AIRBUS

Very Large Space Telescope Mirrors Study

Executive summary report

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1 BACKGROUND

Some of the key questions in science, such as star formation, the search for Earth like exoplanets, can only be answered by telescopes working in UV-VIS wavelength range, with primary mirrors with diameters larger than 8 meters. Future large space telescopes need new technologies to meet their high performance requirements at an affordable cost. Two very different telescopes concepts are studied by AIRBUS for the European Space Agency: a monolithic Telescope with a 4m primary mirror that provides the largest collecting area that can be accommodated in the Ariane 6 fairing; and a large deployable distributed aperture Space Telescope, with a collecting area of 50 square meters achieving a practical resolution limit equivalent to 12 meters diameter. Enabling key technologies are identified and a roadmap for future technology developments is outlined. Among these technologies are large monolithic mirror polishing, active optics, deployable space structures; low-cost, lightweight optics; and wave front sensing and control methods.

Both concepts study were supported by state of the art review, concept trades at both instrument and platform level, including mission analysis. The key technologies development is the main outcome of this study, and will aim at building the future of Voyage 2050 missions.

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

2 SCIENTIFIC CONTEXT AND STUDY OBJECTIVES

The VLST study shall assume a general-purpose astronomy Space Observatory for UV-VIS-NIR diffraction-limited imaging and low to medium resolution spectroscopy as reference mission, similar to the Hubble Space Telescope (HST). The astrophysical fields of research to be addressed by the space observatory are:

- Broad based UV-NIR science
  - Transport processes in the Intergalactic Medium
  - Interstellar Medium
  - Stellar Physics
  - Fundamental Physics
- Exo-Earth discovery
  - Planet formation and the emergence of life
  - Characterization of exoplanet atmospheres
  - Is there life elsewhere in the Galaxy? Detection of Earth-like Planets in habitable zone; Detection of habitability and biosignatures
- Planets of the solar system

As UV range observations cannot be accessible from ground, Hubble Space telescope and Russian-led WSO-UV (170 cm) space telescope are the only high resolution UV observatories. Well-known successor, named James Webb Space Telescope, is dedicated mainly to infrared observations. As shown on Figure 2-1, there is no observatory able to perform UV and Vis observations below 0.1 arcsec resolution. It is the objective of the on-going study to address this kind of missions. EUVO (ESA) and LUVOIR (NASA) mission concept studies prepare the future of UV-Visible space observatories.

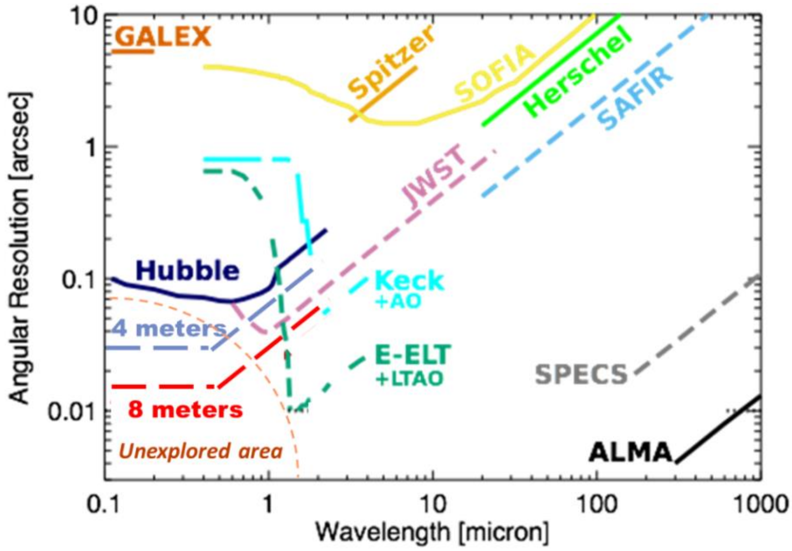


Figure 2-1: UV-VIS high resolution remains unexplored

In the frame of this study, ESA proposed to consider “research for life” domain as reference mission type.

Deployable concepts seems better suited for NIR applications as interstellar medium observation where faintest objects need to be observed and thus the overall aperture / primary mirror size is important

The size of monolithic Space telescopes is limited by the diameter of the launcher fairing. The fairing of Ariane-5 allowed to launch Space telescopes with a diameter of 3.5m, such as Herschel, the largest space telescope launched up to date. Herschel Space Telescope was operating in the sub-millimeter waves, therefore to fulfil the ever-increasing demand of larger Space telescope both for Science in the UV-VIS and for high resolution Earth Observation from geostationary orbit technology developments are required to upscale the current telescope, such as Euclid to exploit the available space of launch fairing.

It is expected that Ariane 6 will provide a 5.4m diameter of useful space for the primary mirror of a Space Telescope. At the same time, some of the key questions in science, such as star formation, search for Earth like exoplanets, can only be answered by telescopes working in UV-VIS wavelength range and with primary mirrors with diameters larger than 8m.

Two main objectives were identified for the study:

- Objective 1: To perform the design of two Space Telescopes based on the following two concepts:
  - Concept 1. Monolithic Telescope: Space Telescope with a primary mirror that provides the largest collecting area and can be accommodated in the Ariane 6 fairing without using foldable or deployable parts in the Payload Module.
  - Concept 2. Deployable Space Telescope, e.g. a telescope with off-axis elliptical primary mirror and a foldable secondary mirror. This solution shall have the largest possible collecting area, given the diameter and the vertical envelope of Arianne 6 fairing, with the goal of achieving a telescope with a collecting area of 50 square meters. The Contractor may propose other solutions of foldable telescopes, provided that they maximize the use of the Ariane 6 fairing and that the TRL 4 of the deployable system can be reached in three years.
- Objective 2: To identify the critical technologies and the cost drivers of the two concepts and define the technology developments plan.

The reference mission is a Space Observatory that shall be able to access any celestial target within one year, with a typical observation duration of one hour, and a total observation efficiency of 70% or higher.

The observatory shall be similar to general-purpose Hubble Space Telescope (HST). It shall provide diffraction-limited imaging and spectroscopy from low to medium resolution across a wavelength range from the far ultraviolet to the near infrared.

	Monolithic Concept	Deployable Concept
Volume Allocation	Ariane 6 Fairing	
Primary Mirror	A primary mirror that provides the largest collecting without foldable or deployable parts.	Telescope with collecting area of 50 square meters, or larger.
Wavelength range	0.1 µm – 2.5 µm.	
FOV	15 arcmin² without any vignetting.	
Payload Instruments	A high-resolution imager with UVIS and NIR Channels	
Observation Time	1 hour	
PSF	80% encircled energy within the airy disk @ 500 nm for one hour observation, including all degradation errors	
Life time	In orbit Operations: 4 years	
LOS – Sun Aspect Angle (*)	90 Degrees (60 degrees goal)	

Figure 2-2: Defined mission requirements from ESA SoW
(*) 180 degrees is when the Space Telescope line of sight is parallel to the Sun light

The instrument specifications for both telescope concepts are given by the following figure.

Instrument Specifications

Volume: 0.5m x 0.5m x 0.5m
Mass: 100 kg
Power consumption: 300W
Data transmission from the instrument to the Spacecraft:
- ECSS-E-70-41A applicable
- Real time downlink rate < 1kbps
- Data rate: 520 Gbits/day

Figure 2-3: Defined instrument specifications from ESA SoW

3 MONOLITHIC TELESCOPE CONCEPT

The domain of applications for monolithic concept is focused on “research for life”, and in particular on habitable exo-planet detection and bio-signatures detection. Very large space telescope could permit breakthrough observation goals corresponding to specific telescope requirements:

- Large collecting aperture is justified by the need to observe faint objects, and to achieve high angular resolution as requested to characterize the star formation in the dust-obscured regions.
- Sharp and highly stable PSF are needed for coronagraph applications (faint object observation next to bright source i.e. high contrast imaging to suppress the light from bright source). This calls for:
    - Telescope WFE optimisation.
    - Line of sight stability. Besides telescope optimisation and associated active control, reduction of micro-vibration has to be ensured at payload and spacecraft levels.
- Large field of view is requested for the measurement of dark matter kinematic properties.
- Straylight is generally critical meaning low diffusion and little energy diffracted out of PSF central lobe.
- Polarisation sensitivity requirement may be stringent.
- UV spectral range measurement is mandatory for Galaxy Halo and Gas Physics.

Derived telescope requirements are provided in Figure 3-1.

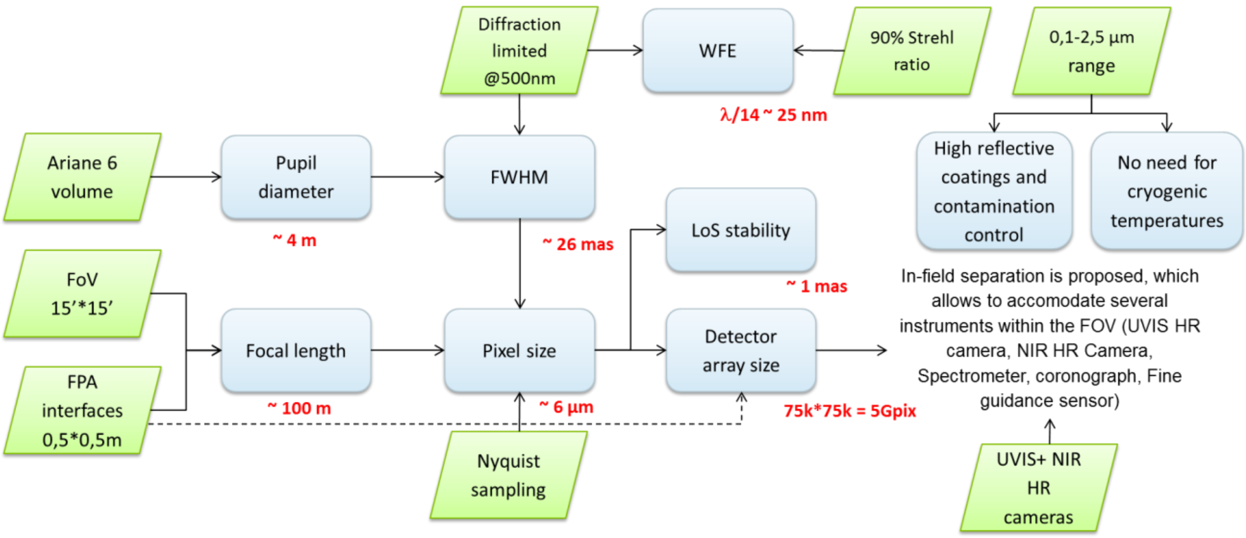


Figure 3-1: Derived requirements for monolithic telescope concept

Besides technical feasibility, the cost of the development is a key parameter to the decision to go-on with missions briefly depicted above. As an example, large monolithic mirrors require initial investment in terms of manufacturing facility.

