

# A development roadmap for critical technologies needed for TALC: a deployable 20m annular space telescope

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## ABSTRACT

Astronomy is driven by the quest for higher sensitivity and improved angular resolution in order to detect fainter or smaller objects. The far-infrared to submillimeter domain is a unique probe of the cold and obscured Universe, harboring for instance the precious signatures of key elements such as water. Space observations are mandatory given the blocking effect of our atmosphere. However the methods we have relied on so far to develop increasingly larger telescopes are now reaching a hard limit, with the JWST illustrating this in more than one way (e.g. it will be launched by one of the most powerful rocket, it requires the largest existing facility on Earth to be qualified). With the Thinned Aperture Light Collector (TALC) project, a concept of a deployable 20 m annular telescope, we propose to break out of this deadlock by developing novel technologies for space telescopes, which are disruptive in three aspects:

- An innovative deployable mirror whose topology, based on stacking rather than folding, leads to an optimum ratio of collecting area over volume, and creates a telescope with an eight times larger collecting area and three times higher angular resolution compared to JWST from the same pre-deployed volume;
- An ultra-light weight segmented primary mirror, based on electrodeposited Nickel, Composite and Honeycomb stacks, built with a replica process to control costs and mitigate the industrial risks;
- An active optics control layer based on piezo-electric layers incorporated into the mirror rear shell allowing control of the shape by internal stress rather than by reaction on a structure.

We present in this paper the roadmap we have built to bring these three disruptive technologies to technology readiness level 3. We will achieve this goal through design and realization of representative elements: segments of mirrors for optical quality verification, active optics implemented on representative mirror stacks to characterize the shape correction capabilities, and mechanical models for validation of the deployment concept. Accompanying these developments, a strong system activity will ensure that the ultimate goal of having an integrated system can be met, especially in terms of (a) scalability toward a larger structure, and (b) verification philosophy.

**Keywords:** lightweight mirrors, active optics, deployable telescope systems, carbon fibre, carbon composite structures, far-infrared space astronomy, actronics, automation

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## 1. INTRODUCTION

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  $30\ \mu\text{m}$  to  $500\ \mu\text{m}$  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 17<sup>th</sup> 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.<sup>1</sup>

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 rather than folding, leading to an optimum ratio of collecting area over volume;
- A lightweight segmented primary mirror, based on electrodeposited nickel, carbon composite and honeycomb stacks, built with a replica process to control costs and mitigate the industrial risks;
- An innovative active optics control layer in the mirror rear shell allows controlling 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 three 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).

## 2. EVOLUTION OF THE TALC CONCEPT

### 2.1 Structure of the annular telescope during observation

Ring telescopes have been proposed previously since they offer higher resolution than filled telescopes for a given pupil surface. Given a proper processing to account for their particular PSF they can also even approach the spatial resolution of filled telescopes of similar diameter for narrow bandwidth images.<sup>1</sup>

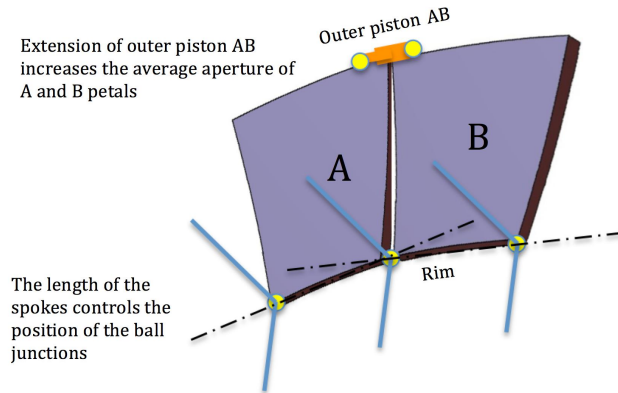


Figure 1. Two segments of the annular mirror in deployed state. The wheel structure (of which we show part of the spokes in light blue) holds the rim in place. The rim structure is made of a series of connected rods and ball junctions. The piston AB that links neighboring segments on their outer rim controls the global opening of the annular telescope. On the complete structure the ensemble of pistons has the authority to control the aperture of all the segments.

