Working efficiency analysis of space mirror antenna reflector made of composite materials

Y A Azhevsky
Bauman Moscow State Technical University, 2-ya Baumanskaya, 5-1, Moscow, Russian Federation, 105005
E-mail: azhevsky.yaroslav@mail.ru

Abstract. The study is devoted to the possibility of using composite materials, composite sandwich panels and composite mesh structures as constructions for space mirror antennas using at space satellites. The modelling of the thermal and stress-strain states of the structure, which are characteristic of radiation heat transfer in open space operating conditions, has been carried out. Based on the results obtained, a design with the best indicators of mass-dimensional stability under operating conditions was selected.

1. Introduction
Space mirror antennas already were highly demanded at the beginning of the satellite communication era. Numerous research has been conducted in the framework of the designing the reflectors structures that are used mostly for space and ground applications. Space mirror antenna reflector (SMAR) have a relatively simple design and high reliability, and, at the same time, a wide transmission band of radio waves as well as a highly orientability. These qualities allow to use the mirror antennas as a part of the spacecraft of various purposes for organizing high-speed radio channels [1-4].

The demand for high-speed communications in the last decade has grown significantly, which in its turn leads to the development of new higher frequency ranges with a reliable communication channel that can transmit data with short delays. A promising solution of this problem is the usage of the V–range frequency spectrum (frequency band of 40-75 GHz). This frequency band will allow reducing the mass and size of satellite antennas, while increasing energy efficiency and data transfer rate. However, one of the main limitations for the mass production of the V-band RSMAs as the main means of communication for spacecraft is the high cost of SMAR [5-8]. The high frequency of radio band restricts the requirements for the quality of space satellite antenna structures. The accepted deviation of the surface of the SMAR from the calculated value should not exceed Δ = Λ/50 (Λ is the working length of the radio wave of the satellite antenna). Thus, for the correct operation of satellite communications, it is necessary to keep the dimensional stability of the reflective surface of the SMAR at a level of 0.1 to 0.4 mm, depending on the selected operating frequency [10, 11].

Space satellites mass reducing allows us to decrease costs of spacecraft orbiting. This fact makes us to think about a more detailed study of satellites constructive scheme and whole construction engineering research. Therefore, there is a necessity to create modern approaches in mirror space antennas reflector design in order to achieve the best results in linear density and dimensional stability of structures. During the operation in the near-Earth orbit, the spacecraft is subject to direct and reflected solar radiation, the Earth’s self-radiation. The mentioned factors coupled with periodic approaches to the shadow part of the orbit, can create a temperature difference from 100 to 180 degrees on the meter
surface of the SMAR. Such operating conditions could adversely affect the dimensional stability of the reflector structure, which in its turn negatively affects the quality of the transmitted (received) signal [12-15]. High performance requirements for satellite antennas gives one thinking about using of advanced materials. Composite materials, especially CFRPs, have great importance for improving the design of SMAR. This material has high specific mechanical characteristics, low coefficients of linear thermal expansion, and relatively high thermal conductivity, which allows not only to reduce the weight of the antenna, but also to increase the stability of its shape and size.

One of the possible solutions to this problem is to use a space antenna structural scheme in the form of a thin-walled shell made of high-modulus carbon fibre with stiffening system made of three-layer panels with a non-woven polyester material filler. Current design can be manufactured in one technological operation. This approach will not only allow the design of a reflector with the required dimensional stability, but also reduce the cost of its production.

In this research, we propose a number of designs with a stiffening variation for thin-walled shell. In the course of finite element modelling, we conducted a comparative analysis of performance under operating conditions (inertial loading during orbiting and radiation heat transfer in open space). Based on the results of our research, we have selected the best reflector structural scheme and then we will conduct a study of design cases with various fastening options and see how certain fastening methods affect the stability of the dimensions of the whole antenna complex.