WFE correction concept

Very large monolithic OTA cannot achieve requested diffraction limited performance at visible wavelength without an active correction function based on: Wavefront and line of sight measurement and correction mechanisms, control loop on-board computer. Metrology may be (partly) provided by sciences instruments themselves.

Active WFE correction is mandatory for very large monolithic space telescopes and especially for VLST where diffraction limit at 0,5µm is required. Main reasons are:

- Gravity release on a > 4 meter-class M1 has a huge effect on its shape: therefore low spatial frequencies of the Mirror Surface Error (low order Zernike) have to be actively corrected.
- Thermo-elastic M1 shape distortion between ground and orbit then during observation period
- WFE metrology knowledge over large mirror may not be compatible of requirement.
- AO can allow to relax polishing requirements to realistic values

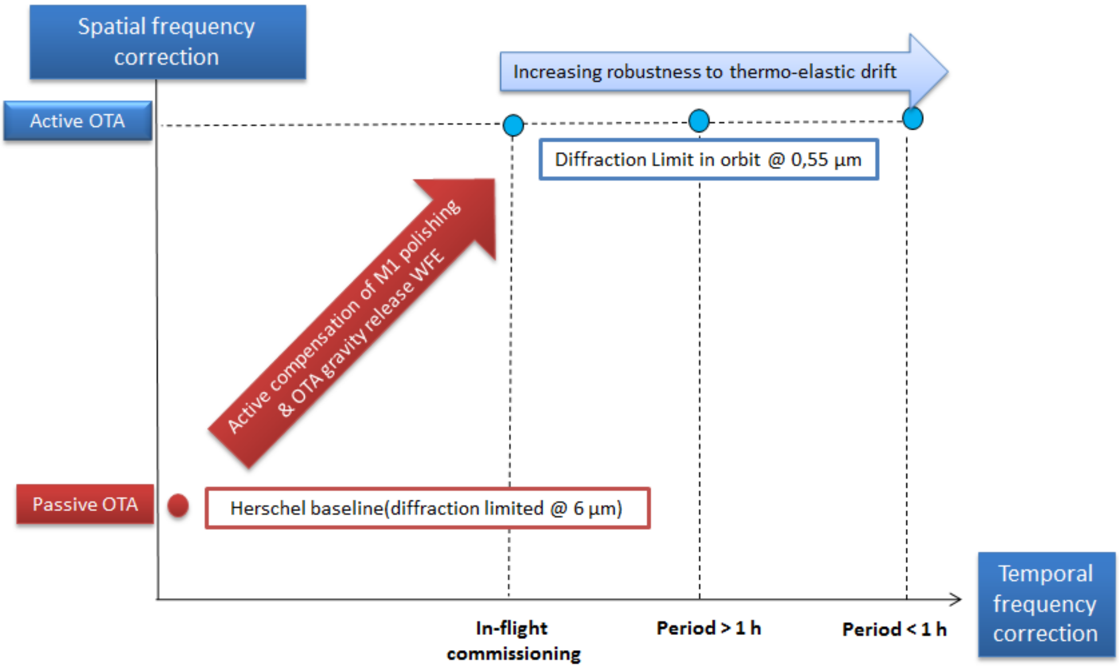


Figure 3-2: WFE correction concept

Optical configuration

At least 3-mirrors configurations are compatible with the FOV and PSF requirements. Korsch telescope has many advantages, as it provides an intermediate image allowing an efficient baffling of out-of-field straylight and a real image pupil which can be used for accommodating a deformable mirror, able to compensate for primary mirror distortions. Two options for Korsch are possible:

- No offset angle: This design asks for an exit pupil mirror located at the intermediary image with a minimum hole diameter at the center, which is not compatible of having a deformable mirror (with a central hole) in the pupil plane. All these constraints, manageable on on-ground telescopes, add complex accommodation constraints on a space telescope design, which can be easily relaxed with an offset angle. This option is therefore not considered for the monolithic concept.
- With offset angle: This is the configuration used on JWST, which provides real and reachable intermediary image and exit pupil. This is the preferred option for the monolithic concept VLST

Configurations with more than 3 mirrors are considered to provide better exit pupil image quality for high spatial frequency correction, as instance.

Main outcome from optical trade is the link between in-field correction performance and wavefront spatial frequencies:

- A korsch configuration is only compatible of very Low Frequency correction, and WFE requirement (25-30nm rms) over 15'*15' is hardly achievable
- Dual imaging option is more appropriate for higher spatial frequencies correction, up to 30 cpa. However, this option has a strong impact on the radiometry, since more mirrors are needed.

Active correction with mid-frequency spatial capability (i.e. large number of actuators) is selected as baseline for the monolithic configuration. The optical configuration is then the dual imaging configuration with 7 mirrors. Main performances are provided on Figure 3-3.

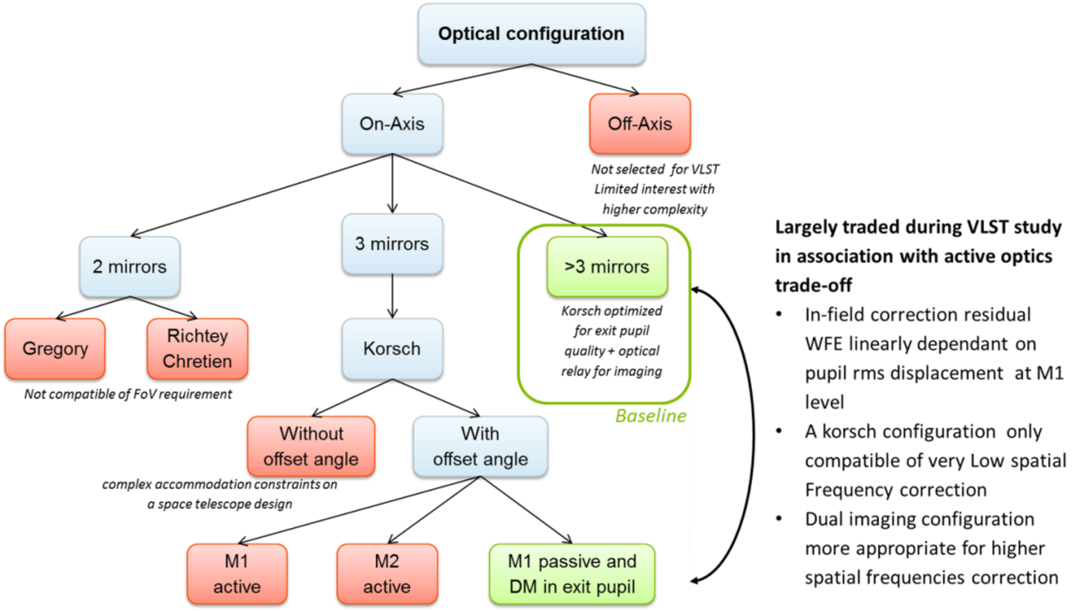
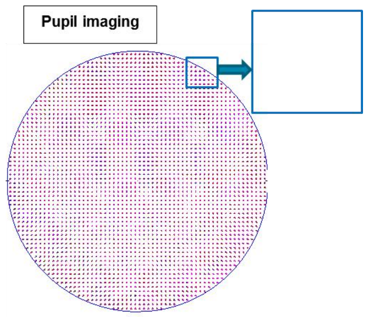


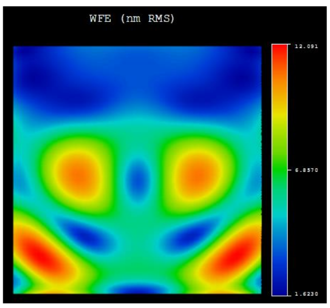
Figure 3-3: optical configuration trade-off for monolithic telescope concept

Item	Value	Comment
Entrance pupil	Diameter 4.0 m Central obscuration 17.5% linear	Entrance pupil located on primary mirror
Primary mirror	Diameter 4.0 m Aperture F/1.3 Distance to M2: 4.48 m	
Focal length	100 m	Aperture: F/25
Object angular field	Square, 0.25°x0.25° (15 arcmin)	
Image plane	Size: 436x436 mm² Pixel size: 6µm square	



WFE field map over 0.25°x0.25°

WFE over field below 12 nm RMS



MTF @ 500 nm
No discernable MTF drop due to geometric effects

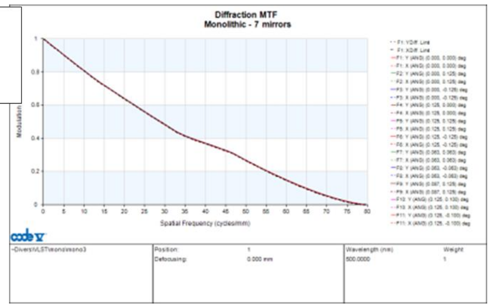


Figure 3-4: Optical baseline performances (dual imaging configuration)

Deformable mirror technology and metrology

Preliminary trade-off is based on pupil exit diameter and spatial frequency correction capability:

- Several tens of actuators are needed to achieve high efficiency correction up to mid-high spatial frequency
- Few millimeters between actuators are needed with narrow influence function

Deformable mirror technologies compatible are few:

- Stacked array mirror and voice coil technologies are compatible
- Mechanical actuators cannot achieve actuator density
- Monomorph or bimorph piezo electric actuators are not enough efficient for mid frequency correction
- MEMS technology still limited in diameter and not considered as credible option for VLST

Voice coil technology, such as the one developed by ALPAO (fr) for on-ground observatories, is promising for space applications, but TRL needs to be increased (part of the proposed roadmaps).

Wavefront sensing baseline is selected in accordance with deformable mirror capability. During commissioning, Phase Diversity associated to Shack-Hartmann, is considered as baseline for calibration. Then, wavefront stability is controlled with Shack-Hartmann, adapted to the low spatial frequency of the wavefront evolution.

The overall roadmap for active optics technologies development is provided on Figure 3-6.

