March 30, 2026

Marlene H. Dortch, Secretary
Federal Communications Commission
45 "L" Street, NE
Washington, D.C. 20554

Re: ICFS File No. SAT-LOA-20250701-00129
Application for Authority to Construct, Launch, and Operate a Non-Geostationary Orbit Satellite in the Space Operation, Space Research, and Earth Exploration Satellite Services (filed August 1, 2025)

Reply of DarkSky International, PEER, Dinah Bear, Esq. and John Fitzgerald, Esq. to Consolidated Opposition and Response to Comments of Reflect Orbital Inc.

Dear Secretary Dortch:

DarkSky International ("DarkSky") (formerly the International DarkSky Association), Public Employees for Environmental Responsibility (PEER), Dinah Bear, Esq. and John Fitzgerald, Esq. respectfully submit this reply in response to the Consolidated Opposition and Response to Comments ("Response") of Reflect Orbital Inc. ("Reflect Orbital") regarding its application to the Federal Communications Commission ("FCC" or the "Commission") for a license to construct, launch, and operate a non-geostationary orbit ("NGSO") prototype reflective satellite ("EARENDIL-1" or an "Orbital Mirror") in the space operations service ("SOS") and space research service ("SRS"). We do so because of the enormous potential of the Space Mirror and similar satellites to alter permanently the human environment and our experience of the night sky, and the necessity of the FCC of complying with the National Environmental Policy Act (NEPA) and other relevant law prior to making a decision on this application.

INTRODUCTION

As an initial matter, DarkSky notes with interest the Applicant's assertion that it "shares DarkSky's overarching objectives" regarding the preservation of the night sky. It is a novel proposition to suggest that the best way to protect the darkness is to sell it to the highest bidder for conversion into "on-demand" daylight. While we appreciate the Applicant's stated desire to collaborate, the fundamental nature of this project—which seeks to monetize the orbital reflection of sunlight onto a sleeping planet—is a direct contradiction of those shared

objectives. To date, "collaboration" has consisted of high-level meetings that have yielded no binding technical mitigations or modifications to the application. Reflect Orbital has offered no automated "keep-out" zones for dark sky places or astronomical observatories, nor have they addressed the "diffuse radiation" and "skyglow" that will inevitably impact observers outside the primary target area. We must clarify for the record that professional courtesy and dialogue is not a substitute for the rigorous environmental and safety protections required by federal law.

In its response, Reflect Orbital principally asserts that the proposed launch of EARENDIL-1 should be categorically excluded from review under NEPA while also briefly arguing that NEPA does not apply to the action at all. As part of this comment, we petition the FCC under 47 C.F.R. § 1.1307(c) to remove the application from its default categorical exclusion and require preparation of, at a minimum, an environmental assessment.

THE NATIONAL ENVIRONMENTAL POLICY ACT APPLIES TO THIS APPLICATION

Reflect Orbital argues that the effects of the FCC's decision are located entirely outside of the jurisdiction of the United States and therefore, the decision is outside the scope of NEPA.[1] Yet the very purpose of this project is to shine light on earth and we can find no indication that the company plans to exclude the United States from their potential operation of EARENDIL-1. We do note that Reflect Orbital "understands and appreciates" that applications for larger deployments in the future might trigger the need for NEPA compliance[2] thus underscoring that its real focus is on whether the effects of this particular proposal should or should not be categorically excluded.

THE FCC SHOULD REQUIRE, AT A MINIMUM, PREPARATION OF AN ENVIRONMENTAL ASSESSMENT (EA) PRIOR TO MAKING A DECISION ON THIS APPLICATION

Reflect Orbital states in their response that comments filed by PEER and individuals and another comment "insist that the Commission must require Reflect Orbital to submit an environmental assessment before acting on the Application" because there are no regulatory standards regarding reflectivity from spacecraft.[3] That is not accurate in regards to PEER's letter. Our letter made no reference to that issue, nor would it affect the applicability of NEPA. NEPA requires agencies to assess the impacts of a proposed action in the context of the specific circumstances and aspects of the human environment that would be affected, regardless of whether a particular effect is regulated under another law. Just because a particular effect may fall within quantitative regulatory parameters, an agency is not excused from assessing the real life effects of an action. As one federal court of appeals explained in an opinion dealing with a proposed molybdenum mining operation in Nevada:

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[1] 42 U.S.C. § 4336e (B)(10)(vi) ("The term 'major Federal action' does not include . . . exterritorial activities or decisions, which means agency activities or decisions with effects located entirely outside of the jurisdiction of the United States . . ." (emphasis added).

[2] Reflect Orbital response, p. 13.

[3] Reflect Orbital's response, p. 8.

> Eurkea Moly argues that the FEIS' air impacts analysis is nonetheless adequate because it relies in part on the fact that the NDEP's Bureau of Air Pollution control issued a Clean Air Act permit for the project. This argument evinces a misunderstanding of the nature of NEPA and its relationship to 'substantive' environmental laws such as the Clean Air Act. [cite omitted]. The failure to explain the zero baseline assumption frustrated the BLM's ability to take a 'hard look' at air impacts, and the reference to the Project's Clean Air Act permit did nothing to fix that error.[4]

Indeed, compliance with NEPA, including interagency and public involvement, for actions with effects regulated by other laws can assist in identifying reasonable alternatives and/or appropriate mitigation measures to achieve a particular goal.

