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CHARACTERIZATION OF REFLECTED LIGHT FROM THE SPACE POWER SYSTEM

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The development and operation of a Space Power System would place very large structures in orbit around earth for several decades. Sunlight reflected off such structures, particularly specular components from large flat areas, is expected to create ground illumination that will attract observers. In order to assure that this illumination does not exceed the irradiance tolerances of the eye, reflections from these satellites must be carefully controlled by vehicle orientation and surface specifications. The solar power satellite (SPS) at geosynchronous altitude (GEO) has 55 km^2 of glass covered solar cells that are oriented normal to the sun, as well as a 1 km^2 microwave antenna. Transportation of construction materials from low earth orbit (LEO) to GEO requires 23 Orbit Transfer Vehicles (OTVs) that have 1.6 km^2 solar panels oriented normal to the sun during their 6 month transits. The Staging Base (SB) at LEO, that accommodates OTV fabrication and cargo transfer, consists of 0.5 km arms protruding from a .44 km^2 open grid aligned with its orbit plane. Diffuse reflections would make the SB/OTVs readily discernible in the daytime and the OTVs and SPSs observable all night (except during eclipse). Sporadic specular glints would appear on the ground from the OTVs and SPSs near the midnight meridian, from the solar panel surfaces of OTVs during LEO fabrication, and from OTVs near LEO at dawn and dusk. The ground level irradiance has been evaluated for several unusually bright configurations using the Baseline System Design. For example, the present microwave antenna on SPS produces ground irradiance comparable to that from the full moon during operations around the equinoxes. Various modifications in the design and operation are suggested to reduce the brightness of these reflections.

Characterization of Reflected Light from the Space Power System

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Limited terrestrial energy sources have led to investigation of Space Power Systems that would collect solar energy and beam it via microwaves to power stations on the ground. The Baseline System[1] consists of a Staging Base (SB) in low earth orbit (LEO), a fleet of Orbit Transfer Vehicles (OTVs) for movement of supplies from LEO to geosynchronous earth orbit (GEO), and assembly and operation of Solar Power Satellites (SPSs) in GEO. All of the structures would be very large in comparison with today's satellite sizes, and include large plane surfaces to collect solar energy.

Due to the enormous size of these spacecraft and their assembly vehicles, they may be viewed routinely by large numbers of ground observers. The brightness of sunlight reflections off various components changes markedly as the vehicles rotate along their trajectories. Many surfaces will undoubtedly be coated with optically diffusing material, but the present baseline configurations also include large flat areas that are specular such as glass, polished metal, and smooth composites. Owing to the large size, relatively low altitude (at LEO), and/or specularity, some reflections will be exceptionally bright.[2]

The level of ground illumination and particularly the concentration of radiant energy in observer's eyes needs to be assessed. For the most part, reflections will appear to ground observers as very bright starlike points of light in relatively dark night sky. Since contraction of the iris is controlled by overall illumination levels, the eye pupil may accept more light energy than desirable from these point sources, and produce abnormally high image irradiance at the retina. If the brightness of baseline vehicles exceeds accepted limits for eye safety, certain constraints on reflectivity of surfaces and the orientation of vehicles are the most likely procedures that would lower ground illumination.

This study reported in detail elsewhere[3] has evaluated the components of the various Space Power System vehicles as presently defined to determine the reflectances which will significantly contribute to the ground illumination.

The calculation of reflected solar intensity from the various satellite system elements requires description of the elements and description of the geometry of potential reflectance paths. To reduce the calculation to a tractable problem only the nominally flat element surfaces were considered since the curved surfaces spread the light making their contribution negligibly small at the large orbital distances. Each surface is further defined by its approximate reflectivity and an estimate of its "flatness". In addition to determining that a surface is likely to reflect a significant intensity, it is also necessary to determine the conditions under which it will illuminate a portion of the earth. The orientation of each reflecting surface is therefore also necessary, so a number of convenient coordinate systems have been used.

The SPS at GEO has 55 km^2 of glass covered solar cells that are oriented normal to the sun, as well as a 1 km^2 microwave antenna. Transportation of construction materials from LEO to GEO requires OTVs that have 1.6 km^2 solar panels oriented normal to the sun during their 6 month transits. The SB at LEO, that accommodates OTV fabrication and cargo transfer, consists of 0.5 km arms protruding from a .44 km^2 open grid aligned with its orbit plane.

In determining possible ground illumination geometries, two cases are considered: 1) the reflecting surface rotates in orbit such that its orientation to the earth is constant (e.g., the satellite antenna), and 2) the orientation of the reflection surface to the sun is constant (e.g., the satellite solar arrays).

The ground irradiance produced by specularly reflected light from Space Power System spacecraft is given by[4]

$$H_s = \kappa N_\odot \frac{r_s\, a \cos(\alpha/2)}{R^2} \frac{\sigma^2}{(\rho + \sigma + \tau)^2}$$

where κ is the degradation due to atmosphere and/or instruments, $N_\odot = 2.0 \times 10^7$ watts/ster-m^2 is the average visual disk radiance of the sun, r_s is the specular reflectance of surfaces, a is the area of the surface in m^2, α is the angle between the incident and reflected rays, R is the distance from the SPS subsystem to the earth in meters, σ is the angle at the SPS subtended by the solar disk, ρ is the diffraction limit for coherent reflection from an element of SPS area δa m^2, and τ is the angular divergence of the solar image due to the fact that the reflectors are not optically flat mirrors.

