SUAVE, a disruptive off-axis SiC far UV Lyman-Alpha solar telescope for long term observations

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ABSTRACT

SUAVE (*Solar Ultraviolet Advanced Variability Experiment*) is a far UV imaging solar telescope (Lyman Alpha, 121.6 nm, Herzberg continuum, 200-242 nm, etc.) of novel design for ultimate thermal stability and long lasting performances over several years instead of, often, a few weeks or months in this wavelength range. SUAVE is a 80 mm Ritchey-Chrétien off-axis telescope with "mushroom type" SiC mirrors and no entrance window for long and uncompromising observations in the UV (no coatings of mirrors, flux limited to less than 2 solar constants on filters to avoid their degradation), associated with an ultimate thermal control (no central obscuration resulting in limited thermal gradients and easier heat evacuation, focus control, stabilization). Design and performances will be detailed as well as results of thermal/optical tests performed on the SiC primary mirror and its regulated support plate also in SiC. Plans for the realization of a representative breadboard for testing of both optical and thermal properties are presented. SUAVE is the main instrument of the Solar/Climate microsatellite SoSWEET mission (*Solar ultraviolet variability and Space Weather Extreme EvenTs*).

Keywords: Telescope, Ultraviolet, SiC mirror, Thermal control, Active control, Stable structures

1. INTRODUCTION

SUAVE, the *Solar Ultraviolet Advanced Variability Experiment*, was first proposed in June 2012 in response to the ESA Call for a Small-Size mission as the major instrument of the Space Weather and Ultraviolet Solar Variability (SWUSV) microsatellite mission. A complete description of the SWUSV mission and payload (including SUAVE objectives) is given in Damé et al.[1] SUAVE, initially, was an evolution of the SODISM (*Solar Diameter Imager and Surface Mapper*) telescope of the PICARD microsatellite mission of CNES (June 2010 – April 2014). The SODISM telescope and its first results and structural performances are well described in Meftah et al.[2] SODISM was a good imaging telescope concept, capable of 0.1 arcsec resolution but thermal issues with the entrance window, the secondary mirror and the CCD prevented using it to its full possibilities. SUAVE, in its first developed version,[3] was using the same structural approach than SODISM with a Carbon-Carbon tube and INVAR plates to guarantee a high mechanical stability, but improved on thermal issues, first by suppressing the entrance window and, second, by using Silicon Carbide (SiC) mirrors. Indeed, SODISM, in its PICARD implementation, was a mid-UV to visible telescope with an entrance window and Zerodur mirrors, highly sensitive to contamination[4] and affected by thermal control problems. Accordingly, a particular attention was given to thermal control (SiC mirrors, new mirror's supports, new radiators) and to the filters' environment to specifically lower the flux level reaching them to avoid premature degradation. As a consequence, since the SiC mirrors are uncoated and since there is no entrance window in SUAVE, coatings' degradation is *totally* avoided.

Since the mission proposal to ESA in 2012, SUAVE/SWUSV was proposed to CNES and received a R&T ("Research & Technology") grant to evaluate the feasibility of the modifications on a representative breadboard altogether with a evaluation of contamination issues and filters' sustainability. Some modeling of the SiC mirrors and work on appropriate filters were reported in Damé et al.[3] We now report on progresses on an advanced off-axis telescope

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*luc.dame@latmos.ipsl.fr; phone +33 1 80 28 51 19 design of SUAVE, and on the breadboard realized to evaluate the opto-thermal properties of its primary mirror. The new mission context for the instrument within the SoSWEET microsatellite mission (*Solar ultraviolet variability and Space Weather Extreme EvenTs*), proposed to ESA and NASA Missions of Opportunity, is also presented.

2. SCIENTIFIC OBJECTIVES AND CONTEXT

The major objective of SUAVE is to predict and monitor large flares and coronal mass ejections (CMEs). SUAVE is addressing this issue by monitoring flares in Lyman-Alpha rather than X-ray or XUV. Lyman-Alpha, much like H-Alpha, is an excellent flares/CMEs precursor indicator since filaments and emerging bipolar region (the two major large flares' precursors) have a high visibility in this line (space weather direct application). Furthermore, comparing sensitivity difference with H-Alpha, formed lower in the chromosphere, might lead to directivity (geoeffectiveness of events directed towards Earth) and better and more robust flare/CME predictions. Lyman-Alpha is, simply, excellent at detecting flares (cf. LYRA/PROBA-2[5]) with an important raise in global integrated light curve (1000 times the one observed in H-Alpha), and this even slightly before GOES X-ray (1–8 Å) or the "Aluminium" LYRA channel (17–80 nm), or the "Zirconium" one (6–20 nm).

Filaments and emerging bipolar region (the two major flares' precursors) are extremely well seen in Lyman-Alpha allowing their detection and tracking, and their configuration changes to anticipate/predict large flare happenings. Coupled with observations in H-Alpha (on ground in dozen of observatories), some directivity could be predicted hours in advance and determine if the flare/CME would be geoeffective, i.e. reaching Earth). Modelling the disruption of the flux rope is possible in Lyman-Alpha[6] while, because of poor contrast and resolution, it is not possible in Helium II line at 304 Å.

However, previous Lyman-Alpha, Tmin (160 nm) or Herzberg (215-220 nm) telescopes have degraded severely, in a few weeks or even days (OSO-8, PROBA-2, SOLSPEC, TRACE, PICARD…) in the past since of internal and external contamination: contaminants are deposited on (cold) surfaces and polymerize under UV flux (transmission affected); coatings are heated and "soft" ones degrade. Moreover secondary mirror and filters of classical **solar** telescopes are submitted to large flux (up to several solar constants) and degrade (impurities and weaknesses in coatings on filters and mirror heat and create "pinholes"). Therefore, new disruptive far UV **solar** imaging telescope concept for **Lyman Alpha (121 nm)** and the **Herzberg continuum (200-242 nm),** capable of long-lasting operation in Space (more than half a solar cycle: 6 years), was required: the SUAVE new design.

