TALC A FAR-INFRARED 20M SPACE TELESCOPE AND THE ELICSIR CONSORTIUM TO REACH TRL 3

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1. INTRODUCTION

Further space exploration in the far-infrared (FIR) requires larger apertures in order to improve the spatial resolution of captured images. To this purpose, the **Thinned Aperture Light Collector (TALC)** concept of a deployable annular telescope has been recently developed at CEA, which offers novel perspectives for FIR space missions. The consortium **ELICSIR** consortium of European institutes and companies has been created to improve the technological readiness level (TRL) of its key systems and components.

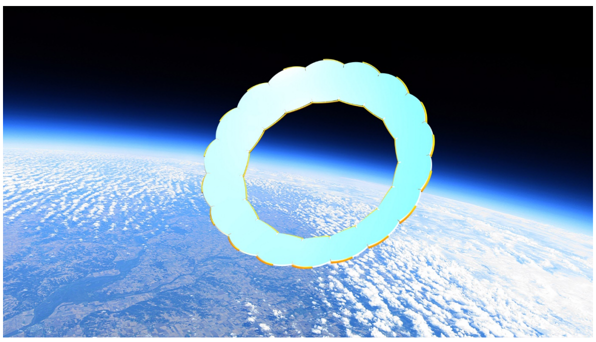


Fig. 1. M1 ring , an assembly of 18 panels

2. TARGETED BREAKTHROUGH, LONG TERM VISION AND OBJECTIVES

Because of the impossibility for astronomers to build experiments to test their hypotheses, astrophysics is likely that part of natural sciences where the largest effort is made on data collection. And since astronomical data essentially mean photons, each domain of the electromagnetic spectrum matters. Some regions of this spectrum are more challenging, among which the mid to far infrared domain (MIR-FIR) is of particular interest. From typically 30µm to 500µm we find a number of unique signatures related to the co-evolution of massive black- holes and their host galaxies, the origin of the initial mass function for stars, or the initial conditions of planetary systems. However, because of our atmosphere, these wavelengths can only be collected from space observatories. This creates a severe technological limitation, as any observing facility needs to be launched into space, imposing strict boundaries in mass and volume to these observatories. This is amplified by the fact that access to space is now driven by recurrent commercial satellites rather than scientific exploration. Those commercial driving needs are not going toward larger launcher capabilities while scientific requirements could be summarized rapidly as a quest for higher angular resolution and sensitivity, and therefore larger observing facilities.

The scientific community has accumulated a string of successes in MIR-FIR astronomy, starting with the IRAS mission in 1983, and culminating with the Herschel Space Observatory in 2009. Europe fared well in this endeavour, with Herschel being internationally recognized as a success. Yet the current approach of monolithic mirrors reached the launcher limits with Herschel. This 3.5 m SiC mirror telescope was an extraordinary achievement of the European community, but in its wavelength range, it delivered an angular resolution no better than Galileo's telescope in the 17th

century. The state of the art facility under construction is the NASA-JWST to be launched in 2018. Its 6.5 m primary mirror design is however still relying on standard mirror fabrication material and process (Beryllium polished mirrors), simple folding topology, and active optics supported by a stiff structure. The cost and development duration of this program revealed clearly the limits of this approach, in terms of technology and processes. As future science needs will require exceeding the capacities of even the JWST, we need to find a path that escapes this deadlock. The mission concept we propose is based on science requirements derived from Herschel's advances, and an innovative system approach for the mission implementation leading to the Thinned Aperture Light Collector (TALC) concept.
The stake of this project is to propose a mission at the cost of a large ESA mission, with resolution to below 1 arc-second at 100µm, 150 m2 of collecting area, and observation capabilities of wavelengths between 30 µm and 500 µm. In order to keep the cost and time schedule of this sub-mm telescope reasonable, with dimension large enough to reach high resolution, radiative cooling will be used on the main mirror. The construction of the main mirror segments will use CFRP structure and replica process. The construction will use of electrically controllable smart structures to set both the mirrors and the optic system at the shape. In addition to the technological innovations, this telescope will require a disruptive reliability analysis since there is no way to test such a large structure under vacuum, working temperature near 40K and simulation of absence of gravity on earth. In order to avoid deadlocks in the design, our strategy relies on simulations and as well as test of breadboards since the early stage of the project. Talc consists of very few sorts of items built in large series, both for cost savings and reliability reasons. A reliability analysis is being initiated at same time as feasibility study in order to decide if any sub-system is made robust to single point failure or may made robust by redundancy.

