

Material science problems of building space antennas with a transformable reflector 100 m in diameter

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Abstract. This paper focuses on the development of a space antenna transformable reflector 100 m in diameter. Accuracy requirements to the materials characterization are based on the thermal state analysis. The paper contains methods and results of thermal physical and optical characterization of the main construction materials to use in the transformable reflector.

1. Introduction

Space communication development, natural resources exploration, and space observations require deployable space reflectors to be developed. According to AstroMesh estimates, the existing technology enables mesh reflectors with a diameter of up to 50 m within the next decade.

Low linear density, 0.3 kg/m^2 in the best cases, is achieved by using radio-reflecting metal meshes made from tungsten, molybdenum or nichrome wires of 15-50 microns in diameter. The reflecting surface is geometrically stable, owing to bracing wires, hinges, props, struts, and power cables. The load-bearing elements are made in the form of straight or curved rods from polymer matrix composite materials, primarily carbon fibre-reinforced plastics.

The greatest challenge when designing space antenna reflectors is to ensure high dimensional stability under varying temperatures and temperature differences in the orbit. The permissible variation in shape and size should not exceed $\Lambda/16$ - $\Lambda/50$, where Λ is the radiation wavelength. In the L frequency band, where transformable reflectors are mostly used, these variations constitute 4-14 mm. A transformable reflector should be compactly stowed under the rocket booster fairing, whose diameter normally does not exceed 4 m.

At this stage of research, a theoretical and technological foundation must be created in the field of designing and manufacturing large transformable antenna reflectors up to 100 m in diameter, with a high-precision reflecting surface for long-life spacecraft.

2. The current state of research in the field of transformable reflectors of space mirror antennas

Large transformable antenna reflectors are currently being developed in Russia, the USA, Europe, China and Japan.

The Russian Joint Stock Company (JSC) Academician M.F. Reshetnev Information Satellite Systems installs umbrella-type mesh reflectors onto the Luch-5 geostationary relay satellites [1, 2].



For example, the Luch 5B has two antennas with umbrella-type mesh reflectors 4.2 m in diameter that can focus on low-orbit spacecraft, capture and follow them along the flight path. One of these antennas operates in Ku-band, the other in S-band.

The JSC S.P. Korolev Rocket and Space Corporation “Energia” has developed several distinctive designs of large transformable reflectors for space antennas [3, 4]. A 6.4 m by 5.2 m model of one of the reflectors was produced by JSC NPO “EGS” (a joint enterprise of “Energia” and the Georgian Polytechnical Institute, Georgia) and tested in the Mir orbital station in 1999 (figure 1).



Figure 1. Mesh reflector prototype during orbital testing at the Mir space station (JSC NPO “EGS”, Russia – Georgia).

The JSC Special Design Bureau of Moscow Power Engineering Institute (OKB MEI) has developed transformable reflectors for radar space antennas (figure 2). TKCA-6K antennas with 6 m by 2.8 m reflectors were successfully tested in orbit in 1985, as part of synthetic aperture radar systems onboard the Kosmos 1689 spacecraft, and in 1996, onboard the Priroda module of the Mir space station. The improved antennas are to be used as part of the Kondor remote probing satellites by the JSC Military Industrial Corporation Scientific-Production Association of Machine building (MIC SPA) “Mashinostroyeniya” [5]. Kosmos-2487, the first satellite of this type deployed in 2013, had a 6 m by 7 m antenna reflector. The hollow rods of the load-bearing frame were not made from metal, as before, but from carbon fibre-reinforced plastics. The overall reflector mass including hold-up mechanisms and all structural elements did not exceed 50 kg. The multi-beam feed system enabled both the beam mode and SCANSAR mode.

The USA-based Harris Corporation equipped the TerreStar, TDRS, ACeS, SDARS satellites with the umbrella-type transformable reflectors, with diameter up to 18 m (figure 3) [6]. The AstroMesh, Northrop Grumman branch, developed the largest transformable hoop type (membrane-cable)

reflectors for the Thuraya-3, MBCO, Inmarsat, and GlobalStar satellites. AM-Lite, AM, AM-1, AM-2 type reflectors have apertures of 3-8 m, 12 m, 6-25 m and 18-50 m respectively (figure 4) [7, 8].

