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# Composite solid surface parabolic reflector of spacecraft mirror antenna: design and testing

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# Composite solid surface parabolic reflector of spacecraft mirror antenna: design and testing

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**Abstract**

This paper presents a novel design for a composite ultralightweight solid surface reflector intended for spacecraft mirror antennas. The reflector comprises reflecting and supporting shells, both sharing a parabolic shape and joined at the aperture edges. This configuration forms a closed structure that provides substantial rigidity. Through parametric finite element modal analysis, a physical prototype of the parabolic reflector with an aperture diameter of 0.6 m and a focal distance of 0.15 m was designed, manufactured, and tested. A fabrication technology was developed to ensure minimal deviations of the reflective shell geometry from the ideal paraboloid. The reflector underwent vibration and thermal testing, which confirmed that the composite design can withstand the mechanical and thermal loads experienced during spacecraft injection into Earth's orbit and subsequent orbiting. The resulting composite parabolic reflector is ultralightweight and meets all necessary requirements for generating narrowly directed electromagnetic radiation at high frequencies.

**Keywords:** Spacecraft mirror antenna, composite ultra-lightweight solid surface reflector, finite-element analysis, vibration and thermal testing.

## 1 Introduction

Space antennas exhibit a wide range of reflector designs [1]. Mirror reflector antennas are commonly employed in space telecommunication systems due to their ability to transmit large volumes of data at high speeds. Their widespread use is attributed to a

high amplification coefficient, a broad frequency band, simple and reliable construction, and relatively low cost [2–5]. The primary structural component of these antennas is a solid surface reflector, which ensures the directivity of the radio signal. Reflectors may be constructed as axisymmetric or offset, depending on the optical configuration, with the paraboloid being the most prevalent surface shape. Technical requirements for solid surface reflectors are defined by their intended function and operational environment. The principal requirement is high shape accuracy. Deviations from parabolic geometry reduce the coefficient of amplification of the radio signal. For efficient mirror spacecraft antennas, the permissible reduction in this coefficient should not exceed 0.15 dB, corresponding to a signal amplification loss of less than 3.5%. To meet this criterion, the root mean square deviation of the reflector surface from the paraboloid should not exceed $0.015\lambda$, where $\lambda$ is the wavelength [6]. The increasing demand for high-speed data transmission in space communication systems is directly linked to the use of high-frequency electromagnetic radiation. Consequently, the reflective surface must closely approximate a paraboloid. For instance, to maintain a stable directivity pattern in the Q band, the root mean square deviation of the reflector surface from the paraboloid should not exceed 0.05 mm [6]. Additional requirements include minimizing the mass and dimensions of the reflector, as these factors are constrained by the high cost of spacecraft launch and orbital insertion, and by limited space within the rocket fairing. The reflector must also withstand vibration and acoustic loads generated during launch. Furthermore, maintaining dimensional stability of the reflector shape throughout spacecraft operation in orbit is essential. The primary challenge is the variation in heat fluxes experienced by the reflector as the spacecraft moves, which induces temperature fluctuations in the structure. It is also critical that the reflector material reflects at least 98% of the incident radio wave energy. A decrease in this parameter increases energy absorption losses and consequently reduces antenna efficiency.

Numerous organizations and industrial companies, including EADS CASA ESPACIO, the Institute of Lightweight Structures, Thales Alenia Space, European Space Agency ESTEC, MDA Corporation, Astrium Space Transportation, HPS GmbH, INVENT GmbH, and Applied Aerospace Structures Corp, participate in the design and development of solid surface reflectors for space applications. Consequently, a wide range of reflector designs has emerged. Taygin and Lopatin conducted a comprehensive review of these structures developed in recent years [7]. The findings from studies on solid surface reflectors have been reported by Reznik et al. [8], Morozov et al. [9], Wei et al. [10], Huang et al. [11, 12], Iwasa et al. [13], Taygin and Lopatin [14], Mihai et al. [15], Park et al. [16], Tanaka et al. [17], and Tan et al. [18].

