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POSSIBLE USES OF EQUIPMENT IN SPACE TO CONTROL EARTH SURFACE ILLUMINATION

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ABSTRACT

The article reviews research and development from Russian and beyond into the use of equipment in space to control illumination of the earth surface. The main engineering challenges associated with structural selection, opening and completion of space reflectors and screens are described. Preliminary estimates of what constitutes an excessive level of illumination, impacting humans and other living organisms are given. Some technological and economic issues associated with the creation of the control systems for the illumination of the earth's surface are presented. A need of additional studies of conditions for people living in the illuminated regions is substantiated.

Keywords: the Sun, orbital illumination, reflector, screen, solar-and-sailing ship, light pollution, ecology

1. INTRODUCTION

Significant consumption of hydrocarbon fuel for electricity generation to power external illumination during the night time (NT) and associated changes in the climate are among the main global environmental challenges.

Both these challenges can be addressed using space equipment to change the illuminance of earth's surface. Reflectors and opaque screens can be placed in the Earth's orbit and at libration points[1] of the Earth – Sun and Earth – Moon systems. This proposed technology assumes that some rare engineering problems can be resolved. For instance, there is currently no comprehensive and versatile evaluation of the potential consequences of a change in the light situation. The purpose of this article is to analyse engineering challenges associated with using space equipment to control illumination of earth's surface and likely indirect consequences for ecology and vital human functions.

2. REVIEW OF PROJECTS TO CONTROL ILLUMINATION OF THE EARTH'S SURFACE FROM SPACE

The Sun's light can be used for external illumination at night in some regions. The light can be directed using systems of space vehicles (SV) with reflectors located in an Earth orbit, Fig. 1. The use of such space reflectors was proposed at the beginning of the 20th century by astronautic pioneers Yu.V. Kondratyuk and G. Obert.

Orbital illumination can be especially important for transpolar regions, which experience the polar night phenomenon, as well as in areas where natural disasters and emergencies have occurred.

In the late 1960s, an orbital illumination system project intended for military and civil applications was published in the USA [1].

These proposals were further developed in the 1970s within the Space Light programme proposed

[1] In libration points (Lagrange points), a third body, which is only affected by gravitation forces from two other massive bodies can remain fixed relative to these two bodies

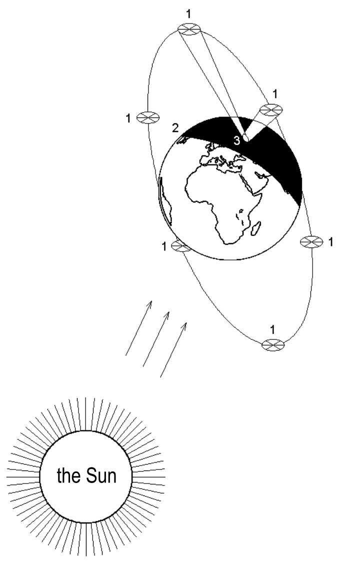

Fig. 1. A system of orbital illumination: ***1*** **–** space reflectors; ***2*** **–** terminator (light partition line); ***3*** **–** illuminated region

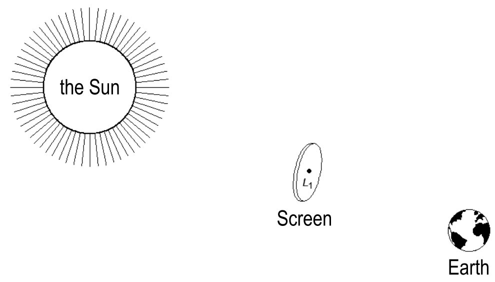

Fig. 2. A screen in the Earth-Sun system libration point used to reduce insolation of the earth surface

by K.A. Ehricke [2], which envisioned placing several systems of space reflectors in Earth's orbit. Taking into account these and other similar projects, a system of orbital illumination for the territory of the USA and adjacent states (densely populated industrial regions, Alaska, and Panama Channel) was developed using reflectors which would total 780,000 m^2 in area (NASA research centre, Langley) [3].

Since the late 1980s, the problem of global climate change has become more and more apparent. In order to slow the greenhouse effect, a method to reduce the solar radiation flow reaching the earth's surface by 2 % by using a screen 2000 km in diameter placed at the Earth – Sun system libration point *L1* has been put forward, Fig. 2 [4].

In research from Russia in 1992 [5], a similar structure is described with a variable transparency. The system consisted of modules, which can adjust screen plane inclination relative to the direction of solar radiation.