The tensegrity structure of a wheel with stretched spokes, compressed rim and compressed axis is among the preferred lightweight structure. Using this structure, Ferris wheels<sup>2</sup> are the largest moving objects on earth. For bicycles, wheels with spokes are used in the entire range of cost and usage with unsurpassed robustness-to-weight ratio. For these reasons we have chosen a wheel structure as the basic structure of our telescope. A close view on Ferris wheels shows that the rim in compression has the shape of a polygon, and we use each side of this polygon as an axis along which we can orient each segment of the annular mirror (see Figure 1).

The rim does not need to be manufactured as a continuous structure. When it is in place, it may consist of a series of connected rods linked by ball junctions at the end of each pair of spokes. The connecting rods can be made very lightweight as the amount of matter in their structures is mainly driven by the risk of buckling. In the case of a wheel with many spokes, the connecting rods are short and resistance to buckling is very high.

The strength of this design is that it suppresses the supporting structure for the mirror. Provided a mechanical solution is found for the deployment, this concept saves a lot of room in the fairing, as well as weight. Moreover the diameter of the telescope is no longer a direct function of the size of the fairing. The expansion ratio between the telescope diameter and the fairing's is related to the number of segments. By making the approximation of trapeze segments with sides at  $1/\sqrt{2}$  times the diameter of the fairing (i.e. when placed horizontally a mirror segment occupies all the space available) we can establish the following relations:

$$\begin{aligned}
 C_{mean} &= D_f \times \frac{N_{seg}}{\sqrt{2}}, \\
 D_{mean} &= D_f \times \frac{N_{seg}}{\pi\sqrt{2}}, \\
 D_{out} &= D_f \times \left( \frac{1}{\sqrt{2}} + \frac{N_{seg}}{\pi\sqrt{2}} \right),
 \end{aligned} \tag{1}$$

where  $C_{mean}$  and  $D_{mean}$  are the circumference and diameter of the mean section of the annular telescope,  $D_{out}$  is the outer diameter of the annular telescope,  $D_f$  is the diameter of the fairing, and  $N_{seg}$  is the number of segments that make the annular telescope. With a fairing of 4.2 m usable diameter (e.g. an Ariane launcher), 18 segments lead to a 20 m diameter telescope, 24 segments to a 25.5 m diameter telescope. We are developing the 20 m telescope only in order to remain well inside a stable structure.

## 2.2 Deployment with a pantograph scissor mechanism

As is the case for large deployable antennas for long wavelength built with connecting rods, ball joints and mesh, we searched for a mechanical design with one degree of freedom to be motorized during its deployment. Among

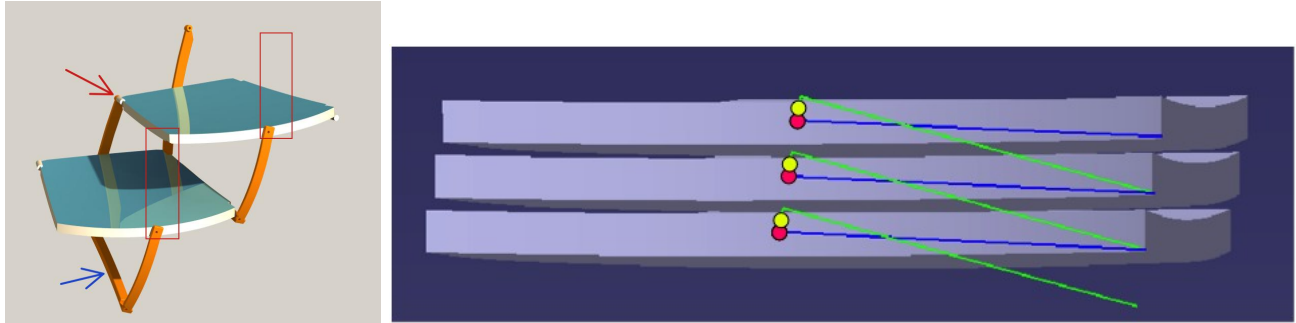


Figure 2. Left panel: the updated pantograph system that connects each mirror segment to its neighbors. Here for simplicity only two segments are represented. The red rectangles highlight the elements of the previous scissor system that have been removed. On the upgraded kinematic, a rod with high torsion stiffness connected to inner and outer scissor is used to synchronise these two scissors. This synchronization bar is indicated by the blue arrow. The leading scissor is the inner one. The red arrow points to the location of the link that has been changed from a pivot link to a ball joint link. Right panel: a side view of a stack of three mirrors to highlight the small offset applied to the position of the outer pivot link (from the red circle to the yellow circle) that allows going from a parallel stack of mirrors in the stored position to their position on a section of a parabola when deployed.

