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ERROR INHERENT IN SIMULATING PLANETARY THERMAL EFFECT ON THE SPACECRAFT SURFACE BY USING ISOTROPIC PLANETARY RADIATION INTENSITY FIELD MODEL INSTEAD OF ANISOTROPIC

A.V. Kolesnikov
P.F. Pronina pronina-p19.94@yandex.ru
A.V. Paleshkin paleshkin.andrey@mail.ru

Moscow Aviation Institute (National Research University), Moscow, Russian Federation

Abstract

In order to mathematically simulate the thermal effect that radiation emitted by planets has on spacecraft, two intensity field models describing planetary radiation may be used depending on the emitter specifics: isotropic and anisotropic. The isotropic model is based on the assumption that the local surface density of outgoing radiation flux is the same for all surface regions visible from orbit. In the case of the anisotropic model this value is assumed to be proportional to the zenith angle cosine for each surface element on the side of the planet that is illuminated by the Sun. Published results of studies concerning developing planetary radiation field simulators indicate that thermal vacuum installations where the working volume is comparable to the total installation volume can only reproduce the sotropic planetary radiation intensity field model. It is a pressing issue to determine whether and when it is possible to replace the anisotropic model with an isotropic one when physically simulating the effect that the solar radiation reflected from a planet and intrinsic radiation flows generated by planets with no atmosphere have on spacecraft. The investigation that we conducted regarding this issue was based on comparing the results of computing the irradiance of spacecraft elements using the models under consideration. These computation results allowed us to conclude that it is possible to physically simulate the effect of solar radiation flows reflected from planets combined with intrinsic (infrared) radiation flows

Keywords

Planet, radiation, radiation intensity field model, spacecraft, heat flux, angle factor, radiation field simulation

generated by planets with no atmosphere by means of using simulators reproducing isotropic radiation fields in their working volumes

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Introduction. When speaking about the influence of radiation emergent from planets on the spacecraft (SC) thermal state, the term "planet" usually means not only planets of the Solar System, but also large natural satellites of those planets themselves, such as the Moon, Phobos, Deimos and others [1–4]. Radiation emergent from celestial bodies could be conditionally divided into two components: reflected solar radiation and intrinsic infrared radiation, which source is mainly the absorbed solar radiation. For the purposes of mathematical and physical simulation of this radiation effect on the thermal regime of near-planetary spacecraft, simplified models of planets are used, including those based on assumption of the diffusive nature of radiation emergent from the planet and on averaging radiation characteristics of its surface [5–9]. These models are rather approximately describing local (in space and time) radiation situations in the near-planetary orbits; nevertheless, they seem acceptable and expedient due to the following circumstances.

1. There is a wide uncertainty in the nature of dependence on direction and time of the planet local radiation characteristics.

2. Thermal inertia of the spacecraft external elements is in most cases so significant that it makes it possible to ignore the irregular nature of the planetary surface radiation characteristics alteration.

3. Hierarchical position of the system ensuring thermal regime is very significant; therefore, results of calculations and especially of experiments should be highly reliable. The applied planet models are attractive due to their simplicity; at the same time, it is possible within the framework of these models to determine such extreme values of the radiation intensity emergent from a planet in calculation or experiment that all the spacecraft elements are ensured with simulation of maximum and minimum probable thermal loads, which source is the planet radiation.

Depending on how the emergent radiation density is distributed over the planet surface, radiation intensity field in the orbit within the planet survey solid angle could be isotropic and anisotropic. According to the accepted models [1–3, 10], intensity field of the Earth and Venus intrinsic radiation is isotropic within the solid angle of these planets survey. In this case, radiation field of planets without any atmosphere is anisotropic, since in this case local radiation density emergent from the planet surface depends on the Sun zenith angle for each surface area. Anisotropy is also inherent in the intensity field of radiation reflected from planets.

Monograph [3] identifies in the study of issue on the prospects for solving the problem of physical simulation of the planet radiation anisotropic field fundamental and today seeming to be insurmountable difficulties in solving this problem. In this regard, the question of possibility and consequences of replacing the anisotropic model with an isotropic one remains relevant, and its reproduction could be carried out even in experimental installations with dimensions commensurable with dimensions of the test object [11] using the radiating systems positioned around it at a certain distance from its surface. [12, 13–17].

