Hazard Analysis and Web-Based Tool for Evaluating Glint and Glare from Solar Collector Systems

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Abstract

This paper extends previous work by the authors evaluating glint and glare from concentrating solar power (CSP) systems. Analytical expressions are derived that provide ranges of distances that can cause permanent eye damage (retinal burn) or temporary flash blindness resulting from specular reflections from different CSP collector systems. In addition, a web-based tool has been developed that evaluates glint and glare hazards. Both analytical and empirical evaluations are implemented by the tool. For empirical evaluations, the user uploads digital photographs of the source reflection causing glint or glare and of the sun for scaling. The web-based tool presents the potential ocular hazard, flux maps, and irradiance profiles.

Keywords: Glint, glare, solar, eye, ocular, hazard

1. Introduction

Recent studies have evaluated the potential hazards associated with glint and glare from concentrating solar power (CSP) plants [1],[2]. Glint is defined as a momentary flash of bright light, while glare is defined as a more continuous source of excessive brightness relative to the ambient lighting. Hazards from glint and glare from concentrating solar collectors or receivers include the potential for permanent eye injury (e.g., retinal burn) and temporary disability or distractions (e.g., flash blindness), which may impact people working nearby, pilots flying overhead, or motorists driving alongside the site. Figure 1 shows examples of specular and diffuse reflections from different (CSP) systems.

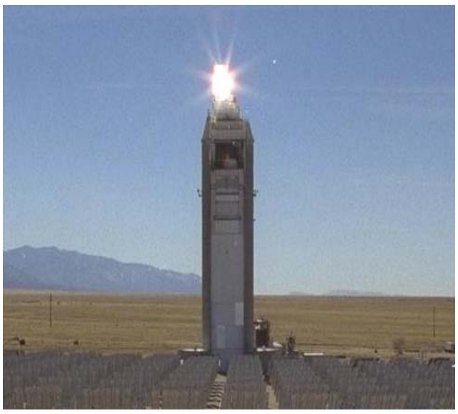

Figure 1. Examples of specular reflections from mirror facets (left) and diffuse reflections from a central receiver (right).

Safety metrics were identified by Ho et al. [1] to evaluate the potential ocular impact resulting from different levels of irradiance received from specular (mirror-like) or diffuse (rough-surface) reflections. Analytical models were developed to estimate the irradiance and subtended source angle of the reflection, and tests were performed to validate the models [2]. Figure 2 shows a diagram of the potential impacts of viewing glint or glare as a function of retinal irradiance and subtended source angle. For scenarios where the glint or glare causes sufficiently high irradiances, permanent eye damage (retinal burn) can occur. Below the retinal burn threshold, a region exists where a sufficiently high retinal irradiance may cause temporary flash blindness, which is caused by bleaching (oversaturation) of the retinal visual pigments. When this occurs, a temporary after-image appears in the visual field (e.g., the effect after viewing a camera flash in a dim room). The size and impact of the after-image in the field of view depends on the size of the subtended source angle. Figure 2 shows these regions derived from empirical data (see references in [1]-[2]).

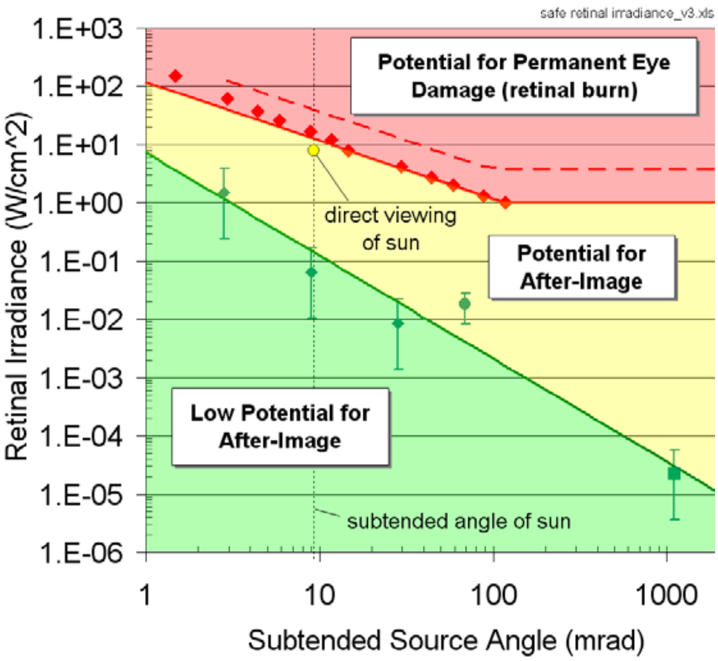

Figure 2. Safety metrics and potential impact of viewing glint and glare as a function of retinal irradiance and subtended source angle (from [2]).