Specialists in a number of companies in Europe and Japan [9-12] are also working on the development of large transformable reflector.

3. Reflector structural design

Contemporary space antenna reflectors comprise load-bearing rod elements to deploy the reflector into the operating configuration. They form the frame for the metal mesh comprising the radio-reflecting surface. Another essential element is polymer ropes, adjusting and supporting the mesh surface and metallic tips jointing the ropes to the frame.



Figure 2. Mesh reflector of the space antenna during ground tests (JSC “OKB MEI”, Russia).



Figure 3. Deployed TerreStar-1 18m reflector at Harris facility.

Designing transformable reflectors for space antennas is a complex interdisciplinary problem, where the initial stages are concerned with the thermal analysis and materials science issues. One of the design layouts for a reflector 100 m in diameter is analyzed below (figure 5). The load-bearing structure comprises carbon composite spokes that unfurl in the orbit forming the supporting ring for the mesh deployment. The parabolic shape is enabled by the tensioning ropes.

4. Reflector temperature state simulation

The flight of a spacecraft with a reflector, on a geostationary orbit, at the March equinox moment was considered. It was assumed that the rotation axis of the parabolic reflector shell is directed toward the Earth and its transverse axis coincides with the spacecraft velocity vector.

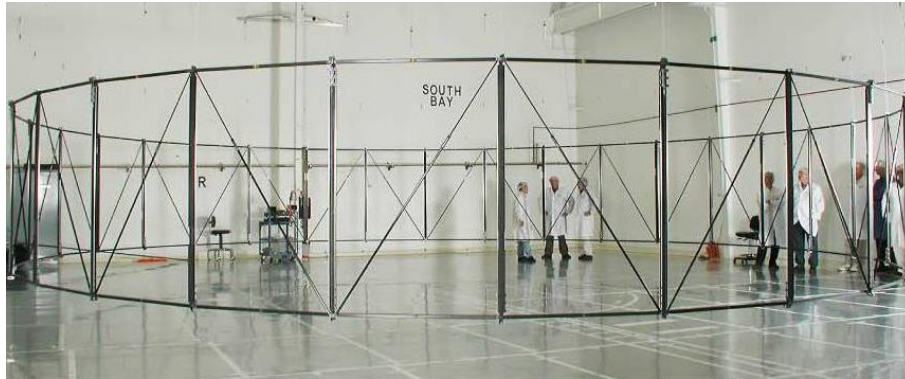


Figure 4. Deployed Reflector at AstroMech Corporation.

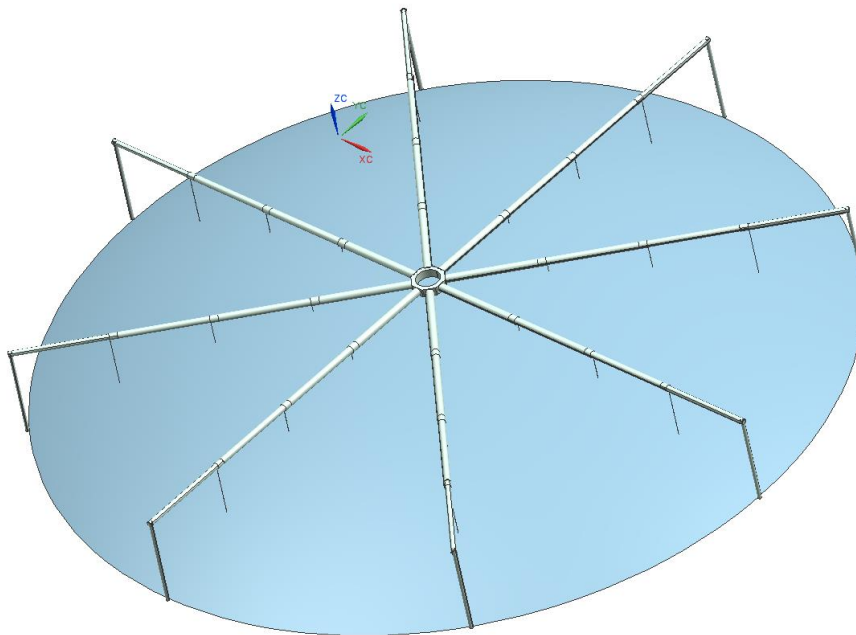


Figure 5. Reflector design layout.

