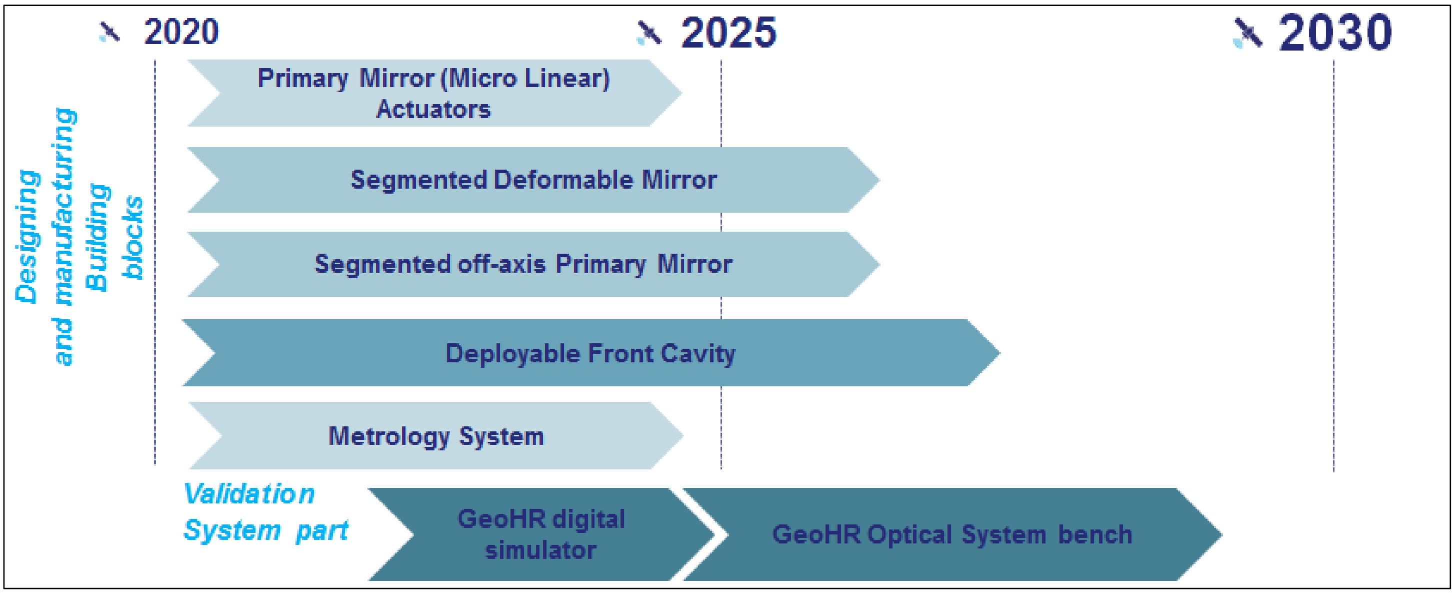


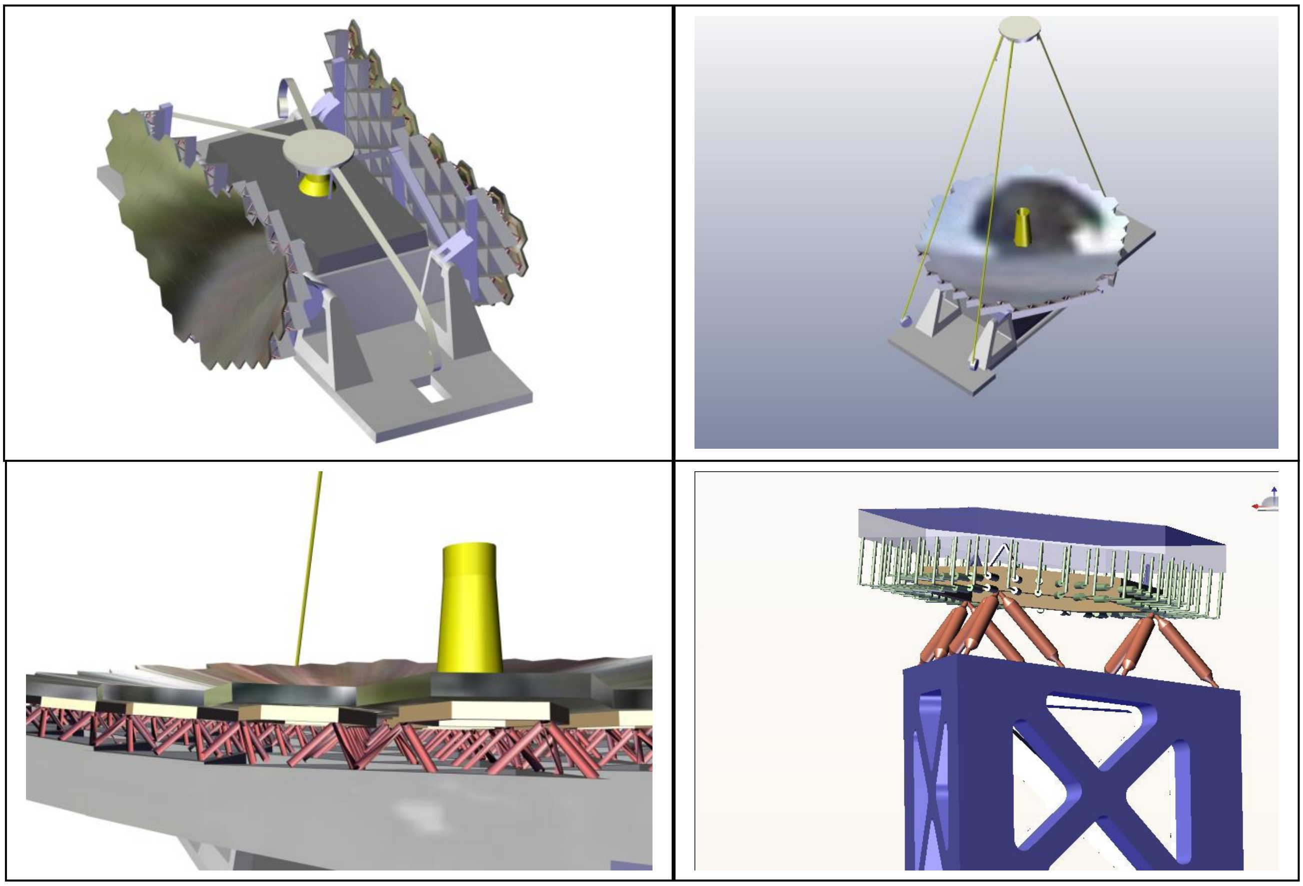
Figure 4-13– Necessary developments roadmap

4.4.2. Proposed technological roadmaps based on Science case

This study highlighted certain design improvements and the associated technological development needs that do not exist today in the commercial market at a high level TRL.

For the Science case, they are linked to:

- The follow-up of the performance management tools (optical control loop, pointing accuracy, image processing)
- the maturation of the proposed technological solutions, especially for the mechanisms.



The following topics to be developed are excluselively dedicated to the telescope system as was the scope of the Study. However, Europe has skills in coronographic instruments, and it seems wise to highlight here that a dedicated roadmap should be proposed for this part as well.

