SPIRALE – the first all-Cesic® telescopes orbiting Earth

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ABSTRACT

SPIRALE is a French Earth observation demonstration project consisting of two satellites. In support of the project and under contract with Thales Alenia Space, ECM manufactured two fully integrated all-Cesic® telescopes, composed of super-light-weighted complex monolithic structures, including two off-axis aspheric mirrors per telescope with integrated interfaces for mounting.

The all-Cesic© telescope assembly was tested under shock and vibration loads, and by exposure to realistic in-flight thermal environments.

In this paper we describe the space-qualified process of manufacturing such high-precision space telescopes based on our Cesic® technology; the advantages of our Cesic® technology compared to traditional materials, such as metals or glass ceramics; and some of the test results.

This project demonstrates that all-Cesic® telescopes have great potential for future space applications, especially under cryogenic conditions, due to their athermal characteristics and the great versatility of the Cesic® manufacturing process.

1. INTRODUCTION TO CESIC®

ECM's Cesic® material is a ceramic matrix composite that is characterized by high stiffness and mechanical strength, high thermal conductivity, low CTE, and quick, relatively inexpensive manufacturing times. These characteristics make Cesic® an ideal material at reasonable cost for high-precision space optical and structural applications.

The starting material in the manufacturing of Cesic® is a short, chopped, randomly oriented carbon fiber material. The fibers are mixed with a phenolic resin and molded into a blank, which then is heat-treated under vacuum. The result is a light-weight, porous, relatively brittle C/C greenbody.

ECM's large CNC controlled milling machine of 2.5 m x 1.75 m allows us to manufacture large, light-weighted, monolithic structures, such as mirrors and components for telescope structures or optical benches. For example, in the manufacture of optical mirrors, curved face sheets (including off-axis designs) can be machined with reinforcing ribs as thin as 1 mm and of any geometry, including ribs with light-weighting holes or of T-shape for increased stiffness.

Upon machining, the greenbody is infiltrated under vacuum conditions with liquid silicon at temperatures above 1600 °C. Capillary forces wick the silicon throughout the porous greenbody, where it reacts with the carbon matrix and the surfaces of the carbon fibers to form carbon-fiber reinforced SiC – i.e., Cesic®. The density of the infiltrated Cesic® composite is around 2.65 g/cm³.

After controlled cool-down, the Cesic® structure is carefully examined visually and by other NDT methods, such as dye penetrant or ultrasonic tests. The structure is then micro-machined with suitable diamond tools or by EDM machining to achieve the required surface figure and interface geometry (e.g., mirror adaptation and mounting). EDM machining is possible because of Cesic®'s good electrical conductivity. This machining method is fast compared to grinding, it is relatively inexpensive, and it yields a surface and location accuracy (e. g., for screw holes and mounts) of about 10 µm tolerance over a large area.

Manufacturing times of Cesic® mirrors and other structures are typically only a few weeks, upon procurement of the C/C raw material, which is much shorter than the manufacturing times of other ceramic or glass structures. Highly complex and large projects take somewhat longer, e.g., mirrors with closed backs, meter-plus-class mirrors that require precision joining of greenbody or infiltrated segments, and large multi-segmented optical benches.

The maximum size of Cesic® components is only limited by the size of the Si-infiltration furnaces. ECM's current largest furnace has a useable diameter of 2.4 m with up to three levels, each of height 1.2 m.

The ECM/TAS team has a long tradition, going back more than seven years, of designing, manufacturing, and testing Cesic® optical mirrors and structures, supported by internal funding and contracts with space agencies, such as ESA. Examples are a 1-m cryogenic optical bench tested down to 10 K and under mechanical loads of up to 80 g (Earth surface gravitational acceleration), a 700-mm focal plane, a 1-m mirror of only 16 kg, and a 3-D ultra-stable structure with dimensions of 800 mm x 400 mm, illustrated in Fig. 1.

