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The SiC Primary Mirror of the EUCLID Telescope

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I. INTRODUCTION

Euclid is a part of the European Space Agency Cosmic Vision program. Euclid mission's goal is to understand the origin of the accelerating expansion of the Universe. This space mission will embark a large Korsch telescope, a visible imager (VIS) and a near-infrared spectrometer and photometer (NISP). The hardware of all of them will be mainly made of Boostec® SiC material.

The SiC telescope has been designed by AIRBUS Defence & Space team in Toulouse (France). Its primary mirror (M1) has been highly optimized for purpose of mass and WFE reduction. It features i) a Ø 1.25 m circular outer contour, ii) a Ø 0.37 m decentered circular inner hole, iii) a on-axis concave optical face, iv) three outer pads to be bolted on the isostatic mounts, v) a mass of only 38 kg and vi) a first eigen frequency of 140 Hz. In addition to the possibility of high mass reduction, the Boostec® SiC has been chosen for its mechanical and thermal properties at cool down operating temperature (125K). The full SiC telescope architecture gives high optical stability; having SiC mirrors and structure enables a good in-orbit behavior prediction of the instruments performance.

The present paper describes the ready-to-polish M1 Flight Model blank and its manufacturing process. It has been manufactured monolithic (without any assembly); its optical face has been coated with a thin layer of non-porous and easily polish-able SiC layer obtained by MERSEN Chemical Vapor Deposition.

II. BOOSTEC® SiC MATERIAL FOR SPACE OPTICS

MERSEN BOOSTEC manufactures a **sintered silicon carbide** which is named **Boostec® SiC**. Its key properties are a high specific stiffness (420 GPa / 3.15 $g.cm^{-3}$) combined with a high thermal stability (180 $W.m^{-1}.K^{-1}$/ 2.2 . 10^{-6} K^{-1}).

Its high mechanical strength allows making mirror but also structural parts, such as the structure of Euclid telescope and its two attached instruments.

Thanks to its isotropic microstructure, the physical properties of this alpha type SiC are perfectly isotropic and reproducible inside a same large part or from batch to batch. In particular, no CTE mismatch has been measurable, with accuracy in the range of 10^{-9} K^{-1} [1].The CTE of Boostec® SiC is decreasing from 2.2 . 10^{-6} K^{-1}@ room temperature down to 0.2 . 10^{-6} K^{-1}@ 100K and close to zero between 0 and 35K. Its thermal conductivity remains over 150 W/m.K in the 70 K-360 K temperature range.

This material shows no mechanical fatigue, no outgassing and no moisture absorption nor release. It has been fully qualified for space application at cryogenic temperature such as NIRSpec instrument which will be operated in space at only 30 K [2].

As the sintering process can't be fully achieved, this pressure-less sintered material exhibits a residual porosity, < 2.5 vol.%. This porosity is closed, thus meaning that the material is perfectly tight. Even if it can be easily polished, such a finished mirror face should contain pores of a few micrometers in diameter which are generally not acceptable for application in the visible or the UV range, due to unacceptable level of stray light. This is the reason why MERSEN BOOSTEC proposes that the mirrors optical faces are coated with a pore-free SiC CVD layer.

TABLE I. BASIC PROPERTIES OF BOOSTEC® SIC

Properties	**Typical Values @ 293 K**
Density	3.15 $g.cm^{-3}$
Young's modulus	420 GPa
Bending strength / Weibull modulus (coaxial double ring bending test)	400 MPa / 11
Poisson's ratio	0.17
Toughness (K_{1C})	4.0 $MPa.m^{1/2}$
Coefficient of Thermal Expansion (CTE)	2.2 . 10^{-6} K^{-1}
Thermal Conductivity	180 $W.m^{-1}.K^{-1}$
Electrical conductivity	10^5 Ω.m

MERSEN BOOSTEC has been successfully manufacturing large size SiC space mirrors since more than 15 years; the most challenging of them are the Herschel M1 (Ø 3.5 m, 25 kg/m², made of 12 brazed segments, without any CVD coating) and the two primary mirrors of the Gaia Astro TMAs (1.5 m x 0.56 m, 38 kg, monolithic, SiC CVD) [3] [4]. Euclid M1 is the largest **monolithic** one, with CVD coating.