Methodical approach to solving the problem. Studying conditions, under which anisotropic model of the planet radiation intensity field could be replaced by the isotropic model in the experimental simulation of a spacecraft external heat exchange, should be based on comparing calculation results of the spacecraft elements irradiation using these two compared models.

When using the isotropic model, it is supposed that the local surface density of the radiation flux emergent from the planet (*E* value) is the same for all parts of the surface visible from orbit. In case of the anisotropic model, *E* on the sunlit side of the planet is proportional to the Sun zenith angle cosine for each surface element, i.e., proportional to the γ_S angle cosine between directions to the element under consideration and to the Sun from the planet center. This is illustrated in Fig. 1, where curve *1* characterizes the plot of the *E* value distribution over the planet surface for the isotropic model, and curve *2* — for the anisotropic model.

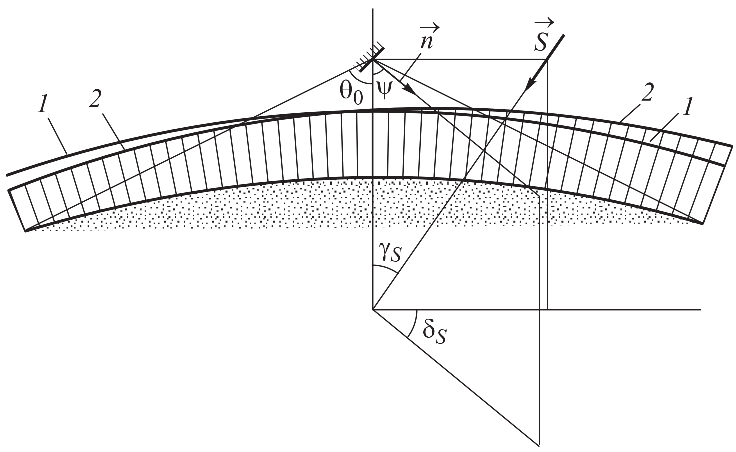

Fig. 1. Emergent radiation density distribution over the planet surface for isotropic (curve *1*) and anisotropic (curve *2*) models of the planet radiation intensity field

When using the isotropic model, density of the radiation flux incident on the spacecraft unshaded heat-receiving elements and emergent from the planet (q) is usually determined by the following expression:

$$q = E\phi_{i-pl},$$

where E is a constant value over the planet surface; ϕ_{i-pl} is the local slope of the spacecraft i-th element and the planet.

The local slope depends on orientation of the heat-receiving element relative to the planet surface and on the θ_0 angle value equal to the half-opening angle of the planet orbital survey cone. Moreover, $\theta_0 = \arcsin\left(R/(R+H)\right)$, where R is the planet radius and H is the orbit altitude. Heat-receiving element orientation is characterized by the ψ angle between the normal to the heat-receiving element and the local vertical directed to the planet center. The procedure for calculating the local slope as a function of the θ_0 and ψ linear angles is described in [1–3, 10, 18].

When using the anisotropic model, density of the radiation flux emergent from the planet and incident on the spacecraft unshaded heat-receiving elements is characterized by the following expression:

$$q^* = E_0\phi^*_{i-pl}, \quad (1)$$

where E_0 is the density of the radiation flux emergent from the sun lighted area of the planet surface, for which $\gamma_S = 0$; ϕ^*_{i-pl} is the so-called combined slope [1, 2], which is the function of four parameters: $\theta_0, \psi, \gamma_S, \delta_S$ is the angle between the vertical plane passing through the normal to the heat-receiving element and the vertical plane containing the vector directed to the Sun.