The mesh was assumed to reflect, absorb and transmit the incident direct and Earth-reflected solar radiation. The thermal physical anisotropy of the carbon composite frame was taken into account.

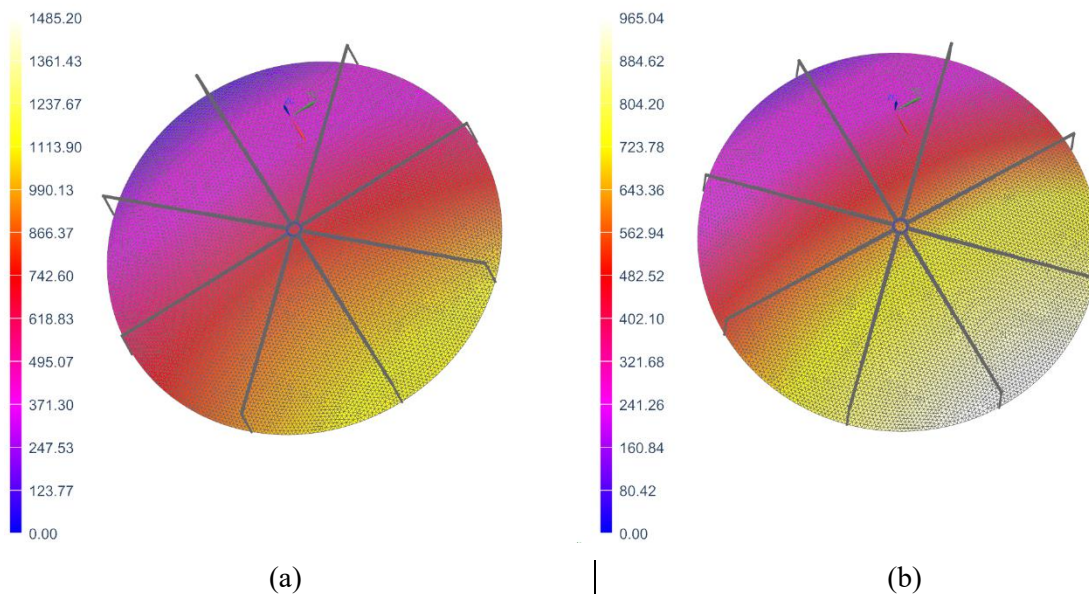


Figure 6. (a) Incident and (b) transmitted solar radiation flux when the angular position of the reflector in orbit, relative to the Earth-Sun line, is 120° , W/m^2