III. MERSEN SiC CVD

A. SiC CVD material

MERSEN chemical vapor deposition (CVD) process produces SiC solid material which is highly pure (> 99.999%), theoretically dense (3.21 g/cm^3), free of void or micro-crack and with cubic β crystal structure. Its physical properties are similar and even better than the one of the Boostec® SiC material; in particular, it is isotropic and homogeneous; furthermore, its coefficient of thermal expansion (CTE) fits very well with the one of the sintered SiC substrate. The CVD SiC / Sintered SiC interface shows a remarkably good continuity of the material; it is free of any defect (Fig.1).

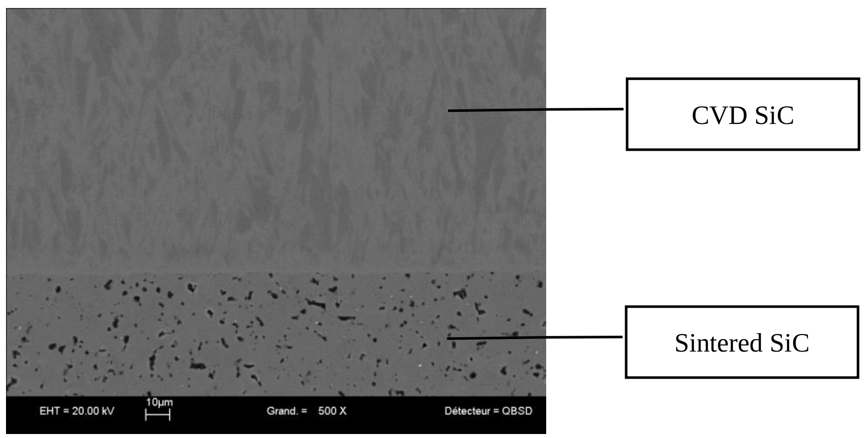

Fig. 1. SEM view of CVD SiC / Sintered SiC interface

B. MERSEN experience in SiC CVD

In close collaboration with MERSEN France Gennevilliers, its affiliated company, MERSEN BOOSTEC offers a SiC CVD coating on its mirror blanks. Various kinds of small mirrors which are widely used in the photonics industry have been successfully coated in "Gennevilliers" furnaces since 2011, at series level. Final product characteristics are good coating homogeneity, reproducible thickness and crystallisation, good cosmetic aspect (SiC-like grey colour obtained) and good ability to further polishing. On the other hand, the process has been qualified for large size (Ø 1.2 m) space mirrors in view of Euclid project; then, a lot of space mirrors have been successfully coated for purpose of export, CNES or ESA projects; in particular the flight models of all Euclid mirrors other than M1 have been successfully SiC CVD coated with MERSEN facilities.

IV. EUCLID

A. Euclid mission

Euclid is an ESA medium class astronomy and astrophysics space mission, to be launched in 2020.
The Euclid mission aims at understanding why the expansion of the Universe is accelerating and what is the nature of the source responsible for this acceleration which physicists refer to as dark energy. Dark energy represents around 75% of the energy content of the Universe today, and together with dark matter it dominates the Universes matter-energy content. Both are mysterious and of unknown nature but control the past, present and future evolution of Universe.

THALES Alenia Space will be in charge of the construction of the satellite and its Service Module while AIRBUS Defence & Space will provide the Payload Module. The mirrors and the structures of all the PLM instruments will be mainly made of Boostec® SiC material, giving required lightweight, stiffness, strength and dimensional stability.
Euclid will embark a 1.2 m Korsch telescope feeding 2 instruments, VIS and NISP: a high quality panoramic visible imager (VIS), a near infrared 3-filter photometer (NISP-P) and a spectrograph (NISP-S). With these instruments physicists will probe the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of dark matter and the 3-dimension distribution of structures from spectroscopic red-shifts of galaxies and clusters of galaxies, with a look-back time of 10 billion years.
The satellite will orbit at L2 Sun-Earth Lagrangian Point for a 6 years mission.

B. Euclid telescope

The Euclid telescope is a three mirror Korsch configuration with a 0.45 deg off-axis field and an aperture stop at the primary mirror. The entrance pupil diameter is 1.2 meters, the optically corrected and unvigneted field of view is 0.79×1.16 deg², and the focal length is 24.5 m.

In order to meet the scientific performance requirements, such as having internal background well below the zodiacal sky background, the telescope must operate at a reduced temperature - a maximum operating temperature of about 240 K can be tolerated for the telescope.

