The effect of the PCB solder mask type of the hull outer surface of the CubeSat 3U on its thermal regime

V N Gorev 1,*, A A Kozlov 1, V Yu Prokopyev 1, Yu M Prokopyev 1, A S Stuf 1 and A A Sidorchuk 1,2

1Novosibirsk State University, Pirogova Street 2, Novosibirsk, 630090, Russia
2OKB Fifth Generation Ltd., Nikolaeva Street 11, Novosibirsk, 630090, Russia

*E-mail: vasily.gorev@gmail.com

Abstract. Rather simple methods to measure the absorbed solar radiation coefficients and IR radiation, as well as optical coefficients measured by these methods for the construction materials of microsatellites and PCB coated with different solder masks are presented. The calculating results of the satellite’s thermal conditions for different PCB solder masks at the satellite outer surface are given. The thermal model is implemented on the orbital motion and insolation calculating algorithm basis, which developed in Matlab Simulink. A CubeSat 3U type satellite with foldable solar panels is considered as an example.

1. Introduction

Designing the thermal regime of a satellite is one of the main tasks of its development [1]. To ensure the regular operation of the satellite, it is necessary to maintain the thermal regime of the functional elements in a narrow operational range in the extreme space conditions. For CubeSat type microsatellites [1-3] the thermal regime is even more critical than for large satellites. Due to its weight, size and power limits, the number of options for ensuring the thermal regime of the onboard equipment has been significantly narrowed. Using less reliable non-specific electronic components requires thermal regime close to normal earth conditions, otherwise the lifetime of electronic components will be reduced. Microsatellites, unlike large satellites, have a lower mass-to-area ratio, which means a more intense specific radiative heat transfer with the environment, therefore, the satellite temperature fluctuations are more significant. Frequent satellite’s body temperature fluctuations at low earth orbit (LEO) also reduces the on-board equipment service.

The satellite is in conditions of radiative heat exchange with the environment, it is heated by external radiation sources, the heat is released into the environment by surface radiation and is determined by the surface properties of the materials – solar radiation absorption and IR emissivity coefficients [4].

The microsatellite surface consists of a frame made of anodized aluminum alloy, PCBs coated with a solder mask or other coating, and photovoltaic converters. As for these materials, only optical absorption/emission coefficients for photoconverters are known with good accuracy. The optical properties of an aluminum alloy surface are generally unknown; they depend on the surface roughness and the thickness of the oxide layer grown by anodizing. The optical properties of different types of solder masks are also unknown.
The calculation results are presented using a simple thermal model of a satellite implemented on the basis of a model of the satellite’s orbital motion and its insolation developed by Matlab Simulink [5]. As an example, the CubeSat 3U satellite with folding solar panels developed at Novosibirsk State University is considered.

2. Methods to measure optical coefficients

2.1. Measurement of the absorbed solar radiation coefficient

The experimental setup (figure 1) consists of a light source S (DXSH-120 arc xenon lamp), an optical system (light filter F and adjustable aperture D), a stand with a sample holder O, and a rotary mechanism with a scale for measuring the rotation angle. A photodetector P, photodiode FDUK-10 [6], is mounted on the rotary mechanism. The lamp, filter, aperture and sample are located on the same optical axis. The photodetector can rotate around a stationary rack with a sample on the rotary mechanism R, while the center of the sample is located on the axis of rotation.

![Figure 1. Experimental setup for the scattering indicatrix measuring.](image)

The optical system forms a spot of light on the sample, mounted in a special rack covered with black velvet paper. An opaque sample 12 mm × 12 mm in size is fixed in a special rotary mechanism T, which allows adjusting the direction of the reflected beam maximum in a vertical plane in the photodetector direction (figure 1). The initial angles are set by visually aligning the maximum of the sample reflection spot with the center of the photodetector.

The sample is covered with a mask of black velvet paper with a round aperture of 10 mm in the diameter to provide the same area of all tested samples. The mask’s thickness is 0.3 mm, and therefore it limits the range of indicatrix angles φ to ± 85 °. To exclude extraneous illumination of the sample and the photodetector, the measuring part is separated from the light source by an opaque wall W with an aperture of the size equals to the diaphragm D holder.

A mask with a rectangle aperture 1x2mm size is applied to the photodetector to increase the spatial resolution of the detector. The photodetector is connected to an electrical circuit measuring the diode photocurrent. The measured current is proportional to the number of photons absorbed by the photodetector, according to spectral sensitivity of the photodetector.