3. DESIGN DRIVERS OF THE NEW TELESCOPE CONCEPT

SUAVE is a **Space Weather** watch-dog for potentially harmful extreme events with a **unique Lyman-Alpha imaging telescope (1 arcsec resolution)**; it also monitors UV variability influence on climate (ozone creation) through Herzberg continuum (200-242 nm) observations. The novel, disruptive, design of this far UV imaging solar telescope is guided by the need, first, to resist contamination/degradation for long duty cycle (observations on more than 6 years, half a solar cycle). This means no entrance window, no coatings on mirrors and "hot" mirrors to avoid deposit of contaminants on cold surfaces. This involve the use of very specific and unusual mirrors' material: silicon carbide (SiC). But not only: the shape of the mirrors is also optimized for stability and control, and to minimize thermal gradients in the mirrors. The SiC mirrors of SUAVE are of "muchroom" type, with 3 feet

Need of long duty cycle (> 6 years, ½ solar cycle) => **SiC mirrors** of "**mushroom**" type since: no coating -> no degradation, thermal conductivity and homogeneity -> heat evacuation preserving the filters (SiC reflect 40% in UV and only 20% in visible).

High resolution imaging implies stability and a **thermally optimized configuration: an off-axis telescope is the solution** => no central obscuration of primary mirror, flux homogeneity minimizes thermal gradients, M2 protected inside structure (no back illumination)

SUAVE is the main instrument of the **SoSWEET (***Solar ultraviolet variability & Space Weather Extreme EvenTs*) **small satellite mission** using a solar observing satellite on a polar Sun-synchronous orbit at 720 km.

Low cost small platforms (< 150 kg; 60-70 kg P/L) are a new reality (OneWeb, Blue Canyon, etc.), not compromising on performances, pointing and telemetry, allowing more ambitious missions in the same project envelope.

4. SUAVE THERMO-OPTICAL DESIGN

Evolution & optimization of SODISM: off-axis, no window, SiC mirrors & new "thermal" door and radiators

SUAVE (*Solar Ultraviolet Advanced Variability Experiment*) is a Far Ultra-Violet (FUV) optimized off-axis telescope with Silicon Carbide (SiC) mirrors for extended observations and ultimate thermal control since of its high conductivity for heat evacuation, and sensitivity to temperature to control the focus. The instrument field of view and its angular resolution are respectively about 35 arc-minutes and 1 arc-second. SUAVE is based on LATMOS experience with space instrumentation and solar observations. Indeed, SODISM/PICARD telescope has taken more than one million images from 2010 to 2014[2] and the Transition Region Camera (TRC) was pioneer in Lyman-Alpha imaging in the eighties[7].

4.1 Heritage

SUAVE is a disruptive evolution of the MUV SODISM telescope flown on the CNES/PICARD mission from 2010 to 2014[2]. From the SODISM design, SUAVE (first and second versions) may keep the structural general design with the Carbon-Carbon tube and INVAR plates holding the mirrors but will improve on thermal issues using SiC mirrors (primary and secondary) associated to large radiators to evacuate properly the solar flux received. This was already implemented in the initial SUAVE[3] (cf. Fig. 1) and is kept for the new off-axis optical design. A larger radiator is also implemented for the detector in the new SUAVE design and the M2 radiator is on top to allow a complete opening of the entrance door (no window – source of severe thermal issues in FUV – in the SUAVE design).

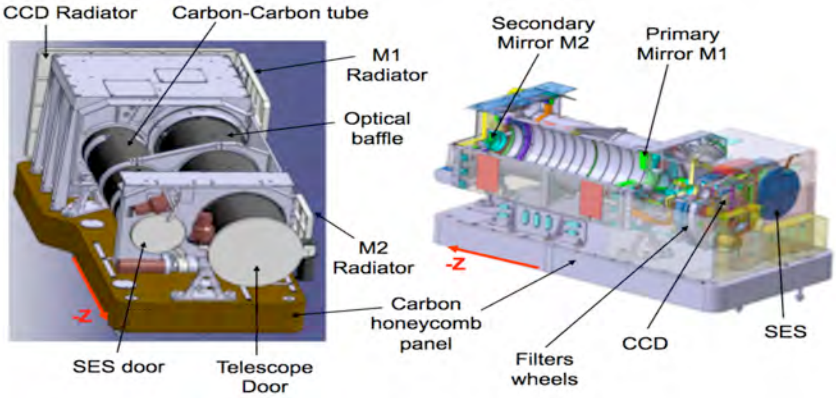


Figure 1. (left) SUAVE initial design (on-axis version with new radiators) and (right) SODISM flown on PICARD.

4.2 Optical definition

SUAVE new off-axis optical design limits thermal gradients in the mirrors and telescope. The off-axis configuration (cf. Fig. 2) without central hole in the primary mirror allows to reduce thermal gradients and, additionally, it protects, inside the telescope structure, the secondary mirror from direct sunlight in its back. The design is without window (transparent material at Lyman-Alpha is hydrophilic) but with a thermal door (painted inside and fully opening at 270° to the side of the telescope structure).