The telescope includes three aspherical mirrors i) a Ø 1.25 m on-axis concave M1, ii) an off-axis convex M2 iii) an off-axis concave M3 and also three large folding mirrors (FoM 1 to 3). All these SiC mirrors are hold by a highly stable and very lightweight structure made of a large baseplate (around 2.5 m x 2.1 m), a truss for purpose of M2 fixation and several large brackets holding various opto-mechanical devices.

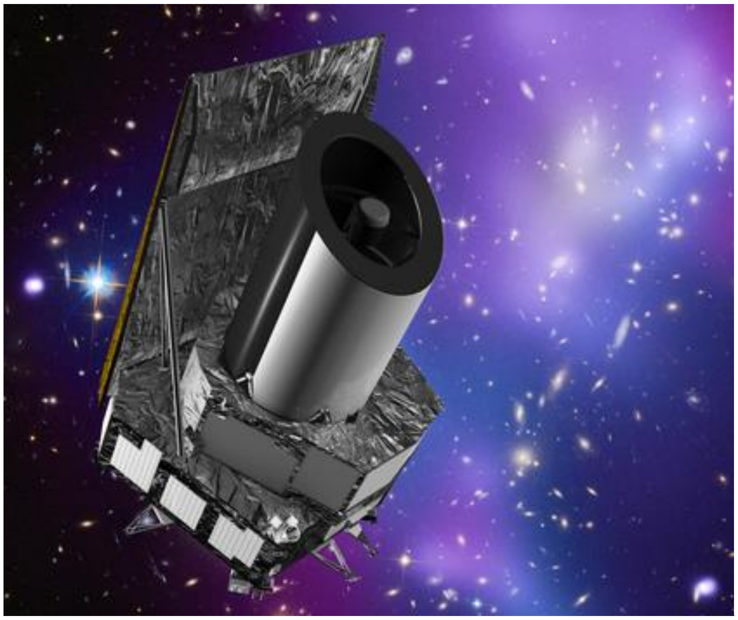

Fig. 2. Artist's impression of Euclid (credit ESA)

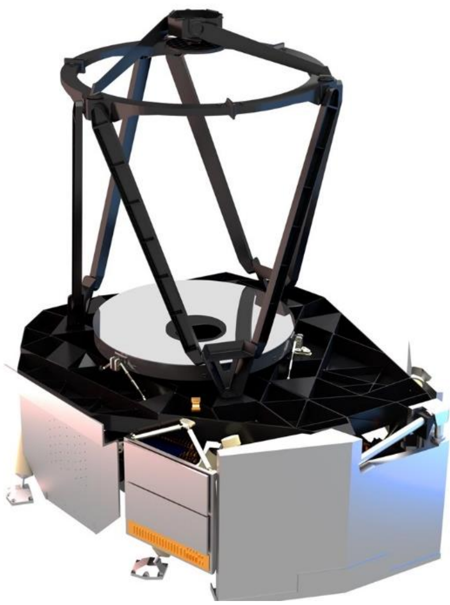

Fig. 3. Payload Module (credit AIRBUS)

C. Euclid telescope Primary Mirror (M1)

The Euclid primary mirror has been designed by Toulouse AIRBUS Defence & Space team, compliant with the following requirements i) weight < 40 kg , ii) WFE < 9 nm rms under 120 K cool-down and iii) global WFE < 25 nm rms, all effects being taken into account. It has been highly optimized for purpose of both mass and cooldown WFE reduction. Fig.4 shows the results of such a preliminary optimization, obtained from an AIRBUS D&S internally developed software. The so optimized design cases have been further optimized afterwards.