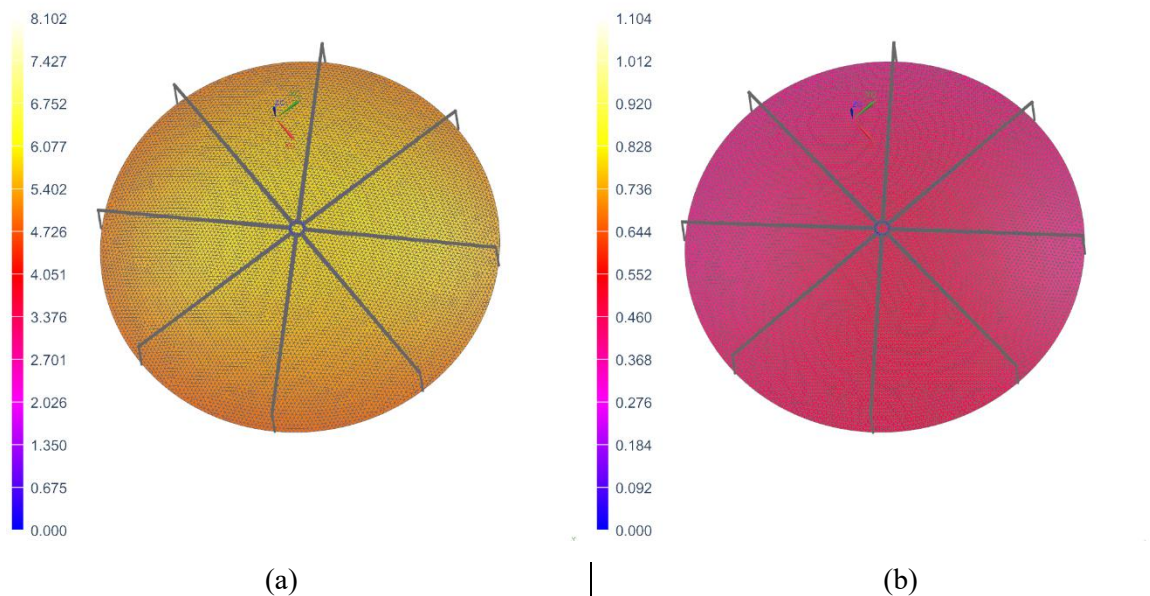


Figure 7. (a) Intrinsic and (b) Earth-reflected solar radiation flux when the angular position of the reflector in orbit, relative to the Earth-Sun line, is 120° , W/m^2

A finite-element model of the reflector was built, using approximately 60,000 3D tetragonal elements for composite arms, and approximately 30,000 2D elements for the grid-curtain and cables. The thermal contacts between separate structure elements were considered to be ideal. The surface of the carbon fire reinforced plastic (CFRP) was considered to be diffusely radiating, and the cables

semi-transparent for downward radiation. The thermal-physical properties of CFRP were taken to be: density 1550 kg/m³, and specific heat 1000 J/(kg·K). The thermal conductivity across the fibres was taken to be 72 W/(m·K), and the values of thermal conductivity along the fibres was variable: 101, 72, 36, 18 and 9 W/(m·K). The emissivity factor and radiation capacity for CFRP were equal to 0.7. The density of the cable material was 1000 kg/m³, specific heat 800 J/(kg·K), and thermal conductivity 1 W/(m·K). The cable emissivity was equal to 0.05, its radiation absorptivity 0.50, and the cable material transmittivity was 0.45.

