TALC, A 20m Thin Aperture Light Collector for infra red observations in space

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ABSTRACT

TALC, **Thin Aperture Light Collector** is a 20 m **space observatory** project exploring some unconventional optical solutions (between the single dish and the interferometer) allowing the resolving power of a classical 27 m telescope. With TALC, the principle is to remove the central part of the prime mirror dish, cut the remaining ring into 24 sectors and store them on top of one-another. The aim of this far infrared telescope is to explore the 600 µm to 30 µm region. With this approach we have shown that we can store a ring-telescope of outer diameter 20m and segments thickness of 0.3m inside the fairing of Ariane 5 or Ariane 6. The general structure is the one of a bicycle wheel, whereas the inner sides of the segments are in compression to each other and play the rule of a rim. The segments are linked to each other using a pantograph scissor system that let the segments extend from a pile of parallel dishes to a parabolic ring keeping high stiffness at all time during the deployment. The inner corners of the segments are linked to a central axis using spokes as in a bicycle wheel. The secondary mirror and the instrument box are built as a solid unit fixed at the extremity of the main axis. The tensegrity analysis of this structure shows a very high stiffness to mass ratio, resulting into 3 Hz Eigen frequency. The segments will consist of two composite skins and honeycomb CFRP structure build by replica process. Solid segments will be compared to deformable segments using oriented shear of the rear surface using ceramic PZT fibres. The adjustment of the length of the spikes and the relative position of the side of neighbour segments let control the phasing of the entire primary mirror. The telescope is cooled by natural radiation. It is protected from sun radiation by a deployable or inflatable solar screen, loosely linked to the telescope. The orientation is performed by inertia wheels and plasma propulsive actuators. This telescope will carry a wide field bolometer camera and a high resolution spectrometer to be operated at 0.3K. This telescope may be launched with an Ariane 6 rocket up to 800 km altitude, and use a plasma stage to reach the Lagrange 2 point within 18 month. The plasma propulsion stage is part of a commercial vehicle used for communication satellites that also includes solar panels, orientation system and communication. The guide-line for development of this telescope is to use similar techniques and serial subsystems developed for the satellite industry. Using serial commercial vehicle and building a telescope using large number of replicated similar parts is the way to think the construction as a object built in serial and think it as a low cost satellite.

Keywords: Thin Aperture Light Collector, **Deployable space telescope**, Sub-millimeter telescope, Passive cooling, Tera-herz telescope, Bolometer camera,

INTRODUCTION

TALC is a 20 m space observatory project exploring some unconventional optical solutions (between the single dish and the interferometer) allowing the resolving power of 27 m telescope in the range of 100 µm to 600 µm. The light collection surface is 20 times larger than the Herschel mirror, giving access to very faint and/or distant sources. With an unconventional optical design comes the necessity to combine data acquisition with unconventional data processing techniques, which are being developed today, based on the notions of sparsity in astronomical signals.

On the optical side, an annular telescope gives access to a higher resolution as compare to a filled telescope of the same diameter. Telescopes or interferometer have limitations in sensitivity and resolution. While an observation time may be increased to observe fainter objects, it will not give access to better angular resolution. For this reason TALC gives the preference to resolution at the cost of loosing sensitivity as compare to a filled telescope of the same diameter. Given a total area of mirrors, a ring telescope will have a larger diameter than a filled telescope that results into direct improvement of the diffraction limit. The PSF of telescope with a central obstruction of half its surface has 70% of its power outside of the main beam, while the first zero of the d'Airy pattern is situated at 0.8 times the angle of the one of a filled telescope of same diameter. With appropriate inversion, we have shown that the angular separation of the half obscured telescope is 20% narrower than the one a filled telescope of same diameter. (Paper of Marc Sauvage, Pierre Chanial)[1]

On the mechanical side, it is simple to build a stiff wheel structure with stretched spokes and compressed rim as invented by Jules Truffault in 1875 with it the first modern bicycle wheel with stretched spokes and tubular rim. This tensegrity axi-symetric structure gives access to the one of the stiffest light-weighted structure. As a result, the big wheels are the largest ground mobile structures built in the world as for example the Singapore wheel with its 150 m diameter.

Figure 1. Singapore flying wheel 150m diameter

In our case, the rim consists of the serial of the inner sides of the mirror segments linked by knee joints. Two sets of spokes are pulling these knees towards the extremities of a central mast. Single pistons installed between the outer corners of adjacent segments suffice to control the orientation of the segments as petals of a flower. As a result this annular telescope does not require an additional support structure: the axis of the telescope, the set of mirrors and the spokes constitute the structure. Moreover by adjustment of the length of the spokes and the pistons between adjacent mirrors, the 3 main degrees of freedom of each mirror (distance + orientation) are tunable. The figures shown here show how to stack 24 segments of 4m in diameter. In order to better use the inner diameter of 5.2m of the fairing of Ariane 5 or Ariane6 we may decrease the number of segments to 16 segments.

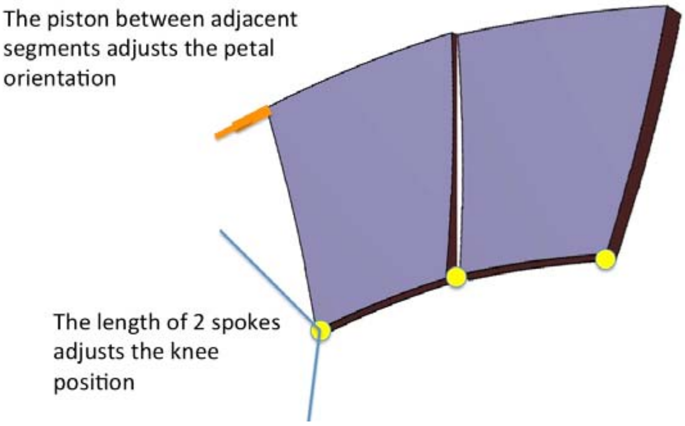

Figure 2. Piston, Tip Tilt adjustment of the segments

Deployment.