The result of multiplication of the spectral density of the incident on the sample radiation, the photodetector spectral sensitivity and the light filter transmission spectrum is the optical system effective working spectral characteristic (figure 2, a). The samples reflection coefficients measured in this effective spectrum. The effective spectrum is somewhat different from the solar spectrum, it does not have a UV part with wavelengths of less than 350 nm, and there is no IR radiation with wavelengths of
more than 1000 nm. This can affect absorption coefficients measured values especially of the colored samples.

The absorption coefficients were determined by integrating of measured scattering indicatrices [7]. Figure 3 shows the light scattering indicatrices of the studied samples. For each sample, two intensity curves of the reflected light depending on the scattering angle for two mutually perpendicular directions were measured. It can be seen that the samples are divided into two categories according to the type of scattering - isotropic in the azimuthal angle and anisotropic one. All samples of copper-plated PCBs with transparent solder masks turned out to be anisotropic. This is due to the microstructure of the copper layer surface covered with oriented micro grooves. The scattering indicatrices of anisotropic samples were measured in the directions parallel and perpendicular to the micro grooves (in the main axes). All indicatrices were symmetrized by averaging the curve and its reflection from the vertical axis passing through the point 0°. To eliminate the error of the initial zero angle choice, an angle offset was used, which was calculated by minimizing the difference between the curve and its reflection. Then background intensity dependence on the angle, measured without a sample (the hole is located in the place of the sample), is subtracted from the obtained samples curves.

For samples with isotropic scattering, the reflected radiation power is calculated by integrating the obtained curve in a spherical coordinate system as follows:

$$W_{\text{isotropic}} = 2\pi C L^2 \int_0^\pi I \sin \theta d\theta,$$

where

- $\Theta$ – the scattering angle,
- $I = I(\Theta)$ – the radiation intensity measured at an angle $\Theta$,
- $L$ – the distance from the sample to the photodetector,
- $C$ - the coefficient determined on the basis of the calibration samples.

It can be seen that the central parts of the indicatrix graphs in two perpendicular directions for each anisotropic sample practically coincide (figure 3). Therefore, it is assumed that the scattering of these samples is the sum of the isotropic (reflection from the outer smooth solder mask’s surface) and the anisotropic parts (reflection from the copper layer):

$$W_{\text{anisotropic}} = W_{\text{isotropic}} + W_{\text{add}}.$$

Additional power $W_{\text{add}}$ can be estimated under the following formula:

$$W_{\text{add}} = 4CL^2 \int_0^\pi \int_0^\pi I(\theta, \phi) \sin \theta d\theta d\phi,$$

where

$$I(\theta, \phi) = (I_{\theta}(\phi) - I_{\phi}(\phi)) \cdot \frac{I_{\phi}(\theta)}{I_{\phi}(\pi/2)}.$$

The center of the intensity distribution over the angle is placed at the point $\phi = 0$, $\Theta = \pi/2$. The anisotropic intensity distribution placed along the angle $\phi$, and isotropic distribution - along the angle $\Theta$. 
Figure 3. Light scattering indicatrix of PCB solder mask samples; (a) – calibration mirror samples; (b) – isotropic samples; (c) – anisotropic samples.

By calculating these integrals, the power of the reflected radiation in relative units obtained. To calculate the reflection (and absorption) coefficient, it is necessary to perform measurements for polished calibration samples with known reflection spectra. In this experiment, measurements for crystalline silicon and an aluminum mirror were made. The reflection coefficients of calibration samples which reflection spectrum is shown in figure 2, b [8] are found by the following formula:

\[ R = \frac{\int I_{SI} S_L S_F S_P \, d\lambda}{\int S_L S_F S_P \, d\lambda}. \]

The absorption coefficients calculated, respectively: \( D = 1 - R \), where \( I_{SI} \) is the sample reflection spectrum, \( S_L \) is the lamp spectral power density, \( S_F \) is the filter transmission spectrum, and \( S_P \) is the photodetector sensitivity spectrum. The absorption coefficients for the calibration samples shown in table 1. Integrating the scattering indicatrices of the calibration samples, the coefficients (\( C_{SI} = 0.306 \), \( C_{Al} = 0.295 \)) are obtained. It can be seen that they coincide with good accuracy. As can be seen from table 1, the calculated absorption coefficients of the calibration samples are close to the known absorption coefficients of solar radiation.