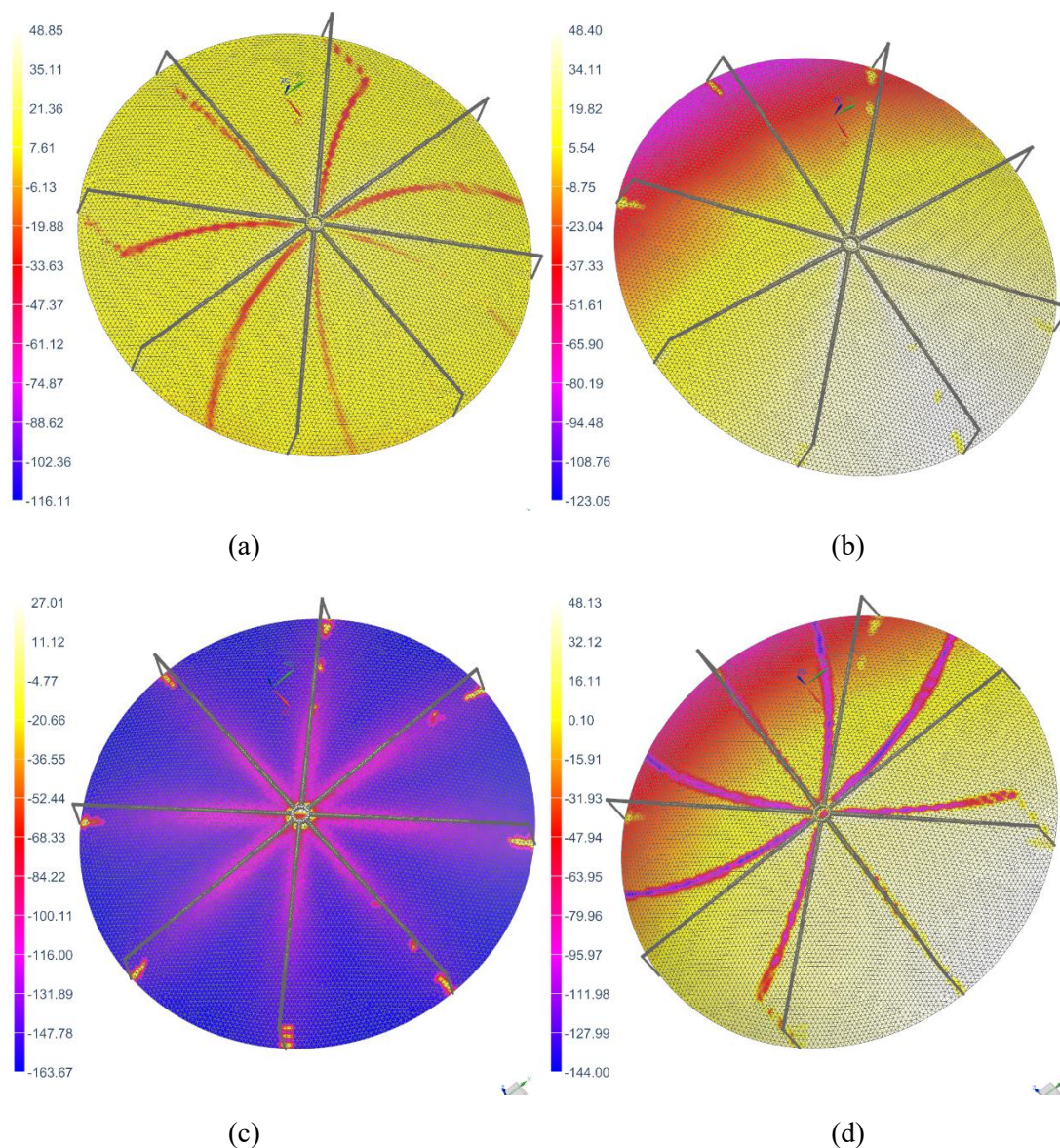


Figure 8. Reflector temperature field, °C when the angular position of the reflector in orbit, relative to the Earth-Sun line, is (a) 90°, (b) 120°, (c) 180° and (d) 300°.

The metal mesh was modelled as a partially transparent shell with the thickness 0.025 mm produced from material with density 3200 kg/m^3 , specific heat $500 \text{ J/(kg}\cdot\text{K)}$, and thermal conductivity varying in the range from 0.45 to $5.40 \text{ W/(m}\cdot\text{K)}$. The metal mesh had transmission capability 0.85, and its emissivity and radiation absorptivity were equal to 0.09.

Incident and Earth-reflected solar radiation flux and flow of the Earth thermal radiation were defined for the temperature state simulation using the Siemens PLM NX 10 finite element analysis package (figures 6, 7). Thermal state modelling also performed with the Siemens PLM NX 10 software package demonstrated temperature differences in the reflector structure as high as 190 K (figure 8).

5. Results analysis

When designing a reflector, reliable initial data on thermal physical and optical materials characteristics are essential. Unfortunately, there is limited information on the thermal conductivity coefficient in the reinforcement plane for composite materials, which is due to the absence of a standardized methodology. In the case of the load-bearing structure, we should calculate the possible effect of its thermal conductivity coefficient error on its temperature field. Figure 9 shows the temperature field of the load-bearing frame at different values of the rod material thermal conductivity coefficient. It is evident that the difference in the spoke temperature values reaches 30 K, which indicates the need to increase the accuracy of the thermal conductivity estimation.