Reznik et al. [8] discussed the design of a composite reflector for a space mirror antenna, demonstrating high stability in both shape and geometry. These properties were evaluated through numerical modeling of heat transfer and structural behavior under operational conditions representative of orbital flight. Morozov et al. [9] proposed an innovative space offset mirror antenna constructed from composite material. This antenna featured a sandwich conical composite shell with a lateral cutout, a solid surface reflector positioned at the base, and a feed located at the apex, resulting in a compact configuration. Wei et al. [10] presented the structural design and optimization of an ultra-high precision parabolic reflector fabricated from a zero-expansion composite.

Huang et al. [11] developed a novel petal-type deployable solid surface antenna, in which the parabolic reflector consisted of 20 petals connected to a central hub. The mechanical design significantly enhanced the overall rigidity of the structure. Additionally, Huang et al. [12] introduced a uniaxial rotation mechanism for the petal-type deployable solid-surface reflector, replacing the conventional two orthogonal rotation mechanisms. Iwasa et al. [13] employed a high-resolution surface shape measurement system, utilizing grating projection and virtual-target registration methods, to measure the surface shape of a parabolic antenna reflector with a diameter of 1.5 m.

Taygin and Lopatin [14] introduced a geometry control method for composite antenna reflectors that leverages elastic shell deformation, induced by multiple local supports through specially designed control actuators. This approach enabled achieving the required antenna geometry with high precision. Mihai et al. [15] conducted the design, analysis, and evaluation of a titanium antenna reflector intended for deep space missions, identifying technology and processing parameters tailored to the PLATO space mission's requirements. Park et al. [16] presented the results of thermal design and analysis for a parabolic reflector constructed from carbon fiber reinforced polymer (CFRP), intended for use in a spaceborne synthetic aperture radar antenna. Their analyses compared reflectors with various thermal coatings to minimize thermal gradients. Tanaka et al. [17] developed an engineering model for a high-precision reflector antenna system featuring a deformable sub-reflector with six actuators and an integrated two-dimensional grating measurement system. They also proposed a novel path length error correction procedure for determining shape control inputs. Additionally, Tan et al. [18] introduced a parametric design approach for petal-type solid surface deployable reflectors, optimizing the division parameters (number of petals) to simplify the structure and enhance deployment reliability.

The increasing demand for high-speed channels in space radio communication, particularly in the $Q$ and $V$ frequency ranges, necessitates the development of new solid surface reflector designs and manufacturing methods. Morozov and Lopatin [19] introduced a composite solid surface reflector comprising two jointed shells: a reflective shell and a supporting shell. These shells were produced using separate moulds, resulting in distinct shapes. The physical prototype featured an aperture diameter of 0.8 m, a focal distance of 0.23 m, and a specific mass of 0.8 $\mathrm{kg/m^2}$.

This paper presents further development of the two-shell composite reflector concept for space mirror antennas. An original ultralightweight composite solid surface reflector structure for spacecraft mirror antennas is proposed. The reflector consists of reflecting and supporting shells, both fabricated from CFRP using the same positive mold, resulting in identical surface shapes. The shells are joined at the aperture edges, forming a closed structure with substantial stiffness. A modal analysis of the reflector was conducted using the finite-element method to determine geometry parameters that ensure sufficient stiffness and minimal mass. Based on these findings, an experimental physical prototype of the solid surface reflector was constructed and tested. The manufacturing technology developed ensures minimal deviation of the reflecting shell from the intended paraboloid geometry. The prototype underwent vibration and thermal testing, demonstrating that the proposed lightweight antenna reflector design possesses

the necessary characteristics and parameters for effective generation of highly directive electromagnetic radiation in high-frequency bands.