This paper focuses on extending the hazard analyses in [2] by evaluating safe distances for different collector systems. Also, this paper presents the development of a web-based tool that evaluates glare for various scenarios and compares the irradiance to safety metrics. This predictive capability is useful for pre-design evaluations to determine if potential hazards might exist at a given site. In addition, raw images of glint or glare can be uploaded to the website, and a Matlab® program processes the image to determine the empirical irradiance resulting from the glint or glare reflection. This empirical capability is useful for evaluating existing systems to determine if mitigating features or controls are necessary.

2. Glint and Glare Hazard Analysis

Ho et al. [2] presented the following equations to determine the corneal irradiance, I (W/cm^2), received at the front of the eye from specular reflections emanating from CSP collectors assuming no atmospheric attenuation:

<u>Point-Focus Collectors (heliostats, dishes)</u>:

$$I = \rho Q \left(\frac{x\beta}{D} + \left| \frac{x}{b} - 1 \right| \right)^{-2} \tag{1}$$

<u>Line-Focus Collectors (parabolic troughs)</u>:

$$I = \rho Q \left(\frac{x\beta}{D} + \left| \frac{x}{b} - 1 \right| \right)^{-1} \tag{2}$$

Ho et al. [2] also presented the following equations for the retinal irradiance, E_r (W/cm^2), and subtended source angle, ω (rad), that can be used to estimate potential glare impacts shown in Figure 2 (for all CSP collectors assuming no atmospheric attenuation):

$$E_r = \frac{\rho Q d_p^2 \tau}{f^2 \beta^2} \tag{3}$$

$$\omega = \beta \sqrt{\frac{I}{\rho Q}} \tag{4}$$

where ρ is the mirror reflectivity (-), Q is the direct normal insolation (W/cm^2), x is the distance between the reflected image and the observer (m), β is the total beam divergence angle (rad), D is the aperture size (effective diameter) of the collector (m), b is the focal length of the collector (m), d_p is the pupil diameter (~0.002 m adjusted to sunlight), τ is the transmission coefficient (-) that accounts for absorption of radiation within the eye before it reaches the retina (~0.5), and f is the focal length of the eye between the nodal point and the retina (~0.017 m).

It should be noted that ω is an effective subtended source angle assuming that the shape of the reflected sun image is circular. The actual shape can be elliptical and skewed, depending on the curvature of the collector and location of the observer relative to the collector. For parabolic troughs that are linear along one dimension and parabolic along another, the reflected sun image can appear as a long thin line (ellipse) along the long (non-curved) length of the collector. The effective subtended angle preserves the area of the reflected sun image on the mirror but assumes the shape is circular. To the authors' knowledge, no ocular studies have been performed using non-circular sources. So, for consistency with the safety metrics provided in the literature, the effective subtended angle shown in Eq. (4) is determined assuming a circular source.

Ho et al. [2] performed tests to validate the irradiance equations for both specular and diffuse reflections. Digital photographs of the reflected sunlight from specular (mirror) and diffuse surfaces were evaluated to determine the corneal irradiance, which was compared to the analytical solutions. Results showed excellent agreement between the measured and predicted irradiances, even for off-axis reflections. The following sections complement the previous work by presenting analytical expressions that estimate the range of distances that could cause either permanent eye damage or temporary flash blindness from specular reflections emanating from CSP collectors.

2.1. Permanent Eye Damage

At sufficiently large retinal irradiance values and/or subtended source angles of the reflected image, permanent eye damage (i.e., retinal burn) can occur. The retinal irradiance threshold for retinal burn, $E_{r,burn}$ (W/cm^2), can be expressed as follows [2]:

$$E_{r,burn} = 0.118 / \omega \quad \text{for } \omega < 0.118 \text{ rad}$$

$$E_{r,burn} = 1 \quad \text{for } \omega \geq 0.118 \text{ rad} \tag{5}$$

Combining Eq. (5) with Eqs. (1), (2), and (4) yields the upper and lower limits, $x_{burn,max}$ and $x_{burn,min}$ (m), of distances between the specularly reflected sunlight image and the observer that can cause permanent eye damage assuming no atmospheric attenuation:

<u>Point-Focus Collectors (heliostats, dishes)</u>:

$$x_{burn,\max} = \frac{E_r \beta / 0.118 + 1}{\beta / D + 1/b} \quad \text{for } x \geq b \tag{6}$$

$$x_{burn,\min} = \frac{E_r \beta / 0.118 - 1}{\beta / D - 1/b} \quad \text{for } x < b \tag{7}$$

Line-Focus Collectors (parabolic troughs):

$$x_{burn,\max} = \frac{71.8\beta^2 E_r^2 + 1}{\beta / D + 1/b} \quad \text{for } x \geq b \tag{8}$$

$$x_{burn,\min} = \frac{71.8\beta^2 E_r^2 - 1}{\beta / D - 1/b} \quad \text{for } x < b \tag{9}$$

The upper limit represents the maximum distance from the collector that is beyond the focal point, *b*, that can cause permanent eye damage for a particular system configuration, and the lower limit represents the minimum distance from the collector short of the focal point that can cause permanent eye damage. In between these limits, the predicted retinal irradiance is sufficient to cause permanent eye damage for a given subtended source angle of the reflected image. If the equations yield non-physical results (e.g., $x_{burn,max} < x_{burn,min}$ or $x_{burn,min} < 0$ or $x_{burn,min} > b$), then Eqs. (1) - (4) should be checked explicitly against the retinal burn threshold given in Eq. (5) to determine if a specific distance, *x*, will yield retinal burn.

2.2. *Temporary Flash Blindness (After-Image)*

At retinal irradiances and/or subtended source angles less than those required to cause permanent eye damage, temporary flash blindness (after-image) can occur. The retinal irradiance threshold that can cause temporary flash blindness, $E_{r,flash}$ (W/cm^2), can be expressed as follows [2]:

$$E_{r,flash} = \frac{3.59\text{x}10^{-5}}{\omega^{1.77}} \tag{10}$$

Combining Eq. (10) with Eqs. (1), (2), and (4) yields the upper and lower limits, $x_{flash,max}$ and $x_{flash,min}$ (m), of distances between the specularly reflected sunlight image and the observer that can cause temporary flash blindness (after-image) assuming no atmospheric attenuation:

Point-Focus Collectors (heliostats, dishes):

$$x_{flash,\max} = \frac{325\beta E_r^{0.565} + 1}{\beta / D + 1/b} \quad \text{for } x \geq b \tag{11}$$

$$x_{flash,\min} = \frac{325\beta E_r^{0.565} - 1}{\beta / D - 1/b} \quad \text{for } x < b \tag{12}$$

Line-Focus Collectors (parabolic troughs):

$$x_{flash,\max} = \frac{1.05\text{x}10^5 \beta^2 E_r^{1.13} + 1}{\beta / D + 1/b} \quad \text{for } x \geq b \tag{13}$$

$$x_{flash,\min} = \frac{1.05\text{x}10^5 \beta^2 E_r^{1.13} - 1}{\beta / D - 1/b} \quad \text{for } x < b \tag{14}$$

The upper limit represents the maximum distance from the collector that is beyond the focal point, *b*, that can cause temporary flash blindness for a particular system configuration, and the lower limit represents the minimum distance from the collector short of the focal point that can cause temporary flash blindness. In between these limits, the predicted retinal irradiance is sufficient to cause temporary flash blindness for a given subtended source angle of the reflected image. If the equation for the minimum distance yields a non-physical result (i.e., $x_{flash,min} < 0$), then the potential for temporary flash blindness may exist at all locations short of the focal length. In these cases, Eqs. (1) - (4) can be checked explicitly against the temporary flash blindness threshold given in Eq. (10) to determine if a specific distance, *x*, will yield retinal irradiances or subtended source angles sufficiently large to cause temporary flash blindness. For most CSP collectors, specular reflections will have the potential to cause temporary flash blindness at all distances less than the focal length. An exception is for flat (or nearly flat) heliostats with large focal lengths ($b \to \infty$). For these cases, Eq. (12) should be used to determine the maximum distance that can cause flash blindness from flat (or nearly flat) mirrors.

2.3. Examples

Table 1 provides examples of minimum and maximum distances that can cause permanent eye damage or temporary flash blindness for different CSP collector systems using the equations from the previous section for specular reflections with no atmospheric attenuation. Ocular parameters presented in Ho et al. [2] for a daylight adjusted eye are used (d_p = 0.002 m, f = 0.017 m, and τ = 0.5).

Table 1. Example of ranges of distances that can cause permanent eye damage or temporary flash blindness for specular reflections from different collector systems.