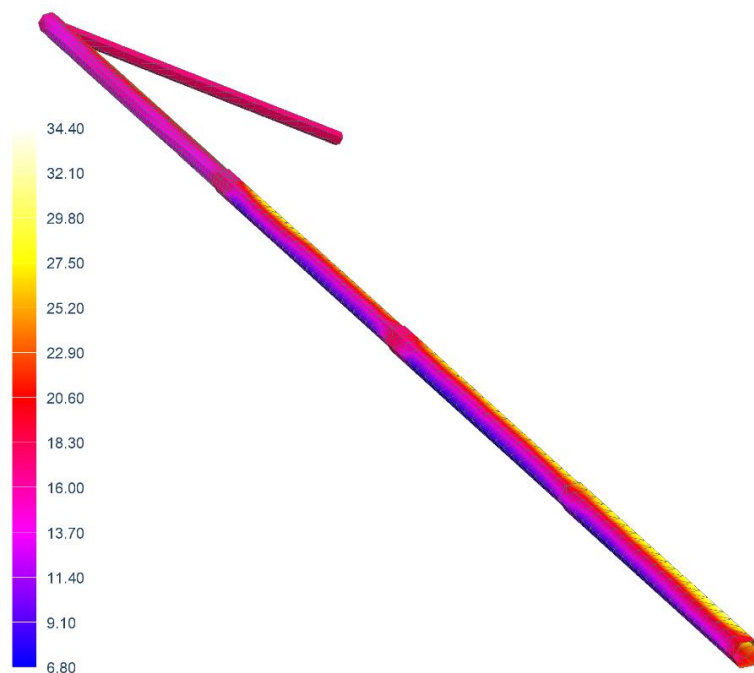


Figure 9. Temperature field, °C, of the reflector rod at longitudinal thermal conductivity $72 \text{ W/(m}\cdot\text{K)}$, when the angular position of the reflector in orbit, relative to the Earth-Sun line, is 120° .

In order to compensate for the deficiencies in the reference literature the authors have developed novel methods of optical characterization of metallic meshes and polymer ropes, as well as a method to determine the thermal conductivity of composite materials directly in the full-scale structural elements in the form of rods and plates [13-17].

The fact is that the traditional methods [18-21] allow defining of thermal conductivity of composites only in the normal direction λ_\perp . Experimental samples are round or quadrangular in shape

and machined very carefully. Information about λ_{\perp} as well as determination accuracy is not of the utmost interest when modelling thermal regimes of thin-walled space structures due to a slight temperature difference through-the-thickness that is equal to just a few degrees. The value of the longitudinal thermal conductivity (in-plane direction along the fibres) λ_{\parallel} is much more important because it influences to the temperature difference over the surface and along the structure. A peculiarity of this method for defining λ is the possibility to use full-size structures such as hollow rods [13, 14]. At the same time, this method is suitable for cables thermal conductivity research. Experiments could be conducted with one-sided [13, 14] and two-sided [15-17] heating of samples. The temperature difference is generated by electrical heating elements and measured by thermocouples or by a thermal imager. A program for solving the nonlinear inverse heat conduction problem is used for the interpretation of experimental data [22-23].

Obtaining reliable data on the mesh thermal conductivity coefficient is a considerable challenge, because of its flexibility when measuring tension. At present, there is practically no information on the thermal conductivity coefficient of the mesh. The thermal conductivity varying in the range 0.45 to 5.40 W/(m·K) indicates that it has only a very slight effect on the reflector thermal state. This must be a result of the fact that with the reflector being large and the mesh being thin, each point of the mesh is close to radiative equilibrium, when the conductive fluxes are significantly smaller than the radiative ones.

At the same time, the variability of the mesh optical characteristics indicates its significant effect on the reflector thermal state (figure 10).