## 2 Design concept

Figure 1 illustrates the reflector structure, which comprises the reflective shell 1, supporting shell 2, and mounting flange 3. Both CFRP shells 1 and 2 are produced using an identical positive mould, resulting in matching shapes and dimensions. The reflective and supporting shells are connected by two conical shells 4 positioned at their aperture edges, as depicted in Fig. 1. This closed configuration provides the reflector with high rigidity. The geometric parameters are as follows: aperture diameter $D$, focal distance $F$, distance between the reflecting and supporting shells $H$, height of the conical shell attached to the aperture edge of the reflecting shell $b$, diameter of the mounting flange $d$, shell thickness $t$, and the semi-vertical angle $\alpha$ of the joining conical shells, as shown in Fig. 1. The reflector serves as the main structural element of the mirror axisymmetric antenna depicted in Fig. 2. The antenna design also incorporates the radiating element and the counter reflector. The antenna is attached to the spacecraft via the mounting flange. Schematics of mirror antennas mounted on the spacecraft are presented in Fig. 3.

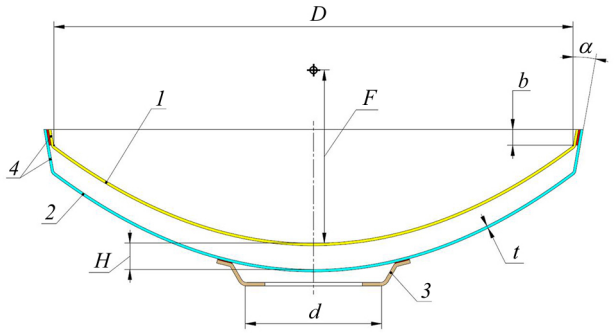



**Fig. 1** Structure of the reflector and its geometric parameters

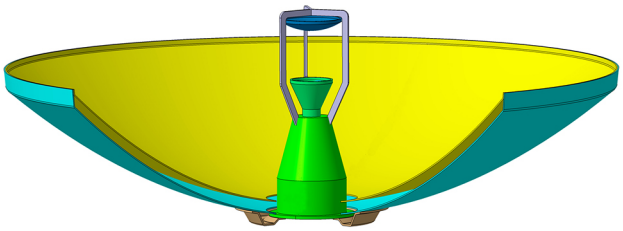


**Fig. 2** Spacecraft mirror antenna

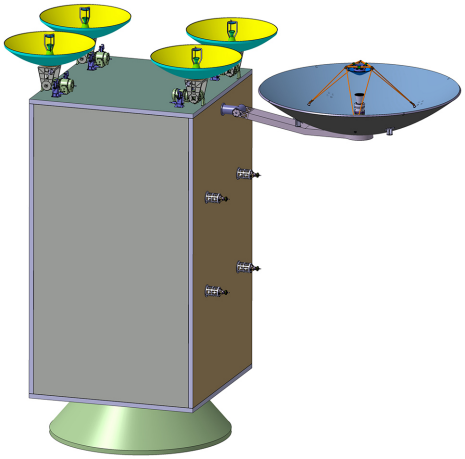


**Fig. 3** Mirror antennas connected to the spacecraft

# 3 Parametric modal analysis and design of the solid surface reflector

The reflector attached to the spacecraft experiences significant dynamic loading from the rocket launcher during injection into Earth orbit. To withstand these dynamic loads, the reflector structure must be sufficiently rigid. In aerospace structural design, the conventional criterion for structural stiffness is the fundamental frequency of the structure. This frequency is determined by the geometric parameters of the reflector, such as $D$, $F$, $H$, $b$, $d$, $t$, and $\alpha$ (see Fig. 1), as well as the elastic properties of the composite material used in its construction. The design process involves selecting parameters that ensure the fundamental frequency meets or exceeds the value specified in the design requirements while minimizing mass. Employing the fundamental frequency as a criterion accounts for the combined effects of stiffness and mass. Typically, not all geometric parameters are varied during design optimization. Some parameters are fixed based on the reflector's radio technical characteristics, its attachment method to the pivoting system, and additional requirements imposed by fabrication technology.