First, a co-engineering study between instrument prime and manufacturers shall be run to:

- co-engineering study between instrument prime and manufacturers (specifications, interfaces, unit's constraints and performance)
- Space design & development of deformable mirror with its electronics
- Environmental qualification
- Complete breadboard including units demonstrator models to perform AO functional and performance tests

Airbus can rely on its strong heritage on active optics and deformable mirrors through CNES project and internal R&D (as shown on TANGO deformable mirror -Figure 3-5).

VLST study has also enabled a fine understanding of the AO constraints and limits, thanks to the very tight performance required for the study

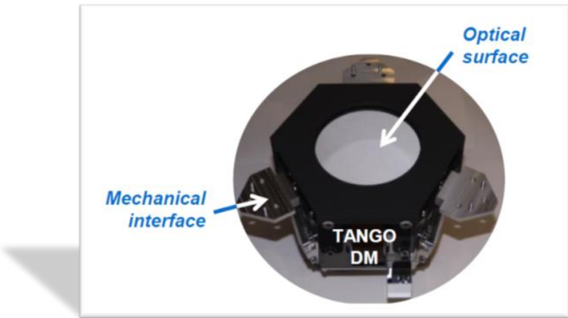


Figure 3-5: TANGO deformable mirror developed for CNES

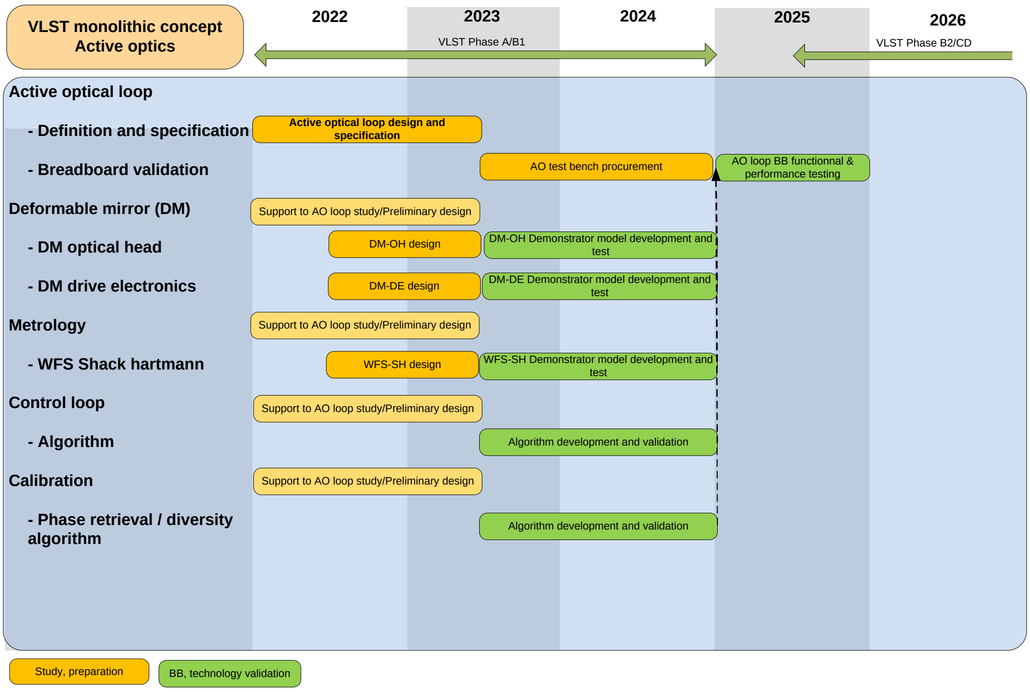


Figure 3-6: Technological roadmap for active optics development

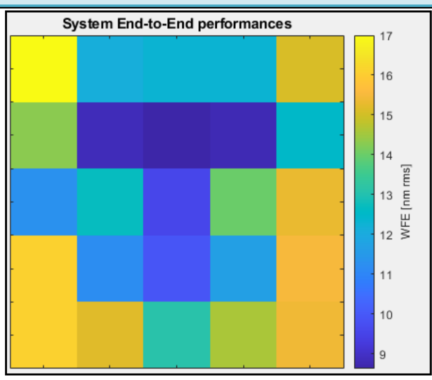
End to end performance:

A numerical E2E model has been created to assess the system performances with its active optic loop, with the following parameters

WFE	Active loop	Optical design
M1 SFE	Number of actuators	Design WFE
M1 quilting	Number of SH lenses	Angle of incidence
AIT defects	Influence function	Pupil Aberration
0g residual		Occultation
Thermal gradients		

Main outcomes are:

- Despite high mirrors WFE, the final performance is excellent (<17nm rms)
- The required DM range to perform the correction is 5% of the full range
- The remaining range can be used for several applications (LoS stabilization, Phase Retrieval, calibration)



Primary mirror

Primary mirror material is selected through following considerations

- **Low mass constraint** taking advantage of Ariane 6 launcher capability: Up to 1 ton for M1 can be allocated for the primary mirror
- UVIS performance asks for sub-nm micro-roughness
- Telescope temperature close to ambient for contamination and stability purpose

SiC and Zerodur materials traded during the study

- Zerodur is selected as baseline offering ultra-stability performance (picometer level) and compatible roughness with UVIS applications.
- SiC mirror can offer lightest alternative (500kg gain) with compliant performance, providing that a cladding technology on 4m diameter mirror, compatible of UVIS applications, is available.
    - **R-SiC** coating on optical surface (©*Safran Reosc)* can offer sub-nm micro roughness but large scale facility needs to be developed. R-SiC deposit is fully compatible of large UVIS coating large facility development.
    - SiC large mirror is very competitive when applications ask for cryogenic environment (IR science) or/and low mass (geo-observation)
- Both materials can take benefit of polishing specification relaxation, thanks to compensation by active optics, which is beneficial for mirror development time

The primary mirror development approach and needs are provided in the following table for both materials.

	Zerodur (Baseline)	SiC (alternative)
UVIS Coating for 4m mirror	Need to develop a new coating facility or adapt an existing one for UVIS Need to design and qualify UVIS coating for space	
Blank substrate	High TRL from SCHOTT on 4m substrates	Provided by MERSEN BOOSTEC – High TRL with large heritage from Herschel up to 3.5m and can be scaled to 3.8m in the same facility. Above this diameter, a larger furnace development is needed.
Mirror blank lightweighting	Need for TRL improvement (acid etching, etc)-Can be done either by SCHOTT either by polisher mastering lightweighting	
Mirror polishing	Many polishers such as REOSC / OPTEON have experience from on-ground large telescope development. TRL has to improved wrt lightweighed mirror polishing, as well as fast polishing technics, metrology for large mirror	
Mirror cladding	No need for cladding. Zerodur roughness is compatible to UVIS applications	R-SiC cladding is assumed to provide low roughness surface but deposition needs to be validated over 4m. RsiC would be compatible of the new coating facility

Primary mirror coating

The VLST UVIS-NIR coating maturity improvement presents a double challenge:

- To select or built a large capacity facility able to perform deposition on such large surface
- To provide a wide spectral coverage from FUV up to NIR [0.1 – 2.5 µm]

Operating metallization of large mirrors is currently only possible in ground based observatories (if we except industrial US facilities). 2 types of metallization can be found in these facilities,

- Al is a common reflective material with high intrinsic reflectivity and good broadband performance but begins to become transmissive below 90 nm. A natural Al_2O_3 layer is created by oxidation in the air and no top coat are usually needed for visible ground applications
- Silver has a good coverage but its reflectivity is much less than Al below 300 nm. Protective topcoats are also deposited to avoid oxidation and tarnishing of the metal.

The technologies used by these observatories are of 2 types:

- Traditional thermal evaporation by Joule effect with heating of aluminium wires using filaments or boats.
- More recently, in the 20 last, years, Magnetron sputtering machines have replaced classical chambers. Targets cathodes are made of row material Silver, Silicon or Aluminium and process gazes are O_2, Ar&Kr, and N_2.

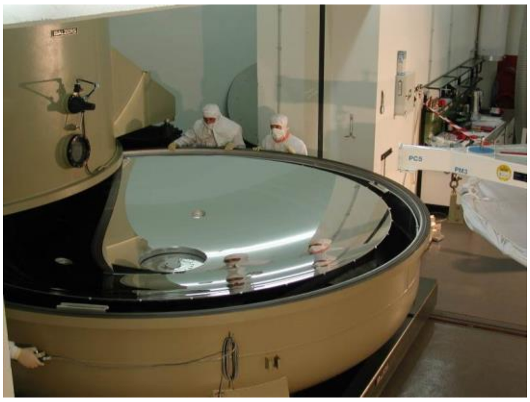


Figure 3-7: Illustration of the technologies available in observatories: (Left) Joule effect Evaporation chamber - Calar Alto (Right) Magnetron sputtering Vessel - Gemini South

Coverage of UV domain requires deposition of transmissive metal fluorides MgF_2 (highly transmissive for λ>110 nm) and lithium fluoride LiF (transmissive for λ > 102 nm). It is done quickly after Al deposition to prevent from the formation of an Al_2O_3 layer from oxygen traces and thus avoid absorption bellow 200 nm. Silver cannot be used because of it has a very low reflectivity compared to Aluminum.

Two approaches can be foreseen to provide UVIS coating capability over 4m scale mirrors:

- Adapt existing facility (CalarAlto or ESO). Prior to implementation, stack validations shall be performed with laboratories
- Develop new large facility or identify potential synergy with future LUVOIR developments

Blank manufacturing

Large Zerodur blank manufacturing had high TRL, especially since a large mass allocation was allowed. However some technological improvements are needed, especially concerning acid etching of the rear face on large blanks.

Primary mirror – Zerodur blank manufacturing

SCHOTT glass made of ideas

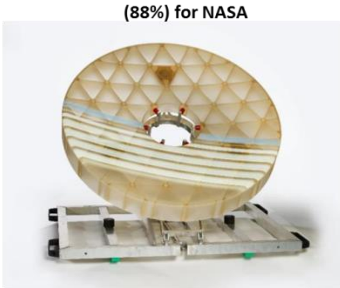
State of the art: Large heritage on 4m blank mirrors over 50 years. Last are:

- Daniel K. Inouye Solar Telescope (DKIST) : 4,26mm with 80mm thickness / Aspheric off-axis
- M2 and M3 for the ESO Extremely Large Telescope (ELT) with a 4.25 m and 4.0 m diameter, respectively
- Aggressive light-weighting design was realized for NASA by SCHOTT on a 1.2 m diameter and 125 mm thick (edge) mirror substrate

E-ELT M2 blank (4,25m)

E-ELT M3 blank (4m)

1,2m lightweighted mirror (88%) for NASA



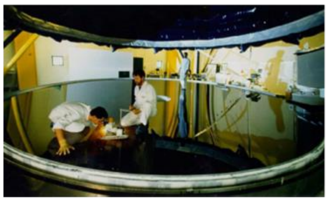
Mirror polishing

In Europe, SAFRAN REOSC and OPTEON are today the well-known and best specialists for large mirrors polishing flows. AMOS did not polish larger than 2,6 m class mirrors but develop large observatory telescopes. They particularly masters compensation technics as well as mirror/telescope system engineering.