Instead of a monolithic screen, 800,000 autonomous small SV screens can be also used to lower solar radiation by 1.8 %, with a general weight of $2.0 \cdot 10^7$ t (the USA, 2006) [6]. The main problem associated with this system is the control of such a large number of objects and their subsequent utilisation.

In Russia, a large programme of work was undertaken to create space equipment for the control earth's surface illumination.

In 1992–1993, a system of 100 space reflectors (called SV reflectors) totalling 30,000 m^2 in area was developed together with the Research centre of M.V. Keldysh for orbital illumination of subpolar cities located at a geographic latitude of 70 ± 2° in the Northern hemisphere (Murmansk, Norilsk) [7, 8].

In 1994, the Znamya-2 (Banner-2) experiment was conducted, which opened out a film reflector with aluminium coating under space flight conditions [9].

In 2009–2013, proposals were published to create a space system to adjust the temperature condition of the earth's atmosphere intended to address power and climate issues [10, 11]. The basis of this system is a solar-sailing ship (SSS) located at the libration points of photo gravitation field[2] of Earth-Sun or Earth-Moon systems. SSSs allow reducing or increasing atmospheric temperature by changing the illumination of the earth's surface by the sun. Aluminium foil is used in their production, which would be manufactured using resources from the moon.

At present, there is no industrial experience of producing space equipment at the described scale and size for the proposed structures. Therefore, a number of critical technological issues need to be resolved to enable their creation.

3. THE MAIN ENGINEERING CHALLENGES ASSOCIATED WITH THE DEVELOPMENT OF LARGE-SCALE SPACE REFLECTORS AND SCREENS

The main structural requirements for an SV reflector structure is a stabile geometry and the ab-

[2] In a photo gravitation field, the influence of gravitation forces and of sunlight pressure is accounted for.

sence of any folds or overlaps. It is also important to decrease the mass and design an effective and reliable opening mechanism for the reflector under space flight conditions.

One of the most encouraging designs uses a frameless structure for the reflectors formed by centrifugal forces. However, although their mass is low, at present, frameless structures do not provide the required accuracy of surface configuration, which is required for maintenance, are influenced by the Coriolis force during reorientation and require damping of oscillations from gyroscopic forces [8].

Vibrations the SV reflector can cause reflector oscillations, which in turn can displace the light beam relative to the illuminated region (a deviation of 2′ corresponds to a light spot shift of 1 km). Therefore, SV reflectors require exact stabilisation.

The SV reflector's turn can be controlled relative to its own centre of gravity due to gyroscopic effect. Therefore, project [7] selected a rope ring flywheel design, which allowed reducing the mass of the construction.

However, the problems connected with active damping of nutation oscillations of the rotating sail and of the rope flywheel, as studied in [12], are not yet resolved. Therefore, only an original design gyro flywheel can be used in practice.

To keep SV reflector operational under space flight conditions, it was suggested that the metal coating cold be deposited by means a correspondent unit and with a reserve of the deposited material onboard [7]. But for now the technology for automatic metal coating deposition onboard is not yet available. Therefore, there is a need for further study of keeping SV reflectors optical properties during their long ground storage in the context of space technology already available today.

Safe keeping of the film and of the reflector coating under the influence of external conditions during space flight is a significant unknown, which can be only checked by long flight tests.

SSSs will be the most large-scale space construction in the history of humanity: the screen's diameter will be of (1500–1960) km, and its mass will be of about $5.6 \cdot 10^7$ t [10, 11]. Therefore, besides the described challenges of creating SV reflectors, there is a need to develop control methods for a structure of such mass and dimension.

To incorporate the impacts of a working SSS structure in lighting calculations, all factors influencing the final result should be accounted for. The influence of a darkening effect of the Sun disc edge on decreasing its radiation flow by means of SSSs has been studied, and it has been shown that to reduce the solar constant by 0.50 %, an SSS of 1500 km (instead of 1690 km) in diameter placed at the centre of the Sun disc is sufficient [13].

Compared to studies of the technological aspect of developing space screens and reflectors, research into the potential indirect impacts of a changing light situation on global ecology and its vital functions for humans is less developed.

4. A PRELIMINARY EXPLORATION OF ECOLOGICAL IMPACTS OF EARTH SURFACE ILLUMINATION CHANGE

Evaluating the ecological impact of excessive illumination created by SV reflectors and SSS is closely related to the study of light pollution created by artificial light sources in cities and industrial areas.

It follows from the study of light pollution [14–17] that the use of artificial illumination during the night time can violate photobiological reactions of different living organisms, including people.

In studies [14.18.19], it is recommended that radiation sources with a high concentration of blue light portion (0.44–0.48) μ are applied with care at night.