The segmented mirrors are stored inside the fairing as a pile of dishes. Such a stack offers the ultimate segment stiffness, since the entire stacked volume is occupied with their reinforcement lightweight structure. The segments are linked to each other with a scissor system such as a scissor lift. The axis and length of these scissors are designed to allow a scotched yoke movement from a stack of dishes up to a large ring of adjacent segments in the shape of a parabola. One branch of the scissor is part of each mirror, the other branch toggles during the extension. The instrument case and the M2 mirror constitute a solid block. Before the start of the deployment of the segments, this block is positioned at the top of the central mast. The set of spokes are stretched by extension of the mast while a spring-loaded mechanism extends the segments from each other. At start of deployment, a launching track still to be designed is used to force the set of mirrors to extend on either side from the central position, in order to keep all spokes stretched at all times. In the midrange, both the launching track and the spokes keep the mirrors along their trajectory. At the end of the deployment the spokes are driving the trajectory to complete the movement until the 2 mirrors at extreme positions meet and are compressed to each other.

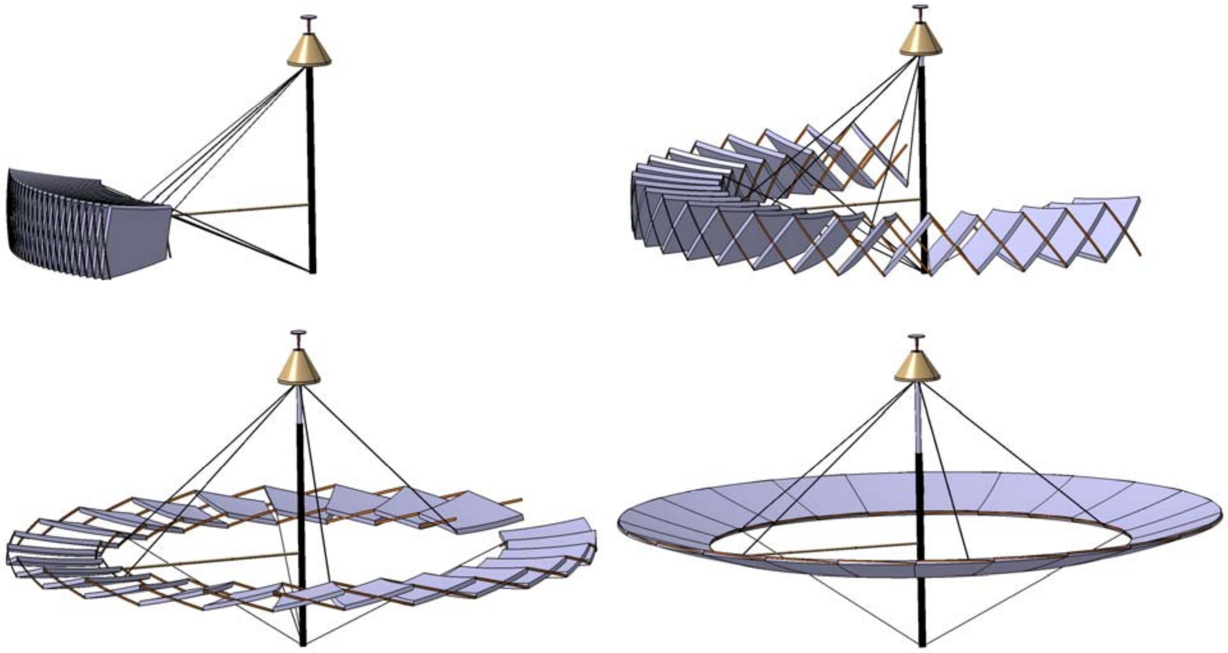

Figure 3. At start of the deployment a launching track is used to force the set of mirrors to extend on either side from the central mirror. At the end of the deployment the spokes hold the entire wheel.

Our simulations and the construction of a 4m prototype have shown that a synchronization rod shall be installed between the inner and the outer toggling scissors, in order to give stiffness to the ensemble of mirrors during its extension. The smaller inner scissor is linked to the larger external scissor by means of a connecting rod. As a result the toggling link between the segments are C shaped arches that surrounds ¾ of the segments when they are stacked. When the mirror is deployed, the synchronization rods are stored at the rear of the parabolic mirror.

Recent update on the deployment mechanism:
We have found an updated axis system that includes knee bearings instead of axis, that allows to stack the pile of segments parallel to each other, thus allowing a much better use of the space inside the fairing. We will use this optimised stacking to make the segments thicker, in order improve decrease the tolerance on the shape without active control.

Construction of a model at scale 1/5. We first made the simulation of the deployment using Catia V5 and Nastran. Later we wished to verify how the scissors would behave with as many as 24 segments on a scaled physic model. While the deployed structure was as stiff as the predictions in the fully deployed, we understood that the absence of synchronization between the inner and outer set of scissors resulted into highly flexible assembly in the starting sequence of deployment. In the new design the scissors consist of a CFRP tube bent in a C shape round the segment that connects the inner leg of the scissor to the outer leg of the scissor. We will next calculate the stiffness of the set of partially deployed structure at each stage. Eigen frequency and damping at all the stages of the deployment will be performed in order to simulate the real deployment including the friction at knees and oscillations during the process. In an advanced status of the project, we will build a set of 3 segments and test the mechanical deployment in cryogenic conditions for a great number of cycles.