Second, Reflect Orbital suggests that critical commenters are invoking NEPA only as a roadblock, not because it is a genuine issue. Were that the case, of course, those same commenters would also logically be filing a petition to deny the application. Reflect Orbital seems unwilling to believe that information and analysis – even if it does not dictate an outcome as a matter of law – can inform decisionmaking. But, facts matter and science matters and NEPA is a law designed to shine a bright light (something the applicant should appreciate) on a proposal before a decision is made. That is the motivation underlying the arguments in our initial comments and it remains so today. Further, it is frankly a bit puzzling that Reflect Orbital objects so strenuously to preparation of an EA when it maintains that concerns expressed by commenters "are being considered, studied, and incorporated" into its technology.[5] If that is so, preparation of an EA should not only be welcome but also not be that burdensome of an undertaking.

Reflect Orbital argues that its application should remain under the FCC's default categorical exclusion because its application focuses on only a single satellite that would shine "*natural* light"[6] on the environment and that EARENDIL-1's light would amount to no more than moonlight when perceived on earth.[7] But while the source of the light – the sun – is natural, the timing of that exposure, by the very nature of this proposed project, and other elements of the project are not. Indeed, there is considerable concern and evidence that the effects of this unnaturally timed stream of light would be quite different than a person or other living being would experience in normal moonlight at a normal time.[8] Furthermore, just because an effect may have "natural" components, it does not render an effect beyond the scope of NEPA's consideration.[9]

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[4] *Great Basin Resources Watch v. BLM*, 844 F.3d 1095, 1103-04 (9th Cir. 2016).
[5] Reflect Orbital's response, p. 14.
[6] *Id*. at 5.
[7] *Id*. at 17.
[8] *See* discussion of Photobiological Hazard and Public Safety Issues, *infra* at p. 6.
[9] *See, e.g.,* Massachusetts Institute of Technology, "Environmental Risks of Mining" (2016) ("Hardrock mining exposes rock that has lain unexposed for geological eras. When crushed, these rocks expose radioactive elements, asbestos-like minerals, and metallic dust." https://web.mit.edu/12.000/www/m2016/finalwebsite/

Reflect Orbital acknowledges concerns about astronomical observations and the enjoyment of dark skies, but believes they are either irrelevant to a single satellite launch or have been dealt with or will be dealt with in some unspecified manner. Other concerns such as effects on ecological issues or changes in circadian rhythms are labeled "secondary" although it is not clear why all such effects would all be secondary.

Reflect Orbital makes the superficially appealing argument that the application for this single launch should be categorically excluded because this launch will help them study real-world effects and mitigate unintended or undesired side effects. Or more bluntly, they are not certain of what the effects will be. That is quite understandable but it is a reason for the FCC to require an EA, not an excuse for not doing one. The EA should make use of reliable data sources that do exist and ensure that the assessment of potential effects comports with scientific integrity by reflecting both what is known and what is not known about the potential effects of the project.[10] Arguing for launching the satellite first and doing the analysis later makes a mockery of the process. As the D.C. Circuit Court of Appeals has explained:

> In passing NEPA Congress emphasized its particular concern with the role of new technologies and their effects on the environment. . .. The legislative history reveals an underlying concern with "[a] growing technological power far outstripping man's capacity to understand and ability to control its impacts on the environment.' One of NEPA's main functions was to bolster this capacity to understand and control the effects of new technology.[11]

To be clear, that does not mean and never has meant that no action can be approved unless there is perfect knowledge about the effects. NEPA has always been interpreted in the "light of reason" and "not to demand what is, fairly speaking, not meaningfully possible."[12] But NEPA does require some degree of forecasting and an indication of what environmental effects are essentially unknown.[13] Again, from the D.C. Circuit Court of Appeals:

> An agency need not foresee the unforeseeable, but by the same token neither can it avoid drafting an impact statement simply because describing the environmental effects of and alternatives to particular agency action involves some degree of forecasting. . . . It must be remembered that the basic thrust of an agency's responsibilities under NEPA is to predict the environmental effects of proposed action before the action is taken and those effects fully known. Reasonable forecasting and speculation is thus implicit in NEPA and we must reject any attempt

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[10] 42 U.S.C. 4332 § (D) (E).

[11] *Foundation on Economic Trends v. Heckler*, 756 F.1d 143, 147 (D.C. Cir. 1985); *see also*, *National Parks Conservation Ass. v. Babbitt*, 241 F.3d 722, (9th Cir. 2001) ("The Park Service proposes to increase the risk of harm to the environment and then perform its studies . . . This approach has the process exactly backwards."

[12] *Scientists Institute v. AEC* 481 F.2d 1079, 1092 (D.C. Cir. 1973

[13] *Id*.