Collector Configuration*	Minimum Distance Causing Permanent Eye Damage (m)	Maximum Distance Causing Permanent Eye Damage (m)	Minimum Distance Causing Temporary Flash Blindness** (m)	Maximum Distance Causing Temporary Flash Blindness (m)
Dish (D=12 m, b=7 m, ρ=0.94, β=0.0114 rad, Q=0.1 W/cm^2)	3.6	10	N/A	71
Heliostat (D=12 m, b=500 m, ρ=0.94, β=0.0114 rad, Q=0.1 W/cm^2)	492	503	N/A	3,500
Parabolic Trough (D=5 m, b=1.5 m, ρ=0.94, β=0.0194 rad, Q=0.1 W/cm^2)	1.4	1.6	N/A	110
Flat Mirror*** (D=12 m, b=1x10^{10} m, ρ=0.94, β=0.0114 rad, Q=0.1 W/cm^2)	N/A	N/A	N/A	8,600

*D=aperture size, b=focal length, ρ=reflectivity, β=total beam divergence, Q=direct normal insolation

**N/A indicates that a negative value was calculated and that the potential for temporary flash blindness exists at all distances less than the maximum distance causing temporary flash blindness.

***The maximum distance causing temporary flash blindness was determined using Eq. (14). Eqs. (1) - (5) were used to evaluate the potential for permanent eye damage. The retinal irradiance was calculated and found to be less than the retinal irradiance required to cause permanent eye damage for all distances (and resulting subtended source angles).

3. Web-Based Tool for Glint and Glare Evaluation

A web-based tool is being developed to evaluate the irradiance from surfaces reflecting sunlight. The tool provides three primary functions: (1) analytical evaluation of glint and glare for prescribed optical characteristics of the collector (e.g., focal length, reflectivity, size, slope error), environmental conditions, (e.g., direct normal insolation), and observer conditions (e.g., distance between observer and reflection, ocular properties), (2) empirical evaluation of glint and glare from user-uploaded digital photographs, and (3) empirical evaluation of irradiance distributions on receivers and other diffuse surfaces. Figure 6 shows a screen image of the web site under development.

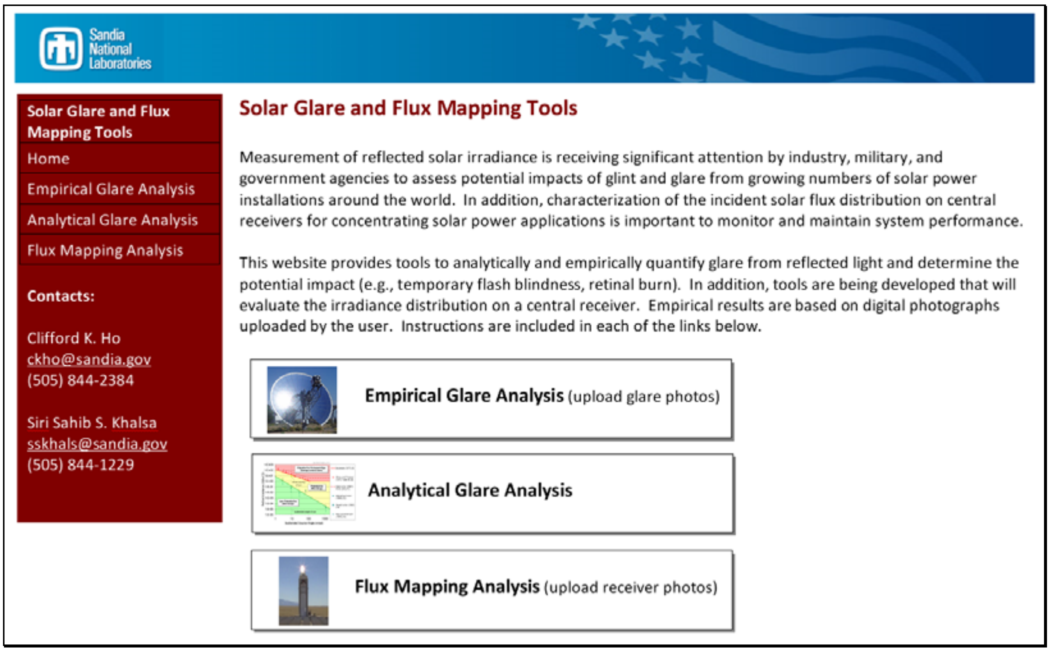

Figure 3. Screen image of website for glint, glare, and receiver irradiance evaluation.