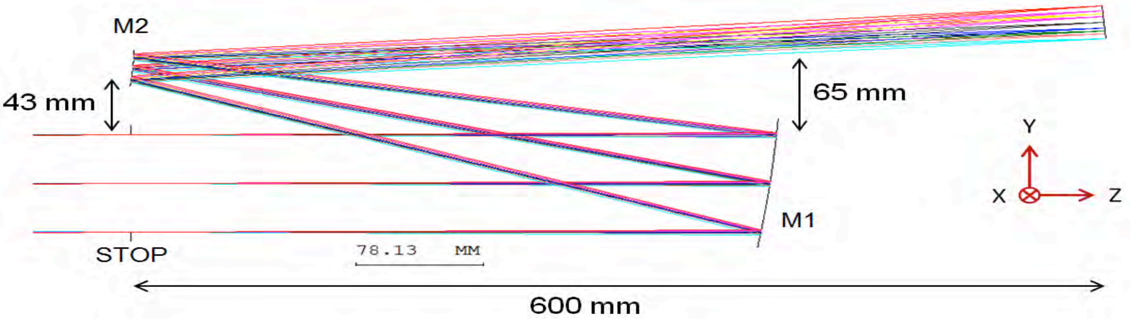


Figure 2. The new off-axis design of the SUAVE telescope.

The pupil, at STOP level is 80 mm and the focal 2630 mm. M1 is 100 mm with a vertex inclined 0.15° (useful diameter is 84 mm). M2 is 28 mm diameter with a vertex inclined 1.26° (useful diameter is 23.5 mm). Dimensions of telescope are 100x200x600 mm^3, 200x300x750 mm^3 expected with the structure.

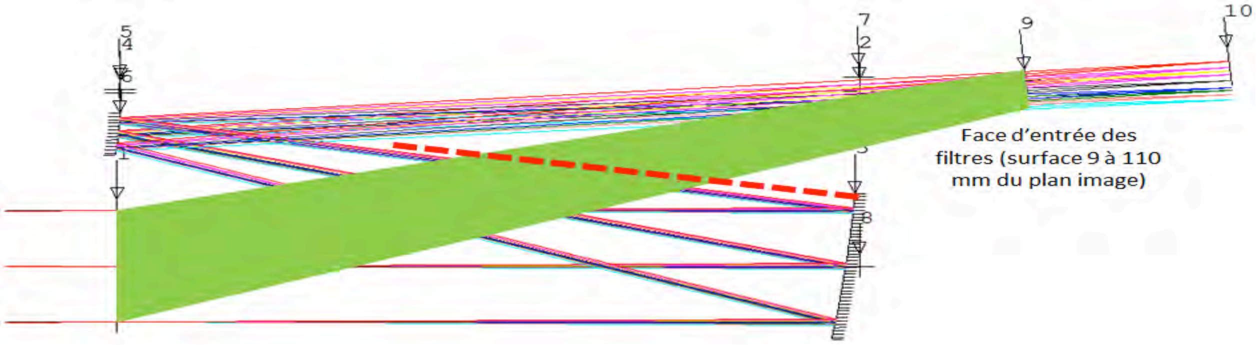


Figure 3. With the off-axis design a simple baffle (red dash) allows to protect the filters and detector from scattered light.

Performances of the telescope are excellent: we achieve diffraction limited imaging in the FUV (7 µm pixels). Defocus and astigmatism compensated by refocalization (MTF min: 0.3, cf. Fig. 2). Note that alignments are still fairly severe: Decentering/Tilts M1/M2: ±10 µm / ±10 arcsec and polishing is based on 3 nm RMS.

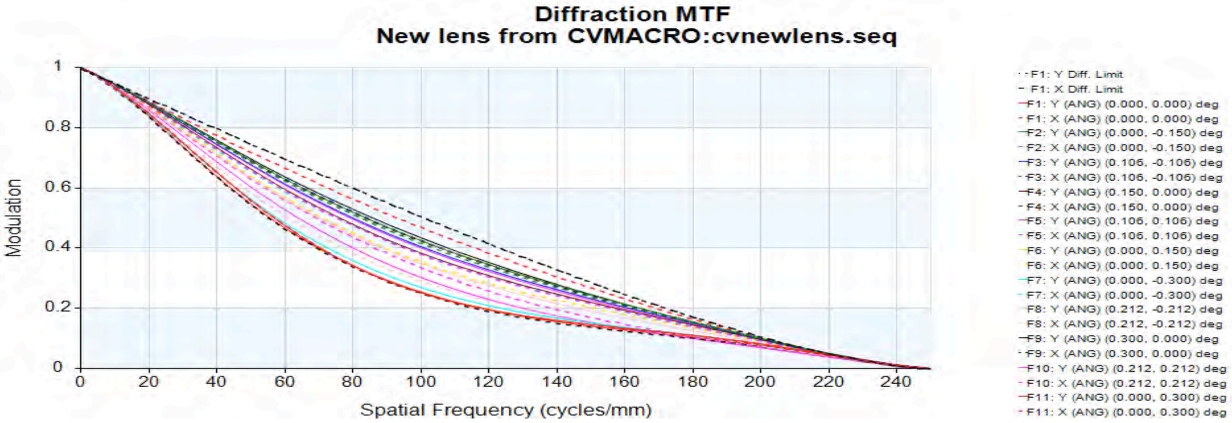


Figure 4. Modulation Transfer Function (MTF) of the new off-axis design of the SUAVE telescope.

SUAVE main optical path consists essentially of a primary SiC mirror (M1), a secondary SiC mirror (M2), interchangeable interference filters, and a CCD that acquires solar images.