These polishers have proven polishing technologies and testing methods with a large heritage on astronomical top class applications and space mirrors. Nevertheless, their existing enabling technologies are at TRL3 to 4 on the space maturity scale needed for large mirrors. The improvements to be done are more on the metrology than on polishing process itself. OPTEON is the only one that has an equivalent TRL9 with the Herschel mirror polishing, but for a specific application: SiC substrate and very far IR-sub millimetric spectral range (60-660µm) meaning few µm accuracy for the optical surface.

Primary mirror – large Zerodur mirror polishing

SAFRAN REOSC has unique expertise in large mirror polishing and is a strategic partner from Airbus on space programs



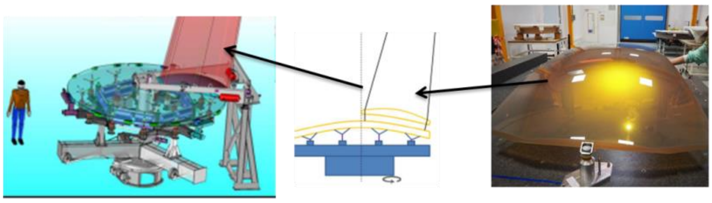
1989-1999- VLT/GEMINI – 8 m

2001-2004 – GEMINI 1m M2

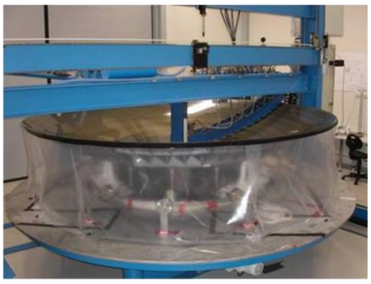
2019 – ELT 4m M2

2001- Sofia – 2,6m

M2 stiching metrology



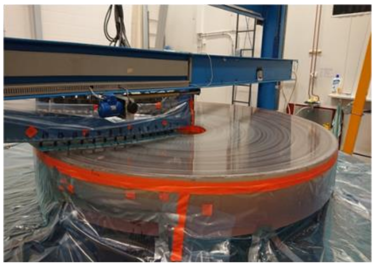
OPTEON (Finland) has polished the largest space primary mirrors for Airbus (HERSCHEL) and ALADIN



2002- HERSCHEL
3,5m SiC M1

2005- ALADIN
1,5m SiC M1

2010 – INO
3,4m M1



2018 –ATHENA 2,6m UV collimator

Large SiC primary mirror option

For a SiC solution, the current TRL, gained through Herschel Telescope and GAIA PLM is quite high. The need for demonstrators is therefore limited.

Nevertheless, for a mirror diameter higher than 3,8 m, investment on larger facilities shall be anticipated to allow their validation and acceptance prior brazing and grinding phases of the mirror flight model.

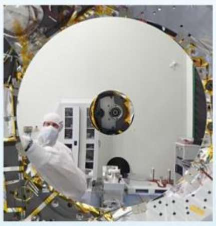
Because of the porous structure of sintered SiC, the mirror shall receive a polishable layer to comply with a polishing roughness of 0.5 nm rms. The layer can be either CVD SiC, deposit by Mersen or R-SiC, coating developed and applied by Reosc. R-SiC cladding is preferred with the great advantage of reversibility. In case of problem the R-SiC layer can be removed and recoat without need for remanufacturing or polishing. R-SiC is easier to polish than SiC. Safran-Reosc already gained roughness less than 0.8 nm rms , with in principle an attainable 0.5 nm rms at the cost of a longer smoothing phase

A High TRL has been achieved through the development of the Herschel SiC Primary Mirror (Raw SiC)

A cladding technology over 4m scale is needed for UVIS application (low roughness)

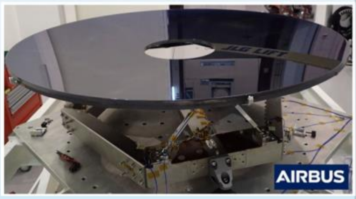
RSiC® developped since 10 years by REOSC

- Good polishability
- Possibility to remove and recoat
- Roughness 0,8 nm rms
- Process : SiC robot lapping /pre-polishing/ deposition/ion beam figuring/smoothing
- Same deposition process than coatings (e-beam)



Needed Improvements :

- Roughness down to 0,5 nm rms
- New coating plant for cladding and coating flash (metrology)



Primary mirror general roadmap

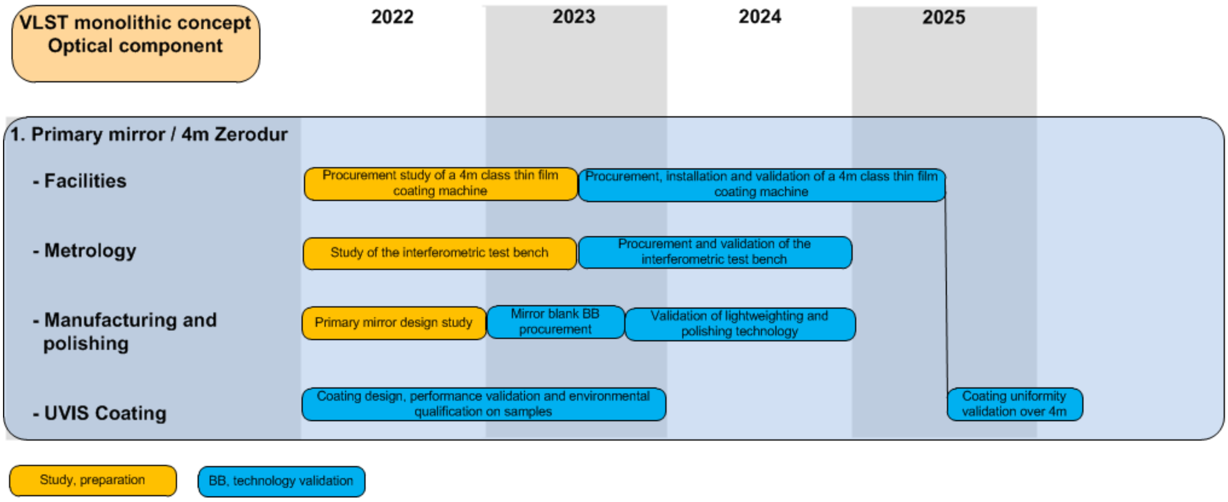


Figure 3-8: Primary mirror general roadmap

Synthesis for monolithic concept

Baseline for monolithic concept is proposed and shown on Figure 3-9:

- 4 meters Primary Mirror made of Zerodur
- A dual stage optical configuration with very good pupil image quality for AO efficiency
- An active optics concept, including
  - Deformable mirror based on voice coil technology
  - WFE metrology based on Shack Hartman measurement associated to Phase diversity at focal plane
- Thermal control at ambient temperature, with open loop concept, providing highly stable M1 heating power

The requested optical quality requirement (25-30 nm rms) over the total field of view 15'*15' is achieved

- The powerful of the selected optical design associated to medium to high spatial frequency correction ensures robustness of the performance limits the risk in mirror development.
- The selected metrology uses phase diversity for calibration in flight thanks to focal plane measurements and shack Hartman technology to monitor WFE in-orbit stability

Transmission was not considered as a driver (no requirement – agreed with ESA), arguing that the main driver is the demonstration of the WFE performance. Study objectives being related to TRL improvement of critical technologies, this was considered not an issue to progress

To go further, it can be imagined that, in a future mission, the total FoV will be shared by different instruments, with different needs in term of optical quality.

- The correction in-field correction efficiency could be relaxed, allowing less demanding optical design with smaller number of mirrors and better transmission.
- Deformable mirror sampling could be adapted to less actuators and primary mirror requirements adapted to this updated system.
- This different set point would not change the technologies needed and addressed in this document.

Moreover, the active optics application to space telescope has been designed and analyzed for a very stringent application, and asked for detailed justification which was very interesting for the understanding of such systems.