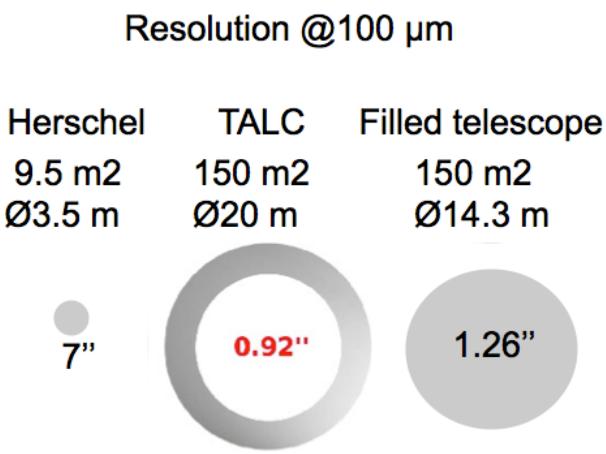
The current design of the TALC telescope features a primary annular mirror of 20 m diameter fitting within mass and volume constraints of the future Ariane 6 fairing.
The TALC concept goes beyond the state of the art by changing the system design approach and relying on:
• An innovative deployable mirror whose topology is based on stacking as a pile of dishes rather than folding, leading to an optimum ratio of collecting area over volume;
• A tensegrity structure of a ferries wheel to hold the segments of the ring mirror in place with stretched spokes surrounding a central mast;
• A lightweight segmented primary mirror, based on electrodeposited nickel, carbon composite and honey-comb stacks, built with a replica process to control costs and mitigate the industrial risks;
• A laminated active compound will be located in the rear layer of the honeycomb to control the shape by in-plane forces instead of the conventional normal-force actuators that require a rigid support structure.
In this paper, we present the progress we have made in the deployment principle that increases its efficiency and robustness, and outline some of the salient points of the roadmap we are building to deliver on each of the four aspects listed above so that these technologies reach a readiness level that is mature enough to allow the astronomical community to prepare a future MIR-FIR large space mission for the post-JWST era (here the term "large" refers to the ESA mission standard, i.e. a mission with a cost of around 1 billion Euros).

3. CONCEPT OF TALC

3.1. Design criteria Active control

In order to reach resolutions below 1 arc second, the shape of all components of the telescope shall be manufactured and kept stable within 10^-6 in the temperature range. Since the telescope will be manufactured at room temperature and will be used near 30K, the unique way to build such a large structure is to make it fully actively controlled. Measurement of the OPD will be performed preferably using phase diversity methods, in the near infrared, with resolution that will surpass the requirement for far-infrared observations. Actuators for the active control will be required at several scales. At large time scales active control will consist of set & forget systems such as remnant piezo or electromagnetic servos. These actuators will be used to control manufacture errors as well as errors due to CTE after cool down. At short time scale the actuators will be used in closed loop to damp vibrations or to control for small temperature gradients.

3.2. Design criteria Ring telescope



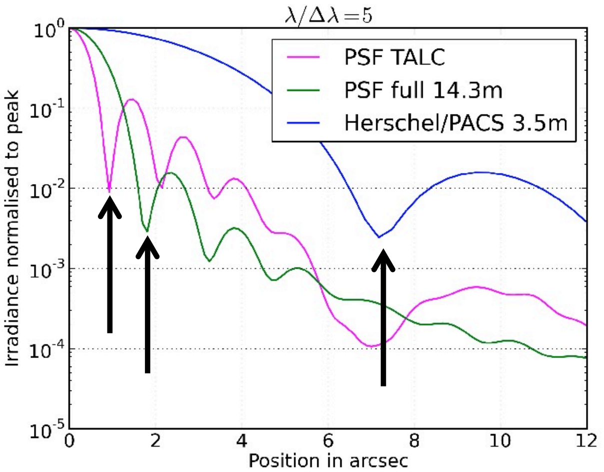


Fig.2 PSF of TALC, first zero of d'Airy disk

Using an reconstruction algorithm the ring telescope provides much higher resolution for a given surface of mirrors.