The instrument is developed with important design features that will increase its capabilities:

- In closed position, a door protects the main optical path telescope against solar radiations. Its mechanism allows several opening and closing of the main optical path telescope. Cover allows protection of the optics from contaminants deposition during ground transport and launch.
- The telescope's mirrors are made of SiC (reflectivity around 40% in the UV and FUV, and around 20% in the visible). Advantage is indeed that the photometry will not change by aging and degradation of coatings since there are no coatings. Further, the primary and secondary mirrors will help to remove 96% of the visible solar flux (and about 84% of the UV), preserving the filters from degradation and, due to the high conductivity of SiC, this flux can be evacuated (CNES R&T breadboard demonstration).
- Two successive filter wheels allow insertion of one of the above-mentioned spectral filters (121.6 nm and 215.0 nm) and a refractive element (a defocusing lens for flat-field operations), or to leave the optical path open. There is also a visible channel (at 535.7 nm) to facilitate ground tests (use of a solar collimator), alignment (theodolites, guiding telescope, etc.), and calibrations (ground-based tests, etc.).
- A 2k×2k frame-transfer CCD is placed in the focal plane. A shutter mechanism provides it with dark conditions except

within the duration of its electronic exposures. The CCD is anti-reflective (AR) coated.

- The SUAVE telescope structure will use the carbon/carbon, invar, and titanium materials for their respective mechanical properties. All items will be fixed on a honeycomb carbon plate (integration and thermo-mechanical decoupling). Alternately the complete telescope could be in SiC (ongoing study and Phase A trade-off).
- A carbon/carbon (CC) composite monolithic structure (located behind the internal optical baffle) is selected to link the mirrors and the CCD because it imparts thermo-mechanical stability thanks to its low coefficient of thermal expansion. The main idea is to maintain a quasi-constant optical telescope point spread function (psf) over time.
- The whole SUAVE instrument is thermally controlled. Primary and secondary mirrors are regulated though control of the their support plates.
- The active secondary mechanism allow to precisely control the focus and to reduce errors on mirrors' figure to less than a nm.

4.3 Thermal modelisation and design

In order to evacuate the visible (and UV) flux received by the mirrors, a very specific and innovative design of the mirrors is proposed (the "Mushroom" design) and calculated (SAFRAN /REOSC realization). Thickness, length of feet is investigated, thermal influence of support plate, deformation of feet/support plate, coalignment of mirrors, etc.

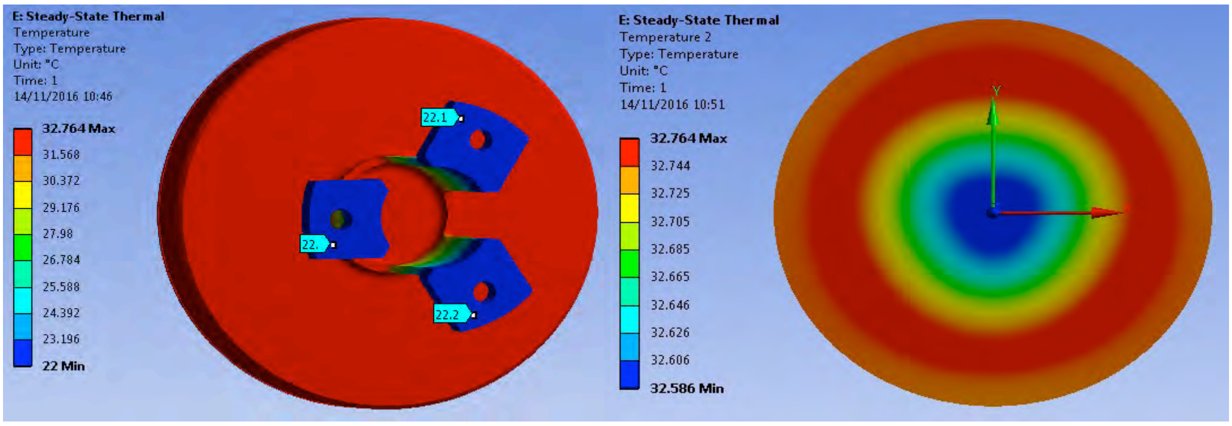


Figure 5. Analysis of the thermal sensitivity of the M1 mirror to the temperature variations of the support plate (to define its required regulation) to varying temperatures (here +/- 0.1° compared to 22° nominal). Deformations are observed up to 9 nm but only 0.57 nm after refocus. Mirror is "hot" at 32° (helpful to avoid contamination) but very homogeneous in temperature (± 0.1°).

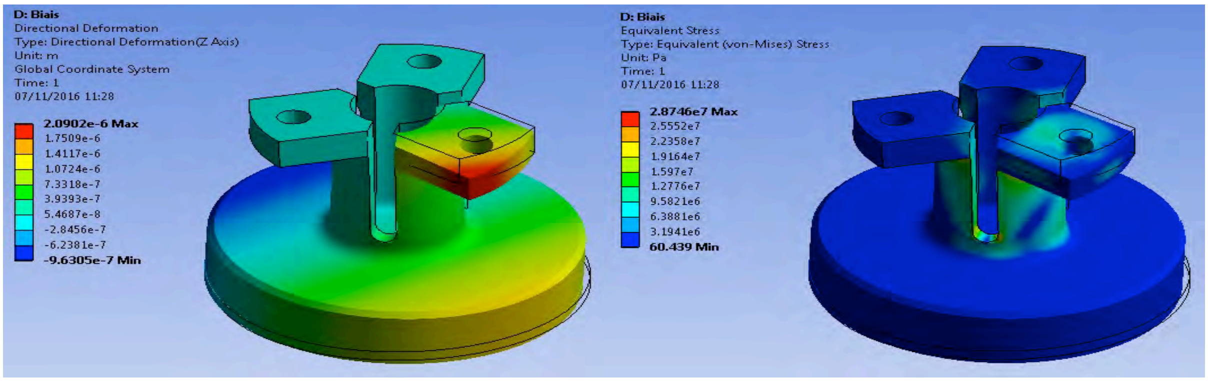
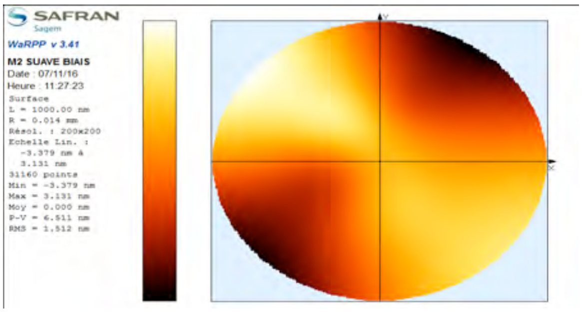