The method for calculating the combined slope is described in works [1, 2]. It follows from Fig. 1 that the approximate q value in low orbits could be determined using the following relation:

$$q = E_0\,\frac{(\cos\gamma_S + |\cos\gamma_S|)}{2}\,\phi_{i-pl}. \quad (2)$$

Introduction of relation (2) is based on the assumption of uniform distribution of the radiation density emergent from the visible region of the planet and equal to radiation density of the particular surface region, over which the spacecraft is currently positioned. The Δq errors of such an approximate simulation would depend on the θ_0, ψ, γ_S, δ_S four parameters noted earlier. By themselves, absolute errors could not be a visual characteristic of the difference degree between q and q^*. However, the $\Delta\overline{q} = (q - q^*)/q^*$ relative error value in this case, when the Sun zenith angle increases, and the q^* value tends to zero, could not serve as a basis for solving the problem of the possibility to replace the q^* value with the q value. It is advisable in such cases to analyze the dimensionless error behavior referring the Δq absolute error to a certain characteristic value, for example, to the maximum q^*, which appears at the considered parameter values θ_0 and γ_S, but with $\psi = 0$.

Let's analyze the $\Delta q^* = \dfrac{q(\theta_0, \psi, \gamma_S) - q^*(\theta_0, \psi, \gamma_S, \delta_S)}{q^*(\theta_0, \psi = 0, \gamma_S, \delta_S)}$ dependence on all parameters.

However, taking into account the nonlinear nature of the $\cos\gamma_S$ dependence on the γ_S angle, it could be noted that with an increase in γ_S in the range from 0 to θ_0 and with an increase in the δ_S angle in the range from 0 to π, the errors would increase. Therefore, it is advisable to focus on errors that occur at the γ_S angle close to θ_0 and at $\delta_S = \pi$.

On the planet side illuminated by the Sun, the Δq^* value taking into account the ratios (1) and (2), could be represented in the following form:

$$\Delta q^* = \frac{(\cos\gamma_S)\,\phi_{i-pl} - \phi^*_{i-pl}}{\phi^*_{i-pl}(\psi = 0)}. \qquad (3)$$

Analysis of the results of calculating the Δq^* dependence on the θ_0 and ψ parameters, would allow to identify conditions, which could make it possible to carry out an approximate experimental simulation of the Moon thermal radiation effect or of solar radiation reflected from planets on the surface of circumlunar or near-earth spacecraft.

Relations used to calculate slopes. In order to calculate local and combined slopes included in relation (3), the well-known method by V.M. Zaletaev was used [1, 2], according to which ϕ_{i-pl} and ϕ^*_{i-pl} are determined using the expressions presented below.

Local slope ϕ_{i-pl}:

$$\phi_{i-pl} = \begin{cases} \cos\psi\sin^2\theta_0 \quad \text{at} \quad 0 \le \psi \le \pi/2 - \theta_0; \\ \dfrac{\cos\psi\sin^2\theta_0}{\pi}[\pi/2 + \arcsin(\operatorname{ctg}\psi\operatorname{ctg}\theta_0)] - 1/\pi\cos\theta_0\sqrt{\sin^2\theta_0 - \cos^2\psi} + \\ + \dfrac{1}{\pi}\arcsin\left(\dfrac{\sqrt{\sin^2\theta_0 - \cos^2\psi}}{\sin\psi}\right) \quad \text{at} \quad \pi/2 - \theta_0 \le \psi \le \pi/2 + \theta_0; \\ 0 \quad \text{at} \quad \pi/2 + \theta_0 \le \psi \le \pi. \end{cases}$$

Combined slope ϕ^*_{i-pl}:

$$\phi^*_{i-pl} = f_2^*(\theta_0,\psi)\cos\gamma_S + f_3^*(\theta_0,\psi)\sin\psi\sin\gamma_S\cos\delta_S;$$

$$f_2^*(\theta_0,\psi) = \frac{f_2(\theta_0)}{\sin^2\theta_0}\phi_{i-pl}(\theta_0,\psi);$$

$$f_2(\theta_0) = \frac{1}{4}\left(1 + \sin^2\theta_0 + 2\sin^3\theta_0 + \frac{\cos^4\theta_0}{2\sin\theta_0}\ln\frac{1-\sin\theta_0}{1+\sin\theta_0}\right);$$

$$f_3^*(\theta_0) = \begin{cases} f_3(\theta_0) \quad \text{at} \quad 0 \le \psi \le \pi/2 - \theta_0; \\ f_3(\theta_0)\dfrac{\theta_0 + \pi/2 - \psi}{2\theta_0} \quad \text{at} \quad \pi/2 - \theta_0 \le \psi \le \pi/2 + \theta_0; \end{cases}$$