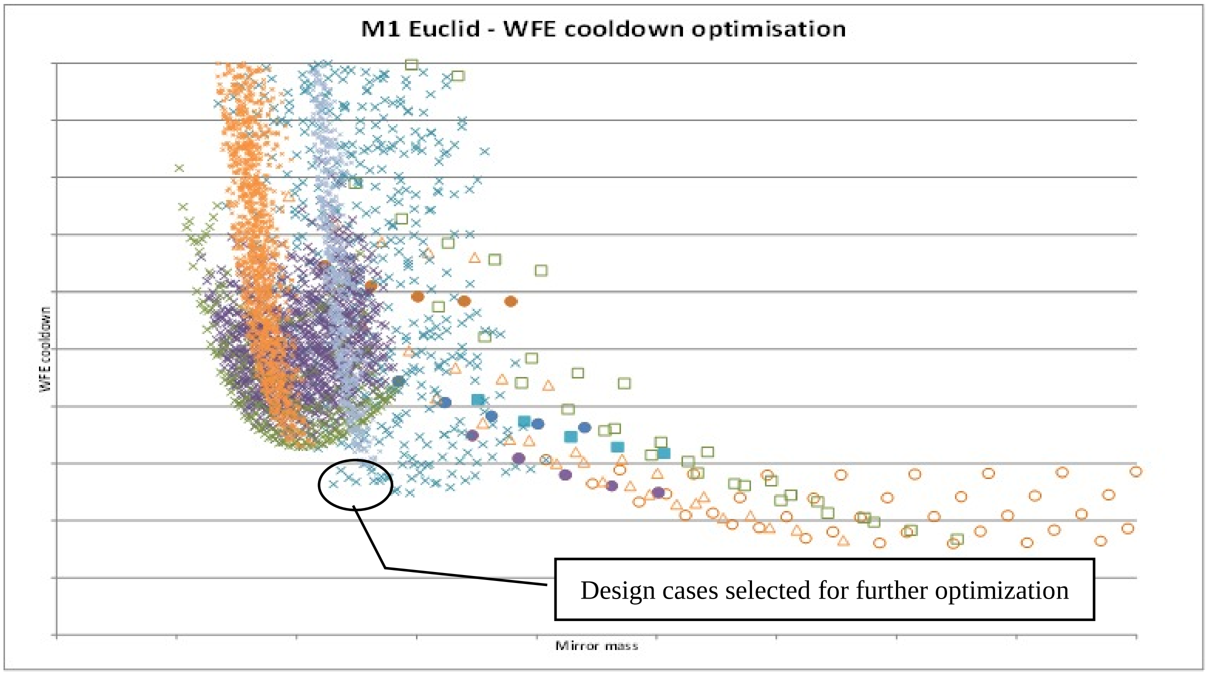

Fig. 4. Euclid M1design, mass and cooldown WFE preliminary optimization

V. DESCRIPTION OF THE EUCLID TELESCOPE PRIMARY MIRROR

The designed primary mirror (M1) features i) a Ø 1.25 m circular outer contour, ii) a Ø 0.37 m decentered circular inner hole, iii) on-axis concave optical face, iv) three outer pads to be bolted on the isostatic mounts, v) a mass of only 38 kg and vi) a first eigen frequency of 140 Hz.

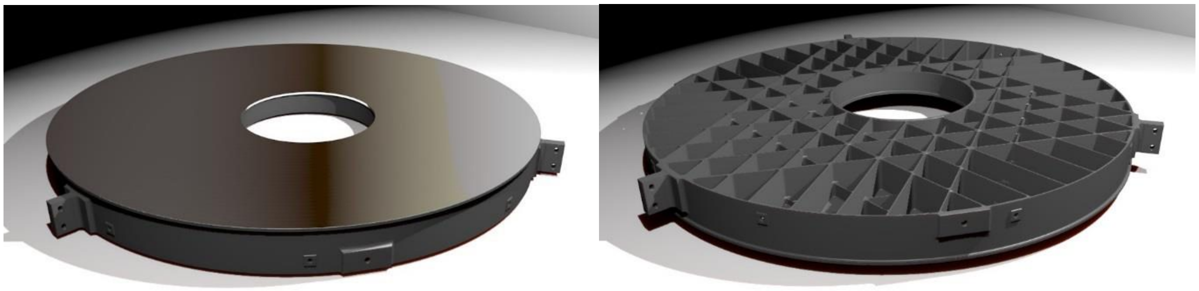

Fig. 5. Euclid M1design, optical face (left picture) and rear face (right)

VI. MANUFACTURING TECHNOLOGY FOR EUCLID M1

A. General process

The ready-to-polish M1 Flight Model has been manufactured according to the following Fig. 6 sequence of steps.