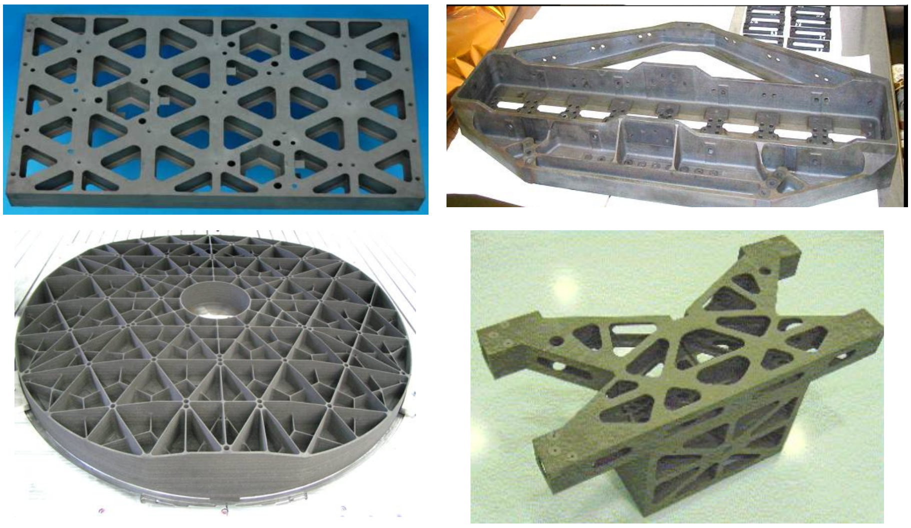

Fig. 1 Examples of optical components constructed of Cesic®

2. FIRST FLIGHT APPLICATION OF CESIC®

SPIRALE, the French acronym for "preliminary infrared warning system," has been developed by prime contractor Astrium, France, for the French defense procurement agency DGA. Thales Alenia Space was selected as the prime contractor for the satellites and IR instruments.

Thales Alenia Space contracted with ECM to manufacture two fully integrated Cesic® telescopes for the technically rather demanding SPIRALE demonstration project. The selection of Cesic® was based on the fact that the manufacture of Cesic® optical mirrors and structures is a mature and thoroughly tested technology.

In particular, Cesic® was chosen for the SPIRALE telescopes because it offers :

- Very high stiffness at low mass;
- great compactness, including the construction of fully monolithic structures with numerous integrated functions;
- high thermal conductivity, allowing Earth observations even with the sun very near the telescopes' field-of-view; and
- cost-effective and rapid production.

Thales' confidence in the Cesic® technology was confirmed during the early development phase of the SPIRALE project. Initially, the project called for one qualification model (QM) and one flight model of the telescope. The QM model was tested for mechanical and thermal performance, giving input for the design and construction of the flight model. The testing of the QM model showed that it met all the specification requirements, which prompted Thales to upgrade its status to that of a flight model. Thus, the SPIRALE project ended up with two flight models. Both models have been space-qualified, including their optical performance.

To meet mission requirements, an off-axis telescope design was selected, which places the M2 mirror outside the entrance cavity and, thereby, prevents disturbance of the optical system even when sunlight enters deep into the cavity.

The two SPIRALE flight telescopes are microsatellites in the 120-kg class, with a height of 90 cm. They are composed of super-light-weighted, complex monolithic structures, including two off-axis aspheric mirrors per telescope with integrated interfaces for mounting, all made of Cesic®.

Due to the limited volume available on microsats, the SPIRALE telescope structure was designed to be as compact as possible, with the optical flux passing through a dedicated opening.

SPIRALE Micro Satellites are demonstrator satellites carrying infrared-sensitive telescopes designed to detect the hot plumes of missiles during their initial boost phase. The objective of developing these microsats — so called because they are a fraction of the size of conventional satellites — is to forge a technical path for the construction of a pair of much larger operational missile-warning satellites by 2020.

Thales Alenia Space, in charge of the space segment of the SPIRALE demonstration project, based the design of the satellites on a modified version of the Myriade Platform developed by the French space agency CNES for scientific microsatellites, such as Demeter and Parasol.

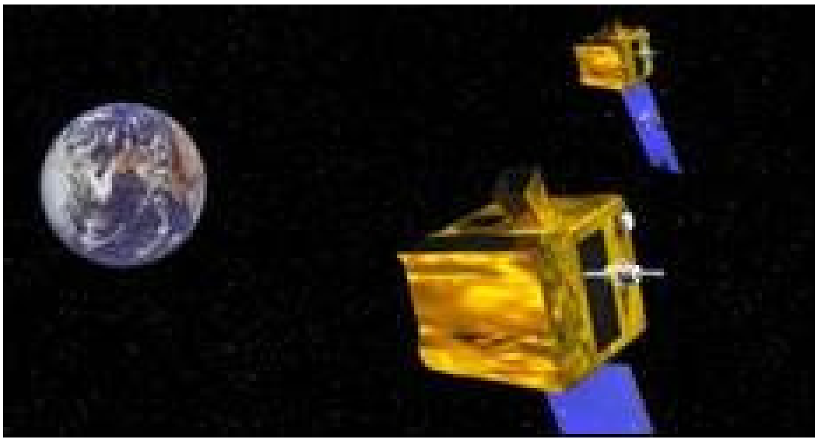

Fig. 2 Two SPIRALE satellites in a high-altitude elliptical orbit observing Earth in IR

The two Spirale satellites were inserted into a high-altitude elliptical orbit in February 2009. Due to the specific environment that characterizes this orbit, we had to significantly modify the Myriade platform, which was designed for low sun-synchronous orbits. This involved both adapting the satellites' attitude and orbit control system to an elliptical orbit, and also protecting them against the high level of radiation when passing through the Van Allen belt.