3.3. Design criteria passive cooling

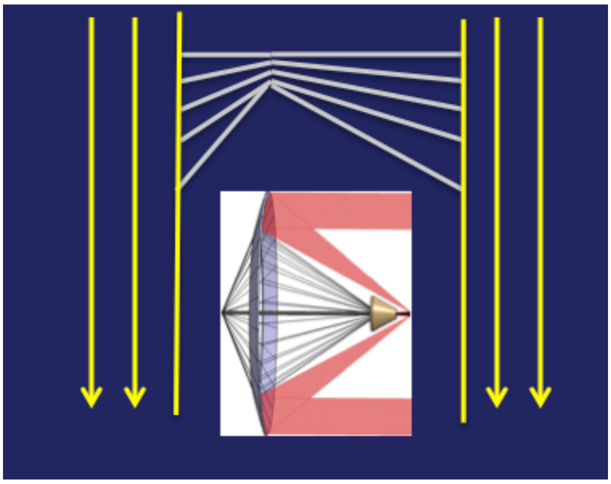


Fig.3 TALC behind V-groove shield.

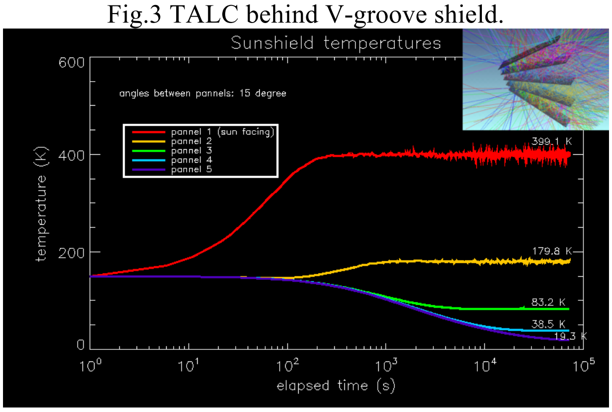


Fig.4 Temperature of the layers of the V-groove versus time

We prefer to search for an efficient passive cooling instead of building a complex cryogenic system to cool the mirror. This design choice gives access to a much larger telescope at smaller cost for a given mass. We envisage to use high TC supra-conductive coating as an alternative to aluminium or gold coatings in order to decrease the infrared background.

To launch effectively large structures at an acceptable cost, their design must rely on elements produced in series, these elements must consist of lightweight material with a low coefficient of thermal expansion, and we must validate efficient, robust and reliable deployable structures. In these three areas our proposal goes significantly beyond the state of the art. The general shape is the one of a ferries wheel with a central pole, spokes and a rim that supports the segments of the M1 mirror.

Innovative deployable mirror: One of the key innovative concepts that will be validated is the topology for a deployable, segmented mirror that has been studied since 2012 at CEA. Inceptive work on this concept started in 2011 for the study of a 40-m Sub-millimetre telescope at Dome C that we re-oriented toward space application due to its high disruptive potential. Three years of mechanical developments, including the realization of a 4-m diameter fully deployable mock-up allowed refining our design.

During launch, the segments of the main mirror are stowed inside the fairing back to face as a pile of dishes, next to the central pole of the telescope. Each spoke consists of a cable that is stretched in straight line by means of a spring-loaded winch between one side of the pole and one side of the scissor system.

The deployment sequence is separated into three successive sequences: extension and positioning of the central pole at final distance from the pile of mirrors until the cables reach a stop, extension of mirrors circumferentially using the panthograph scissor system around the central pole until the end mirrors connect to each other using landing cones, final extension of the central pole until all cables are stretched at their desired constraint.

Fig. 2. Static model of Talc diameter 4m

This topology maximizes the mirror surface for a given stowing capacity. The kinematic of deployment has evolved so that the mirrors are stored parallel inside the fairing (providing higher resistance to launch) and deploy towards a parabolic position (see Durand et al. 2014 SPIE 9143, id91431A).