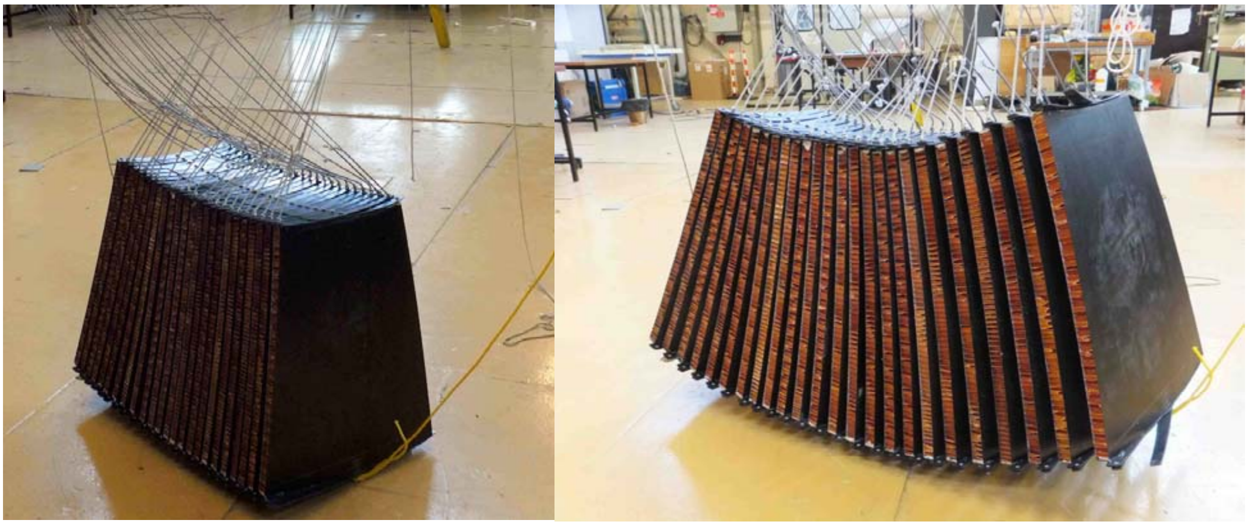

Figure 4. On this model scale 1/5, the segments are built with skins of pre-impregnated UD carbon epoxy on Nomex honeycomb. The model weights 36 kg for 4 meter diameter

Figure 5. The scissors are made of pre-impregnated UD carbon epoxy. We learned that a synchronization system is needed between the inner and outer scissors to help the pack of segments extend on a predictable trajectory. In the next model the toggling scissors will be tubular. The inner and outer scissors will be built as a single piece in shape of C.

A configuration Hexcel data sheet has been created to include all design parameters.
This sheet is linked to the Catia and Nastran files, in order to update all modelling, kinematic and mechanical behaviour for concurrent engineering system analysis. It will be used as well for the optic and thermal model.

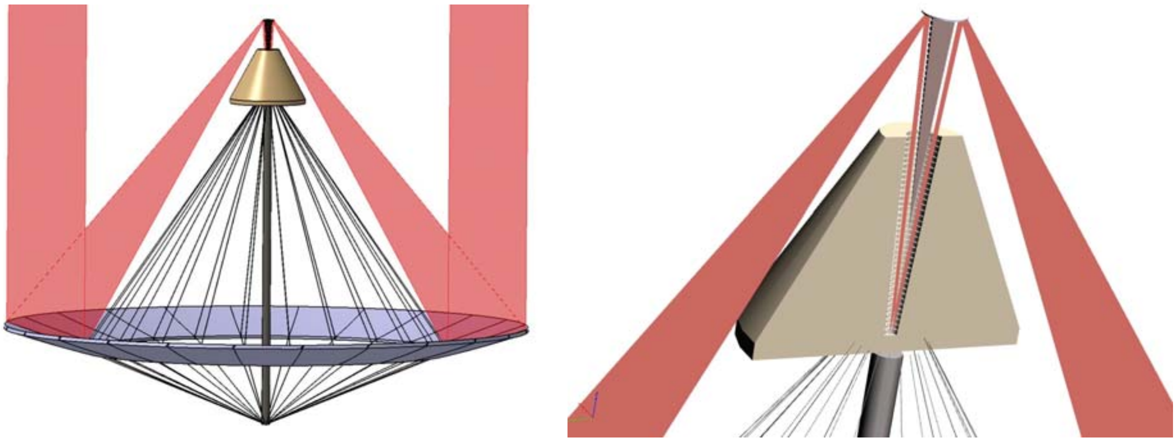

Figure 6. Cut of the TALC, the pupil is unobstructed outside of the instrument case. The spokes follow a route in parallel to the light between M2 and M3. Within the instrument case large baffles are installed between the outside of the beam and the cone that blocks the central pupil area.

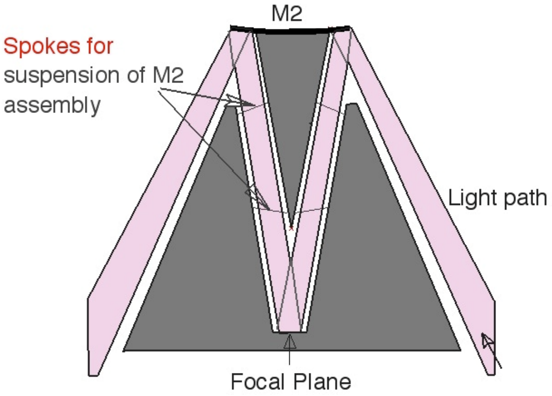

Figure 7. The cone that supports M2 is secured within the instrument case by 6 spokes or laminated transparent film. The obstruction of the pupil is very limited.