> by agencies to shirk their responsibilities under NEPA by labeling any and all discussion of future environmental effects as 'crystal ball inquiry.'[14]

While there obviously is no available documented, peer reviewed literature about effects of this experiment on the lands, waters and population of the United States, there is considerable evidence related to some lighting effects that provide a basis for the type of reasonable forecasting required under NEPA. To take just one example, it has long been known that artificial lighting is highly disruptive to natural sea turtle behavior and especially to nesting females and hatchlings. The Florida Fish and Wildlife Conservation Commission and the U.S. Fish and Wildlife Serviced initiated a statewide sea turtle nesting survey in 1979,[15] resulting in the promulgation of a state statute and numerous county ordinances as well as technical guidance to help mitigate the problem.[16] The body of research generated by this robust effort could surely help inform the FCC and the public about potential affects from Reflect Orbital's proposal as well as any possible mitigation measures. All six sea turtles in American waters are listed as threatened or endangered.[17] Thus any harm to them would likely be a violation of the ESA unless covered by a well-documented incidental taking statement. That process must begin with a Biological Assessment and those are often done in conjunction with an EA under NEPA.

Since it is clear that NEPA applies to the FCC's decision process for this proposal, the issue becomes what level and what type of NEPA analysis is required. As we explained in our initial comment letters, reliance on FCC's overly broad categorical exclusion is inappropriate. With no information about the planned geographic focus of EARNEDIL-1's voyage, we assume that its operation has the potential for affecting wilderness areas and wildlife preserves,[18] threatened and endangered species, critical habitat, and cultural and religious sites of significance - all factors included in the FCC's list of categories that require at minimum, an environmental assessment.[19]

We also note that even if the FCC somehow decides the proposal would not have an impact on any of these categories, the FCC's regulations provide for interested persons to allege that a particular action, otherwise categorically excluded, will have a significant environmental effect that overwhelmingly justifies and necessitates environmental consideration in the decision-making process. We therefore petition the FCC to remove the action from a categorical exclusion and under 47 C.F.R. § 1.1307(c) to require the preparation of, at minimum, an EA.

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[14] *Id*.
[15] https://myfwc.com/research/wildlife/sea-turtles/nesting/monitoring/
[16] https://myfwc.com/conservation/you-conserve/lighting/ordinances/
[17] https://www.fisheries.noaa.gov/sea-turtles#:~:text=Six%20species%20are%20found%20in,feeding%20grounds%20and%20nesting%20beaches.
[18] *See, e.g.,* U.S. Fish and Wildlife Service, "Dark Skies Initiative," https://www.fws.gov/project/dark-skies-initiative; National Park Service, Management Policies, Lightscape Management, Section 4:10 (2006), https://www.nps.gov/orgs/1548/upload/ManagementPolicies2006.pdf
[19] 47 C.F.R. §1.1307(a)(1)-(5).

We further note that the FCC can, under its own authority, determine that the proposal may have a significant environmental impact and require the applicant to prepare an EA.[20] Of course, any applicant-prepared NEPA analysis supporting either an EA or an EIS must be independently evaluated by the FCC.[21]

We also urge the FCC to consider the appropriate timing of a programmatic environmental impact statement for Reflect Orbital's proposed services – if not for this one satellite, certainly very soon. Reflect Orbital's website states that after a planned launch of 36 satellites in 2027, they hope to get approval for a thousand satellites by 2028 with 50,000 satellites projected by 2035. Reflect Orbital believes that they will learn more with each launch, and therefore the FCC should just let them be until they – or others – have documented the effects of, in their words, "launching the future of sunlight."[22] The sooner the FCC – preferably working with the Federal Aviation Administration, NASA, the U.S. Fish and Wildlife Service, the National Park Service and the National Oceanic and Atmospheric Administration and DOD components – launches its own comprehensive NEPA evaluation of the effects, the better – and in the long run, should its venture prove useful and not harmful – the better for Reflect Orbital.

PHOTOBIOLOGICAL HAZARD AND PUBLIC SAFETY

DarkSky submits a new technical hazard analysis (see Appendix A) conducted by Dr. Eric Bretschneider. This analysis demonstrates that EARENDIL-1 poses a direct physical risk to the public that has not been disclosed by the applicant.

According to IEC 62471:2006 standards, EARENDIL-1 would be classified as a Risk Group 3 (High Risk) light source if it were terrestrial. Because the orbital mirror acts as a point source—visually 100,000 times smaller than a full moon—it concentrates light onto a microscopic area of the human retina. At the applicant's claimed intensity of 5x moonlight (14.23 mW/m2), the irradiance is nearly six times greater than that of a 5 mW laser pointer at one mile. Under 18 U.S.C. § 39A, directing such light at aircraft is a federal felony due to the risk of temporary or permanent ocular impairment. Reflect Orbital has identified no mechanism to warn the thousands of households within a 5 km "target zone" before illumination begins, creating an unmitigated safety hazard for anyone looking skyward during an "event."