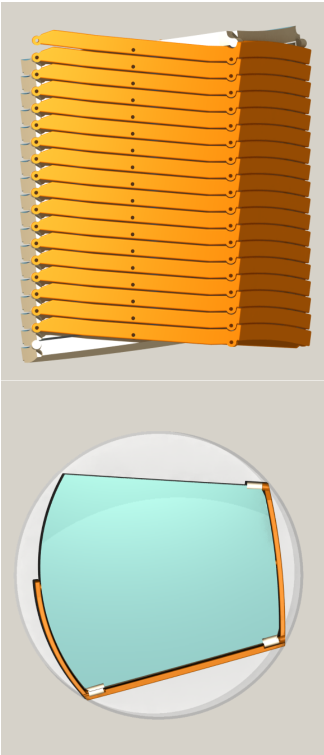
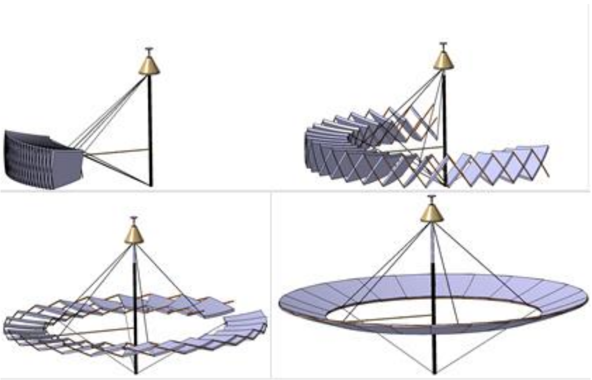


Fig. 3. M1 segments stacked parallel in the fairing

With a fairing of 4.2 m usable diameter (e.g. an Ariane 6 launcher), 18 segments allow to deploy a 20 m diameter telescope, 24 segments a 25.5 m diameter telescope. We are developing the 20 m telescope with 18 segments, in order to keep the structure easily controllable.



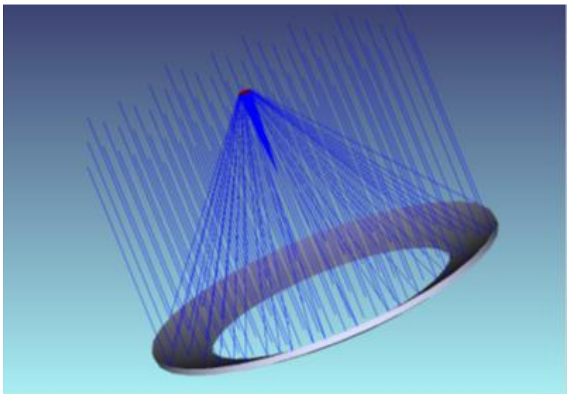


Fig. 4. Deployment of M1 mirror of TALC

Ultra-light weight replicated mirror: Fabrication of lightweight mirrors for space applications has proven to be an extremely difficult problem and is at the core of research and developments at the main space agencies. Carbon fibre reinforced polymer (CFRP) is an ideal candidate for ultra-light weight mirrors working at cryogenic temperature because of its low areal density, high elastic modulus and coefficient of thermal expansion (CTE) that can be tailored to low or zero. However, the capability to build CFRP mirrors with good optical quality is limited by surface distortion called fibre print through. Our study will consolidate the design of CFRP mirrors identified as a key enabling capability for the TALC telescope through test mirror manufacturing, paying special attention to fibre curing and layering processes that lead to print-through. We will focus on mirrors with high optical quality at 30μm, but the knowledge gained will be scalable toward shorter wavelengths, opening new possibilities in the IR and in the visible for astronomy but also for earth-observation programs. We will aim at validating production of mirrors based on replication, which ensures better control of the costs, a particularly important item for a project of the size of TALC.

Active optics control: Implementation of active optics control is a promising avenue to reach high optical quality on large structures. It reduces the mechanical surface front error requirement by ensuring that the final shape is recovered actively through a control loop. The global image quality needs to be ensured by (1) manufacturing for the smallest cell that cannot be corrected by active control (30-cm in this project), and (2) by active optics correction on larger scales. The active optics layers will be incorporated into the rear side of the mirror, departing radically from standard corrective optics that relies on reaction actuators attached to a rigid reference frame. Our design for a typical 4-m panel would rely on 2 layers of active optics grid for shape correction. The first one, coarse and constant, to correct the first low orders of deformation, the second, meshing the mirror with a typical sub-30-cm cell pattern, to correct for higher spatial frequencies.