In the design problem formulation, the aperture diameter $D$, focal distance $F$, mounting flange diameter $d$, conical shell height $b$ (see Fig. 1), and the elastic properties of the composite material are considered prescribed. The unknown design variables are the distance between the reflective and supporting shells $H$, and the shell thickness $t$. The angle $\alpha$ (see Fig. 1) is determined as follows.

$$\alpha = \arcsin\left(\frac{t+\delta}{H}\right), \tag{1}$$

where $\delta$ is the thickness of the adhesive layer.

For the fabrication of the physical prototype of the reflector, the following parameter values were adopted: $D = 0.6\,\text{m}$, $F = 0.15\,\text{m}$, $d = 0.14\,\text{m}$, and $b = 0.005\,\text{m}$. The carbon fibre fabric selected for the mounting flange and shells exhibits a modulus of elasticity

of 75 GPa in both the warp and weft directions. The shear modulus and Poisson ratio are 19.5 GPa and 0.3 GPa, respectively. The material density is 1520 kg/m$^3$.

The dimensions $H$ and $t$ must be determined to achieve a reflector with minimal mass while ensuring that its fundamental frequency is at least 150 Hz. This frequency requirement ensures the reflector can withstand the dynamic loads generated by modern launch rockets.

The search for suitable combinations of $H$ and $t$ that satisfy these requirements was conducted within the following ranges: $H$ varied from 0.005 m to 0.03 m in increments of 0.005 m, and the shell thickness $t$ was set at 0.0002 m, 0.0004 m, and 0.0006 m. The adhesive layer thickness was assumed to be $\delta = 0.0002$ m.

Equation Eq. (1) indicates that the angle $\alpha$ for the specified values of $H$ and $t$ ranges from 0.76° to 9.2°. The dimensions $H$ and $t$ were selected based on a parametric modal analysis conducted using the finite element method. This analysis for the reflector design was performed in ANSYS. The composite shells were represented using `SHELL281` shell finite elements. The reflector was constrained at the plane of the mounting flange. The corresponding finite-element model is presented in Fig. 4.

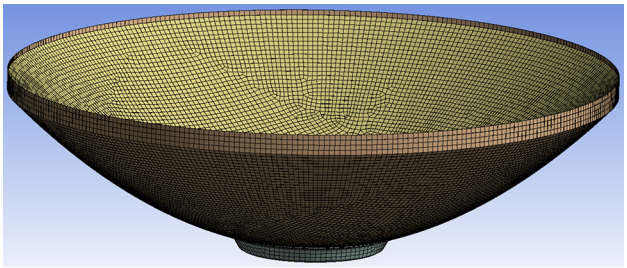


**Fig. 4** Finite-element model of the reflector

Table 1 presents the calculated fundamental frequencies $f$, structural masses $m$, and types of fundamental vibration mode shapes for various dimensions $H$ and $t$. Depending on the combination of values of $H$ and $t$, the fundamental mode shape can be of type A or B as shown in Fig. 5.

**Table 1** Vibration frequencies $f$(Hz), mass of the structure $m$(kg) and type of the vibration mode shape of the composite reflector (as shown in Fig. 5)

| | $t = 0.0002$ m | | | $t = 0.0004$ m | | | $t = 0.0006$ m | | |
|---|---|---|---|---|---|---|---|---|---|
| $H$(m) | $f$(Hz) | $m$(kg) | Type | $f$(Hz) | $m$(kg) | Type | $f$(Hz) | $m$(kg) | Type |
| 0.005 | 101.8 | 0.204 | A | 107.3 | 0.381 | A | 111.1 | 0.559 | A |
| 0.01 | 134.5 | 0.207 | A | 145.9 | 0.386 | A | 154.0 | 0.566 | A |
| 0.015 | 178.7 | 0.209 | A | 191.8 | 0.391 | A | 200.9 | 0.573 | A |
| 0.02 | 227.9 | 0.211 | A | 220.5 | 0.396 | B | 212.7 | 0.580 | B |
| 0.025 | 229.3 | 0.214 | B | 215.5 | 0.400 | B | 208.0 | 0.587 | B |
| 0.03 | 225.2 | 0.216 | B | 211.6 | 0.405 | B | 204.1 | 0.594 | B |