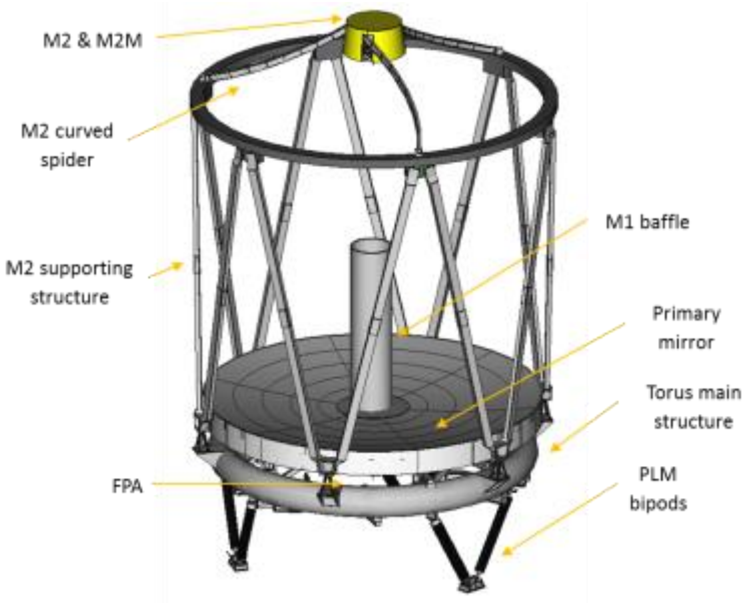


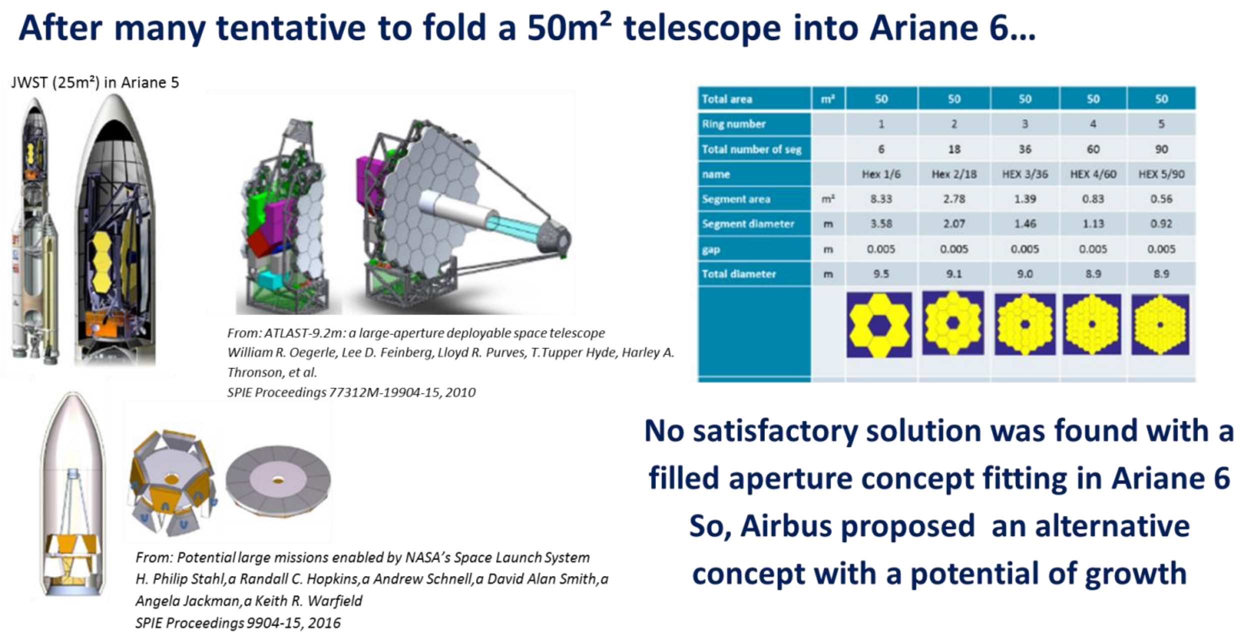
Figure 3-9: Monolithic concept preliminary design

4 DEPLOYABLE TELESCOPE CONCEPT

The domain of applications for deployable concept is focused on "research for life", and in particular on NIR applications such as interstellar medium observation where faintest objects need to be observed.

General

After many tentative to fold a 50m² telescope into Ariane 6, no satisfactory solution was found with a filled aperture concept fitting in Ariane 6. So, Airbus proposed an alternative concept with a potential of growth: the sparse aperture concept was selected as baseline for VLST.



Total area	m²	50	50	50	50	50
Ring number		1	2	3	4	5
Total number of seg		6	18	36	60	90
name		Hex 1/6	Hex 2/18	HEX 3/36	HEX 4/60	HEX 5/90
Segment area	m²	8.33	2.78	1.39	0.83	0.56
Segment diameter	m	3.58	2.07	1.46	1.13	0.92
gap	m	0.005	0.005	0.005	0.005	0.005
Total diameter	m	9.5	9.1	9.0	8.9	8.9

Sparse aperture concept is proposed

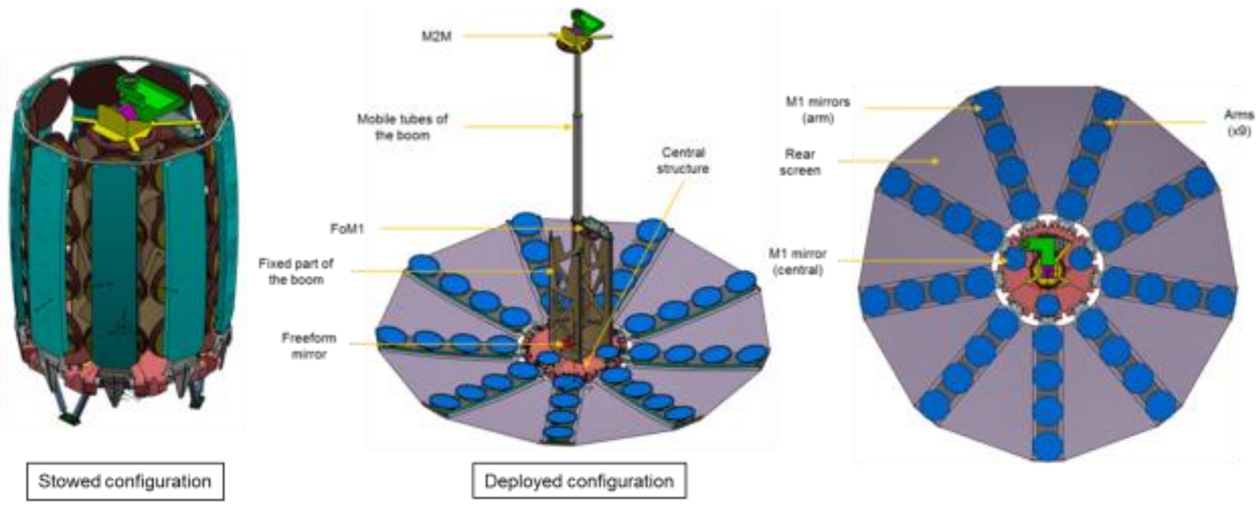


Figure 4-1: Preliminary design of deployable concept in stowed and deployed configuration

Interest of sparse aperture

A comparison between sparse configuration with 50m² collecting area and Hexagonal "extended JWST" type with same collecting area was performed to assess interest of sparse configuration:

- The practical resolution limit (PRL), i.e. the minimum radial frequency where MTF is zero, is 12 meters on sparse aperture configuration. It is 8 meters on hexagonal segmented configuration.
    - FWHM is about 33% shorter on sparse configuration which allows to improve sampling by 33% (2pixels in FWHM)
- Sparse PSF has much more degraded PSF encircled energy, spreading lot of energy in the feet
    - Need to include PSF recovery processing in the system performance
    - Powerful different technics can improve contrast, depending on the scene
- Distribution of sub-pupils were traded from a performance and accommodation point of view

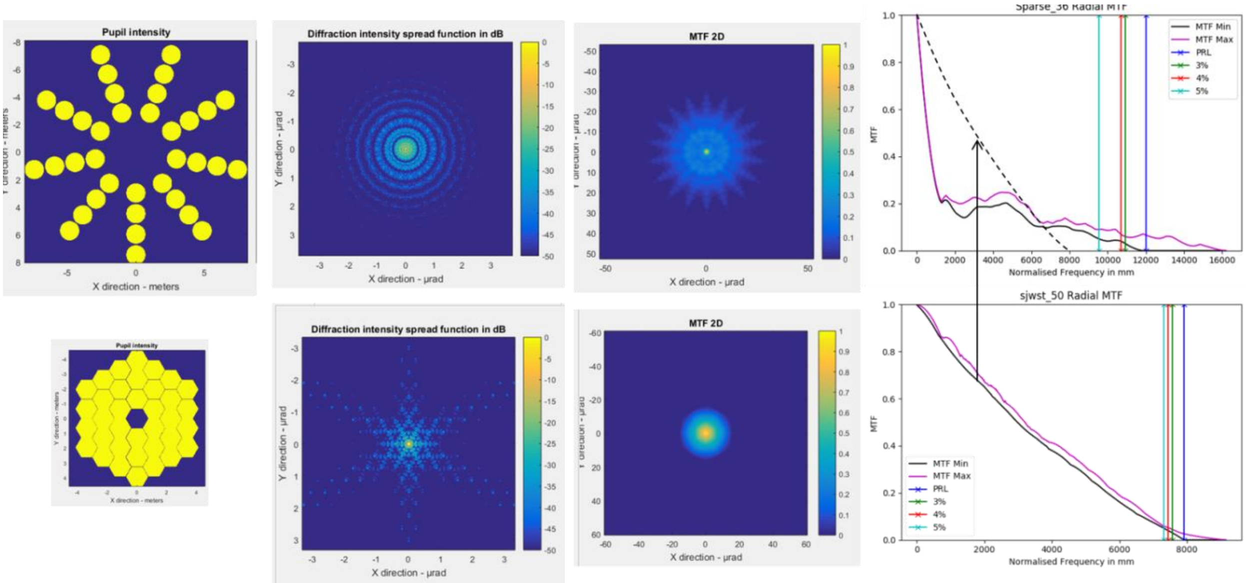


Figure 4-2: Interest of sparse aperture (Sparse 50m² on top – JWST type 50m² on bottom)

Comparison between hexagonal and sparse configurations was pushed un little bit further, showing interest of sparse system when combined with PSF recovery. This is shown on Figure 4-3 and Figure 4-4.