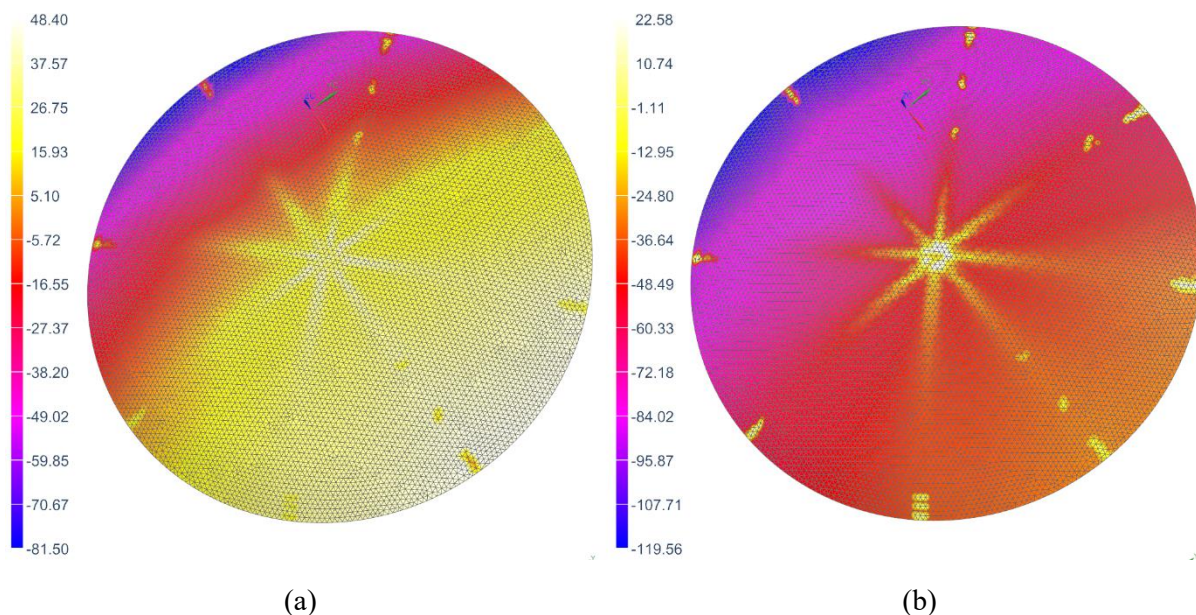


Figure 10. Mesh temperature field, °C, at different values of optical characteristics at time 28800 sec.

Thermal conductivity – 3.6 W/(m·K)

- a) Emissivity and absorptivity – 0.7, transmittivity – 0.85
- b) Emissivity – 0.135, absorptivity – 0.09, transmittivity – 0.85

6. Conclusions

Several transformable reflectors layouts for large diameter space antennas have been considered. The common feature for all the layouts in question is the combination of the load-bearing elements from carbon fibre-reinforced plastics, a metallic radio reflecting mesh and polymer ropes for the surface shape adjustment

The thermal state of a 100 m diameter reflector was modelled for the geostationary orbit, which demonstrated a temperature difference of 190 K in the reflector structure.

The composite material thermal conductivity coefficient was demonstrated to have a significant influence on its temperature state.

At the same time, the mesh thermal conductivity coefficient influence is insignificant, with the data on its optical characteristics being of much greater importance.

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References

- [1] Bessmertnaya JS, Kyzovnikov AV, Vygonitskiy YG, and Viryasov MM 2014 Система ретрансляции «Луч» Решетневские чтения: Матер. XVIII Междунар. науч. конф., посвящ. 90-летию со дня рождения генер. конструктора ракет.-космич. систем акад. М.Ф. Решетнева 11–14 нояб. 2014, г. Красноярск, Россия **1** [“Retransmission system “Luch” *Proc. 18th Int. Sci. Conf. Dedicated to Acad. M.F. Reshetnev*, Krasnoyarsk, Russia **1**, 173-174 (in Russian)]
- [2] Retransmission Space System “Luch”, <http://www.iss-reshetnev.ru/projects>
- [3] Gottero M, Sacchi E, Lorenzo G, Reznik SV and Kalinin DYU, 2005, *Proc. 35th Int. Conf. on Environmental Systems*, Roma, Italy
- [4] Reznik SV, Kalinin DYU and Denisova LV, 2010, *Proc. 32nd ESA Antenna Workshop on Antennas for Space Applications. From technologies to architectures*, Noordwijk, The Netherlands, 8
- [5] Afanas'ev I, 1999, *Astronautics News* (Novosti Kosmonavtiki) **10** (201)
- [6] Semler D, Tulintseff A, Sorrell R and Marshburn J, 2010, *Proc. 28th AIAA International Communications Satellite Systems Conference -ICSSC-2010*, Anaheim, California, USA, AIAA-2010-8855
- [7] Thomson MW, 2002, *Proc. 20th AIAA International Communications Satellite Systems Conference ICSSC-2002*, Montreal, Canada, AIAA-2002-2032
- [8] Marks G, Lillie C and Kuehn S, 2011 *Proc. 33rd ESA Antenna Workshop on Challenges for Space Antenna Systems. Preparing for the Future*, Noordwijk, The Netherlands
- [9] Ihle A, Breunig E, Datashvili L, Migliorelli M, Scialino L, van't Klosters K and Santiago-Prowald J, 2012, *Proc. Workshop on Large Deployable Antennas*, Noordwijk, The Netherlands
- [10] Sinn T, Proetti Zola P, Pfeiffer EK, Datashvily L and Lori M, 2015, *Proc. 36th ESA Antenna Workshop on Antennas and RF Systems for Space Science*, Noordwijk, The Netherlands
- [11] Meguro A, Harada S and Ueba M, 2005, *Proc. 56th International Astronautical Congress*, Fukuoka, Japan, IAF-05-C2.1.B
- [12] Ozawa S, Shintate K, Tsujihata A, 2012, *Proc. Workshop on Large Deployable Antennas*, Noordwijk, The Netherlands
- [13] Reznik SV, Prosuntsov PV, Railyan VS and Shulyakovsky AV, 2007, *Proc. Symposium on*

