Optical characterisation of metallic meshes for space antennas transformable reflectors

RA Mironov, SV Reznik, RV Rukavishnikov, VA Shishulina and VA Zavaruev

Department Rocket and Space Composite Structure Bauman MSTU, 5/1, 2nd Baumanskaya str., Moscow, 105005, Russia

E-mail: sreznik@bmstu.ru

Abstract. The paper deals with metallic meshes for space antenna transformable reflectors. Optical characteristics of four metallic meshes (15 micron tungsten, 15 micron gold-plated tungsten, 20 micron molybdenum, and 50 micron Ni-coated steel) were investigated with the Nikolet IS50 spectrophotometer. The spectral optical characteristics of these metallic meshes in the range from 0.4 to 2.5 microns are required for thermal design of space antenna reflectors.

1. Introduction
The Creation of Large Deployable Antennas (LDA) has been one of the most perspective directions in the development of global telecommunications systems for already more than 40 years [1, 2]. Such companies as Harris Corporation and Astro Mesh (which is a subsidiary of Northrop Grumman Corporation) are designing and manufacturing space transformable reflectors with large diameters of up to 25 meters [3-5]. These structures generally have a membrane or an umbrella layout. Researches in the field of such antennas are conducted in Europe and Japan [6-10]. A number of projects have been performed in Russia by the Joint-Stock Company (JSC) “Special Design Bureau of Moscow Power Engineering Institute”, JSC “SP Korolev Rocket and Space Corporation “Energia”, JSC “Academician MF Reshetnev Information Satellite Systems” [11-15]. Features common for all existing LDA include metallic reflecting meshes, ropes of polymeric fibres and load-bearing elements made of polymer composite materials.

2. Relevance of the research
Increasingly high requirements are imposed on modern space antenna reflectors both in terms of durability and precision. In order to achieve minimal shape and size deviations (maximum value of $\Lambda/16$ where $\Lambda$ is the antenna operating wavelength), the design process must attend to the properties of each and even the smallest element.

When in orbit the reflector of mirror space antenna will be in high vacuum and will be heated by the solar radiation thermal flux, the solar flux reflected from the Earth and the Earth's own radiation. The main source of the external thermal influence is the heat flux of direct solar radiation.

In geostationary orbit, twice a year, at around the vernal and autumnal equinoxes, the satellite will be in the Earth's shadow with the maximum duration of up to 71 minutes. Thin walled elements of the LDA reflectors can be cooled down to low temperatures (less than 100 K) when in shadow and can be heated intensively when in daylight sector of orbit [12]. Temperature dynamic causes temperature gradient, which could become a reason of structure deformations followed by angular pattern break...
down. Therefore, one of the main stages of the mesh reflector design is thermal regimes modelling. For the modelling of the thermal regimes, not only the reflector, but also of the whole telecommunication satellite, the following data is required: the quantity of solar flux absorbed into and transmitted through the mesh surface, the intrinsic temperature of mesh surface, and the amount of heat energy emitted to the external environment. The accuracy of modelling depends on the input data, accuracy of the thermal physical, and optical characteristics of the materials utilized.

Metal meshes are manufactured by weaving tungsten, molybdenum or steel wire with a diameter of 15 to 50 micrometers and have complex spatial structure. Metallic knitted mesh enables both shape stability at larger sizes and lower mass per unit length [14, 15].

The original production technologies for various knitted metallic meshes of radio-technical purpose are presented in the works [16-21]. The main emphasis of the mentioned papers is on getting meshes from various fibres with defined cell sizes and required rigidity. There is little information in literature concerning the characterisation of radio-technical metallic meshes for thermal design. There is also still a need for further research into the optical properties of metal meshes. Their characterization is complicated by the structure, in which voids account for more than 80%, and a need for characterization of the variability of the surface profile and the dependence of the characteristics on the magnitude and direction of the loads.

In paper [12], thermal design results for the prospective LDA, including the reflector fabricated of gold-plated tungsten mesh and the use of a multi-joint manipulator for moving the reflector to the operating position. Optical characteristics of the metallic mesh were obtained theoretically for the fibrous periodic structure model. Independent calculations of the thermal regimes were accomplished by the company Alenia Spazio with the help of ESATAN and ESARAD computer codes, developed by the European Space Agency (ESA) [12] and Bauman MSTU with the help of the Bauman MSTU in-house CAR computer code. The metallic mesh was modelled as a thin layer of semi-transparent material with the heat emitted from surface to the external environment. Results of experiments conducted in ESTEC (Noordwijk, the Netherlands) [12] have shown satisfactory fit with those of theoretical and experimental data.