4. SHARE OF TASKS WITHIN ELICSIR COLLABORATION

4.1. Work package "Deployment and Dynamic Control Studies"

The goal of work package "Deployment and Dynamic Control Studies", led by ULB and INSA, is to design, manufacture and test at ambient and in cryo-conditions the deployment system on mock-ups of different scales chosen to explore scalability laws. ULB, INSA and CEA will perform numerical studies of the vibration modes of the structure during deployment and after closure, as well as of the control and active damping mechanisms needed to guarantee the integrity of the system. This will be correlated with low level vibration tests performed at ambient on a complete scale 1/10th mechanical model. The damping of the vibrations to ultra-low level is required in order to keep the PSF stable for long observing periods. Main sources of vibrations are the compressors of the cryo-coolers, the reaction wheels and the pointing process.

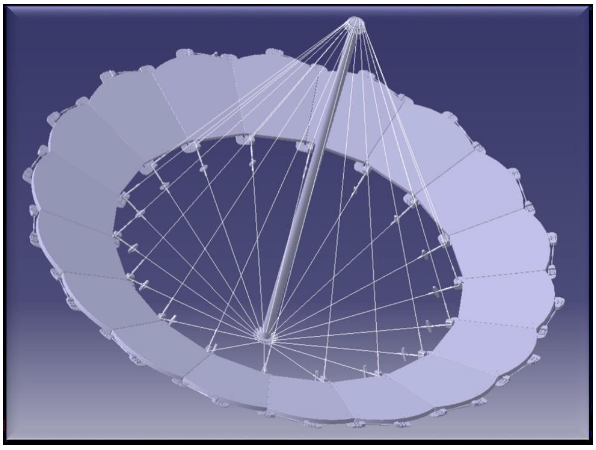


Fig. 5. Scale 1/10 Vibration model on construction at ULB Bruxelles

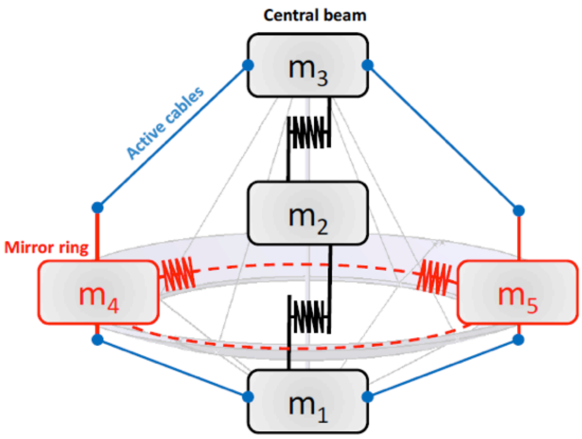


Fig.6 Model of the active damping for TALC

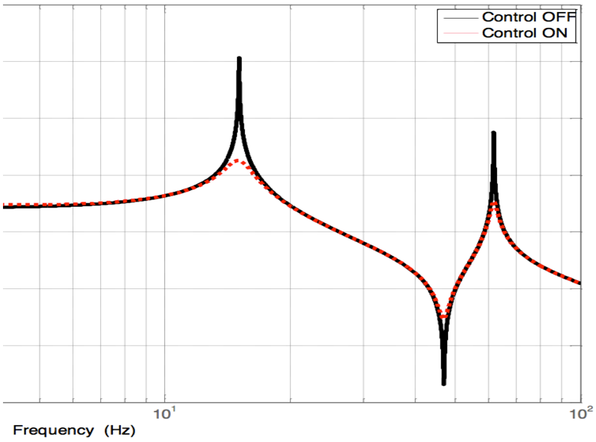


Fig.7 Simulation of active damping using 4 actuators

Mechanical tests will also be performed on a scale 1/3rd model of three articulated segments (Figure 1). The three segments will be representative of the actual mirrors in terms of process, interface, mass and thermal behaviour. The structure will be equipped with metrology targets to qualify the deployment strategy in terms of accuracy, repeatability, and 3-degrees of freedom correction. The deployment structure will be designed by CEA/INSA/ULB, manufactured by Multiplast, and tested at CEA re-using existing and available large cryo-facilities developed for W7X fusion coils testing (4.5 x 4.0 m, operating at 70 K).