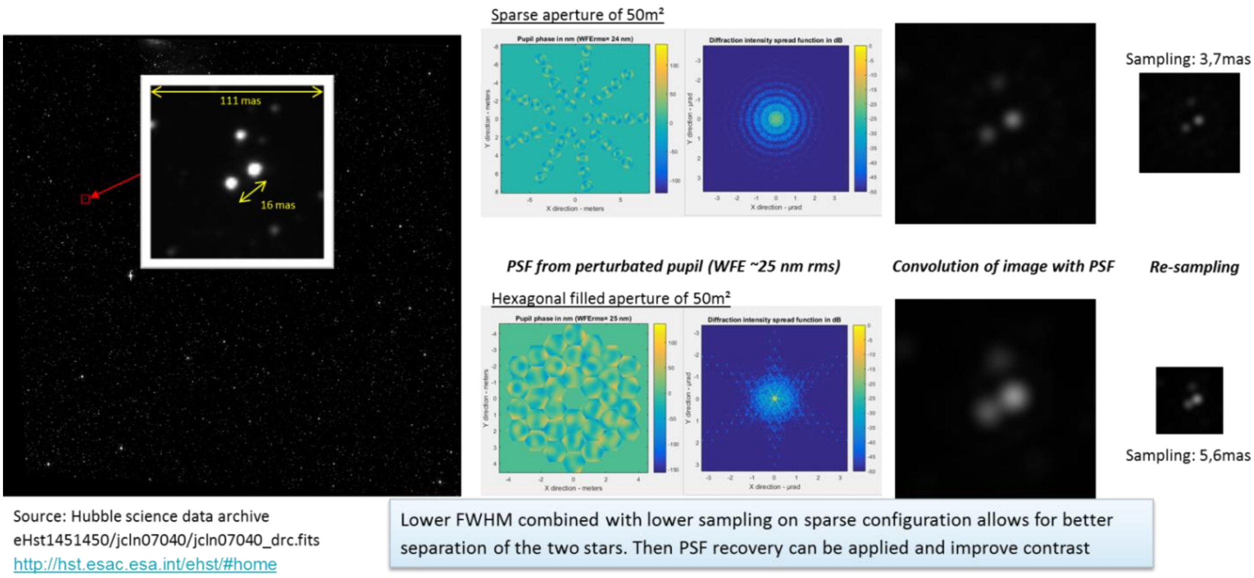
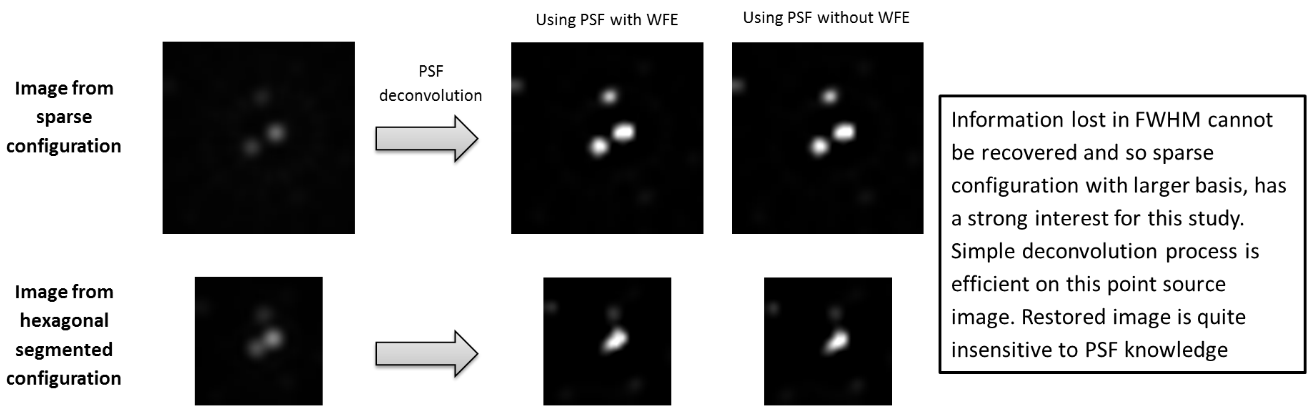


Figure 4-3: Comparison between Sparse aperture and hexagonal low-gap pupil- Nyquist sampling is finer on sparse for equivalent collecting area



Images with more structure inside would ask for more complex algorithms but astronomers have developed many tools, such as adaptive deconvolution, that can support this configuration

Figure 4-4: advantage of PSF recovery on sparse system (point source)

Previous phases of the study have allowed to derive main requirements for the deployable telescope concept (recalled on Figure 4-5).

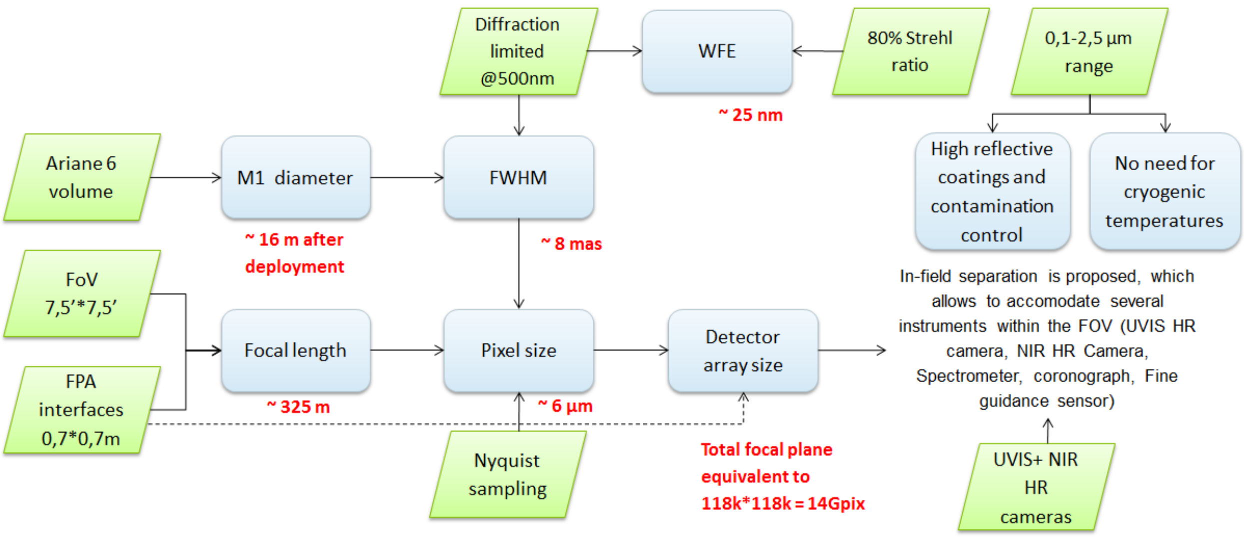


Figure 4-5: Derived requirements for the deployable concept (ESA Requirements in green, derived requirements in blue)

Optical configuration

The selected configuration is a cassegrain telescope with corrective mirror.

- Design features
    - M1 envelope: 16 m diameter
    - Focal surface 709x709 mm²
- Perfect image quality
    - 6.3 nm RMS in 7.5x7.5 arcmin² field
- Detectors are adjusted in focus and 2D tilt
    - With plane detectors, a minimum of 18x18 detectors for having 14 nm WFE performance
    - With identical spherical detectors, larger detectors can be used (the WFE is below 7 nm RMS)

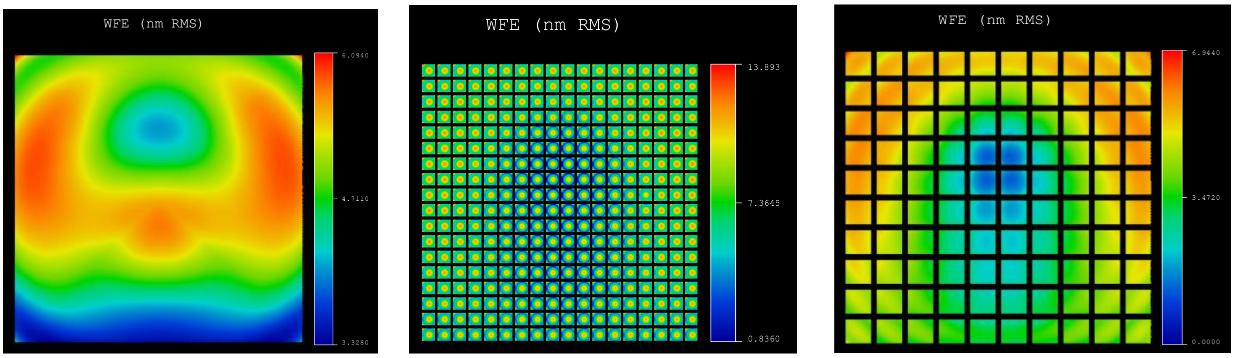


Figure 4-6: (left) WFE field map (middle) with 18x18 plane detectors (right) with 10*10 curved detectors

Primary mirror segment assembly (PMSA)

The overall primary mirror consists of 39 Primary Mirror Segment Assemblies (PMSA), spread into a 16m diameter area.

The Primary Mirror Segment Assembly (PMSA) is a challenging system with many interactions between components. Mass constraint is a critical driver but also adjustability in flight, verification aspects, development, etc.

Following constraints were considered:

- Achieve lightest design compatible of A6 capability
- Provide segment tip-tilt-piston adjustment over large range with nanometric resolution and stability
- Provide segment curvature adjustment to compensate for inter-segment polishing accuracy
- Ensure feasibility of blank manufacturing and polishing with large number of mirrors
- Ensure performance verification on ground and in-flight
- Provide compatibility with thermal control and decontamination means
- Ensure robustness to space environments

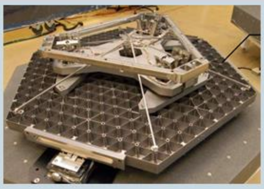
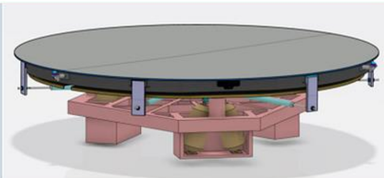
There are many potential applications of PMSA in science and earth observation:

- Alternative to large monolithic mirrors without deployment (Risk reduction, planning improvement)
- Deployable primary mirror: small gap (JWST) or large gap (Sparse aperture like VLST proposed concept)
- Synthetic aperture missions: single S/C (Geo-observation) or formation flying (Darwin type mission)

Airbus proposed a PMSA concept based on SiC mirror segment light-weighted at the same level as JWST beryllium mirror. Comparison with JWST PMSA is provided on Table 4-1. Some VLST technological gaps are identified with respect to JWST:

- Improved WFE : UV & VIS compatibility
- Mechanisms: 2 to 3 time better resolution
- Astigmatism compensation capability
- Ambient Temperature compatible
- No toxicity

Table 4-1: Comparison with James Webb PMSA

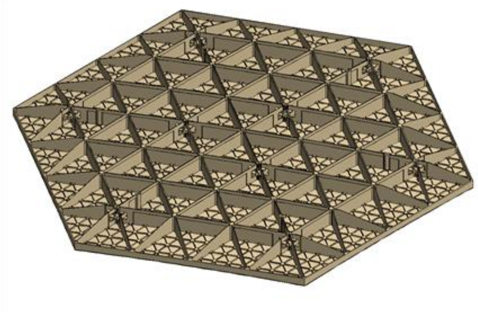
	James Webb PMSA	Airbus proposal with european partners (in the frame of VLST study)
PMSA	 40kg total PMSA / 1.4m² useful area	 Same objectives with european technologies Segment shape not a critical driver at that stage
Mirror	21kg Beryllium hexagonal segment (15kg/m²)	SiC mirror lightweighted @15kg/m² achievable REOSC heritage on E-ELT mirrors production
Mechanisms	Tip-Tilt-Piston and Curvature mechanisms (nanometer resolution class with large range)	Same needs with improved resolution Active suppliers on the subject Need for TDE/GSTP fundings