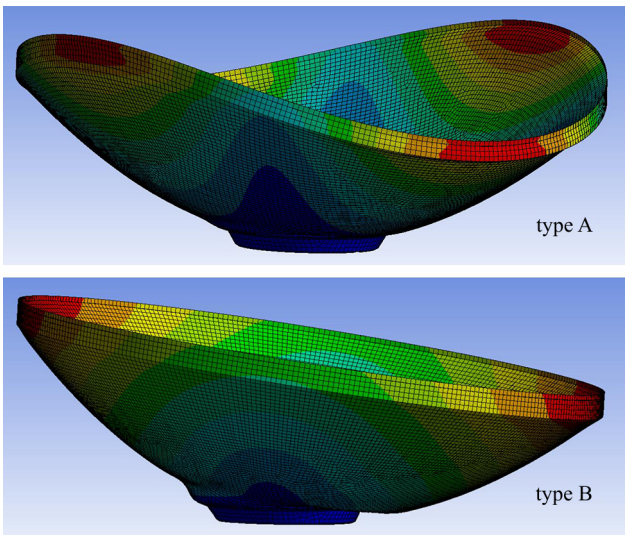



**Fig. 5** Fundamental vibration mode shapes of the reflector

The analysis produced the following values: $H = 0.015\,\mathrm{m}$ and $t = 0.0002\,\mathrm{m}$. These parameters resulted in a minimal reflector mass of $m = 0.209\,\mathrm{kg}$ and a fundamental frequency of $f = 178.7\,\mathrm{Hz}$, which exceeds $150\,\mathrm{Hz}$ (see Tab. 1). The corresponding angle $\alpha$ is 1.5°, as determined by Eq. (1).

# 4 Fabrication of the prototype

The prototype manufacturing process comprised several steps: forming the mounting flange, forming the support shell, adhesive bonding of the flange to the support shell, forming the reflective shell, adhesive bonding of the reflective shell to the support shell, and final assembly machining.

The mounting flange was fabricated from carbon fabric reinforced plastic using compression die molding with matching male and female dies, as illustrated in Fig. 6. These dies were 3D printed from nylon and are capable of maintaining their shape and geometry at operational temperatures up to 180 °C. The completed component is presented in Fig. 7. Fig. 8 displays the aluminum mold and base plate used for manufacturing the reflector shells.

The mold surface exhibits a paraboloidal geometry that transitions into a conical form. The shells are constructed from segments of carbon fabric impregnated with resin. These segments are positioned on the mold surface in an overlapping sequence following the sectorial scheme illustrated in Fig. 9.

The supporting shell of the reflector is fabricated first. After completing the preform, the assembly is sealed in a vacuum bag and placed in an autoclave. The layup is cured at a pressure of 6 Bar and a temperature of 120 °C, with the entire curing cycle lasting six hours. Following cooling, while the shell remains on the mold, the mounting flange is bonded using adhesive. Compacting pressure is applied with weights, as depicted in Fig. 10.



**Fig. 6** Mandrel for the forming of the mounting flange



**Fig. 7** Composite mounting flange

Additionally, twelve removable plastic supports are attached to the shell (see Fig. 10) to ensure precise positioning within the reflector assembly. After installation, the shell is removed from the mold. The reflecting shell of the reflector is then fabricated using the same process and mold. The cured shell remains on the mold to maintain its parabolic shape, and the supporting shell with the flange is adhesively bonded to its conical surface, as shown in Fig. 1. The distance between the shells, $H = 0.015\,\mathrm{m}$, is maintained using twelve metal spacers, upon which the plastic supports attached to the supporting shell are placed, as illustrated in Fig. 11.