All along the life-cycle of the project, an integrated thermo-mechanical model of the full-scale telescope will be developed and maintained by CEA with elements from the different partners. This model will be correlated with the test results on the various mock-ups at warm and cryo-temperature to ensure scalability toward the 20 m size structure. This Finite Element Model (FEM) will allow for prediction of the final performance of the system. At the end of the study, this FEM of the full system will allow for the derivation of the expected performance of the final system at full scale (20 m) and operational temperature (40 K). The reliability analysis of the hinges and the actuators is a challenge. Each of the 18 mirrors panel is equipped with 4 axial bearing and one annular linear connection. Hence the stack of segments has a mobility of one during unfurling, 72 bearings and 18 linear annular links will be actuated in parallel. Since each connection is a single point failure, a strong care will be required to avoid cold-welding in vacuum, slip-stick or excessive friction. Several actuators will be installed on the axis between the segments and the C-beam brace surrounding them. These actuators will be made redundant, using motors without friction torque at stall. During the qualification process a very large number of deployment and furling is foreseen. It is therefore required to build fully reversible mechanisms in order to preform these tests. It will be later decided to keep reversible actuators or to install spring back actuators.

Fig. 6. Deployment of subset of segments of TALC to be tested in cryogenic conditions

The goal of work package "Lightweight Optical-Quality Mirrors", led by Media-Lario, is to manufacture a 1.2 m parabolic demonstrator of a low-density mirror with optical quality (diffraction limited performance at λ = 30µm). The 1.2 m size requirement derives both from the analysis that this is required to identify processes that will scale up to the 4 m size of TALC's panels and from the consideration that this size is required to plan future commercial applications. Scalability toward a 20 m structure imposes an aim of an overall density of 10 kg/m2. The material of choice is carbon fiber and honeycomb, but designing how these elements have to be assembled to achieve the optical quality goal is the major challenge. The baseline proposed by CEA is tailored to the objective of relying on replication methods: the layers of the mirror must be grown from the reflective surface upward such that the process propagates the optical quality of the mould surface toward the structural elements.

The process will start from a nickel layer electro-deposited on an optical quality mould, to continue with adding carbon structural elements on the optical Ni layer still on the mould, all at low temperature to preserve the mould quality. Media-Lario, a specialist of electro-deposition, will perform the first step of depositing nickel on optical quality moulds. This Ni layer will then have to be bonded with a composite of carbon pitch fibre and honeycomb, providing the rigidity of the structure at low weight. Multiplast and North-TPT will develop a European source of Cyanate-ester honeycomb, and of Cyanate-ester pre-preg carbon pitch fibre low ply density (<50 gr/m2), to meet the needs of polymerization at low temperature and low coefficient of moisture expansion (CME). Mating the carbon structure to the nickel skin will be a specific challenge of this research task to be tackled both by Media-Lario and Multiplast. The challenge will consist in defining the bonding process, the optimal angles between each fibre layers and the number of layers so that the honeycomb does not print-through. The industrial partners are up to this challenge, combining significant experience in composite mirrors (Media-Lario), heavy investment in R&D on carbon materials (North-TPT), and worldwide leadership in large carbon structure and manufacturing capacities (Multiplast, where we will make use of an automatic plotter capability of 8 m x 2.5 m), while INAF and CEA provide their expertise for qualifying the optical quality at room and cryogenic temperatures.

4.2. Work package : Active optics control

The goal of the work package "Active Control of Mirrors Segments", led by Muenster University of Applied Sciences, is to design, integrate and test the performance of a planar piezo- electric control layer at the back of a composite mirror. The work shall characterize the transfer function from the back layer to the optical layer in order to determine the capabilities of actively controlling and correcting the deformations on spatial scales larger than the unitary cell on which surface errors can be controlled by manufacturing for a reasonable cost. A number of 40 cm diameter composite mirrors will be manufactured by Media-Lario for this purpose. These will sample different thickness-to-diameter ratios: (a) mirror thickness homothetically reduced from the 1.2 m segment size in order to probe which modes can be corrected by the active optics system, (b) mirror thickness equivalent to the expected final thickness of the 1.2 m mirror in order to characterize the scalability of the transfer function from the control layer to the optical layer, and (c) a thin mirror to allow testing the option of applying correction at a pupil relay position.