The following R&D actions are detailed in [RD 16]:

- Upgrade PASTIS model and ULTRA macro
- Attitude Control System & FSM
- On Board Image Processing to compensate observatory drifts
- M2 & CENTRAL BAFFLE DEPLOYMENT
- ACTIVE M1 SEGMENT DEVELOPPMENTS:
- PICOMETER TRIPOD ACTUATOR
- SUPPORTING STRUCTURE SHAPE AND MATERIAL
- OPTICAL ARCHITECTURE

Schedule for developing and validating new technologies:

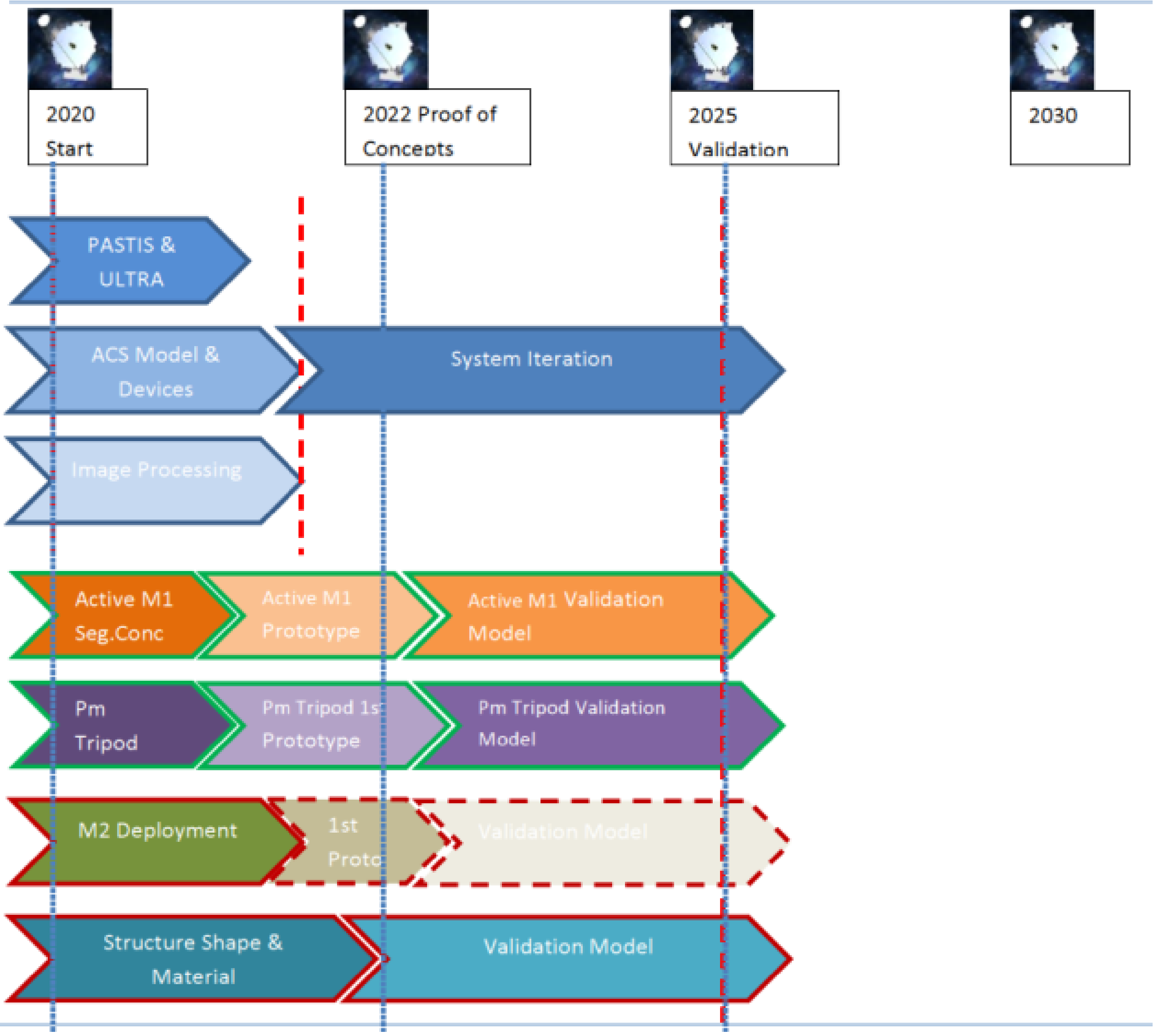


Figure 4-14– Necessary developments roadmap

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