After the bonding process is completed, the reflector assembly is removed from the mold, and the plastic supports are detached from the surface of the supporting shell. The edge of the bonded shells is then trimmed to ensure that the dimension $b$ (see Fig. 1) is precisely $0.015\,\mathrm{m}$. The fully assembled reflector is depicted in Fig. 12.

Dimensional control of the reflector's surface geometry was conducted using the Renishaw measurement system. Surface coordinates were obtained through a rectangular mesh pattern with a step size of $7.5\,\mathrm{mm}$, resulting in a total of 7861 measured points. The measurement error at each point did not exceed $0.0025\,\mathrm{mm}$. The collected data were analyzed using CAD CATIA. Deviations from the theoretical reflector surface are shown in Fig. 13.

The standard deviation of this data set is $0.043\,\mathrm{mm}$. The reflector has a mass of $0.209\,\mathrm{kg}$ and a reflecting surface area of $0.345\,\mathrm{m}^2$, resulting in a mass per unit



**Fig. 8** Mould for the forming of the reflector shells

area (specific mass) of $0.64\,\mathrm{kg/m^2}$. This value classifies the structure as an ultralight reflector [3, 5]. Notably, this specific mass is 1.25 times lower than that of a reflector with different shapes for the reflecting and supporting shells [19].

The proposed manufacturing technology for the axisymmetric solid surface reflector is also applicable to the design and fabrication of the offset solid surface reflector, as illustrated in Fig. 14.

Similar to the axisymmetric reflector design, the offset reflector can be constructed from reflecting and supporting shells fabricated using the same mold.

## 5 Vibration and thermal testing

Vibration and thermal tests were conducted to validate the functionality of the fabricated reflector. Vibration testing is essential due to operational conditions in which the reflector experiences dynamic loads during spacecraft injection into orbit. These loads can deform the reflector and adversely affect its radio technical characteristics. Dynamic loads were simulated using the TIRA vibration table. The reflector was mounted on a massive plate, which was then installed on the vibration table as illustrated in Fig. 15.

Four sensors were installed on the rim of the reflector to measure vibration frequencies and accelerations. The reflector was exposed to sinusoidal vibrations along