linear deployable structures, very simple ones consist of pantograph scissors extending along a straight trajectory. The pantograph is actuated at the angle between the first pair of scissors. The whole pantograph deploys at once while the angle between each branch of scissor is kept constant. This principle is extensively used in pantograph scissor tables in the industry, where two pairs of scissors are synchronized using anti-rotation rods in order to keep the translation of the table parallel to the ground.

Using this source of inspiration, we designed scissors where one branch is materialized by the mirror segment itself, while the other branch is a connecting brace. We distorted the trajectory of extension of this scissor pantograph from a straight path to a circle, on both axis during its extension, by making small modifications in the position of the axis and length of the braces, until the furthest pair of scissors reached the side of the first one at maximum extension. Our initial solution<sup>3</sup> was a kinematic system that allowed the stack of mirrors to expand from a stack of segments with a conical shape to a deployed conical structure around a mast. This design gave high credibility to the feasibility of the kinematic system, however the stored stage of the segments had a conical shape and could not be stored optimally in the fairing, wasting precious space.

To be able to start the deployment from a stack of parallel segments that would extend into a parabolic section, a series of changes were necessary. First, we removed a part of the outer scissor and changed the location of the outer central pivot link of the segment to remove the conical nature of the stack. And, to keep the same kinematic of deployment without blocking, we changed one pivot link by a ball joint link. We also added a synchronization bar between the inner and outer scissors to avoid an observed tilt of the mirror segments with respect to one another during deployment (see Fig. 2).

The kinematic model has thus evolved in such a way that the mirrors are stacked parallel inside the fairing, and deploy towards a parabolic position. All segments and scissors are linked to each other so as to deploy under a unique degree of freedom. During the deployment phase, the leading scissor system is the one situated at the inner diameter of the ring. This scissor system uses the segment itself as one branch and the C-shaped surrounding structure (in orange on the left panel of Fig. 2) as its other branch. During launch the mirrors will be staked and strongly secured to each other at their four corners, in order to behave as a solid block.

### 3. A ROADMAP TO INCREASE THE TECHNOLOGY READINESS LEVEL

In the previous section, we presented the conceptual and design work that has occurred to mature our initial concept<sup>3</sup> to its present incarnation. This approach has been very productive but needs now to move into a different scale that we are presenting now.

### 3.1 Deployable topology

One of the key innovative concepts that will be validated experimentally is the new topology for a deployable, segmented mirror that we discussed in the previous section and displayed in Figure 3. Inceptive work on this concept started in 2011 for the study of a 40 m submillimeter telescope at Dome C in Antarctica that we re-oriented toward space application due to its high disruptive potential. Three years of mechanical developments, including the realisation of a 4 m diameter fully deployable mock-up allowed refining our design. This led us to the optimum topology regarding deployed surface versus stored volume ratio, and the kinematics 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.<sup>3</sup> In the current design, the TALC telescope is made of 18 panels, of approximately rectangular shape and 4 m size, which are all identical to each other in shape, and articulate with a scissor-like structure. The inner side of the scissors are equipped with cables connected to a central mast that provides tension for developing and stiffening the annular mirror.

The goal of the topology roadmap is to design, manufacture and test at ambient and in cryo-conditions the deployment system on mock-ups of different scales ( $1/10^{\text{th}}$  and  $1/3^{\text{rd}}$ ) chosen both from a practical point of view as well as to explore scalability laws (see Ref. 4, in particular chapter 7). Indeed only through the identification of scalability laws can we hope to demonstrate the feasibility of systems that are simply too large to be tested in operating conditions at scale 1. 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 vibration tests performed at ambient on a complete scale  $1/10^{\text{th}}$  mechanical model.<sup>5</sup> This model will be built deployed but equipped with actuators both on the cable systems and on the mirror-holding scissors, as the full-scale model. This way, we will be able to test a complete strategy for active control of the telescope with respect to its vibration modes.