Figure 6. Analysis of the thermal sensitivity of the M2 mirror to planarity variations at the interface feet/support plate (to define its required regulation) of some 50 µrad.



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WaRPP v 3.41
M2 SUAVE BIAIS
Date : 07/11/16
Heure : 11:27:23
Surface
L = 1000.00 nm
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Résol. : 200x200
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31160 points
Min = -3.379 nm
Max = 3.131 nm
Moy = 0.000 nm
P-V = 6.511 nm
RMS = 1.512 nm
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Figure 7. Opto-thermo-mechanical analysis of the secondary mirror of SUAVE on its nominal orbit and solar flux lightning configuration was carried and showed that, even with 50 µrad deformation at feet/plate interface, the peak-to-peak surface error of the mirror stays in within prescriptions, < 1 nm (deformations of a few nm are observed, up to 6 nm, but less than 0.6 nm after refocus).

We conclude from these analysis of the new design of the SiC primary and secondary mirrors of SUAVE (M1 & M2) that, even in extreme conditions, the peak-to-peak surface error of the mirrors stays in within prescriptions.

5. MIRROR M1 REALIZATION

5.1 Mirror fabrication

Modeling allowed to design the "Mushroom" SiC mirrors of SUAVE and its support/interface plate. Design and photo of the M1 are presented in Fig. 8. Mirror and plate have been realized by MERSEN BOOSTEC, and coated with CVD (M1 only).

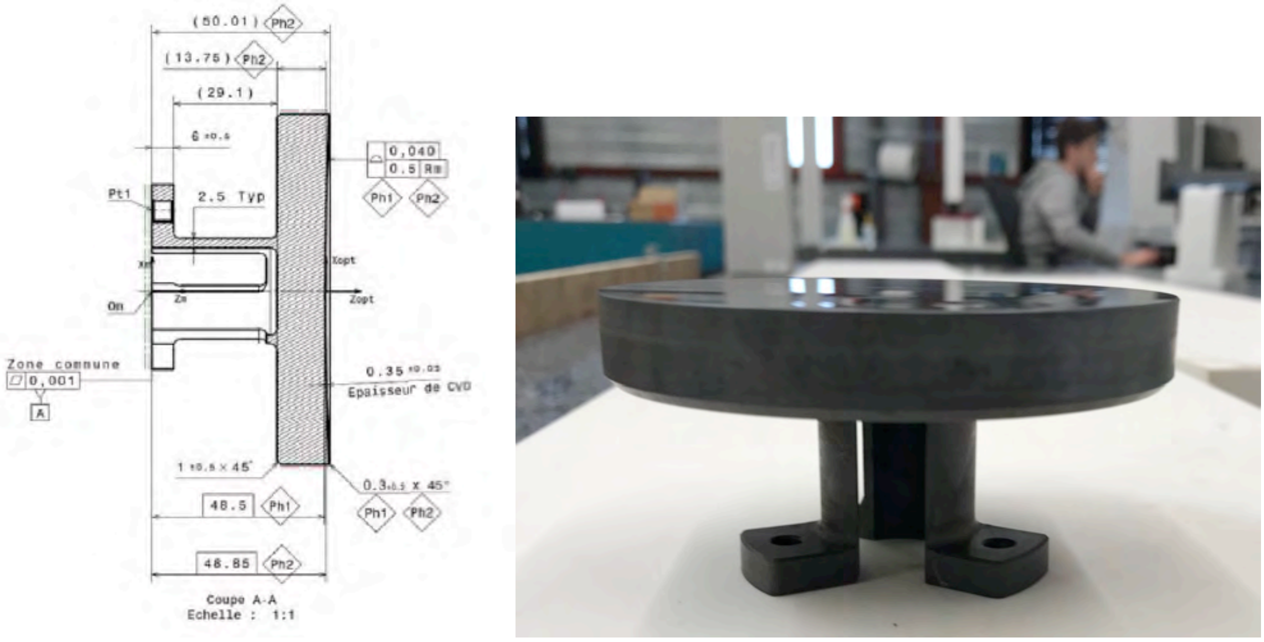

Figure 8. SiC mirror optimized and realized by MERSEN BOOSTEC and coated with CVD SiC.