In papers [22, 23] the method of experimental definition of optical characteristics of mesh made of 50 microns diameter nichrome wire is presented. Transmission and reflection coefficients were determined on the standard optical equipment with the original VL Churkin’s devices [24] within the range of 0.2-10 μm length in Joint-Stock Company “Dolgoprudny Design Bureau of Automatics”. The authors tested plate patterns of mesh in a vacuum chamber simulating single side solar heating [22, 23]. The temperature patterns were measured with high accuracy by using ultra small thermocouples with 30 μm diameter thermocouple wire. In accordance with the theoretical estimations, the temperature measurement systematic error did not exceed 1.5 K in a temperature level of 420 K [22, 23]. The relationship $A_s/ε$ obtained as a result of the experimental data interpretation showed satisfactory agreement with the data obtained with standard optical equipment.

Paper [25] describes the method and results of the experimental research of mesh optical characteristics (absorption coefficient of solar emission $A_s$, coefficient of thermal emission $ε$, and transmission $D_s$, in the range of solar spectrum 0.2 – 2.5 μm wavelength and in the infrared region with $Λ \sim 10$ μm). Standard equipment such as laid-on photometer FM-59 and thermoradiometer TRM-I using laying of mesh on the base with the different coefficients $A_s$, $ε$, including the models of an ideal black body was used.

The mesh transmittivity indicatrix was obtained for different solar emission incident angles using an imitator of using an imitator of solar radiation and PCFS photo sensor. It was determined that transmission of any mesh type has a particular nature: the beam divergence angle does not exceed 15 degrees. The mesh and antenna elements optical characteristics measurements results were used for the analysis of the reflector thermal regimes under operation conditions. The papers referenced give an idea about the current research experience, but the appearance of new mesh materials inspires further updating of the methods.
3. **Test samples and the test setup**

Four types of metal mesh were selected for testing: 15 micron tungsten wire (figure 1), 15 micron gold-plated tungsten wire (figure 2), 20 micron molybdenum wire (figure 3), and 50 micron nickel-coated steel wire EI 708A (figure 4). Samples have different weaving patterns and cell size. The main characteristics of the meshes are shown in table 1.

| Material     | Coating | Wire diameter, µm | Cell size, mm |
|--------------|---------|-------------------|---------------|
| Tungsten     | none    | 15                | 0.2×0.8       |
| Tungsten     | Gold    | 15                | 0.2×0.8       |
| Molybdenum   | none    | 20                | 0.2×0.8       |
| Steel        | Nickel  | 50                | 1.7×1.7       |

**Figure 1.** (a) Tungsten mesh microstructure, (b) Gold-plated tungsten mesh microstructure, (c) Molybdenum mesh microstructure, (d) Steel mesh microstructure.

An important stage of the experiment was to prepare frames for samples. It was necessary to take into account the test stand features, the size of the light beam passing through the samples, the
uniformity of the sample material and their optimal tension. Metal mesh samples were cut from blanks and fixed in a cardboard frame with a 25 to 50 mm hole.

4. Experiment description
Reflection coefficients were determined using the near infrared range (NIR) spectroscopy by means of Nicolet iS50 FT-IR spectrometer (Figure 2) [26, 27].

![Figure 2. Spectrometer Nicolet iS50](image)

The physics of this method is that the source radiates infrared electro-magnetic waves, and the electro-magnetic radiation passes through Michelson interferometer and the sample. The detector registers the dependency of the output light flux intensity on the optical path difference in the different parts of the interferometer. The interferogram contains full information on the spectral nature of the radiation.

Integrating sphere is used as a measuring instrument. The integrating sphere method determines diffuse transmission and reflection in 0.2 – 2.6 μm spectral region. The integrating sphere is a hollow sphere; the inner surface is coated with a diffusely scattering material.

An integrating sphere is used as a measuring device. The diffuse transmittance and reflectance in 0.2 – 2.6 μm spectrum range can be determined with the integrating sphere. This main measuring element in photometers and spectrophotometers is a hollow ball with diffusing internal surface. The device was calibrated immediately before the experiment.

5. Results and discussions
The data obtained using Nicolet iS50 were processed by means of specialized software package OMNIC 9 resulting in spectral dependencies of reflectivity $R_\lambda$ and transmittivity $D_\lambda$. Absorptivity $A_\lambda$ values were calculated using the equation:

$$A_\lambda = 1 - D_\lambda - R_\lambda.$$  

Experimental results are shown in graphs as dependencies of spectral optical properties on the wavelength in the infrared and optical spectra (0.4 – 2.5 micron) at normal incidence (figures 3-6).

The absorptivity of all types of metal mesh did not exceed 0.2 in the whole spectral range. The transmittivity of all meshes, except the molybdenum mesh, decreased smoothly and very gradually with increasing wavelength; however, it still remained in the 0.75-0.85 range. The transmittivity of the molybdenum mesh increases slightly with wavelength in the infrared range, but does not exceed 0.89. The lowest absorptivity over the greatest part of the spectrum was demonstrated by the gold-plated tungsten mesh, which indicates an advantage for solar radiative heating at GEO.