Analysis regarding the ramifications of this impact on both human and wildlife optical impairment also needs to be included in the FCC's NEPA analysis. The policies laid out in the statute itself clearly encompass health:

> SEC. 2. The purposes of this Act are: To declare a national policy which will encourage productive and enjoyable harmony between man and his environment; to promote efforts which will prevent or eliminate damage to the environment and biosphere and stimulate the health and welfare or man; to enrich the understanding

[20] 47 C.F.R. §1.1307(d).
[21] 42 U.S.C. § 4336a (f).
[22] https://www.reflectorbital.com/

> of the ecological systems and natural resources important to the Nation; and to establish a Council on Environmental Quality.[23]
>
> (b) In order to carry out the policy set forth in this Act, it is the continuing responsibility of the Federal Government to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs and resources to the end that the Nation may— (2) assure for all Americans safe, healthful, productive, and esthetically and culturally pleasing surroundings;
>
> (c) The Congress recognizes that each person should enjoy a healthful environment and that each person has a responsibility to contribute to the preservation and enhancement of the environment.[24]

The U.S. Supreme Court has recognized that human health impacts are within NEPA's scope in the sometimes misinterpreted decision of *Metropolitan Edison Co. V. People Against Nuclear Energy.*[25] Plaintiffs lost their case not because the Court viewed health – even psychological health – as being outside of NEPA's purview, but because, "If a harm does not have a sufficiently close connection to the physical environment, NEPA does not apply."[26] Plaintiffs failed to convince the Court of such a connection in that case.

THE "PATHFINDER" AND INTENDED USE

Reflect Orbital argues that concerns regarding a 50,000-satellite constellation are premature. However, the Commission's Public Interest mandate requires an evaluation of the intended use of the spectrum and orbital authority being granted. Reflect Orbital's public business model and stated goal of 50,000 satellites by 2035 cannot be decoupled from this initial license. Granting a "pathfinder" license without establishing optical emission standards would set a dangerous regulatory precedent, essentially allowing the applicant to "pollute first and study later."

VALIDITY OF PUBLIC CONCERN

Reflect Orbital attempts to dismiss the volume of public comments by highlighting the use of a template letter. This dismissive stance ignores the fact that the template represents a unified consensus among thousands of citizens, amateur astronomers, and ecotourism operators who are rightfully alarmed by the prospect of "on-demand" sunlight. The uniformity of these

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[23] 42 U.S.C. § 4321.
[24] 42 U.S.C. §4331.
[25] 460 U.S. 766 (1983).
[26] *Id*. at 778. For more on NEPA and human health effects, *see* National Research Council (US) Committee on Health Impact Assessment. Improving Health in the United States: The Role of Health Impact Assessment. Washington (DC): National Academies Press (US); 2011. PMID: 22379655, ch. 4 and Appendix A.

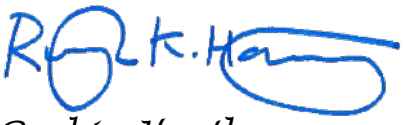
concerns underscores the "significant impact" of the proposal on the human environment, further necessitating a full Environmental Assessment.

CONCLUSION

The Commission must not allow a regulatory vacuum to exist regarding the optical output of satellites. Rather, this proposal must be analyzed as a photobiological safety risk and a potential significant environmental impact under NEPA, including the risks to health and well being in the human environment. The EARENDIL-1 mission requires a level of scrutiny that the applicant has thus far attempted to bypass. We urge the Commission to grant our petition to remove this action from categorical exclusion and require, at minimum, the preparation of an EA.

Attached: Appendix A, E. Bretschneider, Ph.D., *Photobiological Hazard Analysis of Orbital Solar Reflects.*

Timothy Whitehouse, Esq.
Executive Director
Public Employees for Environmental Responsibility
www.peer.org



Ruskin Hartley.
Chief Executive Officer
DarkSky International
www.darksky.org

John Fitzgerald Esq.
John Fitzgerald is a member of the District of Columbia bar, and has served as Counsel to a house subcommittee, Counsel for Defenders of Wildlife, and Policy Director for the Society for Conservation Biology. He helped negotiate the convention on biological diversity and served on the board of the Endangered Species Coalition. He currently serves on the boards of other conservation groups.

Dinah Bear, Esq.
Dinah Bear is a member of the District of Columbia bar and former Deputy General Counsel and General Counsel for the Council on Environmental Quality (1981-1993; 1995-2007).

John moved to rural Maine in part to enjoy the night sky which allows us to see the stars better than any place we have ever lived and for the lack of glare and the quiet of the nights here in Sedgwick on the Bagaduce river where waterfowl and upland birds are plentiful as we are on a tidal river near the ocean.

Dinah moved to Arizona in large part because of the vast swath of public lands there. She is particularly concerned about the impact of lighting on the biological cycles of all living beings, including the health effects on humans and a variety of adverse effects on wildlife and vegetation, such as the effect of nighttime lighting on migrating birds and important pollinators here in southern Arizona.