3. MANUFACTURING THE ALL-CESIC® TELESCOPES

Thanks to the exceptional manufacturing versatility of Cesic®, the SPIRALE telescopes consist of just three main parts: a central structure plus the M1 and M2 mirrors, all assembled together, thereby assuring fully athermal performance (Fig. 3).

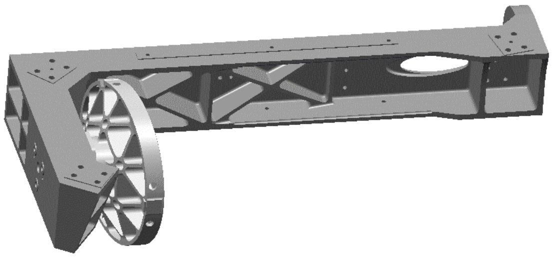

Fig. 3 Monolithic Cesic® telescope

The monolithic structure holds all the optical elements: mirrors, detection units, and dioptres. This required fine-machining via EDM numerous, rather intricate interfaces. In order to be sufficiently stiff, especially with regards to torsion forces, the central part of the structure has a closed-box design. Manufacturing a structure of this complexity was relatively straightforward with our Cesic® technology by machining the components in the greenbody stage and assembling them prior to Si-infiltration.

Upon Si-infiltration, the different optical components were bolted with titanium screws directly to the telescope structure without intermediate and costly inserts. This was possible, due Cesic®'s good fracture toughness, as we had determined in a prior test by bolting Cesic® plates together in the same manner and applying torsional stresses.

The telescope structure was attached by 3 I/F blades to the payload panel, which is the upper panel of the satellite platform, thereby making the entire satellite assembly highly compact and very light-weight.

The main challenge in manufacturing and polishing the flight mirrors was their off-axis design. We dealt with this challenge by precisely machining via EDM both the surface curvatures of the front sides of the mirrors and the mounting interfaces in their backs to ensure close alignment. The EDM machining, which is possible with our Cesic® material, saved much time and, hence, money because during grinding of the off-axis mirrors no special and difficult metrology was required. After completing the EDM machining, the mirrors were coated with SiC CVD prior to polishing.

Fig. 4 View of the 2 telescope structures (flight models)

The mirrors were polished by Sagem, France, to less than 20 nm RMS WFE.

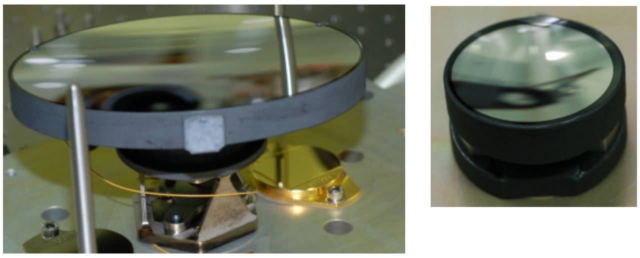

Fig. 5 SPIRALE M1 & M2 flight mirrors

Fig. 6 SPIRALE M1 - backside with interface

In order to stay within the project budget, Thales Alenia Space decided, upon the successful testing of the SPIRAL QM model for mechanical and thermal performance, to upgrade it to the status of a flight model. Upon construction of the second, identical flight model, both models were fully tested, including for optical performance.

The testing was carried out in two steps: In the first step, the mirrors and structures were tested and space-qualified separately. In the second step, the mirrors were integrated with the structures into all-Cesic® telescopes. Each telescope was then tested. They both met mission specifications and, thus, were designated as being space-qualified.

The space-qualification included the following tests:

- The mirrors were tested and qualified under vibration and shock loads as follows:
  - First, the mirrors were tested separately up to 40 g equivalent quasi-static loads at the mirror I/F.
  - After the integration of the mirrors to the telescope structure, the mirrors were again tested up to 30 g at their interfaces during the sine & random qualification tests of the satellite.