Mechanical tests will also be performed on a scale  $1/3^{\text{rd}}$  model of three articulated segments. The three segments will be representative of the actual mirrors in terms of process, interface, mass and thermal behaviour. This 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, to be manufactured by Multiplast in carbon fiber or nomex, and tested at CEA re-using existing and available large cryo-facilities developed for W7X<sup>6</sup> fusion coils testing (the chambers can accommodate  $4.5 \times 4.0$  m of experimental apparatus, operating at 70 K). While the operational temperature of a telescope such as TALC would likely be lower thanks to proper shielding from the sun, most of the effects due to a temperature lower than ambient will have already taken place once we reach 70 K so that the mechanical behaviour of the model can readily be extrapolated to lower temperature.

All along the project, an integrated thermo-mechanical model of the full-scale telescope will be developed integrating all results from tests and measurements performed on the various mock-ups at warm and cryogenic temperature to ensure scalability toward the 20 m size structure. This finite element model will allow for prediction of the final performance of the system once built to full size and operating in representative conditions (e.g. zero-gravity and around 40 K).

### 3.2 Lightweight mirrors for far-infrared applications

Although our topological concepts of deployment can accommodate a large range of deployed sizes, TALC is an annular telescope that is intended to reach 20 m in external diameter, with an internal diameter of 14 m. This makes for  $160 \text{ m}^2$  of mirror to carry in orbit. Given the mass constraints of current and future launchers, we have to aim for a weight significantly smaller than  $10 \text{ kg} \cdot \text{m}^{-2}$  for the mirrors themselves. This kind of weight performance is already challenging to reach with materials currently used in space telescopes (e.g. SiC or Beryllium). Furthermore, the cost of manufacturing the mirrors has to be considered and kept low, again given the number of individual mirrors to build (18 in the current concept). One key aspect of the TALC mirror is that since we have chosen an annular configuration with a single row of mirrors, all mirrors are strictly identical in shape and we must capitalize on this to reduce the manufacturing costs.

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. To fully exploit the repeated-cell property

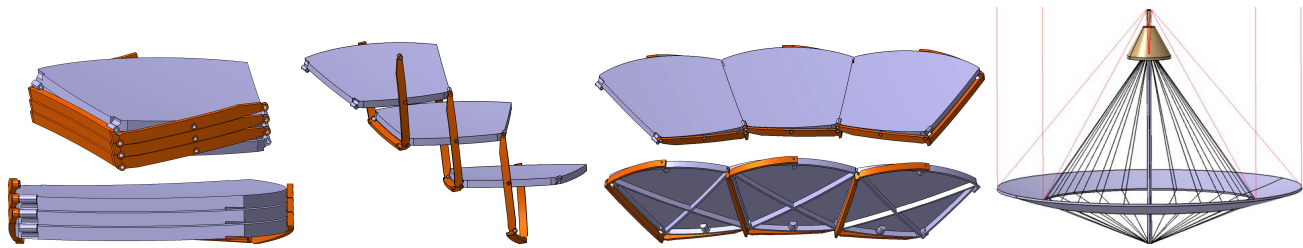


Figure 3. Key steps in the deployment topology of TALC. The three panels on the left show only three of the current 18 segments that make the complete annular telescope. The leftmost panel shows the segments in their fully stored position where all panels are parallel to each other. The second panel shows how the panels are articulated to one another to allow deployment to a complete annulus. The third panel shows the fully deployed stage, where panels are no longer co-planar, but rather belong to a parabola. The rightmost panel shows the fully deployed structure, with the secondary mirror and instrument housing on top of the cable structure that provides tensegrity to the system.

of the TALC telescope, we need to identify a mirror manufacturing technique that allows repeatability. In that respect building mirrors with carbon fibres on a mold appears quite promising. Indeed, carbon fibre reinforced polymer (CFRP) is an ideal candidate for lightweight mirrors working at cryogenic temperature because of its low areal density, high elastic modulus and its coefficient of thermal expansion (CTE) that can be tailored to be low or zero. However, the capability to build CFRP mirrors with good optical quality is limited by a surface distortion effect called fibre print-through (i.e. the hexagonal structure of the carbon honeycomb that makes the bulk volume of the mirror, or the individual fibers that are used for the outer shells “print” through the final surfaces creating periodic shape defects, which are devastating for mirrors). 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  $30\ \mu\text{m}$ , 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.