$$f_3(\theta_0) = \frac{\cos^2\theta_0(3 + \sin^2\theta_0)}{16\sin\theta_0}\ln\frac{1+\sin\theta_0}{1-\sin\theta_0} - $$

$$-\frac{(1-\sin\theta_0)(3 + 3\sin\theta_0 + 2\sin^2\theta_0)}{8}.$$

Analysis of the results of calculating the Δq^* dependence on parameters θ_0 and ψ. Results of calculating the dependence of the Δq^* maximum possible dimensionless errors on the $\theta_0 \in [60°;\ 90°]$ angle for a number of the $\psi \in [0;\ 150°]$ angle values are shown in the graphs in Fig. 2. Calculations are provided for values $\delta_S = 0,\ 90°,\ 180°$ and $\gamma_S = \theta_0$.

For convenience in analyzing calculation results, Fig. 3 presents the θ_0 dependence on the *H* orbit altitude for a near-earth spacecraft.

Results presented could serve as the basis for generating an opinion on probability and consequences of replacing in experimental simulation of the SC heat exchange conditions of the planet radiation intensity field the anisotropic model by the isotropic model.

For example, if the Δq^* dimensionless error not exceeding $0{,}1q(\theta_0, \psi = 0, \gamma_S, \delta_S)$ is taken as the acceptable errors in simulating $q(\theta_0, \psi, \gamma_S, \delta_S)$, then, as follows from the graphs presented, replacement of the planet radiation intensity field anisotropic model with the isotropic model is possible with simulating the near-earth SC irradiation up to the altitude of about 1000 km, which corresponds to the orbital altitude of 270 km for a circumlunar spacecraft.