Some organisms use celestial bodies to orient in space [20, 21]. At present, this biological mechanism is insufficiently researched. Therefore, it is difficult to estimate the influence upon it of changing external illumination.

A weak UV radiation in the UV-B interval (0.28–0.32) μ is critical for many organisms. Annual cycles of this radiation in the mid and high latitudes can be considered to activate season migrations and sleep of some animals [22].

One more important aspect of the potentially changing the natural light situation it the light polarisation of celestial bodies in the atmosphere. Light pollution is created by unpolarised radiation of land-based light sources, which additionally complicates orientation of some live organisms [23]. Thus, illumination using SV reflectors would be closer to natural.

In study [24], characteristics of the reflectors and safety of orbital illumination system SV reflector operation were analysed. Reflectors with alumini-

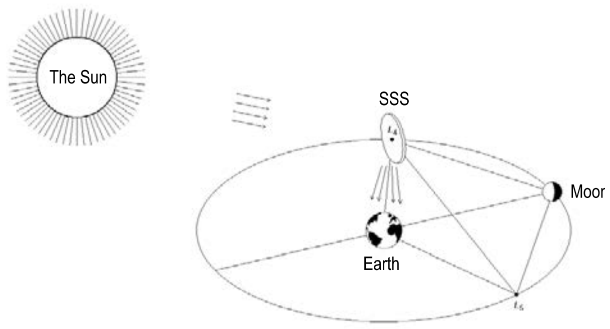

Fig. 3. Placing an SSS in the Earth-Moon system ***L4*** libration point

um, silver, titanium, gold and copper coatings were considered.

A calculation of the correlated colour temperature showed that optimal visual perception by an operator at night is achieved with gold or copper reflector coatings.

In article [25], an analysis of spectral characteristics of reflected solar radiation for the five reflector coatings mentioned above is performed. To decrease reflected UV-B radiation level, reflectors with silver coating are suitable, and to decrease both it and the light blue portion level (0.44–0.48) μ, reflectors with copper or gold coatings can be used.

Spectral characteristics of the Sun's reflected radiation for different metal coatings of SV reflectors are given in Table 1.

Evaluation results [24, 25] suggest that the load on visual organs of an operator and undesirable ecological exposure can be reduced by using different metal reflector coatings depending on the local time of day in the illuminated region of the earth's surface.

An important operational safety concern for orbital illumination systems is the constant control of the earth surface illumination level. Therefore, there is a need for the possibility to quickly turn off the reflectors from the earth surface's to recover natural illuminance level.

By their level of environmental impact, SSSs considerably surpass orbital illumination systems. Operating one of the proposed SSS designs assumes a decrease of earth surface illuminance by 0.5 % [10.11], which is enough to control atmospheric temperature mode. To ensure safety, the possibility of quickly return to natural levels of illumination needs to be envisioned.

The structure with weakening adjustment proposed in [5] is complex because of a large number of moving parts and final control elements. Therefore more likely, a reliable and quick recovery of natural illumination is only feasible by an emergency dismantling of the SSS structure.

There is no unity of opinion concerning trends and reasons of earth climate in the scientific community, as well as concerning anthropogenic contribution to this process. Besides the widely known and discussed hypothesis of global warming, there is a counterhypothesis of global cooling. Quantitative evaluations of the contribution of each factors determining earth climate are approximate [26].

So any artificial exposure on the climate should lead to its unpredictable and irreversible changes.

For this reason, the SSS design for strengthening illumination of the earth surface was examined in detail [11].

It has a two-way reflecting surface 1960 km in diameter and is placed in libration points *L4 or L5* of the Earth-Moon system, Fig. 3.

Table 1. Characteristics of the Sun's reflected radiation for different metal coatings

	Metal coating				
	aluminium	**silver**	**titanium**	**copper**	**gold**
Correlated colour temperature, *K*	5200	5180	5130	3655	3650
Total illuminance in spectral interval of (0.36–0.83) μ, lx*	7.2	7.6	4.7	5.2	6.1
Irradiance in spectral interval of (0.28–0.38) μ, mW/m^2*	1.8	1.4	1.1	0.7	0.7
Irradiance in spectral interval of (0.44–0.48) μ, mW/m^2*	4.3	4.4	2.7	2.1	2.0