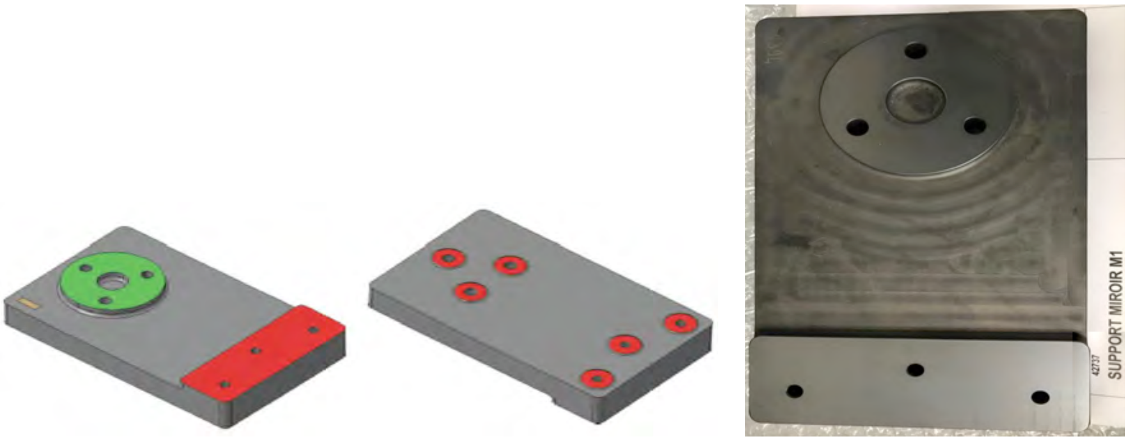

Figure 9. Support plate in SiC with rectified contact areas (not polished and without CVD).

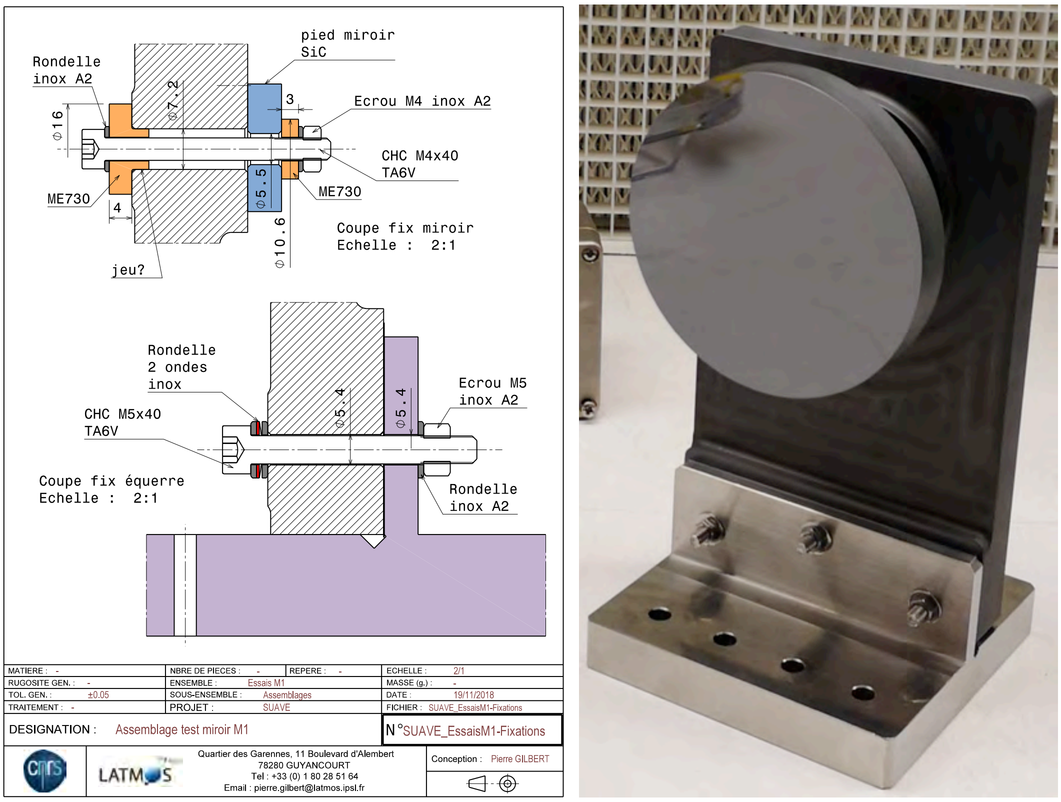

Figure 10. The test assembly of the primary mirror and of its support plate has been carefully designed as well as the interface between the support plate (in SiC) and the interface to structure and radiators (INVAR base).

5.2 Optical characteristics and polishing

Realization of the mirror by BOOSTEC was excellent, largely over the required tolerances:

- SiC Density: 3.14 g/cm^2
- Planarity of mirror "feet" : 1 µm (vs. 5 normally)
- Porosity: ~ 2 % (not important since of CVD; no CVD on mechanical interface)
- Roughness: less than 0.2 µm (~0.1 µm since of shinning)

- Plate: < 1 µm roughness on contact pads (lapped) and ~ 2 µm elsewhere (just rectified)
- Figure: "slight" hole in center (0.37 µm) but yet in tolerances (0.4 µm)
- CVD thickness: between 0.3 and 0.37 µm

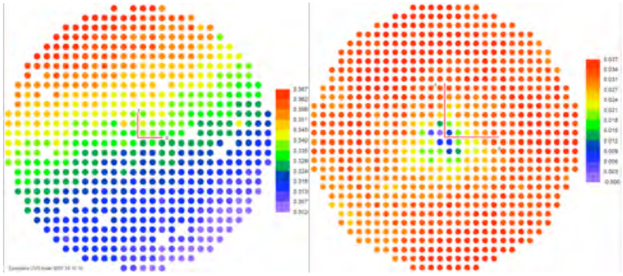

Figure 11. (left) Final figure of mirror; (right) SiC CVD thickness on mirror.