Reflectivity of all samples except gold-plated tungsten mesh decrease smoothly with the wavelength increase. The greatest reflectivity values were registered for the nickel-coated steel mesh;
greater than 0.8. On the whole, the data obtained were in alignment with the previously obtained data for metal meshes.

**Figure 3.** Tungsten mesh spectral optical characteristics
1 – reflectivity $R_\nu$; 2 – transmittivity $D_\nu$; 3 – absorptivity $A_\nu$.

**Figure 4.** Gold-plated tungsten mesh spectral optical characteristics
1 – reflectivity $R_\nu$; 2 – transmittivity $D_\nu$; 3 – absorptivity $A_\nu$. 
Figure 5. Molybdenum mesh spectral optical characteristics
1 – reflectivity $R_\nu$; 2 – transmittivity $D_\nu$; 3 – absorptivity $A_\nu$.

Figure 6. Nickel-coated steel mesh spectral optical characteristics
1 – reflectivity $R_\nu$; 2 – transmittivity $D_\nu$; 3 – absorptivity $A_\nu$. 
6. Conclusion
The optical characteristics of four types of metal mesh were experimentally determined: 15-micron tungsten, 15-micron gold-plated tungsten, 20-micron molybdenum, and 50-micron nickel-coated steel wires at normal incidence beam. Based on these data we can draw conclusions about the feasibility of using one of the studied meshes when creating large size deployable reflector. The lowest absorptivity over the greatest part of the spectrum was demonstrated by the gold-plated tungsten mesh, which indicates an advantage for solar radiative heating at GEO.

The reflectivity of all the samples except gold-plated tungsten mesh decreased gradually with the wavelength increasing. The greatest reflectance values were registered for steel mesh (more than 0.8).

Transmittivity of all meshes except molybdenum decreased gradually with the wavelength increasing, but remained in the range 0.75-0.85. The transmittivity of the molybdenum mesh increased slightly. The absorptivity of all meshes remained almost unchanged throughout the range and did not exceed 0.2.

7. Acknowledgment
Some results of this work were obtained in the framework of the Agreement on grant No. 14.577.21.0129 of the Ministry of education and science of the Russian Federation. Unique identifier for applied scientific research (project) RFMEFI57714X0129

References
[1] Archer JS 1980 “High performance parabolic antenna reflectors” Journal of Spacecraft and Rockets 17(1) 20-26. DOI: 10.2514/3.57702
[2] Fager JA 1980 “Large space erectable antenna stiffness requirements” Journal of Spacecraft and Rockets 17(2) 86-92. DOI: 10.2514/3.57712
[3] Thomson MW 2002 Proc. 20th AIAA International Communications Satellite Systems Conference ICSSC-2002 (Montreal, Canada), AIAA-2002-2032
[4] 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)
[5] 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
[6] Ihle A et al 2012 Proc. Workshop on Large Deployable Antennas (Noordwijk, The Netherlands)
[7] Sinn T, Proetti Zola P, Pfeiffer E K, Datashvily L and Lori M 2015 Proc. 36th ESA Antenna Workshop on Antennas and RF Systems for Space Science (Noordwijk, The Netherlands)
[8] Meguro A, Harada S and Ueba M 2005 Proc. 56th International Astronautical Congress (Fukuoka, Japan), IAF-05-C2.1.B
[9] Harada S, Meguro A and Ueba M 2007 NTT Technical Review 5(1) 70
[10] Ozawa S, Shintate K and Tsujihata A 2012 Proc. Workshop on Large Deployable Antennas (Noordwijk, The Netherlands)
[11] Zimin V N and Sdobnikov A N 2010 “Особенности моделирования динамики крупногабаритных трансформируемых космических конструкций” Труды XIV Международ. научн. конф., посвящ. памяти ген. конструктора ракетно-космических систем акад. М.Ф. Решетнева 1 57-58 (“The features of large transformable space structures dynamic simulation” Proc. XIV Int. Sci. Conf. dedicated to Acad. M.F. Reshetnev (Krasnoyarsk, Russia)] 1 57-58 (in Russian)]
[12] Gottero M, Sacchi E, Lorenzo G, Reznik S V and Kalinin D YU 2005 Proc. 35-th Int. Conf. on Environmental Systems (Roma, Italy)
[13] Evdokimov AS, Ponomarev SV and Buyanov YuL 2011 “Совместный расчет напряженно-деформированного состояния и диаграммы направленности космических рефлекторов”] Вестник Томского государственного университета. Математика и механика 1(13) 74-82 (“The joint calculation of the stress-strain state and the directive...
pattern of the space reflectors” *Herald of Tomsk State University. Mathematical and Mechanics* **1**(13) 74-82 (in Russian)]