![Figure 1. SMAR with three-layer-type DLS.](image1)

![Figure 2. SMAR with the DLS of ribbed reinforcement.](image2)

2. The design-layout schemes of SMAR
Since the beginning of the use of composite materials as the main materials for space satellite antennas, the design-layout scheme (DLS) in the form of a three-layer panel with thin-walled skins and a honeycomb core has been widely used (figure 1). As a rule, CFRP panels are used as skins, while aluminium foil, carbon or organic plastic is used as the material for the honeycomb core. Such an approach makes it possible to obtain a rigid, dimensional-stable structure with the areal density at the level of 3 kg/m2 [16,17]. Another solution for the SMAR structure is DLS in the form of a thin-walled
composite shell with developed thin-walled spatial ribbing (figure 2). Such structures are produced of CFRP. Ribbing allows to develop rigid structure with a high dimensional stability and areal density at the level of 2.5 kg/m² [18].

3. Development of the Design-layout scheme of SMAR

If we consider antennas of the V-range frequency spectrum, then, as a rule, antenna complexes located on spacecraft have small geometric dimensions. I would like to try out my ideas for the design of this kind of structures on just such design options. For further research, the antenna parameters were selected for the considered frequency range. The linear dimensions and arrangement of the elements were calculated using the Antenna Magus software package (figure 3). The following parameters were used as input data: Gain = 45 dB, Frequency = 40-75 GHz, Antenna type – parabolic offset.

As a result of calculations, we obtained the following parameters of the elements: D = 618 mm – the height of the reflector mirror, Θ = 44 ° – the angle of feed rotation, F = 488 mm – focal length, H = 123 mm – the coordinate of the mirror positioning.

![Figure 3. Geometric parameters of antenna construction](image)

The geometry of the SMAR reinforcement set location could vary depending on the conditions for fixing the satellite dish and the mechanism of its deployment, while the design must comply with the requirements for stability of shape and size demanded for the operating conditions of orbital flight. Based on a domestic and foreign experience, several DLS of reflectors were designed with variation in the arrangement of reinforcement ribs that implies fastening to the spacecraft through the central zone (figure 4). A distinct feature of the presented designs is the original ribbing scheme. The reflector itself is made as a thin-walled CFRP shell, and the ribs are CFRP with an additional set of layers. The width of the stiffeners of the samples under the study is 15 mm, and the thickness is 2.2 mm. The thickness of the reflector shell is 0.6 mm.

4. Refining the characteristics of the composite material

One of the important steps of the successful design of any structure is the creation of the correct mathematical model of the material. The current study deals with composite materials, which in its turn sufficiently complicated the task. Due to their specific nature, composites do not have their standardized libraries with the unambiguous defined characteristics. Since manufacturing and testing of structure in order to define the material characteristics cost a lot, it is necessary to use up-to-date mathematical modelling approaches in the preliminary design stages. Using of special software is one of such approaches. In current study MSC Digimat software package is used. This software complex allows to predict the orthotropic characteristics of a composite material based on the realistic representative volume element of the material (figure 4).
Analysis showed, the smallest modelling of heat transfer process was conducted with the 

Next, we exported the obtained temperature difference to a structural solver and the finite element analysis showed, the smallest

Figure 4. The ribbing schemes of RSMA.

In current study, the characteristics of CFRP with the epoxy resin (Cytec 950-1) and high modulus carbon fibres (Cytec Thornel Carbon fibres P-75S) were calculated. The following data were used as input data for further definition of CFRP characteristics: the modulus of elasticity of the resin – 4.2 GPa; the shear modulus – 1.6 GPa; the Poisson’s ratio – 0.3; the coefficient of linear thermal expansion of the resin – $4.5 \times 10^{-5}$ K$^{-1}$; the specific heat of the resin – 1000 J/(kg K); the coefficient of thermal conductivity of the resin – 0.22 W/(m-K); the modulus of elasticity along the fibre – 517.1 GPa; the modulus of elasticity across the fibre – 9.1 GPa; the shear modulus – 13.1 GPa; the Poisson's ratio – 0.23; the coefficient of linear thermal expansion along the fibre – $1.46 \times 10^{-6}$ K$^{-1}$; the coefficient of linear thermal expansion across the fibre – $12.5 \times 10^{-6}$ K$^{-1}$; the specific heat of carbon fibre – $660$ J/(kg-K); the thermal conductivity coefficient along the fibre – $185$ W/(m-K)); the thermal conductivity coefficient across the fibre – 2.4 W/(m-K).