Our short-term goal is to thus manufacture, with carbon fibre and honeycomb, a 1.2 m parabolic demonstrator of a low-density mirror with optical quality (diffraction limited performance at  $\lambda = 30\ \mu\text{m}$ ). 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 a likely standard in future commercial applications. Scalability toward a 20 m structure imposes an aim of an overall density limit of  $10\ \text{kg}\cdot\text{m}^{-2}$ . Designing how these elements have to be assembled to achieve the optical quality goal is the major challenge in this roadmap.

The baseline we will follow is tailored to the objective of relying on replication methods. To avoid having to polish each of the mirrors, the process will start from a nickel layer electro-deposited on an optical quality mold. We will then continue with adding carbon structural elements on the optical Ni layer still on the mold, all at low temperature to preserve the mold quality. Media-Lario, a specialist of electro-deposition, will perform the first step of depositing nickel on optical quality molds. 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 cyanate-ester honeycomb, and cyanate-ester pre-preg carbon pitch fibre low ply density ( $< 50\ \text{g}\cdot\text{m}^{-2}$ ), 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, consisting 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 roadmap will test a range of carbon structures for the mirrors, in order to achieve the best trade-off possible between manufacturing costs, manufacturing complexity, stiffness of the mirror, quality of the surface at small-scale, reproducibility of the large scale shape of the mirrors. The quality of mirror surfaces will be measured both at ambient and cryogenic temperatures using deflectometric methods developed at Brera Observatory.<sup>7</sup>

### 3.3 Active control of mirror surfaces

Implementation of active optics control (i.e. active control of the surface shape of the mirrors) is a promising avenue to reach high optical quality on large structures. It reduces the requirements for the as-manufactured surface front error 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 ( $\leq 30$  cm in the TALC telescope project), and (2) by active optics correction on larger scales.

For this latter part, led by Muenster University of Applied Sciences, we will 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 1.2m 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 1.2m 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. The mirror size chosen for this active control development (30-40 cm) 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.

Our design for a typical 4 m panel (the width of TALC's annular primary) relies on two layers of active optics grids for shape correction: the first one, coarse and constant, corrects the first low orders of deformation, the second, meshing the mirror with a typical  $\leq 30$  cm cell pattern, corrects higher spatial frequencies. It is important to note that by incorporating the active optics layers into the rear side of the mirror itself, we depart radically from conventional active optics that use actuators attached to a rigid reference frame. Such a rigid frame would contradict our deployment strategy. The as-manufactured surface errors of our replicated CFRP mirror will be larger than that of conventional mirrors but correction to several  $\mu\text{m}$  is sufficient for far-infrared observations. If successful, our new approach of active optics based on in-plane actuation can be extended to large primaries of telescopes for shorter wavelengths. This line of work is in contrast with, and in fact complementary to, current research on active optics for space telescopes, pursued at various space agencies, that is geared towards nm-precision wavefront control for primary mirrors or mirror segments that will have much smaller as-manufactured surface errors, typically below a  $\mu\text{m}$  (hence prohibitive costs for large collecting areas). The main driver for these activities is direct detection of exoplanets in the visible, which requires very high contrast, a very different science objective than ours.

To summarize, in this part of the roadmap, we will develop systems where a layer of the mirror itself provides the capacity to adjust its shape, and will define a path to meter-sized mirrors. Furthermore, CFRP has never before been used to build deformable mirrors, but its high Young's modulus is beneficial as it actually leads to a larger amplitude of achievable deformations.

## 4. CONCLUSION

The concept of a deployable 20m annular space telescope has significantly matured, giving rise to a system that is now more compact and robust when in stored position, and better behaved during deployment. This higher level of maturity now requires that we project ourselves one step further and mature the critical technologies that will be required to actually build TALC. The roadmap to achieve this is ambitious but has the capacity to deliver these advances in a few years.

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