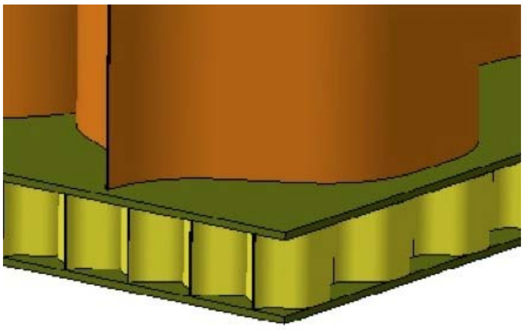

Figure 8. The segments of mirrors are 25 cm Thick. They consist of a carbon honeycomb core in sandwich between composite skins. In order to limit the footprint of the large cell honeycomb core, the skin on the mirror side consists itself of a carbon honeycomb sandwich 10mm thick cells + CFRP UD skins. The skin at the rear of the mirror is monolithic. It is equipped with PZT uniaxial pads arranged in triangle, in order to fine tune the mirror shape.

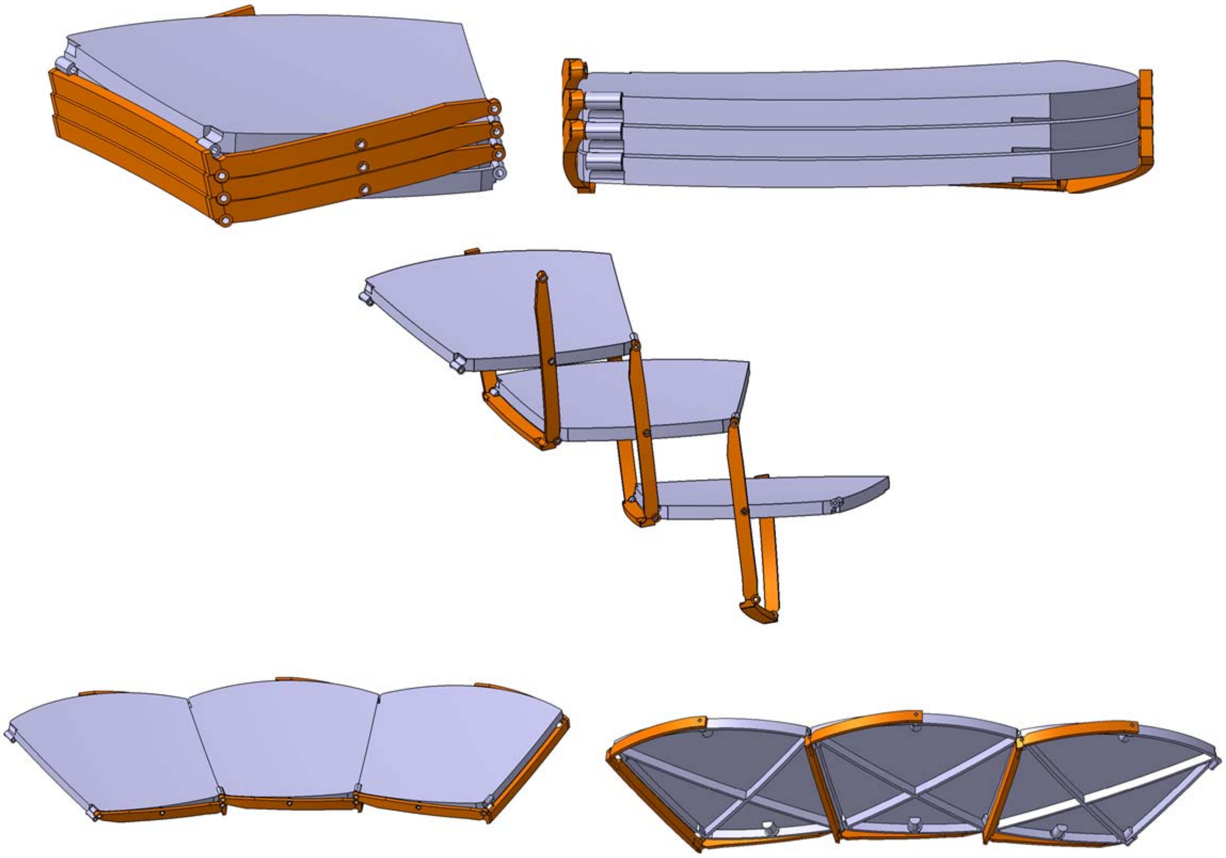

Figure 9: Model of the deployable structure for 3D printing to show the deploying principal. The kinematic model has evolved until the mirrors are stacked parallel inside the fairing. They deploy towards a parabolic position. All segments and scissors are linked to each other so as to deploy under a unique degree of freedom. The spokes are used to fine tune the segments to their final position.

Baseline: passive segments. The design of the panels is at a very preliminary status. Most promising is to build the segments by replica on a steel polished mould. A first layer of nano-laminated metal reflective surface is first deposited at vacuum or electrodeposit. 70 layers of ultrathin carbon UD 25 gr/m2 are stacked at angles of 15°. A porous honeycomb core with 3mm cells 10mm thick will be placed and be covered with similar layers of UD carbon fibre. This ensemble will be cured. The rear skin composite skin is built as a multilayer UD at 15°. After completion of these two composite skins, the main structure will be built by assembling the front and rear skins on both sides of a carbon honeycomb with porous larger cells. The structure will be cured and unmoulded.
This structure has been used for our dynamic model.