This range of structures will allow testing a number of strategies both for manufacturing the mirror and for implementing the correction layer, thus feeding the trade-off analysis activity. Here as well the mirror size is driven by an analysis of the scale at which the performance becomes scalable to the full scale and at which we will have demonstrated a significant disruption with respect to the state of the art.

4.3. Work package : System Engineering

The goal of the work package "System Engineering and Trade-Off Analysis", led by CEA, is to ensure that the three lines of R&D are fully coordinated toward the ultimate goal of ELICSIR.

The design of the large TALC mirror is a sweet spot between stability of the deployed structure, optical surface quality on small scale of composite mirrors, and capacity to correct accurately the full-scale 4 m segments through active optics, all geared toward delivering performance that is requested by science objectives. Therefore, all along the life cycle of the project, the system-engineering group will integrate the latest results into a trade-off analysis in order to rebalance the ultimate requirements between the different actors. This will prevent the study from being locked on local issues that can be solved at system level. In addition, as the verification approach of such a large system cannot rely on ground testing at full-scale (the JWST is already using the largest facility available on the planet), we will also focus system activities on the correlation of analyses based on mathematical models of the full-scale structure with hardware tests and measurements on physical models (full telescope 1/10th mechanical model for vibration, 3-segment mechanical 1/3rd model for deployment, mirror segments for optical quality tests).

5. ROADMAD FOR THE FOLLOWING YEARS

TALC is a proposal for a large mission. While a medium mission as Euclid requires 15 years of development, TALC requires about 25 years from concept to launch. As a European flagship, TALC shall include high innovation content both for the telescope and the instrumentation part.

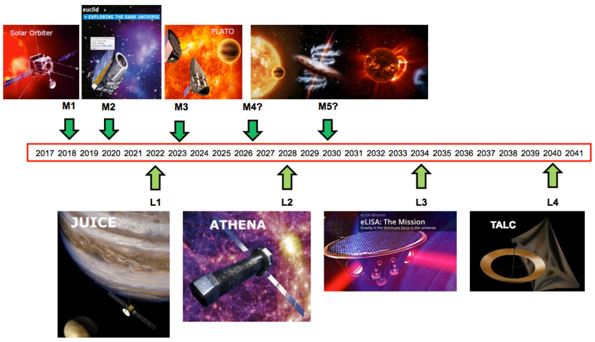


Fig. 6. Framework: Cosmic Vision Program

Period 2013 – 2020: Initial technology development shall be initiated with focus on:

- Lightweight mirrors
- Deployable structure
- Tensegrity structure
- Active optics

Period 2021-2023

- TRL5 must be demonstrated at beginning of implementation phase
- Some technological developments are accepted for L-class within the 2-3 years following adoption.

Period 2020-2022:

- Selection / Approval: 2020-2022
- Development / Implementation: 2022-2040
- Operations: 2040-2045

On the scientific field, the roadmad of the Talc team is to prepare Far-IR mission and to gather a scientific community from multinational contributors that have experience and interest in the post – Herschel/ALMA/JWST era.

On the technical field, the roadmap is to consolidate the System Engineering at Mission levels through trade off analysis and preliminary design of Mission (Telescope / Instrument / AOCS / Concept of Operation and Ground Segment) to support a future Mission concept costing and proposal.

The first action was to identify the key critical components and take actions to raise them to acceptable level in order to match Cosmic Vision TRL requirements. This is the purpose of the TALC H2020 proposal supported by the ELICSIR collaboration.

When the key components will be validated at a level of TRL3, the next action will be to use funding from ESA within TRP, CTP or GSTP programs to raise the programs to TRL5.

6. CONCLUSION

The concept of a deployable ring mirror whose structure uses the tensegrity of a wheel is a rupture innovative concept. It gives access to large collecting area, high stiffness and lightweight. The maturity of the key components will allow to build telescopes for telecom as well as for shorter wavelength.

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