As the result of homogenization using the MSC Digimat software package (figure 5), the following characteristics of CFRP with the layup scheme of [0/90/45/-45] were obtained: the thermal conductivity coefficient – $26$ W/(m-K); the specific heat – $762$ J/(kg-K); the density – 1 550 kg/m$^3$; the emissive factor – 0.85; the absorption factor – 0.735; the coefficient of linear thermal expansion – $6.1 \times 10^{-7}$ K$^{-1}$; the modulus of elasticity – 110 GPa; the Poisson's ratio – 0.3.

5. Thermal and thermal-mechanical analysis of the SMAR schemes under study
The most important stage in the design of an SMAR is to recreate operating conditions by the modelling of the temperature and stress-strain state of the structure that are typical for the radiation heat transfer in open space. The mathematical modelling of heat transfer process was conducted with the Siemens Simcenter 3D software by means of the Space System Thermal solver. The modelling results obtained for the finite-element model were used as input data for the definition of the stress-strain state of SMAR by means of the Siemens Simcenter Nastran solver. It was assumed that the studied variants of reflectors are operating as a part of the spacecraft in the geostationary Earth orbit.

A comparison of design variants was performed for moment of time of 108 000 seconds of operation in geostationary orbit, starting with a complete shading by the Earth. This moment of time corresponded to a rotation of the spacecraft by 150° relative to the Earth–Sun axis, when the temperature difference on the SMAR surface reaches its maximum value. Simulations of the orbital flight of the considered model and the following cases were carried out for the flight on the second orbital around the Earth. Since the temperature pattern on subsequent turns remains similar and the influence of the initial flight conditions is not levelled. According to the finite element modelling results, the best design from the position of dimensional stability is variant with the “Mark 1” identifying symbol (figure 6).

As a result of the antenna mirror temperature state, we calculated the temperature difference (maximum temperature = 37.19 °C, minimum temperature = 0.79 °C). Next, we exported the obtained temperature difference to a structural solver and the finite element analysis showed, the smallest
displacement values correspond to the “Mark 21” structural scheme and amount to 0.037 mm, which satisfies the requirements for dimensional stability of the space satellite reflector design in orbital flight conditions. The mass of the antenna reflector is equal 1.622 kg, the areal density – 1.354 kg/m².

Figure 5. The stages of composite material characteristics homogenization by means of MSC Digimat software package.

Figure 6. The results of the modelling of radiation heat exchange in “Mark 21” variant.

6. Reflector’s power Bracket designs
The power bracket used to attach the reflector to the hull of the spacecraft is another important design element of the satellite dish. Its dimensions are comparable to the dimensions of the reflector, but strict requirements are imposed on it in terms of dimensional stability and weight.

For this study, I have tried to use the types of structures that can be scaled and applied to larger ones. I settled on two types, radically different from each other. These are: sandwich panel construction and composite mesh construction. (figure 7).

These types of power brackets are often used for space applications. However, they had to take into account some features. These types of mounts are meant to be connected to the structure of the reflector mirror. Therefore, within the framework of structures, it is necessary to leave the possibility of making this connection. Therefore, for the mesh structure, a printed bracket will then be made, and for a sandwich panel, a mortgage is required to also insert the bracket or then attach it mechanically. Just for this, structural foam is used, which makes it possible to significantly lighten the structure in comparison with metal and prevent breakage as in the case of honeycombs in the attachment points.

For the structure obtained, a similar modelling was carried out, recreating the orbital flight in the geostationary orbit of the Earth. The modelling results are presented in figure 8. Although good results were obtained when simulating a reflector mirror, it is just as important to see how the whole structure works as an assembly. Therefore, we will repeat the thermal analysis for the entire antenna structure, taking into account the re-reflection from the surface of the spacecraft.