Construction of active segments:
At the present time, we do not know if the segments may be built within the required shape or if an active control within the segment is necessary. In the case such a control is necessary to reshape the segment, we expect to use piezo-actuators within the rear skin of the segments. By stretching or extending locally the rear skin in the given directions, it will be possible to accurately reshape each segment.[3,4]
Hence we did not work on active segments, we envisage to use piezo pads immersed inside the rear CFRP layer of the segments to compensate for CTE errors at large scales and reach higher surface accuracy required for smaller wave length[3,4].

Uniaxial piezo pads arranged in triangle shape parallel to the rear skin allow all degrees of freedom to adjust the mirror shape as well as pistons on a reaction mandrel would do the job.

The uniaxial piezo pads are built with ceramic PZT-5 square fibres with Curie point 320°C and stiffness 70 GPa.
They will consist of mono-axial piezo pads, with range of 1800 ppm per pad.
The goal is to use microfiber piezo axial pads declared Invention of the year by the NASA "http://www.wired.com/2007/12/micro-fiber-com/"
They will be arranged in triangular pattern, in order to provide control vector control of the rear skin at a pattern size that will be decided after completion of a sample of the mirror at real thickness.
Since these piezo-actuators behave as condensers, many pads may be driven by a single amplifier, which is multiplexed to polarise each pad at a time. Each pad memorises in an analog way the voltage and therefore the actual constraint between refreshing writing cycles. This process does not dissipate power. The mirrors may be cooled down by heat radiation down to 30K.
Dissipation of vibrations at launch:
As a gratis add on, the microfibers piezo pads will also be used as vibration damping system at launch. The pads we propose are also used as anti-vibration systems for the blades of helicopters. It is needed to connect the piezo pads to resistors during the launch period. This is of prime interest since the carbon fibre honeycomb structure of the panels do not develop any damping, which could result in catastrophic vibration at launch.

Stiffness of the ring telescope: We have simulated the Eigen-frequencies for the telescope taking into account the mass of the instrument, the mast, without any connection to the rest of the satellite. This represents the real case if the telescope is linked to the satellite and solar panel using a flexible arm, equipped with non-rigid knees for the control of the orientation of the telescope by torque only. We tested several configurations of cables honeycomb structures, masts and spokes at various pre-stress within a total mass near 2.5 tons. We could obtain the lowest Eigen-frequencies above 3 Hz. Due to this high frequency, this structure will be damped passively or actively if necessary. It will react rapidly to active control. In the deployed status, all articulation shall be designed by only flexure in order to avoid hysteresis.
The calculations of the Eigen-frequencies has been performed for the following conditions :
Upper cables diameter 2.5mm pre-stressed 182 N
Lower cables diameter 4mm pre-stressed 300 N
Compression on the mast 3500 N
Length of the mast in the axis of the telescope : 12 .7 m
Diameter of the mast : 230*250 mm,
Weight of the mast : 400 kg
Mass M2 + instrument :1500 kg
Segments: 24 segments at 10 kg/ m2

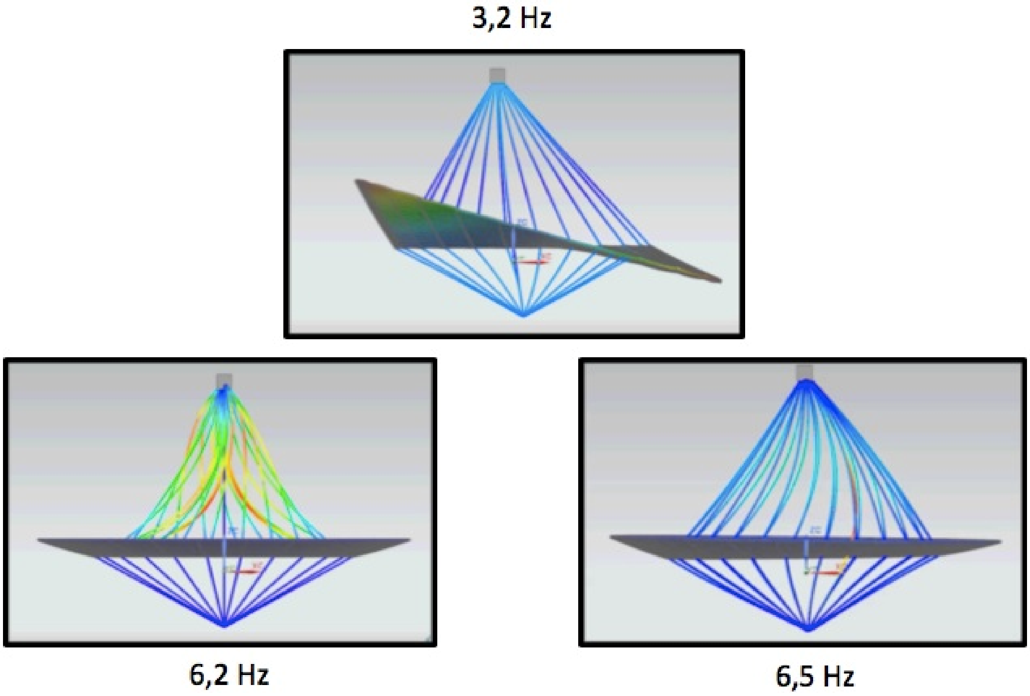

Figure 10. The lowest Eigen-frequencies are shown after trimming of the mass of mast, spokes and segments. The pre-stress on the spokes is related to the pre-stress calculated on the inner side of the segments at their construction. In this case, the telescope is considered as free flying as compare to the rest of the satellite.