Inverse Problems, Design and Optimization, Miami, Florida, USA

- [14] Reznik SV, Denisov OV, Prosuntsov PV, Timoshenko VP and Shulyakovskiy AV, 2012, Термовакuumные испытания полых композитных стержней для космических конструкций *Vse Materialy. Entsiklopedicheskiy Spravochnik* **7**, 8-12 [Thermal vacuum tests of hollow composite rods for space structures *All the Materials. Encyclopedic Reference Book* **7**, 8-12 (in Russian)]
- [15] Reznik SV, Timoshenko VP, Prosuntsov PV, Minakov DS 2013 “Моделирование и идентификация параметров теплопереноса в тросовых элементах космических конструкций. I. Обоснование условий эксперимента” *Тепловые процессы в технике* **5**(5) 235-9 [“Modeling and identification of heat transfer parameters in rope elements of space structures. I. The rationale for the experimental conditions” *Thermal Processes in Engineering* **5**(5) 235-9 (in Russian)]
- [16] Reznik SV, Timoshenko VP, Prosuntsov PV, Minakov DS 2014 “Моделирование и идентификация параметров теплопереноса в тросовых элементах космических конструкций. II. Экспериментальные исследования. Определение теплопроводности тросового элемента” *Тепловые процессы в технике* **6**(8) 378-84 [“Modeling and identification of heat transfer parameters in rope elements of space structures. II. An experimental study. Determination of the thermal conductivity of the rope element” *Thermal Processes in Engineering* **6**(8) 378-84 (in Russian)]
- [17] Denisov OV, Kirbai AA and Minakov DS, 2015, *Proc. Conf. Heat and Mass Transfer in the Thermal Control System of Technical and Technological Energy Equipment*, Tomsk, Russia, **23**, 01016 [Doi: 10.1051/Mateconf/20152301016](https://doi.org/10.1051/Mateconf/20152301016)
- [18] ASTM C 177: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus <http://www.astm.org/Standards/C177.htm>
- [19] Johansson P, Adl-Zarrabi B and Hagentoft CE, 2012, *Frontiers Architect. Res.* **1**(4) 334-40.
- [20] Krupa P and Malinaric S, 2014, *Int. J. of Mathematical, Computational, Physical, Electrical and Computer Engineering*, **8**(5) 735-40
- [21] Ponomarev SV, et al, 2008, *Теоретические и практические основы термофизических измерений* ФИЗМАТЛИТ, Москва [Theoretical and practical bases of thermophysical measurements FIZMATLIT, Moscow (in Russian)]
- [22] Reznik SV et al 1997 “Математико-алгоритмическое и программное обеспечение исследования процессов радиационно-кондуктивного теплообмена в частично прозрачных материалах” *Труды I-го междунар. симп. Передовые термические системы и технологии*, Katsiveli, Crimea, Ukraine, Bauman MSTU Publisher House, Moscow 40-49 [“Mathematical algorithms and software for the study of processes of radiative-conductive heat exchange in partially transparent materials” *Proc. 1st Int. Symp. Advanced Thermal Engineering Systems and Technologies Part 2*, Katsiveli, Crimea, Ukraine, Bauman MSTU Publisher House, Moscow (in Russian)]
- [23] Polezhaev YuV, et al, 2002, *Материалы и покрытия в экстремальных условиях. Взгляд в будущее: В 3 т. – Т. 1. Прогнозирование и анализ экстремальных воздействий* vol. 1, Ed. SV Reznik, Bauman MSTU Publisher House, Moscow [Materials and Coatings in Extreme Conditions. Looking to the future. Forecasting and Analysis of Extreme Impacts vol. 1, Ed. SV Reznik Bauman MSTU Publisher House, Moscow (in Russian)]