Attached: Appendix A, E. Bretschneider, Ph.D., *Photobiological Hazard Analysis of Orbital Solar Reflects.*

Appendix A

Photobiological Hazard Assessment of Orbital Solar Reflectors

E. Bretschneider, Ph.D.
CTO EB Technology & Consulting
eric@led.expert

Technical Report: Photobiological Hazard Assessment of Orbital Solar Reflectors

Prepared by: Eric Bretschneider, Ph.D.
EB Technology & Consulting
27 March 2026

I. Executive Summary

This report details a photobiological hazard assessment of the general concept of Orbital Solar Reflectors (OSRs). A recent proposal, Reflect Orbital's proposed Earendil-1 satellite is used as an exemplar. The analysis was conducted following IEC 62471:2006 Photobiological Safety of Lamps and Lamp Systems. OSRs are intended to provide primary or supplemental lighting and thus a photobiological safety assessment should be a prerequisite to launch and operation. The assessment demonstrates that in general OSRs pose a significant photobiological risk to persons at ground level and would be classified as Risk Group 3 and would require significant warning and safety considerations before deployment.

II. Introduction

The ocular hazards associated with unprotected viewing of an eclipse proximal to totality are well known.[1,2,3,4] The high intensity and high levels of illuminance provide some inherent degree of protection from sunlight due to maximal constriction of the pupil and discomfort and aversion reflexes. However, during an eclipse, only a fraction of the sun is visible resulting in significant reduction in illuminance and dilation of the pupils. This minimizes or reduces aversion reflexes which mean that the solar surface can be directly imaged on the retina for extended periods of time. Additionally, there are no pain receptors in the retina so there is no conscious indication of damage.

[1] Bradley, Arthur and Peabody, Todd. "Ocular Hazards Associated with Eclipse Viewing." (2023).

[2] Atmaca, L. S., Idil, A., and Can, D. "Early and Late Visual Prognosis in Solar Retinopathy." (1995)

[3] Mainster, M. A. "Solar Eclipse Safety." (1998)

[4] Thanos, S., Heiduschka, P., and Romann, I. "Exposure to a Solar Eclipse Causes Neuronal Death in the Retina." (2001)

Orbital Solar Reflectors (OSRs) are large reflective surfaces in orbit above the earth that are expressly intended to reflect sunlight towards the earth for supplemental lighting.[5] Even at the lowest orbital altitudes OSRs subtend visual angles significantly smaller than the sun. The sun subtends a visible angle of 0.52°. While a 100 m OSR in an implausibly low 500 km orbit would subtend a visible angle of 0.011°. The difference in apparent size between the sun and this hypothetical OSR would be more than a factor of 2000x. Both would have similar surface brightness and viewing the OSR would be similar to viewing a solar eclipse just before or just after totality.

III. Reflect Orbital: Earendil-1

Reflect Orbital has proposed to launch an OSR (Earendil-1) into a low earth, sun synchronous orbit for the express purpose of providing lighting on demand. The nominal solar reflector dimensions are 18 m x 18 m and the orbital altitude is specified to be 625 km.

Reflect Orbital has marketed their services as providing "precise and uniform" lighting that is "highly localized". However, they also admit that the illuminated area will be 5 km in diameter.

Reflect Orbital has also claimed they will be able to provide ground level illuminance at up to 5x moonlight. The maximum illuminance under a full moon is 0.32 lux, thus Reflect Orbital intends to provide illuminance levels up to 1.6 lux.

Moonlight by default is considered safe and illuminance at 1.6 lux falls within the mesoscopic range. The most significant difference between moonlight and the light provided by an OSR is the perceived size of the light source.

A full moon subtends an angle of 0.52° (2.59×10^{-4} sr) while Reflect Orbital's OSR would subtend an angle of 6 arc-sec (2.66×10^{-9} sr). While 1.6 lux is a low lighting level, the light would be delivered from a point source at is visually almost 100,000x smaller than a full moon. A human at ground level looking at Reflect Orbital's proposed OSR would experience maximum retinal irradiance levels many times higher than looking directly at the sun.

[5] Canady, Janet and Allen, J.L. "Illumination from space with orbiting solar-reflector spacecraft." (1982).

At issue is the fact that during the day, the illuminance levels from sunlight are high enough that the pupil is maximally constricted and would have a diameter of about 3 mm. In contrast, the illumination levels from Reflect Orbital's OSR would be in the mesoscopic range and the pupil would be maximally dilated and have a diameter of about 7 mm. The overall difference in maximum retinal irradiance is approximately a factor of 5x higher for Reflect Orbital's proposed OSR than staring directly at the sun.

A previous report concluded that an OSRs posed a hazard to viewers when viewed through binoculars or telescopes.[6] The conclusion that OSRs posed a hazard is notable as the authors assumed a low optical efficiency and also estimated a larger spot size on the ground. Given these facts, the hazard associated with Reflect Orbital's proposed OSR is greater than this estimate. Notably, Laframboise and Chou assumed a ground level irradiance for direct sunlight of 678.03 W/m^2 which is significantly below the accepted AM1.5 solar irradiance of 971.94 W/m^2.[7] Laframboise and Chou also used a slightly lower reflectance for aluminum and the combination of these factors resulted in an underestimation of the retinal irradiance by more than 30%.

It is however noted that using the assumptions of Laframboise and Chou along with the Earendil-1 dimensions, orbital altitude and illumination area results in a maximal retinal irradiance for a naked eye observer that is more than 5x higher than reported by Laframboise and Chou and thus would clearly pose a significant (ocular) safety hazard.