Table 1 shows the absorption coefficients of the studied materials, calculated using the average coefficient \( C \) over three calibration samples.

| Samples                        | Measured coefficients (effective spectrum) | Reference values (solar spectrum) |
|--------------------------------|--------------------------------------------|-----------------------------------|
| Copper textolite, white mask\( ^a \) | 0.21 0.96 | - - |
| Copper textolite, black mask\( ^b \) | 0.94 0.97 | - - |
| Copper textolite, red mask\( ^c \) | 0.51 0.88 | - - |
| Copper ground polished         | - 0.08 | - 0.07 |
| Photoconverter\( ^d \)         | 0.90 - | 0.86-0.91 0.84 |
| Polished silicon               | 0.63 - | 0.62 - |
| Polished aluminum              | 0.13 - | 0.1-0.15 0.05 |

\( ^a \) PSR-4000 H85, TAIYO INK,  
\( ^b \) IMAGECURE XV-501 Coates Electrografics Ltd,  
\( ^c \) Saturn PJSC [9].
2.2. IR emissivity coefficient measurement

IR absorption coefficients are measured by the calorimetric method [10, 11]. The measuring stand is an aluminum box B (figure 4). The surface of the box is sandblasted, anodized and painted black with aniline dye. The box is an octagonal prism which is put into a cylindrical vacuum chamber C to exclude heat transfer by gas. Thermal contact of the box with the chamber wall is provided through the adapter S (cylindrical segment) with a diameter equal to the chamber inner diameter. The contacting surfaces of the box, adapter, and chamber wall are covered with thermal grease. The pressure in the chamber was about $10^{-5}$ Torr and monitored by the sensor P.

Sample O is hung inside the box on two cotton threads. An ohmic heater R (thermostable resistor) and To electronic thermistor (DS18S20) are glued on the sample with heat-conducting sealant. The same two sensors Tw are mounted on the upper and lower walls of the box. Sensors and a resistor are connected inside the chamber with a vacuum connector by thin copper wires with a diameter of 65 microns in varnish insulation. To reduce radiation losses, the resistor and sensor are coated with aluminum foil (figure 5a).

The resistor is connected to a pA precision picoammeter (Keithley 2611B), operating as a current source and measuring power consumption. The required heating power of the sample was set by selecting the current. To determine the heat emission in the wires, the power released in the wire was measured depending on the current with a shorted-out resistor, the measured loss is not more than 3% of the heat generation in the resistor and is taken into account when measured results processing.

Before vacuum chamber closing, the measuring circuit was tested at atmospheric pressure, a thermal imaging camera was used to control of the sample heating uniformity (figure 5, b). For heat uniformity of the copper-plated laminate samples were made like a sandwich which consisted of two layers of laminate and a copper layer 0.5 mm thick between them glued with a heat-conducting sealant.

After aligning the sample and testing the measuring circuit, the heating of the sample is turned on and data reading from the sensors is started, then the chamber closes and pumping starts. The sample temperature ceases to change with decreasing pressure when the pressure reaches $10^{-4}$ to $10^{-5}$ Torr. Each measurement continues for several hours to ensure thermal balance. Equilibrium temperature was measured for five power values for each sample.

![Figure 4. Experimental set-up for IR emissivity measurements.](image)

Since the box size is several times larger than the sample, the infrared radiation of the sample multiply reflected from the box walls before it gets onto the sample again. Given that the box walls reflection coefficient is small, it can be assumed that the sample exchanges heat with a black body. Therefore, the sample heat loss of power due to infrared radiation is related to its temperature, according to the Stefan–Boltzmann law, by the following formula:

$$P_i = \sigma S \epsilon (T_S^4 - T_0^4),$$
where $\sigma$ – Stefan–Boltzmann constant, $S$ – area of the tested surface (coating or solder mask), $\varepsilon$ – grayness coefficient or in this case - IR emissivity, $T$ – sample temperature, $T_0$ – box temperature, $P_i = P - \Delta P$ – the difference between the power supply $P$ and the total heat power loss $\Delta P$.

Thus, the desired coefficient can be calculated as follows:

$$
\varepsilon = \frac{P - \Delta P}{\sigma S (T^4 - T_0^4)}.
$$

Here, in order to correctly calculate the value of $\varepsilon$, it is necessary to accurately calculate all the losses. Simple estimates of thermal conductivity show that losses through wires and threads are small compared to supplying power. Small but measurable power is released in the resistor power wires. It is also necessary to take into account the power loss through radiation from the sample’s surface, which is not covered by solder mask (the sensor’s surface, resistor, their leads, the ends of the PCB without a solder mask, etc.).