Mirror blank manufacturing

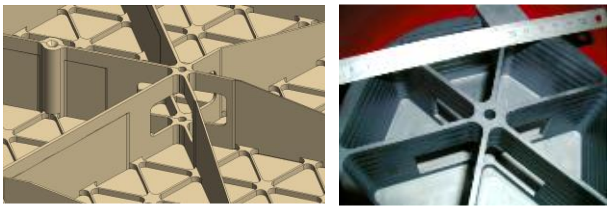
SiC material is selected as baseline for mirrors:

- Nearly the same areal density as Beryllium mirrors on JWST
- Only material option that can reach VLST mass allocation
- Can be used for cryogenic and ambient temperature applications
- Technological development identified on manufacturing and polishing domains
- Synergy identified for earth observation

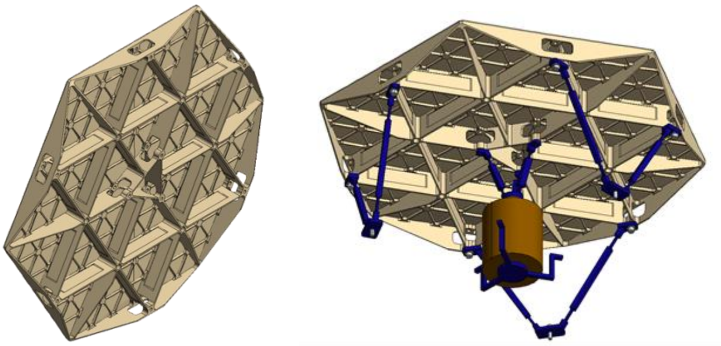
Airbus and Mersen Boostec were contracted more than 20 years ago by an US company to design a SiC mirror as an alternative to the JWST Beryllium mirrors. A less than 15Kg/m2 SiC mirror was proposed. Design, analyses and manufacturing assessment have shown that it was achievable. A mockup was also defined and proposed to validate performances under cryogenic environment.



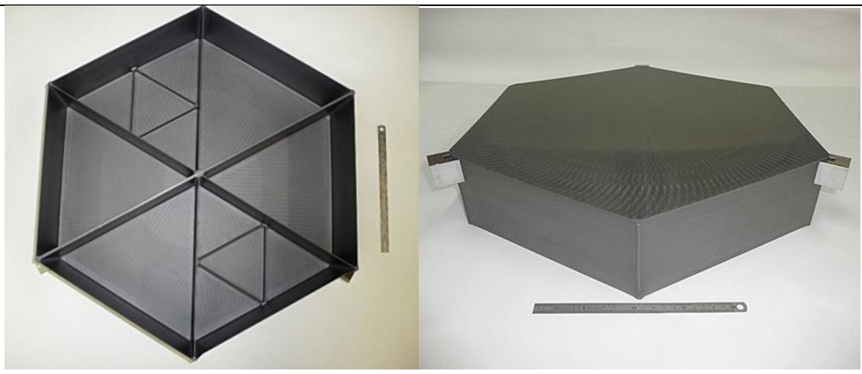
JWST M1 segment :
SiC definition (1,2m flat to flat)



Undercutting mockup

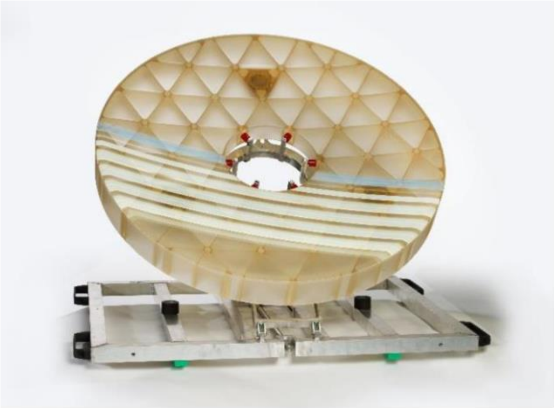


JWST M1 segment : mockup definition (0,5m)



OTOS SiC mockup (0,5m)

Zerodur could be also an interesting alternative for UVIS missions with much smaller collecting area. Technology is mature, and manufacturing tolerances could be allow high lightweighting ratio, but mechanical design would lead to 40kg minimum for one zerodur mirror segment (1st frequency, interface design, rods or mechanism supported by the mirror). Compared to the SiC mirror ~20kg, it leads to 780kg additionnal mass for zerodur option. Delta mass was not compatible of VLST requirements and SiC mirror was selected as baseline



Diameter:	1200 mm
Edge Thickness:	125 mm
Rib thickness:	2 mm
Light weighting factor:	88 %
Face sheet thickness:	8 mm
Weight:	45 kg
First Eigenfrequency:	> 200 Hz
Front figure tolerance:	< 15 µm

Passed thermal test confirming
NASA Technical Readiness Level (TRL) 6

Figure 4-7: Photo and characteristics of SCHOTT's extremely light-weighted polished mirror substrate

Very lightweighted Mirror polishing

In Europe, SAFRAN REOSC has demonstrated with GTC and ELT their ability to manufacture large number of high quality segmented mirrors. The production line dedicated to ELT mirrors will be compatible of VLST segments of the primary mirror polishing whatever the substrate material.

Figure 4-8: GTC Primary Mirror (Courtesy Safran-Reosc)

The extremely large class (ELT) of ground telescopes has also opened the field of large size convex secondary. Segmented primary sub-mirrors request industrial capacities and organization to produce numerous serial pieces.

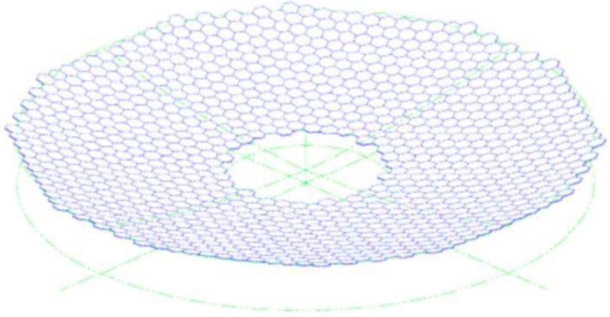
On ELT each of the 133 different types of mirror segment, depending on its location in the assembled primary mirror has its own CGH for WFE test.

The transfer of technology for SiC segments is applicable, except the quilting management which might be improved for very lightweighted SiC segments.

The management of quilting will be a fundamental aspect for the polishing of these mirrors:

- Safran Reosc has already set-up an anti-quiliting tool on the TANGO 1.5m M1 mirror (CNES)
- On the other hand Safran Reosc has past experiences of specific polishing tools which can limit quilting and for which tests are to be expected.

On mirrors less than 2.5 m in diameter, Safran Reosc has IBF machine that reduces the effects of quilting.



Main data	
Diameter	39m
Primary	Np = 6x133 = 798
Spares	Ns = 133
Total	Ntot = 931
Thickness	50mm
ROC	68685mm
K	-0.996473
Weight	175kg

Figure 4-9: ELT Primary Mirror (Courtesy Safran-Reosc)

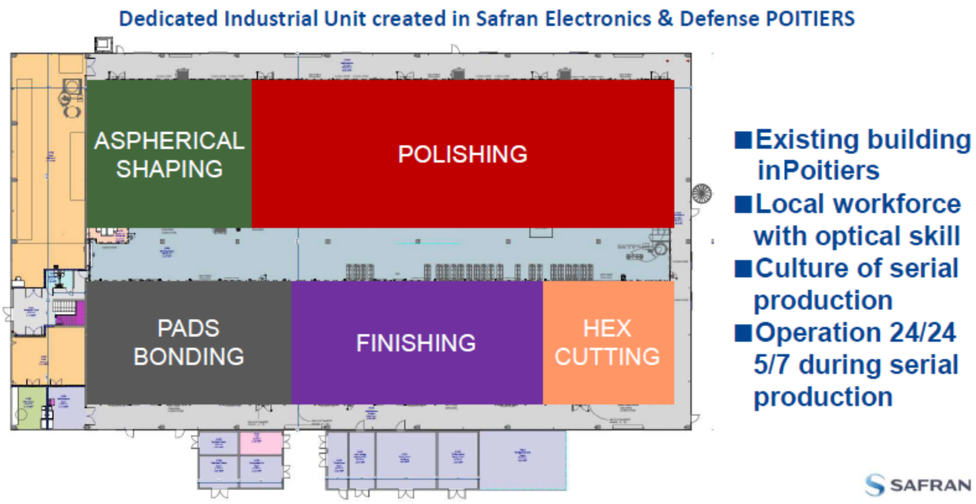


Figure 4-10: Safran-Reosc plant for ELT M1 segments polishing in Poitiers

__**Tip-Tilt-Piston mechanisms**__

This mechanism is very challenging:

- Very stringent requirements : nanometric resolution, millimetric range, high supported mass (30 kg). Hexapod derivated configuration 3 dof - actually (very) low TRL in Europe.
    - Closest heritage : refocusing (1 axis) and M2 mechanisms – but resolution far from sufficient (~ 50 nm)
    - US heritage : JWST (Ball Aerospace). Resolution to be slightly improved (ratio 3 typ) Combination of [Coarse + Fine] stages (stacked)
- TRL 'push' activities to be completed :
    - technologies feasibility assessment and preliminary specification iteration : identification of key requirements and design drivers.
    - mechanism concept : trade off (architecture, building blocks), baseline establishment, interface definition. Mass and recurring cost optimization (large amount of units)

This mechanism was largely addressed during the study, and roadmaps to develop such an actuator were established.