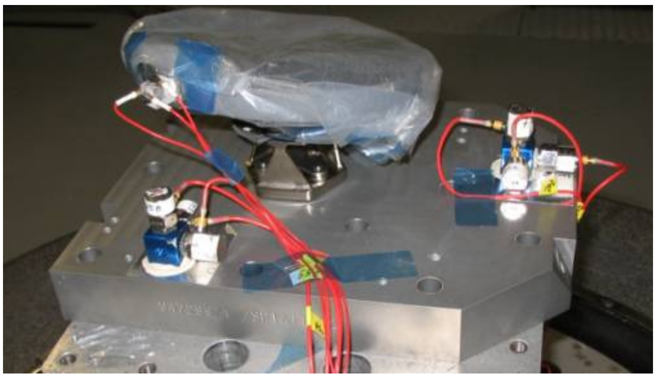

Fig. 7 Flight mirror on shaker (protected by bag from pollution)

- Each of the telescope structures was tested and qualified with mirror dummies (having the same mass as the mirrors) under vibration and shock loads:

  - The specifications in vibration (sine & random) required testing the structure in sine vibration up to 21 g equivalent quasi-static loads at the structure I/F. During this test, a maximum acceleration response (g_{max}) on the structure of 23 g was measured .

  - During the random vibration test on a shaker, the structure was tested up to 20 g RMS (at 3 σ) at the structure I/F. This produced locally a g_{max} of 34 g RMS (at 3σ), Fig. 8.

  - The measured first frequency of the structure was 200 Hz, which corresponded closely to the 202 Hz predicted by FEM analysis.

Fig. 8 FM structure equipped for vibration tests

The assembled telescope, mounted on the STM satellite structure (Fig. 7), was tested and qualified under shock loads equivalent to those generated during launch, using a “pyrotechnic Dassault kit.”

During this shock test, the maximum shock acceleration measured at the I/F of the Cesic® telescope structures was 700 g; and that measured at the I/F of the Cesic® mirrors was 400 g.

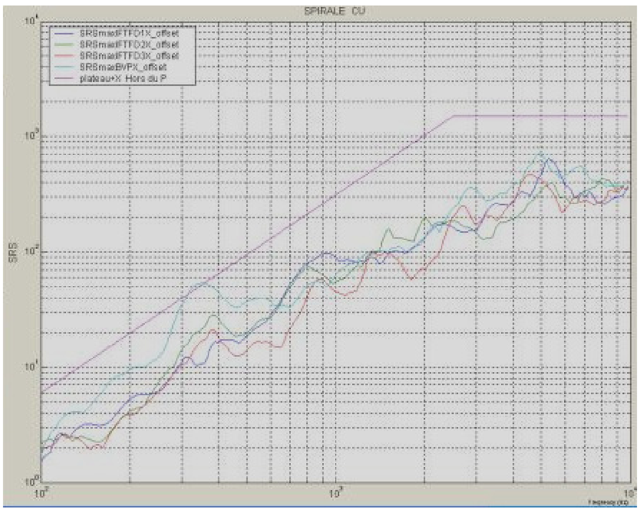

Fig. 9 Structural dynamical response answer during the pyro shock tests

These test results demonstrate that the two SPIRALE all-Cesic® telescopes withstood flawlessly the demanding mechanical and thermal conditions of a space launch. The tests also confirmed the excellent damping coefficient (1.5% - 2 %) of our Cesic® material.

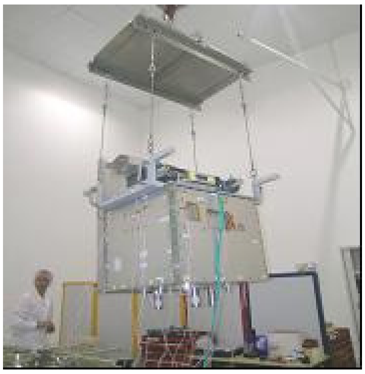

Fig. 10 FM flight telescope structure under shock tests

After integration and final optical alignment, the first all-Cesic® telescopes were designated as space qualified and accepted by the customers – ASTRIUM/CNES/DGA.