* Under clear atmosphere conditions

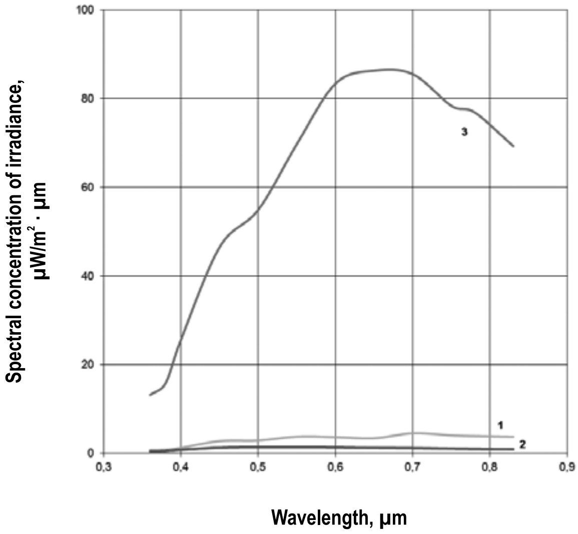

Fig. 4. Radiation spectra for the full Moon (1), SSS (diffuse component) (2) and for a SV reflector with reflector copper coating (3)

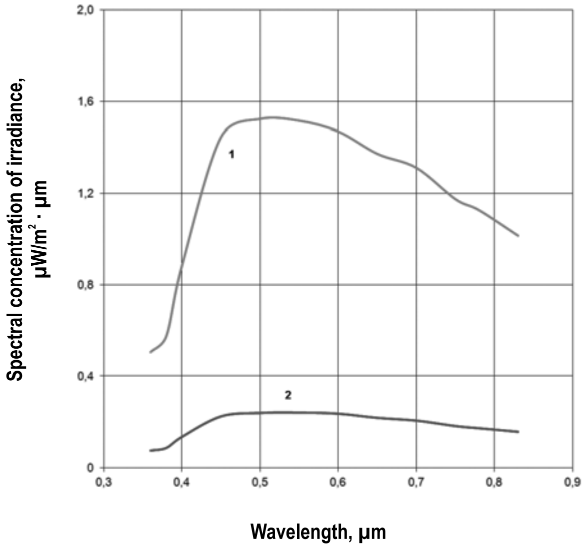

Fig. 5. Radiation spectra for the Sun (1) and SSS (a specular component) (2)

An evaluation of earth surface irradiance from this SSS [27] shows that:

1. The reflected UV radiation is not a direct risk for people, and special measures to protect against it are not required.

2. The irradiance in the UV and in the visible spectrum intervals is excessive during the night time (as it exceeds natural illumination by 5–8 orders of magnitude in the case of specular reflexion). As to the radiance, the SSS observed from Earth, will be comparable with the Sun and the Moon.

3. The spectrum of the reflected radiation can create discomfort for the operator's work during night time.

The calculation results for the illuminance from an SSS are given in Table 2.

Fig. 4 allows to estimate the spectra of visible radiation for full Moon, SV reflector with copper coating and SSS (diffuse component) under clear atmosphere conditions, and in Fig. 5 visible radiation spectra for the Sun and SSS (specular component) under the same conditions are presented.

When opening orbital illumination and SSS systems, the influence of illumination change on ozone formation processes in the atmosphere and related weather changes should be also investigated [13].

A final assessment of light exposure modes can be only made from the results of real tests.

It should also be stated that in order to understand negative impacts on nature and people, long term exposure is required, just as it has occured with light pollution in big cities and industrial areas.

Thus, space experiments of short-term irradiation of the earth's surface by low-power flows of reflected radiation of the Sun are not dangerous for people and nature.

After the safety boundaries for earth's surface illumination change are determined, an engineering and economic analysis of developing the space equipment for these projects should be carried out.

5. ENGINEERING AND ECONOMIC ASPECTS OF DEVELOPING ORBITAL ILLUMINATION SYSTEMS AND SSS

In the near future, developing orbital illumination systems will be associated with the operation of new super-heavy carrier rockets capable of placing several SV reflectors into orbit from one start.

The results of research (2013) performed at the University of Pennsylvania show that the development of orbital illumination systems will be economically practical once the cost of placing objects into orbit drops to within several hundred dollars per kilo of payload [28].

To produce the reflectors, there are two types of polymeric films currently manufactured which are most suitable by their physical and mechanic characteristics, as well as their production availability: polyethyleneterephthalate (PETF, mylar) and polyimide (PM-1EU, kapton) [7, 8, 28].