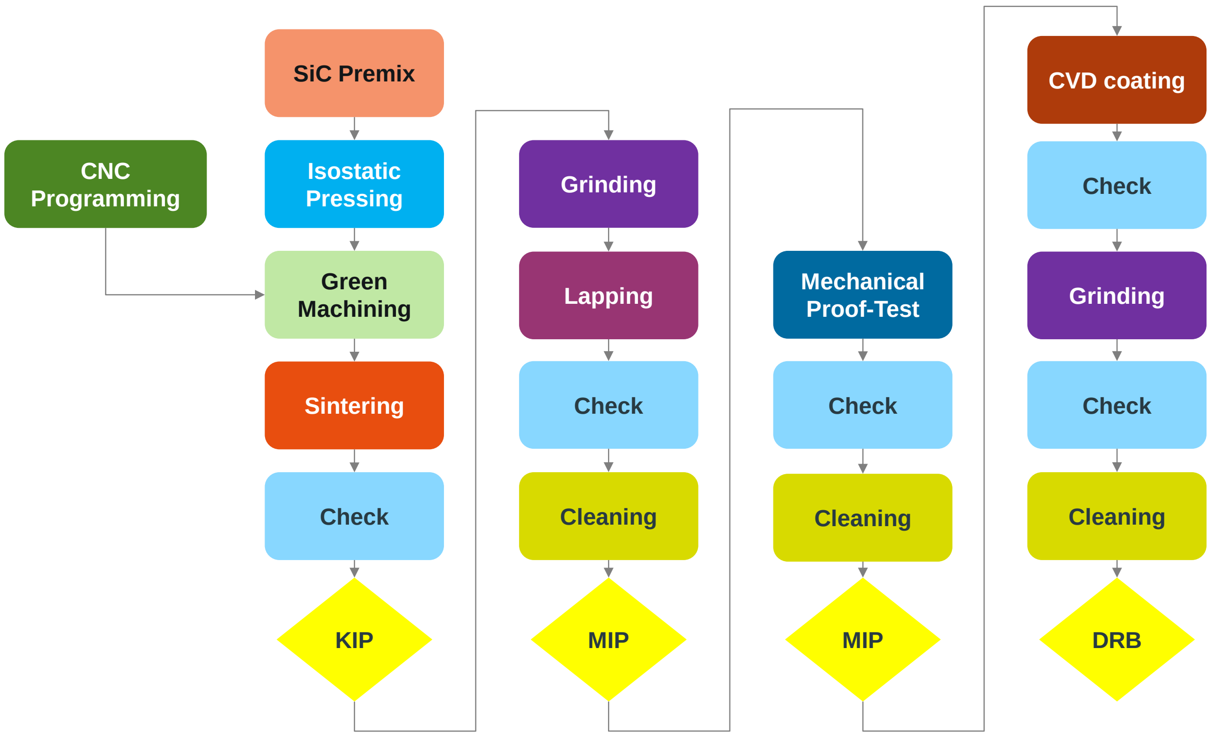

Fig. 6. Sequence of steps for manufacturing ready-to-polish M1 Flight Model

The SiC part is fully checked after sintering (measurements, material quality), in the frame of KIP (Key Inspection Point), before engaging next steps. It is again fully checked (measurements, material quality), in the frame of MIP (Mandatory Inspection Point) at the end of some sequence of manufacturing steps, thus giving authorization to proceed with next critical step: mechanical proof-testing or CVD coating. The DRB (Delivery Review Board) is the final review, giving customer acceptation and authorization to set-up the part in its container.

B. Monolithic substrate made of Boostec® SiC

Commonly, MERSEN BOOSTEC manufactures and tests monolithic SiC parts of up to 1.7 m x 1.2 m x 0.6 m or Φ1.25 m according to the three left columns of Fig. 6. The parts are machined very close to the final shape at the green stage i.e. when the material is still very soft (similar to chalk). The collected chips are reused for producing new raw material. During the last ten years, the reliability and also the speed of this process have been continuously improved. New software has been invested for programming the CNC milling machines and also to verify the machining programs, thus allowing the green machining of very complex 3D shapes with a high reliability. These are some of the reasons why BOOSTEC process is so cost effective, reliable and quick.
These shaped parts are then sintered by heating-up to around 2100°C under a protective atmosphere, thus transforming the compacted powder blank into a hard and stiff ceramic material. The "as-sintered" surfaces look highly smooth (typically Ra 0.4 µm); they can be used as is, without any sand blasting or any other rework. The optical face and also the interface of the mirrors are then generally ground in order to obtain accurate shape (from 50 µm down to 1 µm) and location; the Euclid M1 interface pads have been further lapped for an even better flatness and roughness.
As they are significantly mechanically loaded; these M1 interface pads have been proof-tested, thus reducing the risk of hidden defects in the material; even if unlikely, this is above all an easy way to really prove that the SiC blank is able to withstand with the predicted most critical loads. The SiC parts are checked crack-free with help of UV fluorescent dye penetrant, before and after such a proof-test. They are measured with a large size accurate CMM or a laser tracker.