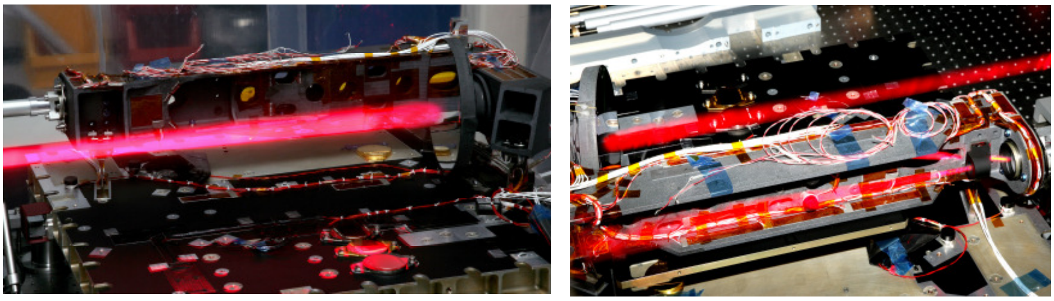

Fig. 11 All Cesic telescope during optical alignment tests

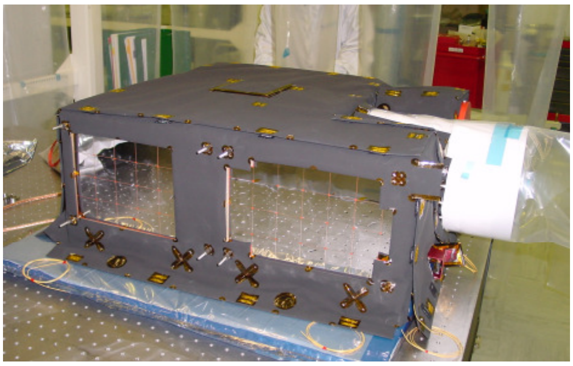

Fig. 12 FM flight instrument before integration on Myriade Platform

Due to the compactness of the all-Cesic® SPIRALE telescopes and their low mass it was possible to integrate them on the Myriade Platform, a micro-satellite. This allowed launching the telescopes in piggy-bag fashion as an auxiliary passenger with two large commercial satellites, Hot Bird™ 10 and NSS-9. Hot Bird™ 10 will provide television, radio and interactive services across Europe, North Africa and the Middle East; and NSS-9 will provide relay services for broadcasters, government users, and carriers across the Pacific region and for the maritime industry.

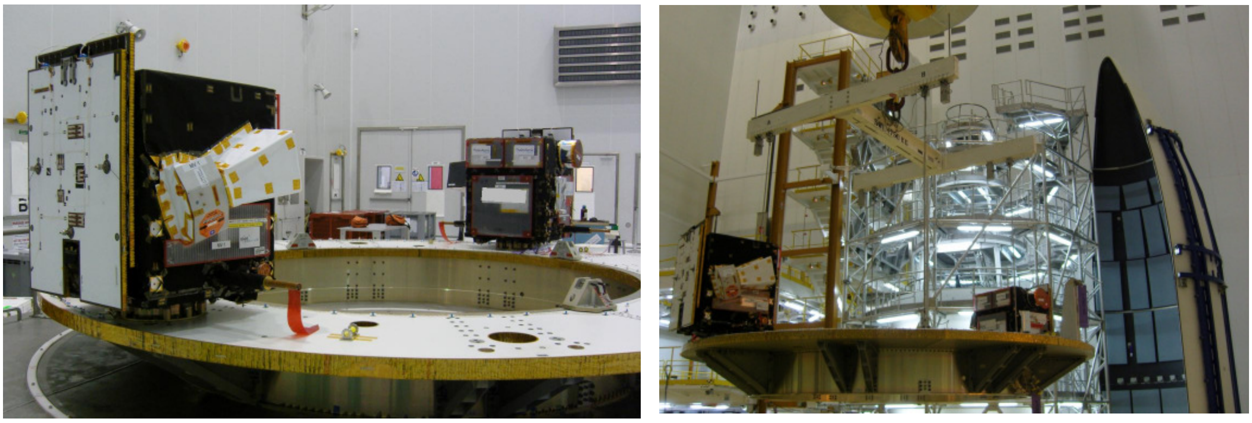

Fig. 13 SPIRALE satellites integrated on Ariane V launcher

The two SPIRALE telescopes were launched on an Arianne 5 rocket (Flight V187) in February 2009 and inserted into an elliptical Earth orbit with a perigee of 600 km of the Earth's surface and an apogee of 30,000 km The satellites observe Earth intermittently, once from the high point of their orbits, and again from low orbit. Both satellites have been fully checked out and declared operational.

Based on the lessons learned from the SPIRALE mission, the French defense procurement agency, DGA, is now planning to develop more efficient and sensitive infrared sensors for future missile-warning space missions.

4. CONCLUSION

The success of the two SPIRALE all-Cesic® telescopes is due to the superior properties of the Cesic® composite material, as discussed in the text, as well as to the dedicated development efforts by ECM and Thales Alenia Space, with the support of CNES, DGA, & ESA.