It is also noted that the report of Laframboise and Chou relied on retinal irradiance to determine hazards and did not consider the possibility of photochemical damage.[8] Indeed, Laframboise and Chou predated standard methods to determine photobiological safety of lamps and light sources which considers the spectral irradiance delivered by a light source as opposed to the integrated irradiance. This report refines the hazard analysis and estimates photobiological hazards of an OSR as defined by IEC 62471.[9]

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[6] Laframboise, James G. and Chou, Ralph. "Space Mirror Experiment: A Potential Threat to Human Eyes." (2000).

[7] G173-03 "Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface." (2021).

[8] Wu, J., Seregard, S., and Algvere, P. V. "Photochemical Damage of the Retina." (2006)

[9] IEC 62471:2006 "Photobiological Safety of Lamps and Lamp Systems." (2008)

IV. Delivered Light Analysis

NASA has studied the concept of orbital solar reflectors and determined nominal performance parameters based on reflector dimensions and orbital altitude.[10] However, for brevity and simplicity, Reflect Orbital's stated operational and performance parameters are used in this study. The differences in illuminated area and photobiological hazard are not sufficient to change the conclusions of this study.

The AM1.5 spectrum is used as a baseline for sunlight as it accounts for atmospheric absorption and scattering. The AM1.5 solar spectrum[11] corresponds to an irradiance of 971.94 W/m^2 and an illuminance of 109,495.65 lux. It is noted that the actual irradiance is 43% higher than assumed by Laframboise and Chou who admitted some degree of conservatism in their calculations.

Reflect Orbital has proposed to use an aluminum-based reflector. It follows that the ground level spectral irradiance from Earendil-1 would be the product of the AM1.5 spectrum and the spectral reflectance of aluminum.[12] This equates to an effective irradiance of 896.61 W/m^2 and an effective illuminance of 100,807.94 lux.

[10] Canady, Janet and Allen, J.L. "Illumination from space with orbiting solar-reflector spacecraft." (1982).

[11] G173-03 "Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface." (2021).

[12] CRC Handbook of Chemistry and Physics. (1992)

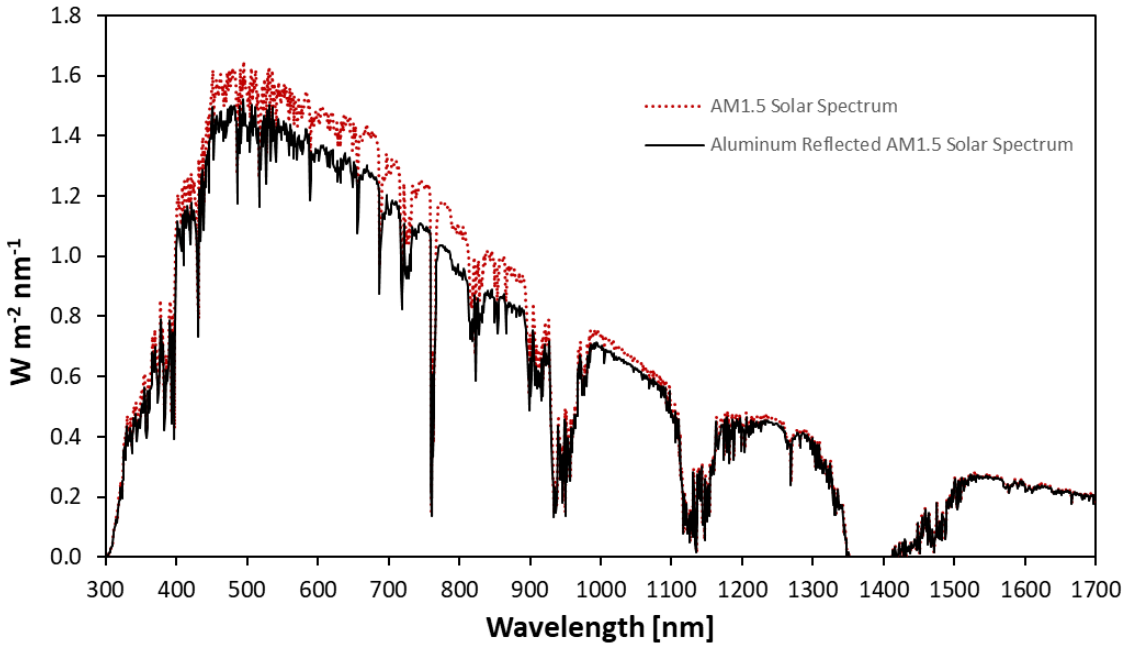

Figure 1. Spectral irradiance for sunlight and sunlight reflected from a specular aluminum reflector.