Actuators for the control of the position of the mirrors. The coarse position of one point of each segment will be sensed using a fish eye reflector and interferometer distance sensor for coarse adjustment of the mirrors in piston to the focus. A wave front sensor using an infrared star will be used to sense the error orientation of each segment. The spokes length and the pistons to trim the petal orientations will be adjusted with piezo actuators.

V-Groove sun shield

For the time being we have not started the study of the sun shield. The mirror is too large to be cooled down actively. It is preferred to install TALC behind a V-groove shield in order to reach a thermal equilibrium as low as possible. During the next system analysis we will compare two sorts of sun shields. For a V-Groove rigidly connected to the telescope, as it is the case for the JWST, the reliability is improved since there are no movements between the thermal shield and the telescope. The shield must be built wide enough to keep TALC in the shadow of the telescope while the whole satellite is rotated away from the pointing transverse to the sun. Due to the size of TALC, this results into a very large sunshield area, typically ten times larger in area as compare to the shield of the JWST of 21m * 14m. In another design, the V-Groove sun shield is built as a circular axi-symmetric structure at a size just larger than the projection of the telescope in all orientations. The shield is kept aligned to the sun at all times. The mast in the axis of the telescope is articulated to the mast that holds the telescope away from the sunshield. In this case the size of the V-Groove could be deceased to 28 meters in diameter. In such a case passive cooling down to 30K may be expected.

Figure 11. TALC represented with a preliminary solar shield at the time of the study of the deployment of the telescope

We have simulated the time constant of a V-groove consisting of 5 layers of aluminized Kapton to reach a stable temperature without a telescope in its shadow. Next step is to add the telescope with pure passive cooling in order to estimate the temperature gradients and time constants using pure radiating cooling.

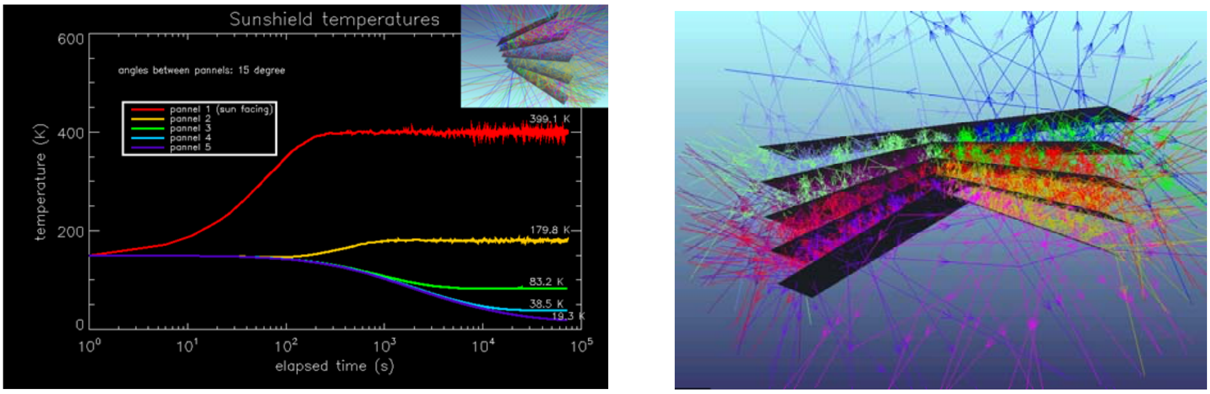

Figure 12. Cooling down of a V-groove stack, without parts in its shadow.

Cooling system for the detector and instrument case. In order to allow for a life-time of TALC in the range of 10 to 15 years, cryo-coolers will be preferred to a tank of liquid helium. The 30 Hz compressor of the cryo-cooler will be installed on the warm side of the sunshield. The radiative cold source shall be installed just next to the compressor. Behind the sunshield, there will be no additional cold sources. A long counter-flow heat exchanger built with tubes into tubes will be extending from will cross the sun shield, extend along the masts and reach the Joule Thomson valve at the location of the two or three stage He4 and He3 sorption coolers near the detectors. Temperatures below 0.25K will cool the bolometers as in the case of the PACS camera of Herschel.