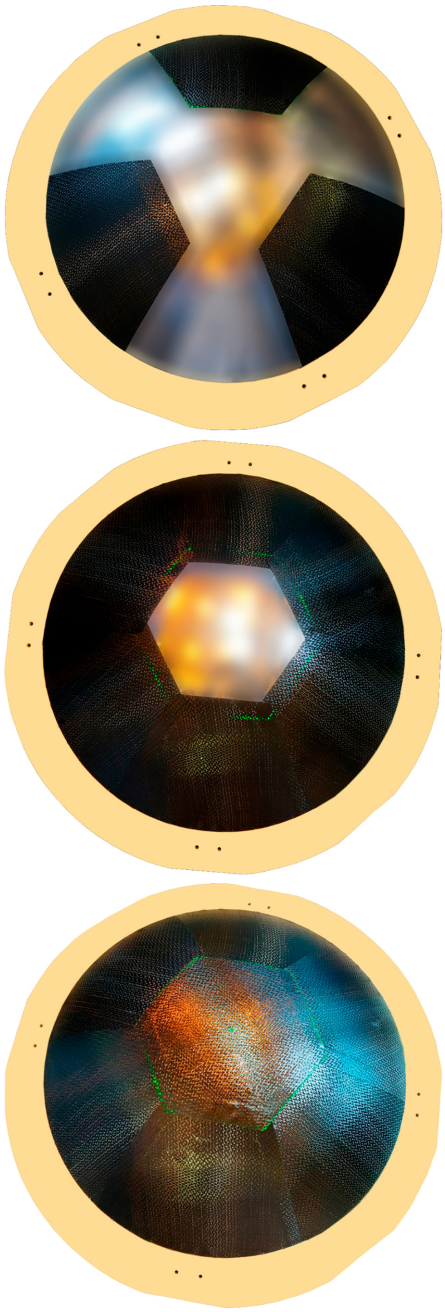


**Fig. 9** Scheme of the forming of the reflector shell

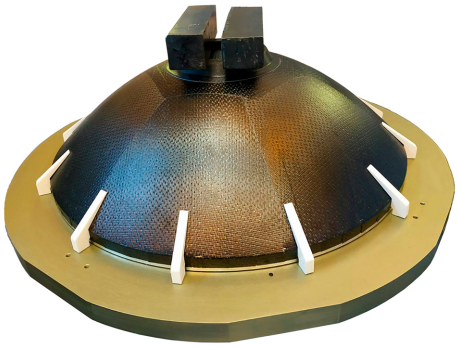


**Fig. 10** Connecting the supporting shell and the mounting flange

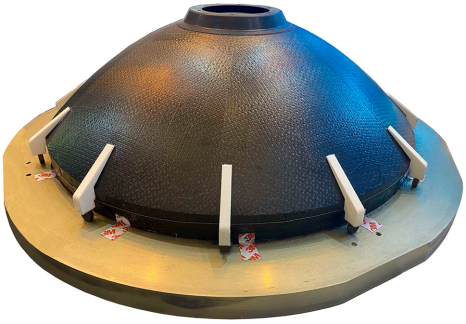


**Fig. 11** Connecting the reflector shells

the focal axis, with frequencies ranging from 5 Hz to 200 Hz. The vibration tests were conducted in three stages.

During the first stage, the vibration table generated an acceleration of $0.5g$ ($g = 9.81\,\mathrm{m/s^2}$). Within the tested frequency range, the fundamental frequency was identified. The relationship between the reflector's acceleration and the vibration table frequency is presented in Fig. 16.

Analysis of the function indicates that the fundamental frequency identified by the test is 165.6 Hz. In the second stage, the vibration table acceleration was set to $12g$ to simulate the dynamic loads experienced by the reflector at the end of spacecraft orbital injection. In the third stage, the vibration table acceleration was set to $0.5g$ again. Within the frequency range of 5 Hz to 200 Hz, the fundamental frequency of the reflector was again observed. Comparison of the fundamental frequency values determined in the first and second stages revealed a difference of less than 1%, indicating that the testing did not induce damage that could reduce the structural stiffness of the reflector. The experimental vibration testing results confirmed the accuracy of the fundamental frequency calculation obtained through finite element analysis. The difference between the numerical (178.7 Hz) and experimental (165.6 Hz) values is 13.1 Hz, or 7.9%. This level of correlation is considered satisfactory for the pilot version of the reflector structure.



**Fig. 12** Solid surface reflector

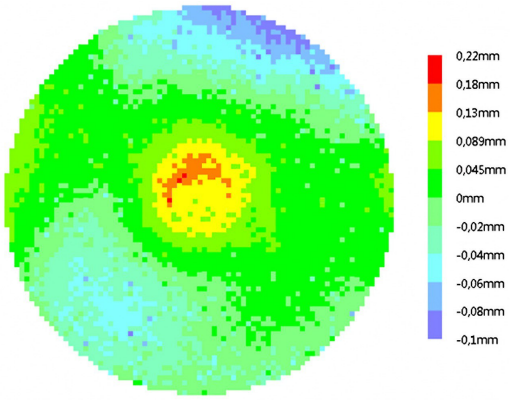



**Fig. 13** Deviations from the theoretical shape of the reflector surface

Validation of prototype performance under thermal loading is essential, as the reflector is exposed to a wide range of temperatures during spacecraft operation in Earth's orbit. Thermal loading may distort the reflector's shape and adversely affect its radio technical characteristics. Thermal testing was conducted using a vacuum chamber manufactured by ABBESS INSTRUMENTS. The chamber temperature ranged from $-140\,^{\circ}\mathrm{C}$ to $+150\,^{\circ}\mathrm{C}$. The reflector was placed in the chamber (see Fig. 17), and the vacuum was drawn to a pressure of $-10^5\,\mathrm{Pa}$.