[14] Kisanov YA, Feyzulla NM, Kudryavin LA, Zavaruev A 1981 “Материалы для отражательных поверхностей космических складных антенн (КСА)” *Антенны* **29** 20-25 [“Materials for reflectors of folding space antennas (FSA)” *Antennas* **29** 20-25 (in Russian)]

[15] Belyaev OF, *et al* 2007 “Трикотажные металлические сетеполотна для отражающей поверхности трансформируемых наземных и космических антенн” Технический текстиль **16** 59-64 [“Knitted metal meshes to the reflecting surface of the transformable ground and space antennas” *Technical textiles* **16** 59-64 (in Russian)]

[16] Kudryavin LA 1975 Основы теории строения, свойств и процессов выработки сетеизделий трикотажных переплетений Дисс. на соиск. учен. степени д.т.н. Москва: МТИ [Fundamentals of the theory of structure, properties and processes of the production of knitted weave interlacings sitesdaily” Thesis of Doctor of Science (Technique) Moscow: Moscow Textile Institute (in Russian)]

[17] Zavaruev VA 1980 Исследование особенностей переработки металлических мононитей на вязальных машинах с целью получения полотен технического назначения Дисс. на соиск. учен. степ. к.т.н. [Research of the features of metallic monofilaments processing on knitting machines for obtaining cloths for technical applications” Thesis of Candidate of Science (Technique) Moscow: Moscow Textile Institute (in Russian)].

[18] Zavaruev VA 2006 Разработка технологии производства трикотажных металлических сеток для космических и наземных систем связи Дисс. на соиск. учен. степ. д.т.н. [Development of knitted metal meshes technology for the products of space and terrestrial communication systems” Thesis of Doctor of Science (Technique) Moscow: Moscow State Textile University n.a. N.A. Kosigin (in Russian)]

[19] Stigene LYa 1990 Дисс. на соиск. учен. степ. к.т.н. Москва: МТИ [The development of structures of knitted fabrics for technical applications from metal threads for the purpose of optimization of their physical-mechanical characteristics” Thesis of Candidate of Science (Technique) Moscow: Moscow Textile Institute (in Russian)]

[20] Ritikova IV 2005 Разработка технологии формирования сложноконструктивных изделий из металлических трикотажных полотен Дисс. на соиск. учен. степ. к.т.н. [Development of technology of formation of complex structural metal products knitted fabrics for technical purposes” Thesis of Candidate of Science (Technique) Moscow: Moscow State Textile University n.a. N.A. Kosigin (in Russian)]

[21] Kotovich OS 2008 Проектирование структур, свойств и технологии металлических основовязанных сетеполотен для гибких отражательных поверхностей антенн Дисс. на соиск. учен. степ. к.т.н. [The design of the structures, properties and technologies of knitted metal meshes for flexible reflective surfaces of antennas” Thesis of Candidate of Science (Technique) Moscow: Moscow State Textile University n.a. N.A. Kosigin (in Russian)]

[22] Denisova LV, Reznik SV, Kalinin DYu 2011 “Теоретические и экспериментальные исследования тепловых режимов сетчатых рефлекторов космических антенн” Вестник МГТУ им. Н.Э. Баумана. Серия Машинностроение **1**(82) 92-105 [“Theoretical and experimental studies of space antennas metal meshes reflectors” *Herald of Bauman Moscow State Technical university. Machine building* **1**(82) 92-105 (in Russian)]

[23] Reznik SV, Denisova LV, and Churkin VL 1991 “Исследование радиационного теплообмена в металлических сетеполотнах космических антенн” Research report No. 18/91 (Moscow: Joint-Stock Company “Automated Information Systems and Technologies” (AIST) [“Study of radiation heat transfer in metal meshes of space antennas” (in Russian)]

[24] Vasil'ev VN, Mishin GS and Ryabov PM 2004 “Экспериментальное исследование оптических характеристик сетеполотна и элементов антенны КА” *Актуальные*
проблемы российской космонавтики: Труды XXVIII Академич. чтений по космонавтике. М.: Комис. РАН по разраб. науч. наследия пионеров освоения космич. Пространства [“Experimental study of the optical characteristics of metal meshes and elements of the space vehicle antenna” Proc. XXVIII Academic readings on Cosmonautics 360 (in Russian)]

[25] 2012 Fourier transform IR spectrometer Nicolet iS50 (Intertech corporation) http://intertech-corp.ru/aboutproduct.asp?gr=15&subgr=33&prid=231

[26] 2012 Method of Fourier Transform Infrared Spectroscopy (ROSNANO) http://rusnano-mc.com/ru/node/229