As a result of the antenna mirror temperature state, we calculated the temperature difference (maximum temperature = -49.07 °C, minimum temperature = -109.18 °C). Next, we exported the obtained temperature difference to a structural solver and the finite-element modelling results, the thermal displacements in the “Mark 21” reflector structure with power bracket made by composite mesh
design are 0.0943 mm. The total weight of full construction is 550 g. These indices fully satisfy the requirements previously presented to the design, which indicates its performance for orbital flight conditions.

The conducted research showed that the SMAR design made according to the “thin-walled shell with three-layer ribbing” scheme can meet the requirements for the stability of shapes and sizes when flying in the geostationary orbit of the Earth and is promising for further in-depth studies.

![Figure 7. Variants of power brackets for SMAR.](image)

![Figure 8. The results of the modelling of radiation heat exchange in the sample “Mark 21” with power bracket.](image)

7. **The conditions for the antenna structure operability during the spacecraft launch into orbit**

Another important point to determine the operability of a structure is the integrity analysis under transportation and orbital conditions. Each launch vehicle has its own loading parameters. Since I have no clear limitations on this point, I decided to conduct a small analysis and take the most loaded one. These are the Falcon family missiles with minimum load (figure 9). For my analysis, I will choose the point marked in the figure, which represents the highest launch load. This is 8.5g along and 2g across the rocket. As before, I will carry out my simulation in the Simcenter 3D software package with the Simcenter Nastran solver. I will do the fastening in the same way to prevent the rotation of the structure. As a result of the simulation, displacements on the mirror do not exceed 0.492 mm on the reflector mirror and 0.226 mm on the power mount. The stress also does not exceed the permissible.

8. **Discussion**

Although my work considers a sufficient number of design cases, it still does not affect those areas that may be important for the operation of the structure as a whole. First of all, all thermal characteristics for my materials are constants. This is not entirely true for the materials I have used, especially composites. More testing needs to be done to see if the property change is critical for the materials I have selected.
During operation, my design is exposed to significant temperature changes, and the surfaces of objects both heat up and cool down. Therefore, the correct solution would be to consider cyclic heating and take into account the parameters of durability for these structures. However, this work did not have such goals. The most important thing was to develop approaches that allow adapting the calculation methodology for more complex and important designs. Therefore, in the framework of this work, I consider these shortcomings not critical.

9. Conclusion

As part of my work, I went through several design stages that will further help me develop more complex structures for aerospace engineering. My research is not ideal, I have already described some of the shortcomings in the previous paragraph, but it is quite complex and allows us to speak with confidence about the applicability of a particular design to the conditions under consideration.

Firstly, the choice of the shape of the antenna mirror. Typically, these parameters are passed to the constructor as boundary conditions and this task is to improve the design in such a way that it satisfies the necessary constraints. In my work, I selected the necessary antenna parameters using the well-known expressions implemented in the Antenna Magus software product. For your research, you can also use this method to calculate the characteristics of your antennas. The choice of the power circuit of the reflector mirror is a creative task and there is no single approach. As a result, I got the geometric parameters of my future antenna and came up with finning schemes and then compared them under operating conditions.

Secondly, modelling the structure of the composite. This method allows you to easily calculate the required characteristics as thermal, mechanical and thermo-mechanical. This greatly facilitates the calculation process and allows both to simplify the design model and to reduce the number of tests. As a result, I obtained the thermal, mechanical and thermomechanical characteristics of materials and then used them for finite element analysis.

Thirdly, the simulation of the loading of our structures. In my research, I used the Simcenter 3D software package. It allows an integrated approach to the calculation process. I was able to run the analysis of orbital heating, determine the position in orbit with the largest temperature difference, determine the magnitude of the temperature movements. I was also able to calculate the loading conditions for the launch into orbit. As a result, I determined the parameters of my antenna. This antenna mirror is made of carbon fibre reinforced plastic with a thickness of 0.6 mm and fins made of CFRP in the form of 6 beams with a thickness of 2.2 mm. I also determined the shape of the power bracket in the form of a carbon fibre mesh structure. This engineering solution made it possible to achieve the stability of the mirror dimensions at the level of 0.0943 mm in orbital flight conditions and 0.492 mm from rocket launch.