C. SiC CVD coating

The SiC CVD coating of Euclid M1 has been feasible thanks to the large size of MERSEN Gennevilliers furnace. An important requirement was the saving of un-coated zones (ribs and pockets of backside, interface pads). MERSEN BOOSTEC has designed and mounted additional tooling in order to prevent from SiC deposition on such desired areas. After coating, the CVD layer thickness and also the optical face shape have been measured directly on the M1 blank with help of the large CMM. Some witness samples have also been checked for purpose of i) coating thickness measurement, ii) cut-out microstructure investigation and iii) crystal structure analysis.
According to right column of Fig. 6, the SiC CVD layer has been then slightly ground again in order to obtain a smoother surface, a more homogeneous CVD layer thickness and a shape closer to the final target.

VII. MANUFACTURING RESULTS

The ready-to-polish Flight Model M1 (including CVD coating) has been successfully manufactured conform to specifications, tested and delivered to SAFRAN-REOSC during second half of 2015 (Fig.7). Its main characteristics are exhibited in Table II.

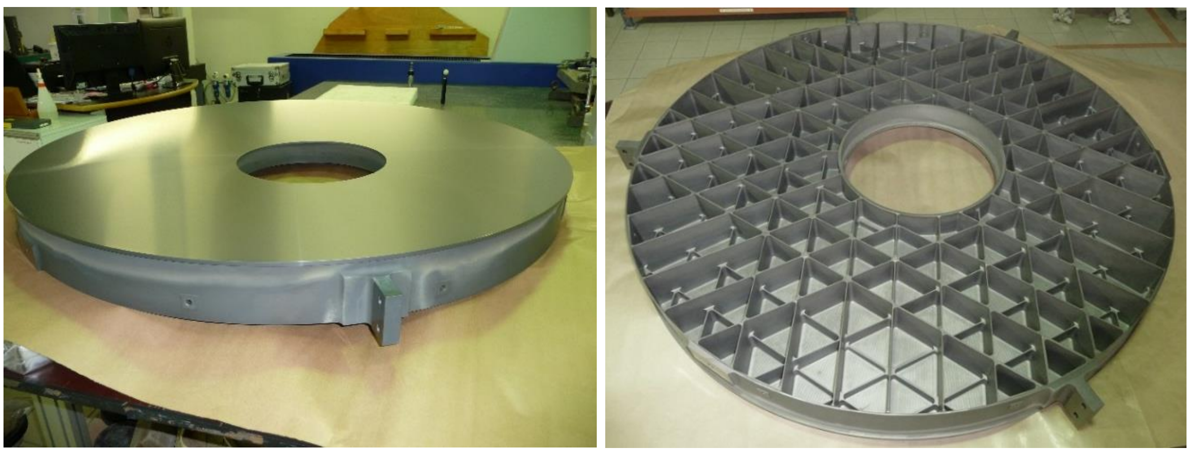

Fig. 7. The ready-to-polish M1 blank Flight Model, front face (left picture) and rear face (right)

TABLE II. MAIN CHARACTERISTICS OF THE READY-TO-POLISH EUCLID M1, FLIGHT MODEL

Properties	**Measured Values**
Weight	39.0 kg
Outer diameter	1250.05 mm
Decentered inner hole diameter	367.29 mm
Average SiC CVD layer thickness	365 µm
Flatness of ISM pads	1 µm PV
Optical face shape defect	80 µm PV

VIII. M1 STATUS AND PERSPECTIVES

The M1 Flight Model is now being polished by SAFRAN Reosc, under AIRBUS Defence & Space specification. In order to fulfil the in-flight WFE budget, the surface error of the polished and coated mirror has been allocated to 9 nm rms under 0g condition.
The polished and coated mirror will be then mounted by AIRBUS Defence & Space on the large SiC baseplate of the telescope with help of bolted isostatic mounts.

IX. CONCLUSION

AIRBUS Defence & Space and MERSEN BOOSTEC are developing the large Euclid Korsch telescope. The Boostec® SiC concept allowed to obtain highly optimized mass and cooldown WFE of its large primary mirror.

The present work confirms the ability of MERSEN BOOSTEC to manufacture ready-to-polish, up to Ø 1.25 m monolithic SiC mirrors at space standard, capable of 120 K cryo condition; their optical face is coated by a MERSEN pore-free SiC CVD layer which can be easily polished prior to receiving a suitable reflective coating.

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