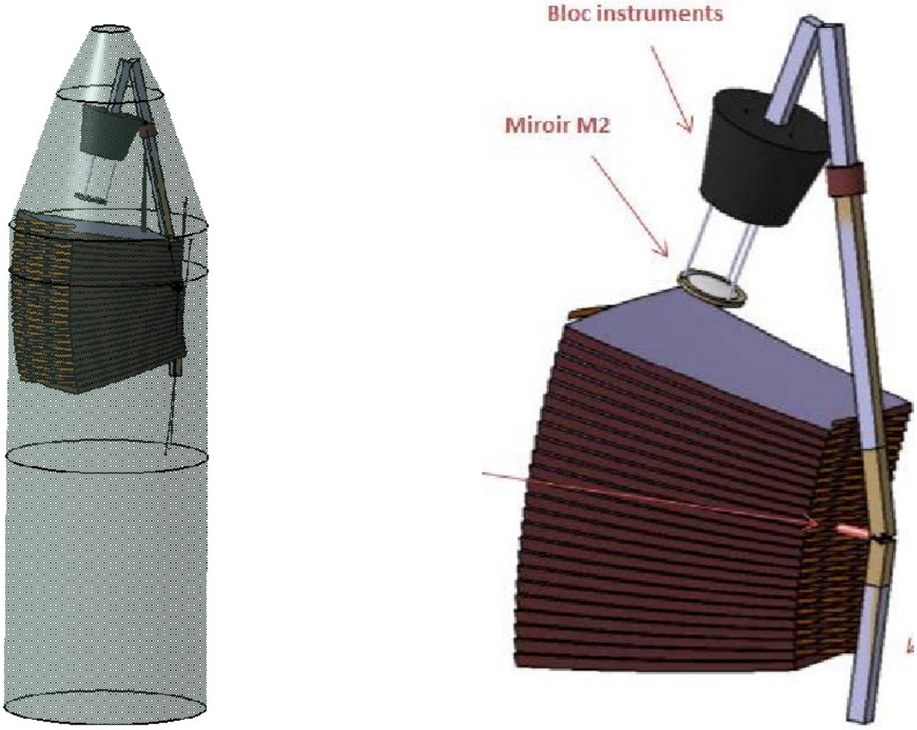

Figure 13. Talc folded inside Ariane 5 fairing. The masts consist of telescopic tubes and knees. The flexible spokes are not shown. During the launch, they are kept aligned inside a tubular holder as for a parachute.

Launching rocket

The total weight of the Instrument + telescope + mast + sun-shield + cryocooler is 4.2 tons.

The vehicle including solar panels, inertia wheels, telecom, jet gas orientation system is 1.2 tons,

Launch with ARIANE 5: TALC was optimized to fit the fairing of Ariane 5 with a diameter of 5.4m. The total weight to be launched to Lagrange 2 is 6 tons. Ariane 5 ECA may launch TALC directly to Lagrange 2 point as in the case of the 6.2 tons JWST.

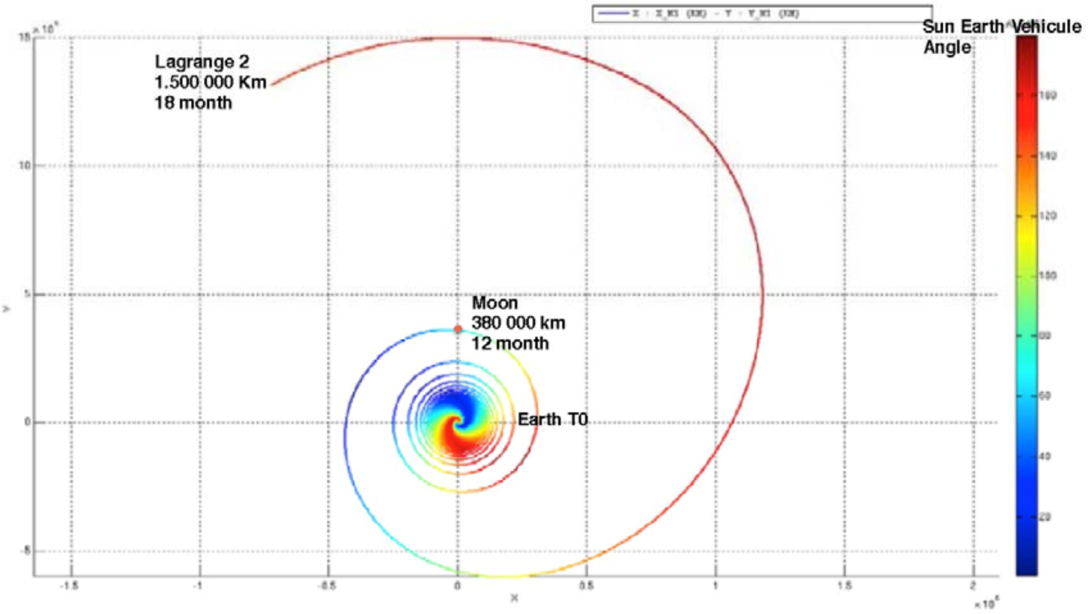

Figure 14. Mission profile – LEO to L2 transfer of TALC with an electric kick-stage (AIRBUS & CNES)

Launch with ARIANE 6 + Electric propulsion kick-stage : this is a promising alternative to heavy launchers such as ARIANE 5. The size of the fairing is kept identical, but scientific payload is injected in LEO or MEO. The implemented advanced propulsion is based on SNECMA HET engines developed for the coming NEOSAT generation satcoms. thus reducing costs. Total TALC mass after launcher separation is to exceed 9 tons, which includes scientific payload, stage working as mission spacecraft, necessary xenon fuel, communication means. The electric kick-stage is to transfer TALC's 4.2 tons instruments from LEO/MEO to final L2 position. Injection orbit is to be optimized to ensure mission safety. Moon vicinity can be managed with additional chemical propulsion. After TALC full commissioning at L2 point the propulsion module will be used for energy supply, coarse orientation and fine tuning of orientation with its reaction wheels. The main antenna for astronomical data will be stowed retracted, sun shield will be deployed first. The telescope will be deployed later at cold in order to avoid reflected light from the sun.