Concerning the polishing of the mirror, it was realized by OPA-OPTICAD (Mitry-Mory, France) with reduced specifications for cost reasons. Although the CVD deposit was very well realized the mirror was polished spherical since this is not affecting the thermal issues (temperature control and deviations to the figure are monitored whatever the exact figure is…). Specifications are:

- Roughness < 1 nm
- Planeity < 0.1 fringe (best effort)
- Radius of curvature: 1053 ± 2 mm

Results are excellent though the radius of curvature was out (problem of bad reference setpoint – 1063 – and not difficulty of realization):

- Measured roughness < 0.7 nm
- Planeity < 0.15 fringe
- Radius of curvature: 1064.78 mm (in within the 2 mm with reference at 1063)

6. TEST BENCH OF THERMO-OPTICAL TESTING OF M1 & SUPPORT PLATE

For the test of the thermal regulation of the "Mushroom" mirror and its thermalized support plate, both in SiC, the support plate is first equipped with 3 heaters and 6 control temperature sensors (3 at feet level and 3 near the heaters, cf. Fig. 13). The M1 is now equipped with the heaters and temperature sensors (Fig. 14). In the final configuration, to improve the modeling of the control software, up to 22 control temperature sensors could be used as shown on Fig. 13.

The thermal control system for the laboratory tests is built around an Arduino Mega 2560 board (cf. Fig. 14) that is regulating the temperature of mirror support plate at 22° ± 0.1°. Tests have been carried with a flux limited to a fraction of the 1400 W/m2 required but proved the control system software hability to properly regulate the temperature to 22° A solar simulator with a 300 W Xenon lamp will soon be used to approach the 1400 W/m2 of the solar flux.

For the final test, the mirror (with its support plate regulated at 22°) will be placed in a thermal vacuum chamber with an appropriate solar flux source simulator capable of the 1400 W/m^2 flux on the mirror (cf. Fig. 15). The INVAR base of the support plate holding the mirror will be linked to a thermal sink coupled to the regulated interface.

With the support plate fixed on the interface plate in INVAR itself on the regulated (heat sink) interface (in red on Fig. 15) in the thermal vacuum tank 3 testing protocoles (temperature and optical; flux transmission) will be applied:

Hot case: Tintf (banc sous INVAR) = 10°, Treg = 22°, Ti-rad = 20°, Fsol = 1420 W/m2
Cold case: Tintf = 0°, Treg = 22°, Ti-rad = 20°, Fsol = 1300 W/m2
Transiant case: Fsol = ON = 1420 W/m^2
Fsol = OFF = 0 W/m2

Objective is to reach TRL 6 "Prototype demonstration in operational environment".

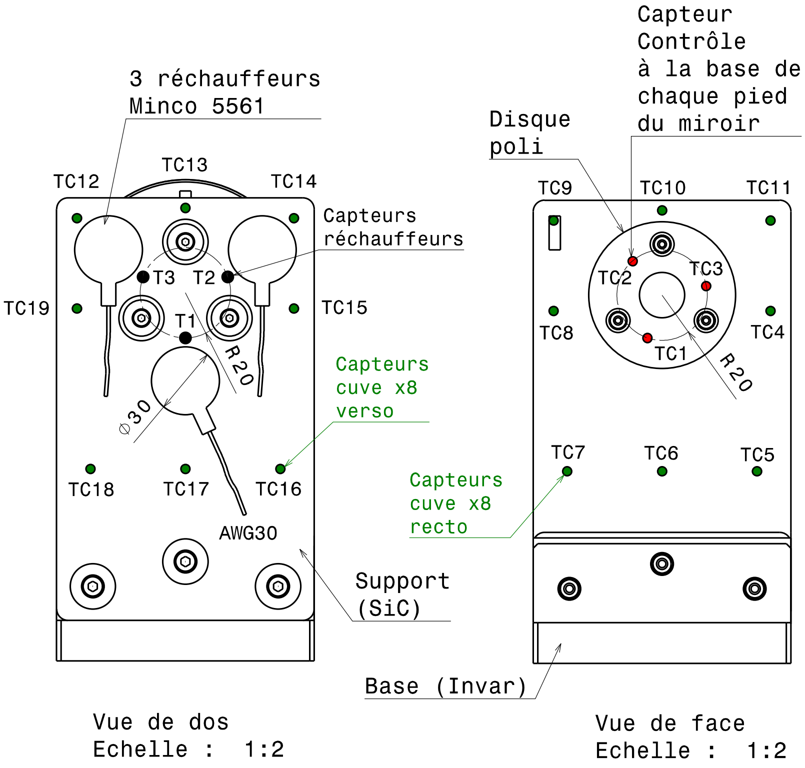

Figure 12. 3 heaters (Minco 5561) are implemented on the support plate to regulate it to 22°. The control loop uses 3 sensors to control the heaters (T1, T2, T3) and 3 to monitor the temperature at the feet of mirror (TC1, TC2, TC3). In the final version up to 22 sensors to control the temperature could be used.