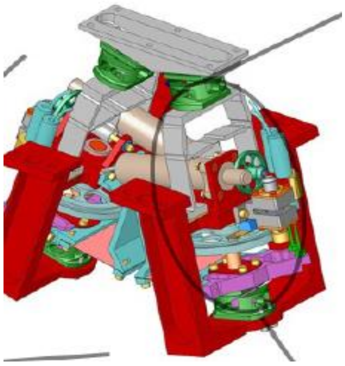
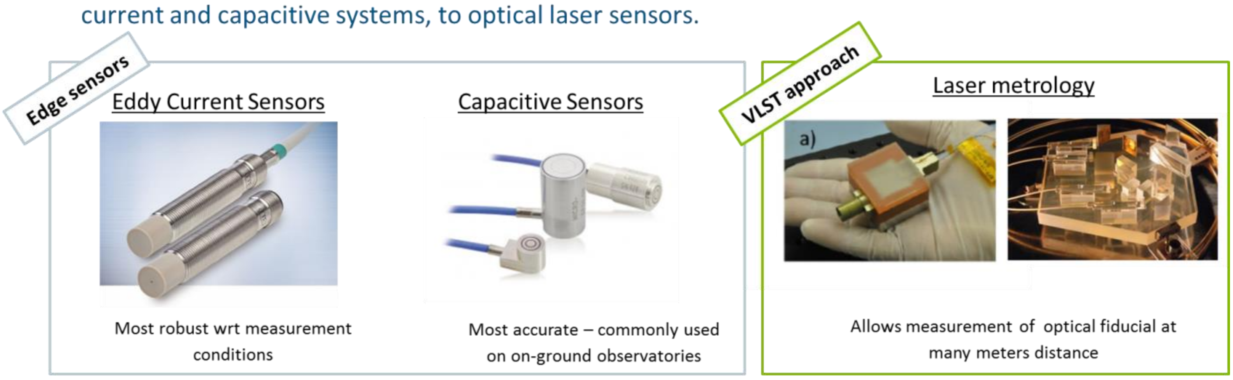


Figure 4-11: JWST actuator

<u>Nanometric positioning metrology</u>

- Once calibrated the M1 segments are monitored with non-contact metrology
  - When possible, edge sensors can be used as it is already the case on JWST and earth based telescopes (E-ELT, KECK), when gaps between segments are small
- These metrologies can use different technics from traditional electromagnetic sensors such as eddy current and capacitive systems, to optical laser sensors.



<u>Cophasing technics</u>

The deployment of the Keck telescope, in which the primary mirror consists of 36 hexagon mirrors and the diameter reaches 10 m, demonstrated the success of the solution of a segmented mirror in the application of a large aperture telescope. The James Web Space Telescope (JWST) also employs a segmented mirror to design the primary mirror with an advanced accurate control device and algorithm.

Generally, cophasing contains several steps: segment searching, coarse alignment, coarse phasing, and fine phasing. The Jet Propulsion Laboratory (JPL) developed a multi-step stacking process to realize cophasing for JWST based on combined techniques such as phase retrieval and dispersive fringe sensing.

For VLST, we propose a direct tip–tilt and piston error detection approach for a segmented mirror without introducing any extra sensor or device such as the above mentioned cophasing techniques. Depending on future definition of focal plane instruments, the cophasing technics could be adapted using he instruments features. As instance, on JWST, coarse phasing baseline uses Dispersed Hartmann Sensors (DHS) in the NIRCam short wave pupil wheel in order to infer large relative piston offsets between individual segment pairs.

PMSA technological roadmap

The PMSA is a small system associating critical technologies where Europe can be competitive!

Experience gained by SAFRAN REOSC on E-ELT is a major asset, in particular on large number of segments. TDE/GSTP funding is needed to develop TTP mechanisms technology.

A general roadmap is proposed on Figure 4-12with the first objective to develop and qualify a PMSA demonstrator including all individual technologies:

- Mirror manufacturing, polishing and coating
- Tip-Tilt-Piston mechanisms
- Curvature adjustment technology
- Needed metrology

The second objective is to develop a complete breadboard with 2 PMSA units, in order to demonstrate co-phasing capability and performance.

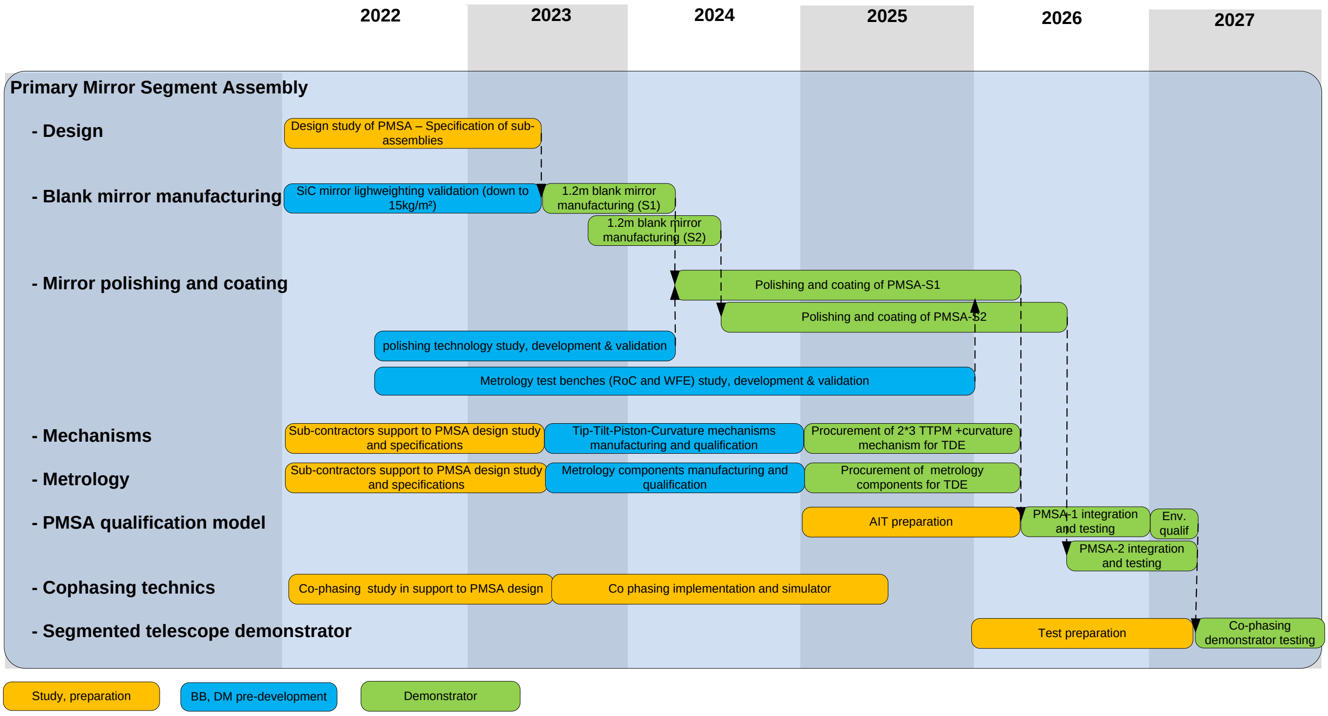


Figure 4-12: Technological roadmap for primary mirror segment assembly (PMSA) development

Secondary mirror boom

The key requirements are:

- 10 m deployment stroke - plus 5 m fixed base segment
- Deployment accuracy : 5 mm target / < 50 mm
- Deployment eigenfrequency

To comply with the very demanding volume allocation in stowed configuration (arms stowed), the reference concept is relying on a deployable boom for the M2 assembly erection as shown on Figure 4-1.

Other concepts were considered, such as a tripod but with detrimental consequences in terms of accommodation and overall stowed bulkiness. In that extend, the review of the state of the art is focused on deployable mast concepts.

Technological roadmap is proposed:

- Specification refinement : environments, resistive and disturbing forces, etc
- Design optimization : number of segments, section dimension, stiffness
- Demonstrator build to consolidate functional / repeatability / accuracy / stability
    - achieve TRL 4
    - balance performances between M2MM & boom : stroke and resolution
    - positioning tuning capability – axially in particular.
- Demonstrate suitability wrt the environments : mechanical vibrations, TED. Evaluate effects on performances (repeatability, etc).

Synthesis for deployable concept

Baseline for deployable concept is proposed and shown on Figure 3-9:

- Cassegrain telescope with a reflective corrector
- Featuring 39 Primary Mirror Segment Assemblies (PMSA)
    - Mirrors of 1,3m diameter on each of the 9 arms
    - 3 mirrors on central structure
    - SiC Mirrors lightweighted @15kg/m²
    - Each mirror is adjustable in Tip-Tilt-Piston and curvature at nanometric level
- 9 deployable CFRP arms supporting 4 PMSA each
- A deployable boom of 16meters height supporting:
    - M2 SiC mirror of 1,4m diameter
    - M2 mechanism with 5 degrees of freedom
- Central CFRP structure supporting the boom and one folding and one freeform mirror
- Rear screen supported by primary mirror arms

Main predevelopments were identified as critical to enter into B2/CD phase for such mission:

- Nanometric TTP mechanisms
- Very lightweighted mirrors manufacturing and polishing with large number of segments
- Primary mirror segment assembly design, development and qualification
- Telescope breadbording with 2 segments for cophasing validation
- UVIS coatings
- Boom deployment

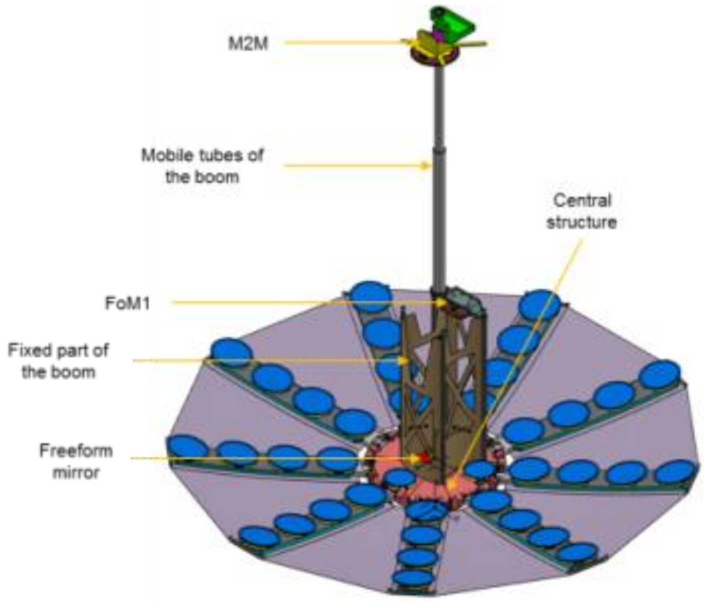


Figure 4-13: deployable concept preliminary design

5 CONCLUSION

This document describes briefly the outcomes of VLST study. A complete set of documentation of 13 technical notes were provided to ESA. Recommendations on technological roadmaps are proposed for the next upcoming years in relation with relevant heritage gained on previous programs, current R&D, as well as current development on on-ground observatories such as E-ELT. European companies have relevant expertise to face these new challenges of UVIS large telescope for space.

Airbus team was excited and invested all along the study and thanks ESA, Dominic Doyle and Luca Maresi to have placed their trust in Airbus to address these fascinating telescopes. We are looking forward to pursue activities in the continuity of this study.