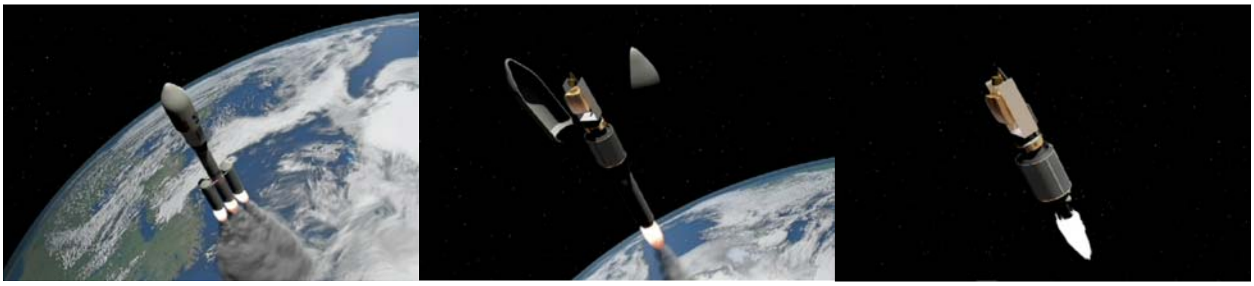

Figure 15. The 2 solid stages and the hydrogen / oxygen VINCI stage

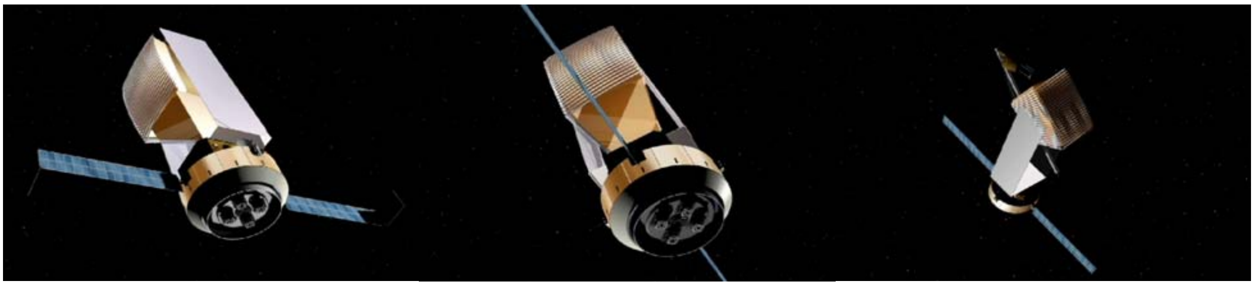
Figure 16. Electric kick-stage used as mission spacecraft to support TALC observatory deployment

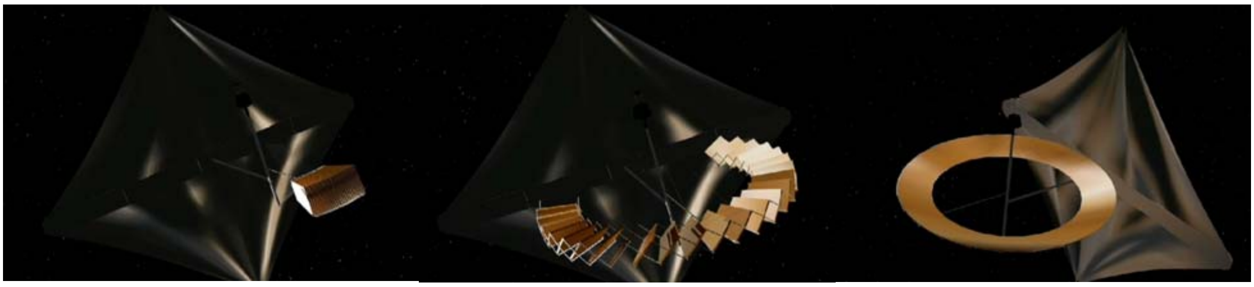
Figure 17.Deployment of the sun shield and the telescope

Size of TALC There is no direct proportion between the size of the fairing and the size of the telescope since other numbers of mirrors of different thickness could be chosen. We have proposed a 20m telescope as a demonstrator. It may be considered as a pathfinder to larger annular telescopes using the same wheel structure. Larger annular telescope designed for smaller wavelength will require additional control systems.

GOING TOWARDS A H2020 PROGRAM:

Since the SPIE conference at Montreal 2014 we have understood that TALC might be a good pathfinder towards space telescope towards very large space visible telescopes both for astrophysics and earth observation.

We could see the maturation of active mirrors using piezo-actuators at the rear of composite structures give access to easy control of large structures.
We propose to build within 3 years:

- A spherical convex stainless steel mould at scale 1/3 of the segment, polished to visible wavelength
- Use the technique described above to build a carbon honeycomb mirror at the thickness of TALC (15cm) in order to check the surface quality we may reach so as to define which is the scale of the acticve correction pattern for which wavelength.
- The specification is to reach 3 µm RMS on the surface using active control. Further on, we will work on basis of best effort in order to estimate which ultimate RMS surface quality with visible mirror in perspective.
- Build a second mirror at the thickness of TALC equipped with uniaxial microfiber pads at 3 orientations in order to reach the 3 µm RMS surface quality.
- Build 3 mirrors at scale 1/3 of TALC segments, in order to test the repeatability of positioning of segments of TALC next to each other. A great number of cycles will be performed on a subsystem of 3 mirrors + scissors, until we reach reliability and smoothness in the movement and locking system.
- Inside a cryostat at 77K with size ø3.5m, H3.5m demonstrate the repeatability of the positioning of 3 segments relative to each other. Check the stability of the segments at

cryogenic temperature. (Vacuum enclosure, vacuum pumps and LN2 precooling available at CEA Saclay.)
- Build an optical control system to check the mirror quality at room and cryogenic temperatures.

The next step beyond JWST is as follows: we propose to demonstrate that structures larger than what may be tested inside a single cryostat on earth may be modelled and tested as serial subunits.

- Develop the coarse positioning measuring system (using cat eyes and metrology by multi-wavelength laser interferometry)
- Develop a fine OPL control of the mirror shape

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