Table 2. Illuminance and irradiance from the SSS of a reflector 1960 km in diameter located at libration points of *L4 or L5* of the Earth-Moon system (under clear atmosphere conditions)

Factor	Value
Correlated colour temperature, *K*	5200
Total illuminance in a spectral interval of (0.36–0.83) μ, lx: specular component diffuse component	 $1.7 \cdot 10^4$ 0.1
Irradiance in a spectral interval of (0.28–0.38) μ, W/m^2*	4.2
Irradiance in a spectral interval of (0.44–0.48) μ, W/m^2*	10.1

* Specular component

Aluminium, titanium and copper are widely used in space equipment production. Therefore, it will not be difficult to use these materials in manufacturing SV reflectors. The high cost of gold and silver coatings could be a limitation to production, but according to a proposed concept [24, 25], reflectors of different material types should be used together in orbital illumination systems. Therefore, gold and silver coatings would only need to be applied to a part of the reflectors.

Developing orbital illumination systems will lead to changes of living and working conditions for a large number of people. So, besides ecological impacts, social, psychological and medical aspects of the design should be also studied carefully.

An evaluation of the influence of illumination change on the daily life of people, on their work and rest modes, on domestic and industrial room structure and on the length of time spent outdoors is necessary. As there is a connection between some social phenomena and the length of the light day and Moon phases, theoretical a possible influences of changes in illuminance on behaviour of different social groups, on number of law offences, frequency of mental illmess, etc. among the population of the illuminated regions should be investigated.

An in-depth study of the influence of external illumination on the photobiological reactions of different living organisms could suggests that there are wide opportunities for intentional exposure for the benefit of the economic activity of people. Fundamentals of developing a technology of light ecosystem control are formed, as well as of creating favourable conditions for the life and work of people.

This technology could increase the efficiency of marine and land organisms, control their migration, create unfavourable conditions for harmful and dangerous organisms in the illuminated areas. At the same time, a light situation can be created which would increase work efficiency, improve life, prevent diseases and mental disorders.

Article [2] describes a system of orbital illumination, which could control climate and increase agricultural efficiency over large areas of the earth's surface (so-called Biosoletta). The system of orbital illumination currently under consideration [7, 8] covers a circular region 15–17 km in diameter, which ensures greater ecological safety in comparison with the Biosoletta.

Within a limited region, different light exposures can be applied to living organisms, without the risk of global ecological consequences.

Light channels of exposure on the ecosystem have the following advantages compared with other instruments (chemical, radiation, etc.): zero lag control, universality, comparatively low risk (negative impacts only arise in cases of long exposure).

As to the SSSs, it should be noted that to operate them in the libration points of Earth – Moon or Earth – Sun systems, the development of the Moon would need to be advanced: building there a permanent base with the associated infrastructure and creating an assembly production in circumlunar space. In such case, the power should be enough to produce SSS structure elements of opaque glass [4] or aluminium foil [10, 11] obtained on the moon surface.

Construction of SSSs made of nickel iron from asteroids resources [5] is a more complex challenge for the present.

From the engineering point of view, a detailed study of the structural solutions used in the SSSs and of the methods of their opening at orbit is necessary.

A final question is the decommissioning of space equipment, which has exhausted its life time.

Termination of SV reflectors and SSS operation

It has been proposed to take end of life SV reflectors of the orbital illumination system [7, 8] to a higher orbit for burial by means of partly keeping solar sail properties of a reflector.

Concerning SSSs, it should be stated that the problem of decommissioning large-scale space structures placed higher than a low Earth orbit has no practicable solution at present.

The big mass of an SSS creates risks of control loss for such a huge structure. Thus, a constant or periodic presence of the crew on-board to control and maintenance the working capacity is required.

Upon completion of its life time, it was planned to return the SSS to the assembly production [10], however, big mass reserves make it possible to have material resources necessary for its periodic repair, and a gradual mass consumption can be compensated by a gradual delivery of the "ballast" using different space transport systems. This suggests that in principle such structures have a long life time.

From the point of view of operation safety, an SSS structure made up of separate sections is preferable. Taking into account the big mass of the SSS, safety measures can include technological solutions, which enable the quick dismantle and dissolution of the structure's elements (for example, using pyrotechnic technologies).

For a the quick decommissioning of reflectors with a large area, one technique of interest is that initially proposed for the burial of radioactive waste in space [29]. These proposals were developed further within a concept of an SV engine system using the recovered material (space debris) as a fuel [30]. Use of this technology allows de-escalating the reflector and simultaneously controlling the SSS movement (for example, to direct its trajectory to the assembly production).

CONCLUSION

The presented review describes the current international level of space equipment development for earth surface illumination control. Evaluations of excessive illumination and its influence on people and other living organisms are presented, an engineering and economic aspect of development of earth surface illumination control systems is described, and a need of further studies of possible indirect consequences of a change in the light situation change is substantiated.

Further studies should determine the practicability of orbital illumination and adjustment of earth surface insolation use by means of SSSs taking into account the risks of climate change and their possible consequences.

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