Earendil-1 is intended to be launched into a sun-synchronous, low earth orbit at an altitude of 625 km. This orbit will allow delivery of sunlight to the earth's surface after local sunset or before local sunrise. This orbital geometry necessitates the reflector be positioned at an approximate 45° angle to the earth's surface which reduces the area available for collection and redirection of sunlight.°

Accounting for this, the total luminous flux that reaches the ground is:

$$(18\,m\,x\,18\,m)\;\times\;cos(45°) \times 100{,}807.94\frac{lm}{m^2} = 23.0954\;\;\times 10^7\;lm$$

Similarly, the total radiant flux reaching the ground it

$$(18\,m\,x\,18\,m)\;\times\;cos(45°) \times 896.61\frac{W}{m^2} = 2.054\;\;\times 10^5\;W$$

Dividing these fluxes by the area of the illuminated spot on the ground yields an average irradiance of 10.46 mW/m^2 and an average illuminance of 1.18 lux. This is a factor of 3.77x

greater than the illuminance of a full moon which is less than the factor of 5x claimed by Reflect Orbital. Variation in lux levels are expected across the illuminated area and Reflect Orbital's claim of 5x the level of moonlight may reflect this fact.

V. Photobiological Hazard Assessment

IEC 62471[13] includes many hazard categories including: UV Hazard, Blue Hazard, and Burn Hazard. The UV hazard function primarily deals with light below 320 nm which is essentially absent from the solar spectrum. Therefore, no formal photobiological UV hazard assessment was conducted. This analysis differs significantly from that of Laframboise and Chou as it considers the spectral content of light as opposed to the radiant energy. Given the low illuminance and irradiance levels, and small source size the relevant hazards for analysis are blue light and retinal thermal (burn hazard) which have emission limits with units of W m^{-2} sr^{-1}.

IEC 62471 describes blue light hazard as "Potential for photochemically induced retinal injury resulting form radiation exposure at wavelengths primarily between 400 nm and 500 nm. This damage mechanism dominates over the thermal damage mechanism for times exceeding 10 seconds."[14] The threshold for thermal or burn damage is much higher due to the ability of heat to be carried away from the retina via conduction of convection via blood flow in the retina. In contrast, the photochemical damage from blue light exposure is localized to the region illuminated/irradiated portion of the retina.

[13] ANSI/IES RP-27-20 Photobiological Safety for Lighting Systems includes the same hazard categories and calculation methods. It is mentioned here for completeness and the photobiological hazard under this standard would be the same as for IEC 62471.

[14] IEC 62471 p15

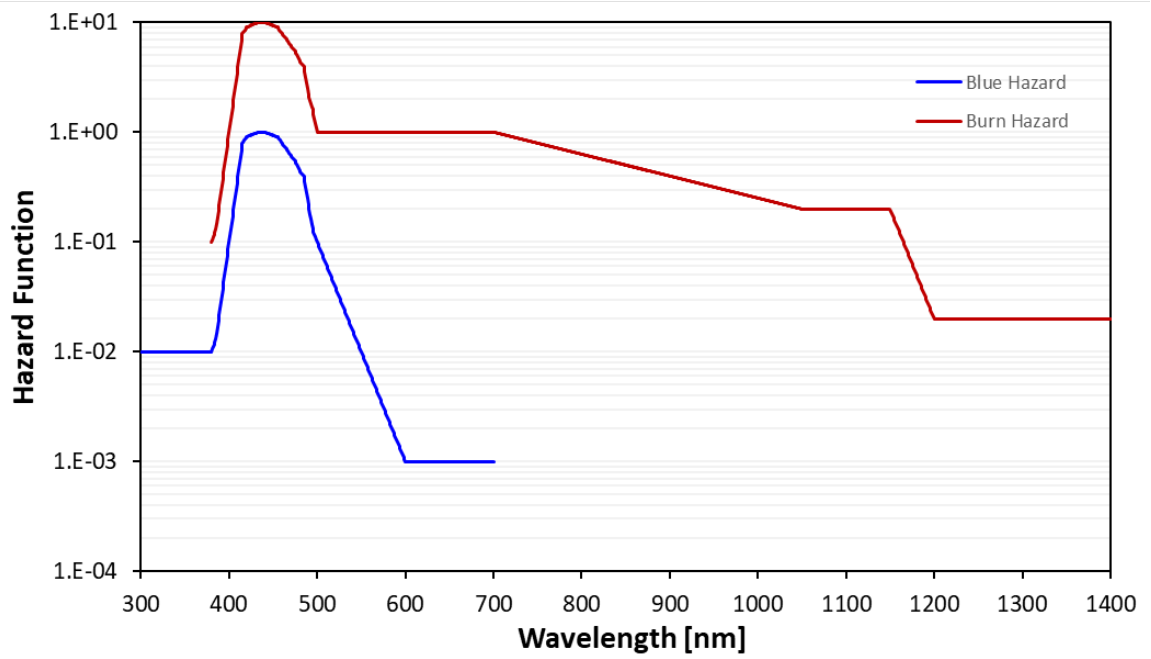

Figure 2. Blue Hazard and Burn Hazard Functions.

It is understood that light will be delivered from an OSR as it crosses the sky. The actual distance between an observer on the ground and the OSR will necessarily vary with angle. If it is assumed that light delivery requires that the OSR be with 60° of zenith, then for an OSR in a 625 km orbit, the distance between a ground observer and the OSR will vary between 625 – 722 km during a delivery transit. This variation in distance results in an approximate variation in subtended visual solid angle of about a factor of 1.88x with the smallest visual angles corresponding to ±60° from zenith.

Because the solid angle subtended by a light source is a part of the blue hazard calculations, the calculations were conducted at the limits of solid angle which correspond to the OSR at zenith and at 60° from zenith.