The ground illumination from sunlight reflections off the Space Power System spacecraft have been evaluated for a variety of configurations, orientations, and operational conditions, that are thought to produce the brightest irradiances. A summary of ground irradiance levels that have been calculated is presented in the accompanying table.

The diffuse cases are all relatively bright in comparison with stellar sources. For example, the SPS in GEO casts an order of magnitude more light than Venus at its brightest. The OTV/SB combination in LEO is visible during daylight hours but, of course, is at too low an altitude to be illuminated at night.

The specular cases cited in the table produce much brighter ground illumination. However, this irradiance is restricted to small, fast moving spots. The actual duration of these "glints" of specular reflections varies from about one second for the OTV/SB in LEO to two minutes for the SPS antenna. An important consideration is the sudden onset of the specular irradiance compared to the much dimmer diffuse irradiance. Enhancements of 10^5 are common. An exceptionally bright specular reflection is produced by the backside of the OTV solar panels during LEO construction. Although perfectly flat solar panel surfaces are assumed as worst cases for the OTV and SPS, more realistic situations are represented by the curved or misaligned surfaces that are also analyzed.

These worst case conditions in the table have ground irradiance levels that may exceed acceptable limits. Evaluation of the ocular irradiance levels that correspond to these ground irradiance levels is required to completely assess the reflection limitations that will be imposed on the Space Power System. Nevertheless, it is prudent to consider options for reduction of reflected sunlight from these vehicles. Possible methods for reducing reflections fall into three major categories.

Vehicle Orientation. Since the major ground illumination is produced by large flat surfaces on the OTV and SPS, it is appropriate to inquire about reorienting the vehicles to direct specular reflections away from earth. Since solar power collection falls with the cosine of the tilt angle, for example, an 8° tilt of the solar panels causes a 1% power loss, but specular reflections are shifted 16° off the sun-earth direction.

Surface Curvature. Most of the large surfaces that produce strong reflections are nominally flat in the Baseline Design. In practice, however, the vehicles are expected to flex under thermal and propulsion loads causing some misalignment of flat elements. Intentional misalignment of large solar panels is also feasible. Both conditions will spread specular reflections and reduce the local intensity of ground irradiance by distributing the light over a larger area. For example a 5° misalignment results in a 100-fold reduction in ground irradiance.

Surface Quality. The Baseline Space Power System Design includes many surfaces that have specular characteristics in visible light. This surface quality can be altered for some of the applications without affecting the serviceability of the element. For example, the surface of the SPS antenna is an electrical ground plate that presently is polished aluminum; but its electrical properties at the microwave frequencies of interest would not be affected by surface roughening (etching) on the scale size of visible wavelengths to create a diffuse reflector.

Clearly there are options available to reduce ground irradiance from sunlight reflections off the Space Power System spacecraft. How effective they would be and how practical they are for overall performance and cost remains to be assessed.

1. Satellite Power System, Concept Development and Evaluation Program, Reference System Report, U. S. Department of Energy, Office of Energy Research and National Aeronautics and Space Administration, October 1978.

Solar Power Satellite, System Definition Study, Phase I Final Report, Contract NAS 9-15636, Boeing Aerospace Company Document D180-25037-3, April 1, 1979.

2. Livingston, L. E., "Visibility of Solar Power Satellites From the Earth", Johnson Space Center, NASA JSC-14715, February 1979.

3. Tingey, D. L. and H. B. Liemohn, "Characterization of Reflected Light from the Space Power System", Boeing Contract Report D180-25923-1 to Argonne National Laboratories, March 1980.

4. Liemohn, H. B., "Optical Tracking of Deep-Space Probes", ICARUS: International Journal of the Solar System, Vol. 9, No. 1, July 1968.

Summary of Ground Irradiance

Case	Condition	Midday M Dawn/Dusk D Night N	Range km	Irradiance W/m^2
Controlled Orientation - Worst Case Geometry				
Diffuse 1	OTV/SB in LEO	M	910	3×10^{-4}
2	SPS in GEO	N	35,700	1×10^{-5}
3	OTV Powered Near LEO	D	2,570	4×10^{-6}
4	OTV at 2 R_e	D	11,000	2×10^{-7}
	4 R_e	N	24,700	5×10^{-8}
Specular 1	OTV/SB in LEO around solstices	M	910	
	flat front solar panels			1.2
	flat back aluminum			19
	misaligned front (1.5°)			0.1
	misaligned back (1.5°)			2
2	SPS solar panel in GEO around equinoxes	N	35,700	
	flat surface			0.03
	misaligned surface (5°)			0.0003
3	SPS antenna in GEO around equinoxes	N	36,000	0.01
4	OTV Powered Near LEO	D	2,570	0.19
5	OTV at 2 R_e	D	11,999	0.01
	4 R_e	N	24,700	0.002
Out of Control Orientation - Worst Case Geometry				
Specular 6	OTV in LEO	D	500	56
7	SPS in GEO flat back aluminum	N	36,000	0.4