![Figure 5](image)

**Figure 5.** Photo (a) and thermogram (b) of a copper-plated PCB sample with a green solder mask placed in a test box in a vacuum chamber.

For PCB samples, the heat loss power was calculated as follows:

$$
\Delta P = P_{\text{wires}} + P_{\text{end FR4}} + P_{\text{end copper}} + P_{\text{probe}} + P_{\text{pins probe}} + P_{\text{res}} + P_{\text{pins res}} =
$$

$$
= P_{\text{wires}} + \sigma \cdot (T^4 - T_0^4) \cdot \sum_i \varepsilon_i \cdot S_i + \sigma \cdot ((T + \Delta T)^4 - T_0^4) \cdot \sum_j \varepsilon_j \cdot S_j
$$

To calculate, it is necessary to know the $S_i$, $S_j$ areas and IR emissivity factors $\varepsilon_i$, $\varepsilon_j$ of the corresponding surface areas. The areas of the sensor, resistor and their legs are calculated from the photo in relation to the sample’s size, the area of the end face of the board is calculated by direct measurement of dimensions. IR emissivity coefficients for the end of the board is taken equal to 0.95 (estimated by thermal imager), other coefficients are known. In addition, overheating of the resistor and its legs relative to the sample is taken into account, overheating is estimated by the thermal imager camera measurement.

The absorbed IR coefficients calculated under the described procedure are shown in table 1. It can be seen that the rough anodized and blackened surface of the box does have an emissivity close to unity. The emissivity for brushed copper corresponds to the reference value.

3. Thermal regime calculation model

3.1. Orbital motion

The calculation software is developed in MatLab Simulink. Standard equations for six degrees of freedom of motion in Earth-centered Earth-fixed (ECEF) coordinates are used to calculate ballistics. The EGM2008 gravity model is applied. The interface to visualize orbital motion (figure 6, a), orientation and insolation of a satellite has been developed (figure 6, b) for ease of use and debugging of motion calculation algorithms.
Initial coordinates, velocity vector and time when the motion starts are set as initial data. The program implements the position of the Earth and its illumination by the Sun, depending on the UTS time [12]. For simplicity, the calculation is made for the vernal equinox (figure 6, a).

The initial satellite orientation angles and its angular velocity components are set equal to zero (or random) since the module that rotates the satellite is included into the program. The module at each step of time calculation based on the specified pointing parameters, current satellite pointing and its angular velocity calculates the torque, which is transmitted to the motion equations block that calculates the new satellite orientation angles at the next time step.

Figure 6. Satellite motion (a), 3U CubeSat orientation, lighting and computational mesh (b).

The following orientation designations are used: $AbCd$ where $A$ and $C$ are vector of directions to objects in the surrounding space (to the Sun, nadir, ground antenna, etc.), $b$ and $d$ are vectors of specific satellite directions (unit vectors of axes of the body fixed coordinate system, vector of the solar panels maximum insolation, the camera’s optical axis etc.). In this case, the $A$ and $b$ vectors are fully aligned (priority 1), and the $C$ and $d$ vectors, are aligned if possible (priority 2). For example, $NxSp$ means the following: the satellite $x$-axis ($x$) is aligned with the nadir vector ($N$); the vector of the solar panels maximum insolation ($p$), whenever possible, is aligned with the Sun vector ($S$).

3.2. Insolation
The simplified 3D model consisting of one body is considered to be the initial data for calculating the satellite’s insolation. The model should reproduce the basic volumetric contours of the satellite, location, number and size of its photoconverters. Such a model is specially drawn in CAD (for example, SolidWorks) and exported in one of the standard formats (*.step or *.iges). Then the file is imported into the program for building computational mesh: Salome, AnSys Mesh, or others. The photoconverters and, if necessary, the remaining elements of the satellite’s structure are assigned unique names in the program. That allows grouping the elements of the corresponding structures in the calculation program. Then a mesh is constructed with a set specification consisting of triangular cells (figure 6, b). As a rule, the minimum required specification is used, since calculating of lighting is a resource-intensive computational task. The model’s geometry and the grid are saved in the standard *.msh format in the mesher software.

Then the grid file is loaded into the calculation program using the function given in [13]. In the program, the satellite grid model, as a set of vectors, is rotated within the selected coordinate system by the rotation matrix (DCM) synchronously with the satellite orientation calculation. The lighting of each (triangular) surface element is calculated depending on the satellite pointing and position in space.
corresponding to the Earth and the Sun, considering the surface element shading by neighboring satellite structures (figure 6, b).