IEC 62471 defines blue light hazard thresholds in units of W m^{-2} sr^{-1}. These thresholds define different risk groups: RG1 is the lowest risk group and corresponds to products that do not pose a hazard due to normal behavior limits on exposure. RG2 corresponds to moderate risk and corresponds to products that do not pose a hazard due to the aversion responses to very bright light sources or due to thermal discomfort. RG3 products are high risk products that may pose a hazard for momentary or brief exposure.

Using these definitions the threshold for an OSR at zenith and at 60° was calculated for each risk group in terms of ground level illuminance.

Risk Group	Threshold W m^{-2} sr^{-1}	Maximum Ground Illuminance	
		Zenith	60°
RG1	100	5.38 x 10^{-5} lux	2.85 x 10^{-5} lux
RG2	10,000	5.38 x 10^{-3} lux	2.85 x 10^{-3} lux
RG3	4,000,000	2.15 lux	1.14 lux

The RG3 threshold for an OSR at zenith is at an illumination level of 2.15 lux or 6.72x moonlight. This is the highest threshold and it is noted that an OSR at zenith has the lowest probability of being within the field of view of an observer at ground level.

Conversely, the RG3 threshold for an OSR at 60° is at an illumination level of 1.14 lux or 3.57x moonlight. It is further noted that an OSR at 60° would be well within the field of view of a ground level observer provided they are facing in the direction of the OSR.

VI. Discussion

At the angles most likely to be seen by an observer at ground level, an OSR would exceed the threshold for RG3 and would be classified as a hazardous light source. The intensity of the light source is sufficient to cause damage in a fraction of a second, less time than required for aversion or blink reflexes.

Even when providing illumination levels corresponding to a full moon (0.32 lux), an OSR would appear as a star with a visual magnitude of -13. As such it would be easily visible in daylight and would be brighter than any historical supernova. The state illuminance levels of Earendil-1 (1.6 lux) correspond to a visual magnitude of -14.2.

Light sources classified as RG3 are of sufficient intensity to cause damage or injury in less than the 0.25 seconds required for an aversion or blink reflex. Because of this RG3 light sources require warning and safety interlocks to prevent injury to individuals in the exposure area. Such interlocks are not possible with an OSR which will illuminate an area with a diameter of about 5 km. This corresponds to over 6,000 acres which at suburban population densities

would correspond to more than 10,000 households and potentially tens of thousands of residents.

A 5 mW laser pointer with a divergence of 0.5 mrad at a distance of 1 mile will illuminate an area about 1.61 meters across (2.03 m^2). The irradiance at this distance would be about 2.46 mW/m^2. This level of illuminance is considered a severe hazard for pilots and could result in significant legal penalties.

An OSR that provided illuminance equivalent to a full moon (0.32 lux) would result in an irradiance of 2.85 mW/m^2, and thus present more of a hazard than a laser pointer. An OSR providing illuminance equivalent to 5x moonlight or 1.6 lux would result in an irradiance of 14.23 mW/m^2, almost 6x that of a 5 mW laser pointer at 1 mile. It follows that visual characteristics of Reflect Orbital's Earendil-1 approximate those of a laser pointer at distances of less than half a mile, with the notable difference of color and location in the sky as opposed to being directed from the ground.

In the United States, per 18 USC §39A, it is a felony to aim a laser pointer at an aircraft. The penalties for this offense are a maximum fine of $250,000 and/or imprisonment for not more than 5 years. Canada has a similar law that uses a broader definition. Canadian law prohibits "projecting a bright light source" into airspace.[15]

Penalties in the UK are not restricted to incidents with aircraft. Under UK law, it is illegal to shine or direct a laser beam towards a vehicle with is moving or ready to move and the laser beam distracts, or is likely to dazzle or distract a person in control of the vehicle.[16] German law is similarly broad as it is illegal to interfere with the safety of traffic by railway, suspension railway, ship, air, or road.[17]

VII. Conclusion

Delivery of light from an OSR has been shown to be a potential photobiological hazard that should require warnings and safety interlocks before delivery of light. However, as of yet, no mechanism has been identified that would even allow a warning for all personnel within the target illumination zone of an OSR.

[15] Canadian Aviation Regulations 601.22

[16] Laser Misuse (Vehicles) Act 2018, Chapter 9

[17] German Criminal Code §315

Visually, the appearance of an OSR is equivalent to a laser. Both are high intensity light sources that subtend an extremely small solid angle. Because of the known hazards of laser devices, legal penalties apply to individuals who knowingly point a laser at an aircraft or vehicle. The laws regarding safety of or interference with traffic in some countries are broad enough that light from an OSR directed toward the operator of an aircraft, train, ship, or vehicle would constitute a criminal offense.

Eric Bretschneider earned his Ph.D. in Chemical Engineering from the University of Florida working on MOCVD growth of compound semiconductor structures for light emitting applications. He has over 30 years of experience in design, production, testing/reliability, and characterization of LED based lighting components and products. He also has 20 years of experience in development of industry testing standards and is a noted expert in test and measurement of lights and lighting products.