Figure 9. Payload loading scheme for the Falcon launch vehicle family
References

[1] Gao S, Rahmat-Samii Y and Hodges R 2018 Advanced antennas for small satellites, Proc. IEEE 106(3) 64–9
[2] Rao S, Shafai L, and Sharma S 2013 Handbook of Reflector Antennas and Feed Systems Vol III Applications of Reflectors (Boston: Artech House)
[3] Rao S K 2015 Advanced Antenna Technologies for Satellite Communications Payloads Proc. IEEE Transactions on Antennas and Propagation 63(4) 169–75
[4] Rao S K 2003 Parametric design and analysis of multiple-beam reflector antennas for satellite communications Proc. IEEE Antennas & Propagation Magazine 45 26–34
[5] Keen K M 1976 Surface efficiency measurements on a high-modulus carbon fibre composite reflector antenna at L- and S-band frequencies Electronics Letters 12(7) 160–1
[6] Nicholson K J, Rowe W S T, Callus P J and Ghorbani K 2011 Split-ring resonator loading for the slotted waveguide antenna stiffened structure IEEE Antennas and Wireless Propagation Letters 10 1524–1527
[7] Galehdar A 2012 Capacitively fed cavity-backed slot antenna in carbon-fiber composite panels IEEE Antennas and Wireless Propagation Letters 11 1028–1031
[8] Galehdar A 2011 The effect of ply orientation on the performance of antennas in or on carbon fiber composites Progress In Electromagnetics Research 116 123–136
[9] Reznik S V 2018 Thermal regimes of space composite structures. Part I MATEC Web of Conferences 194 01048
[10] Reznik S V 2018 Thermal regimes of space composite structures. Part II MATEC Web of Conferences 194 01049
[11] Reznik S V, Prosuntssov P V and Mikhailovskii K V 2018 Thermal regime of large space structure with transformable elements from hybrid composite J. Phys.: Conf. Ser. 1134 012048
[12] Mikhailovskii K V, Reznik S V and Prosuntssov P V 2019 Method for modeling the interaction between transformable shells of spacecrafts and small space debris objects AIP Conference Proceedings 2171 030017 DOI: 10.1063/1.5133183.
[13] Reznik S V, Prosuntssov P V and Novikov A D. 2018 Prospects of Increasing the Dimensional Stability and the Weight Efficiency of Mirror Space Antenna Reflectors Made of Composite Materials in Proc. Higher Educational Institutions. Machine Building.(Moscow: HEIMB) 71–83 (in Russian)
[14] Bitkina E V, Denisov A V and Bitkin V E. 2012 Design-Engineering Methods of Creating of Dimensionally Stable Space Structures of Integrated Type Made of Composite Materials Izvestia of Samara Scientific Center of the Russian Academy of Sciences (Moscow) 555–60. (in Russian)
[15] Manach L, Castel X and Himdi M 2012 Performance of a Lozenge monopole antenna made of pure composite laminate Progress In Electromagnetics Research Letters 35 115–23
[16] Artner G and Langwieser R 2016 Performance of an automotive antenna module on a carbonfiber composite car roof Proc. European Conf. Antennas and Propagation (Davos) 243–8.
[17] De Assis R R and Bianchi I 2012 Analysis of microstrip antennas on carbon fiber composite material J. Microwaves, Optoelectron. Electromagn. Appl. 11(1) 154–61
[18] Artner G, Gentner P K, Nicolics J and Mecklenbräuker F 2017 Carbon fiber reinforced polymer with shredded fibers: Quasi-isotropic material properties and antenna performance Int. J. Antennas Propag. 2017 154-161
[19] Mehidipour A 2013 Mechanically reconfigurable antennas using an anisotropic carbon-fibre composite ground IET Micro. Antennas Propag. 7(13) 1055–63