In the calculation, the intensity of the solar radiation in the Earth's orbit assumed 1367 W/m². To calculate Albedo, the Earth grid model, similar to the satellite grid model, is loaded into the calculation program. For each element of the satellite surface, the radiation from all elements of the Earth grid model visible from the satellite is calculated.

3.3. Radiation heat transfer

A simplified thermal model has been used, in which the thermal conductivity of the satellite elements is not taken into account. That is, means that the thermal conductivity of the satellite elements is infinitely large.

Thus, the calculation program solves the following equation:

\[ \sum_i c_i \cdot m_i \cdot \frac{dT}{dt} = \sum_j S_j \cdot \alpha_j \cdot I_j + \sum_k S_k \cdot \epsilon_k \cdot J_k - \sigma \cdot T^4 \cdot \sum_n S_n \cdot \epsilon_n. \]

With its weight of 4 kg, of which the payload is 2.5 kg (aluminum ingot in this calculation), for the satellite body \( C_b = 3526.3 \) J/K, folding panels \( C_p = 119.2 \) J/K. The first term on the right-hand equation part is the sum of the powers absorbed by the elements illuminated by the Sun and Albedo, \( I_j \) is the light intensity on the \( j \)-th element surface. The second term is the sum of the powers absorbed by the elements illuminated by the heat of the Earth, \( J_k \) is the IR intensity on the \( k \)-th element surface. The third addendum is satellite IR radiation. The insolation calculation module for each position of the satellite, taking into account its orientation and self-shadowing, calculates the intensities of solar (including Albedo) and infrared radiation on each element of the surface.

The satellite’s surface consists of three materials: anodized aluminum, photoconverters, and PCB covered with a solder mask (table 1). Four options for PCB with different solder masks are considered - black, white, green and red with fixed optical coefficients for sulfuric anodized aluminum alloy 5052-H34 \( \alpha/\epsilon = 0.32/0.82 \) [14] and photoconverters \( \alpha/\epsilon = 0.90/0.92 \). In the case of transparent solder masks (green and red), it is believed that most part of the board is covered with copper polygons under the solder mask, which is advisable for efficient heat removal from the board to the satellite body frame.

For heat exchange, the satellite body and foldable panels are loosely connected, therefore their temperatures are calculated individually, but their mutual shading is taken into account. When calculating the satellite radiation, it is considered that the satellite surface elements radiation does not fall back onto the satellite surface. Such an approximation is admissible since the satellite’s geometry is not very complex, the maximum angle of mutual visibility of surface elements does not exceed 45°, and about 50% of the surface is smooth and emit IR quite directionally (photo-voltaic converters).

4. Calculation results and discussion

The satellite movement in a polar orbit 450 km high at various angles between the orbit plane and the direction to the Sun \( \beta = 0^\circ, 45^\circ, 70^\circ \) and \( 90^\circ \) is considered. The calculations were performed for two satellite orientations: SpVz — the best insolation and VzNp — orientation with a lower projection perpendicularly to velocity vector (figure 7, 8).

For the LEO, depending on the angle between the orbit plane and the direction to the Sun, the duration of shadow orbit part is reduced, and its maximum temperature increases, respectively. In the calculated case \( \beta = 90^\circ \), the satellite does not enter the shadow, its equilibrium temperature will be close to the maximum possible.

The amplitude of temperature oscillation will be the greater, the longer the satellite is in the Earth shadow, that is, the amplitude is maximum at \( \beta = 0^\circ \), and the thermal regime will be stationary for \( \beta = 90^\circ \) (in this calculation, it is a flight over the terminator line). The average value of the satellite in this orbit reaches its maximum value at \( \beta = 70^\circ \). In this case, the satellite still does not go into the shadow and absorbs a certain amount of Albedo radiation. For the considered satellite design, the PCB solder mask occupies 26% of the satellite body surface and 33% of the foldable panel’s surface.
Figure 7. Schemes of the considered satellite orientations (a). Dependences of the average temperature of the satellite’s hull on time for different angles $\beta$ (b).
Figure 8. Dependences of the average temperature of the satellite’s panels on time for different angles $\beta$ (b).