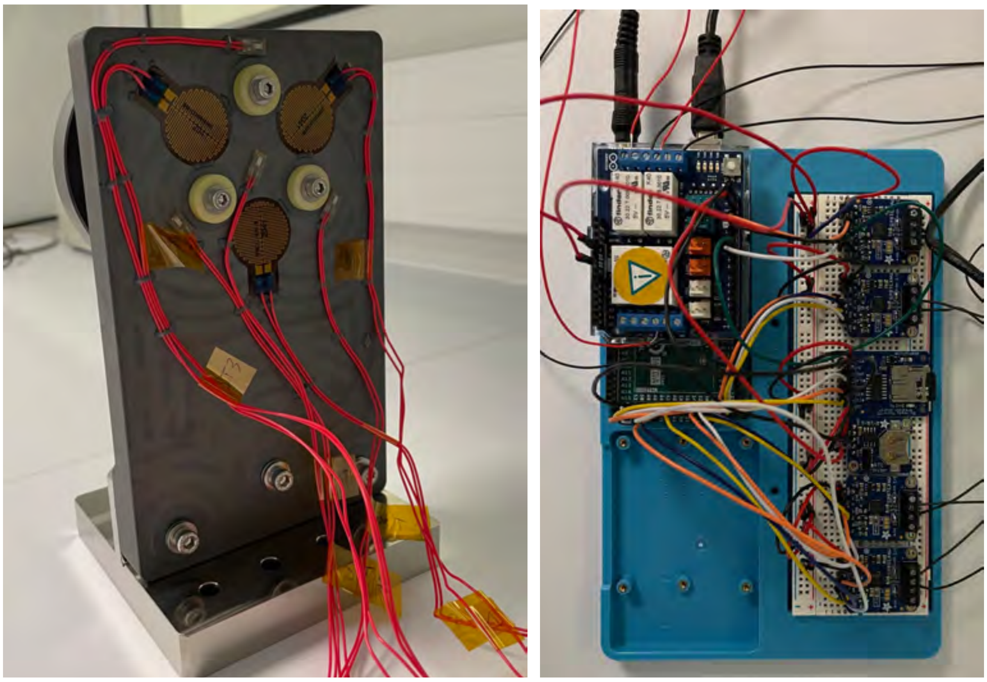

Figure 13. (left) Support plate and mirror on the INVAR base equipped with 3 heaters and 3 temperature sensors; (right) Arduino Mega 2560 temperature control and regulation system implemented for the laboratory tests.

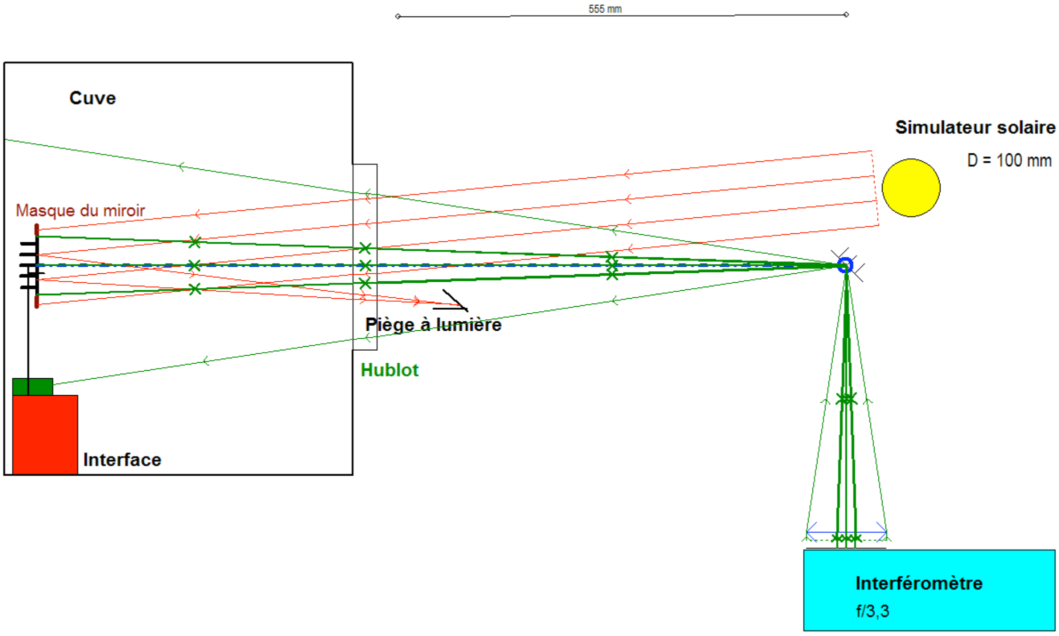

Figure 14. Possible test set-up for the thermo-optical tests of the temperature regulation of the SUAVE primary mirror. The solar simulator is expected to deliver 1400 W/m2 what requires, for the 10 cm mirror, a lamp of 300 W or more in practice.

7. SUMMARY/CONCLUSIONS & PERSPECTIVES

SUAVE is a novel disruptive far UV imaging solar telescope for FUV (Lyman-Alpha 121 nm) and MUV (Herzberg continuum 200-220 nm. It uses SiC mirrors for long duty cycle (> 6 years) since:

- **no coating** (**no degradation** of coatings)
- thermal **conductivity** and homogeneity -> **heat evacuation**
- **40% UV reflection** and 20% in visible -> **filters preserved** (flux inferior to 2 solar constants)

SUAVE design is thermally optimized since of:

- **off-axis** mirrors (no central obscuration, flux homogeneity minimizing thermal gradients, secondary preserved from direct light: easier heat extraction and activation)
- no insert on mirrors (no distortion) since of "**mushroom**" type mirrors

Thermal control tests of the mirror M1 and its support plate have been carried and demonstrate stability and feasibility of the control to 0.1°C under a limited flux. Further tests in vacuum chamber with a representative solar flux on the SiC/CVD M1 mirror are planned in 2023 to lead this promising design of FUV telescope to TRL 6. Following this effort, we plan to propose the development of a more complete exploratory breadboard of the SUAVE telescope including the secondary mirror M2, filters and the appropriate structure (Carbon-Carbon tube and INVAR or a SiC only structure) to reach TRL 8 and a "Qualification for Flight" of the telescope.

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