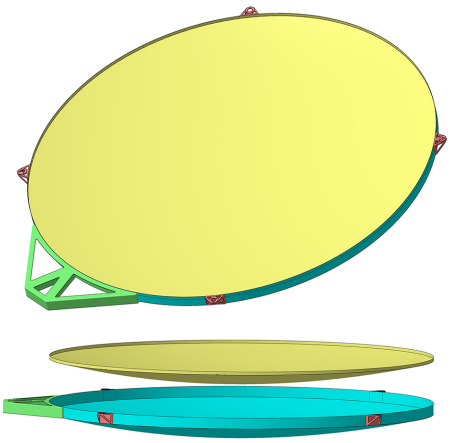


**Fig. 14** Offset solid surface reflector




**Fig. 15** Composite reflector attached to the vibration table

The temperature distribution across the reflector was measured using sensors affixed to its surface. During each loading cycle, the reflector was heated to +150 °C and subsequently cooled to −140 °C. This process was repeated five times. Post-test inspection of the reflector structure confirmed its structural integrity.

Following completion of the vibration and thermal tests, the reflecting surface of the reflector was remeasured. Measurements conducted with the Renishaw system indicated that deviations from the original geometry were negligible. The standard deviation of the measurements for the original shape was 0.005 mm. These dynamic and thermal test results confirmed that the composite reflector structure can withstand operational dynamic and thermal loads.

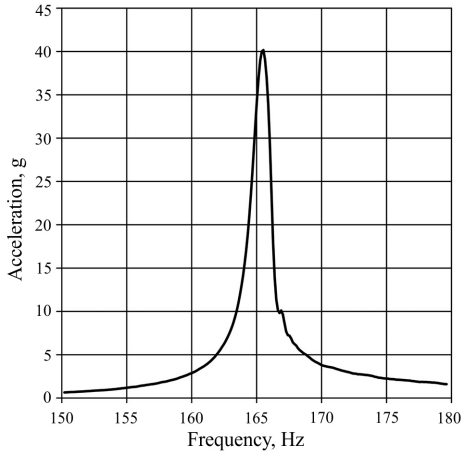



**Fig. 16** Function of the reflector acceleration vs the vibration frequency of the table

# 6 Conclusions

This paper proposes and investigates a novel design for a composite ultralightweight solid surface reflector intended for spacecraft mirror antennas. The reflector consists of two shells with identical parabolic shapes, joined at their aperture edges. One shell serves as the reflecting surface, while the other provides structural support. Using a single mold ensures identical geometry for both shells. When joined, the shells form a closed, thin-walled box-shaped structure that exhibits significant stiffness. Parametric finite element modal analysis guided the design of a composite parabolic reflector with an aperture diameter of 0.6 m and a focal distance of 0.15 m. A physical prototype was fabricated from carbon fiber fabric-reinforced polymer, with manufacturing techniques that minimize deviations from the ideal paraboloid shape. The prototype has a mass of 0.209 kg and a specific mass of 0.64 $kg/m^2$, qualifying it as an ultralight reflector. Vibration and thermal testing confirmed the design's validity and demonstrated robust structural performance under loads typical of spacecraft injection into Earth's orbit and subsequent orbital operations. Fabricating a parabolic reflector with identical reflecting and supporting shells requires significantly less effort than constructing reflectors with shells of differing shapes and geometries. The developed composite ultralightweight solid surface parabolic reflector is suitable for use in space communication systems that transmit high-frequency radio signals.

# Declarations

- The authors state that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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**Fig. 17** Vacuum chamber for the thermal testing

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