The area of anodized aluminum is 15% of apparatus body surface. The difference between a white and black mask is 12 W of absorbed solar power at the position of maximum insolation. For the stationary thermal regime $\beta = 90^\circ$, the mean temperature difference between satellites with a black mask and a white mask reaches 16°C. In the case of using a black mask at $\beta = 70^\circ$ and $90^\circ$, the temperature reaches 31°C. The temperature of the satellite with a red solder mask does not exceed 24°C. In the case of a white solder mask, the temperature does not exceed 15°C, which is acceptable (figure 7).

For angle $\beta = 0^\circ$, the largest amplitude as expected is achieved in the case of using a black solder mask ($\Delta T = 21^\circ$). The smallest amplitude is in the case of using a white mask, which makes 16°C.

Apparatus with the red masks have intermediate thermal regimes. It should be noted, the green mask provides a slightly larger maximum temperature at $\beta = 70^\circ$ and $90^\circ$ and satellite temperature fluctuations at $\beta = 0^\circ$ than the black mask (figure 7). This is observed because of the green PCB $\alpha/\varepsilon$ ratio is greater than that of a black one. However, in fact, this difference is not significant due to the measurement error of the optical coefficients.

Thus, despite the fact that the PCB area does not exceed 30% of the satellite surface, the difference in the average temperature over the body of satellites with black (or green) surfaces and white is a noticeable value of 16°C, and the amplitude of temperature oscillations is 5°C. For folding solar panels, these values are equal to each other and amount to approximately 20°C (figure 8). The temperature difference between the minimum and maximum temperature points along the satellite body can be
several tens of degrees. At satellite’s thermal regime designing, the choice of the external surface material, in particular, the type of PCB solder mask of the housing surface, can help to set an acceptable temperature range both for equipment inside the satellite housing and for elements mounted on external boards.

5. Conclusion
Methods for measuring the absorption coefficients of solar radiation and IR radiation are described. The coefficient values for PCB coated with different solder masks measured by these methods are given.

Based on the model of satellite orbital motion and insolation developed at Matlab Simulink, an algorithm for calculating the average temperature of the small satellite’s hull is implemented. Using the CubeSat 3U format satellite, with folding solar panels, developed by Novosibirsk State University as an example the average temperature of the satellite hull and panels was calculated using the measured optical coefficients.

It is shown that the choice of a PCB solder mask type forming the outer surface of a small satellite CubeSat type significantly affects the thermal regime of the satellite.

The best thermal conditions for this satellite configuration can be achieved if a white solder mask is used. In this case, the satellite hull mean temperature at orbits with constant insolation does not exceed 15°C, and at the LEO with the longest Earth shadow duration is in the range -13 - 3°C.

Acknowledgements
This work was supported by the Ministry of Science and Higher Education of the Russian Federation under Project RFMEFI57517X0154.

References
[1] ISO 17770:2017: Space systems - Cube satellites (CubeSats)
[2] M Swartwout 2018 Reliving 24 Years in the Next 12 Minutes: A Statistical and Personal History of University-Class Satellites
[3] CalPoly SLO 2014 CubeSat Design Specification Rev. 13 The CubeSat Program
[4] Gilmore D G 2002 AIAA, The Aerospace Press, ISBN 1-884989-11-X vol 1
[5] Gorev V N et al. 2019 IOP Conf. Ser.: Mater. Sci. Eng. 537 022079
[6] Technoexan LTD Precision silicon photodiodes Retrieved from http://technoexan.ru/en/products/sildet.php
[7] Vasiliev V N 2003 9th International Symposium on Materials in a Space Environment ESA Publications Division pp 699-701
[8] Palik E D and Potter R F 1985 Handbook of Optical Constants of Solids 1 804
[9] Saturn PSC Solar Arrays Retrieved from http://en.saturn-kuban.ru/production/solar-arrays/
[10] Millard J P and Streed E R 1969 A Comparison of Infrared-Emittance Measurements and Measurement Techniques Applied Optics 7(8)
[11] Richter W 1994 Calorimetric support of directional-hemispherical reflection measurements in the infrared spectral range Applied Optics 7(33)
[12] McCarthy D D 2011 Evolution of timescales from astronomy to physical metrology Metrologia 48 132–44
[13] Wouter 2013 MSH (fluent mesh) reader MATLAB Central File Exchange Retrieved from https://uk.mathworks.com/matlabcentral/fileexchange/44337-msb-fluent-mesh-reader
[14] Silverman E M 1995 Space Environmental Effects on Spacecraft: LEO Materials Selection Guide NASA Contractor Report 4661(2)