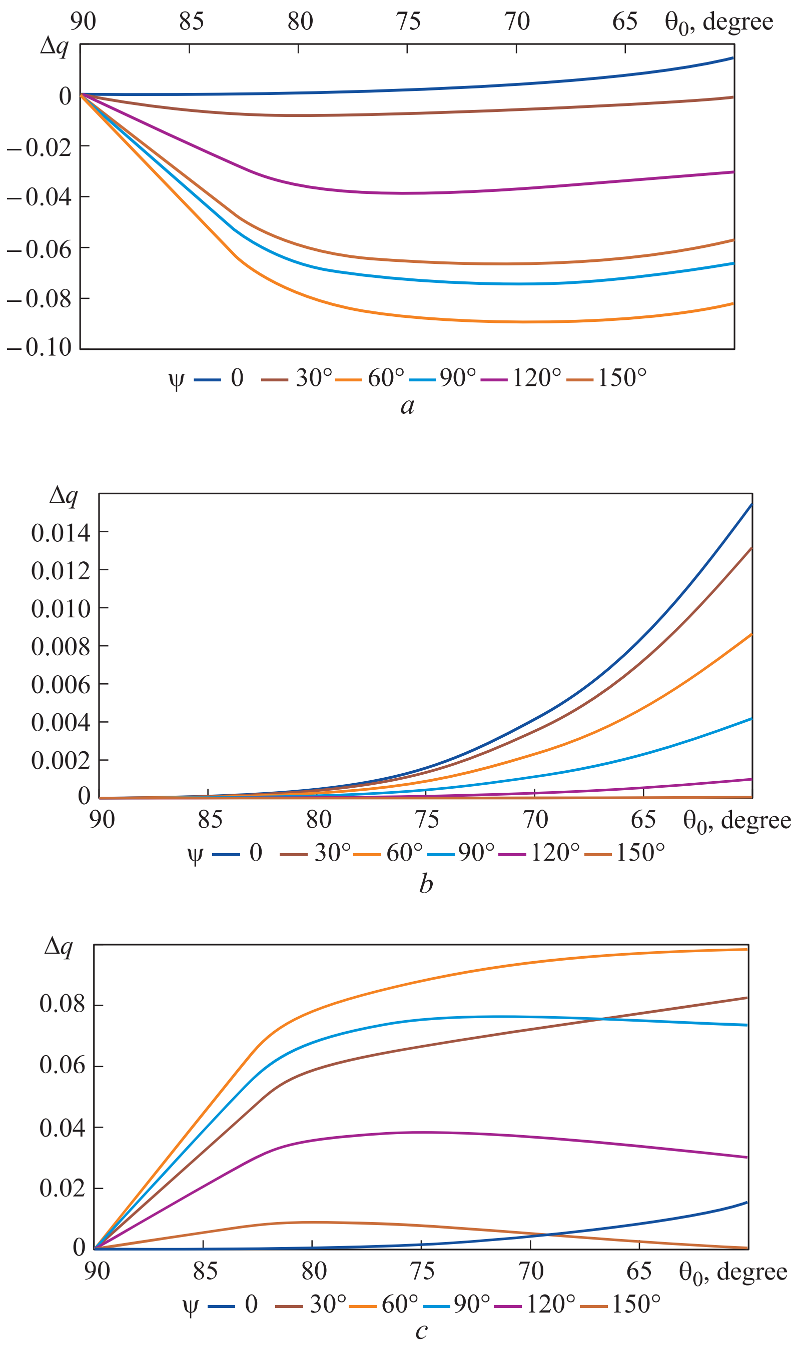

Fig. 2. Dependences of the Δq^{*} maximum probable errors of a spacecraft elements heat-receiving irradiation on the θ_0 angle with replacing the radiation field anisotropic model by the isotropic model $\delta_S = 0$ (*a*); 90° (*b*); 180° (*c*)

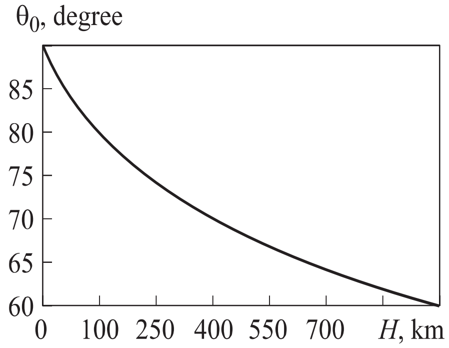

Fig. 3. Dependence of the θ_0 angle on the *H* near-earth orbit altitude

It should be noted that primarily for these relatively low near-planetary orbits, the problem of experimental simulating the radiant heat fluxes from planets stays relevant, since at high altitudes the influence of planetary radiation on the SC thermal state is insignificant compared to exposure to direct solar radiation.

Conclusion. Comparison of the results of calculating the SC elements irradiation by the radiation flux emergent from planets using anisotropic and isotropic models of the radiation intensity field provides the basis for recommendations regarding methods of simulating the impact on SC of solar radiation reflected from planets and of intrinsic thermal radiation of planets.

Possibility of replacing the planet radiation field anisotropic model with the isotropic model appears to be a prerequisite for elaboration of an effective technique for numerical simulation of the SC elements irradiation from the arbitrary external surface by the radiation flux emergent from planets, namely, a technique based on replacing the planet surface visible from orbit with a simple isothermal surface (for example, a disk) enclosed in the planet solid viewing angle.

Physical simulation could be carried out introducing the methods used to simulate an isotropic field, but radiation intensity emergent from the radiation simulator elements should be changing over the time in accordance with the law of Sun zenith angle cosine alteration for those planet surface areas, over which the SC is currently positioned.

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Kolesnikov A.V. — Dr. Sc. (Eng.), Professor, Senior Research Fellow, Department of Operation Management of Aerospace Systems, Moscow Aviation Institute (National Research University) (Volokolamskoe shosse 4, Moscow, 125993 Russian Federation).

Pronina P.F. — Post-Graduate Student, Department of Operation Management of Aerospace Systems, Moscow Aviation Institute (National Research University) (Volokolamskoe shosse 4, Moscow, 125993 Russian Federation).

Paleshkin A.V. — Cand. Sc. (Eng.), Assoc. Professor, Department of Operation Management of Aerospace Systems, Moscow Aviation Institute (National Research University) (Volokolamskoe shosse 4, Moscow, 125993 Russian Federation).

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