An example of the empirical glare analysis is provided in Figure 4 through Figure 6. Photographic images of the reflection (using appropriate neutral density filters to prevent saturation) are uploaded to the website along with an image of the sun for scaling using RAW formats. Figure 4 shows the interface requesting data from the user (e.g., direct normal insolation, filter factors). A color image (JPEG format) of the glare caused by solar reflection from an off-axis dish collector similar to the RAW images uploaded to the web tool is also shown in Figure 4.

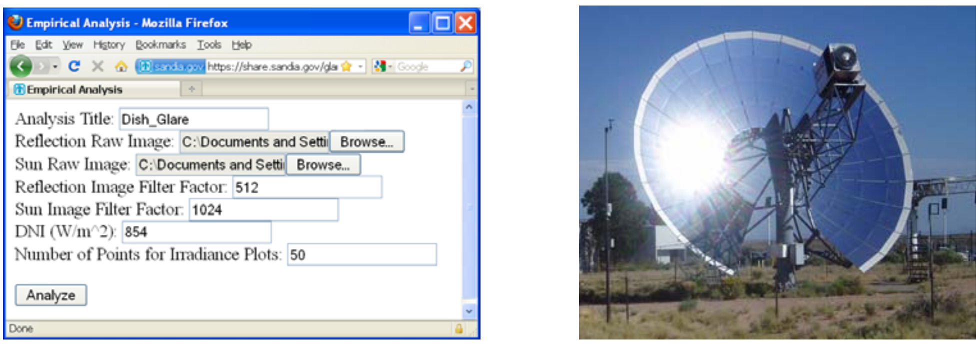

Figure 4. Web-based input for empirical glare analysis (left). Image of glare from off-axis dish (right).

After the images are loaded, the user is prompted to outline relevant portions of the photographs using drawing tools (circles and ellipses) as shown in Figure 5. The selected outline of the sun provides scaling for both the irradiance magnitude and subtended source angle of the reflection. The web-based tool then outputs the hazard analyses using the metrics and thresholds shown in Figure 2, normalized flux maps, and normalized irradiance plots of both the reflected image and the sun (Figure 6). The results shown in Figure 6 are for a specular reflection from an off-axis dish (as shown in Figure 4) located 29 m from the observer. The hazard analysis shows that the potential for temporary after-image (flash blindness) exists at this distance.

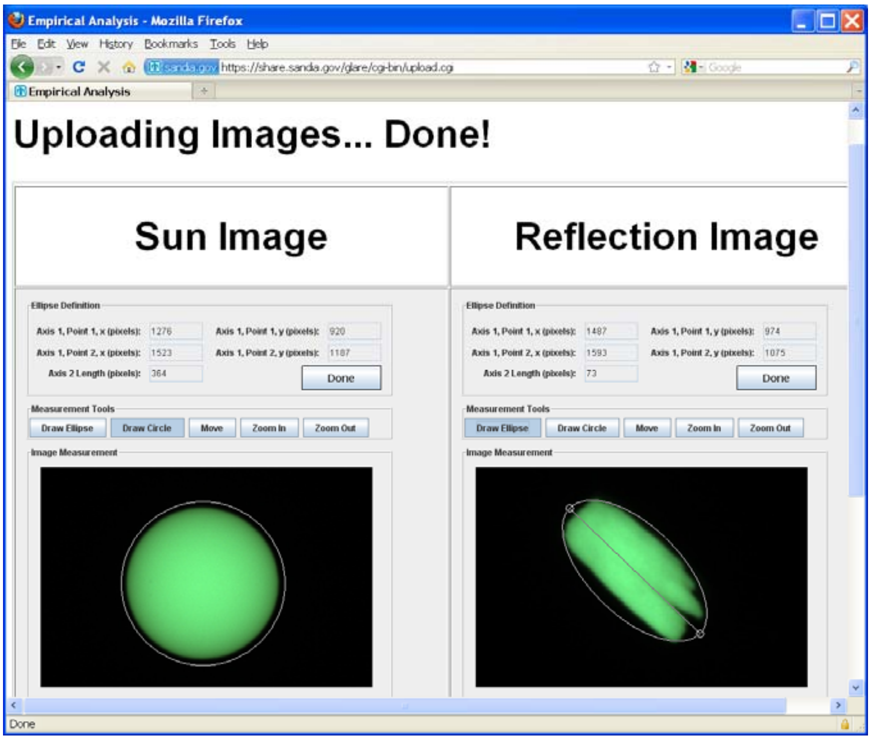

Figure 5. Images of the sun and reflection (glare) taken using RAW image format. The user selects drawing tools (circle, ellipse, zoom, move) to outline relevant portions for processing.

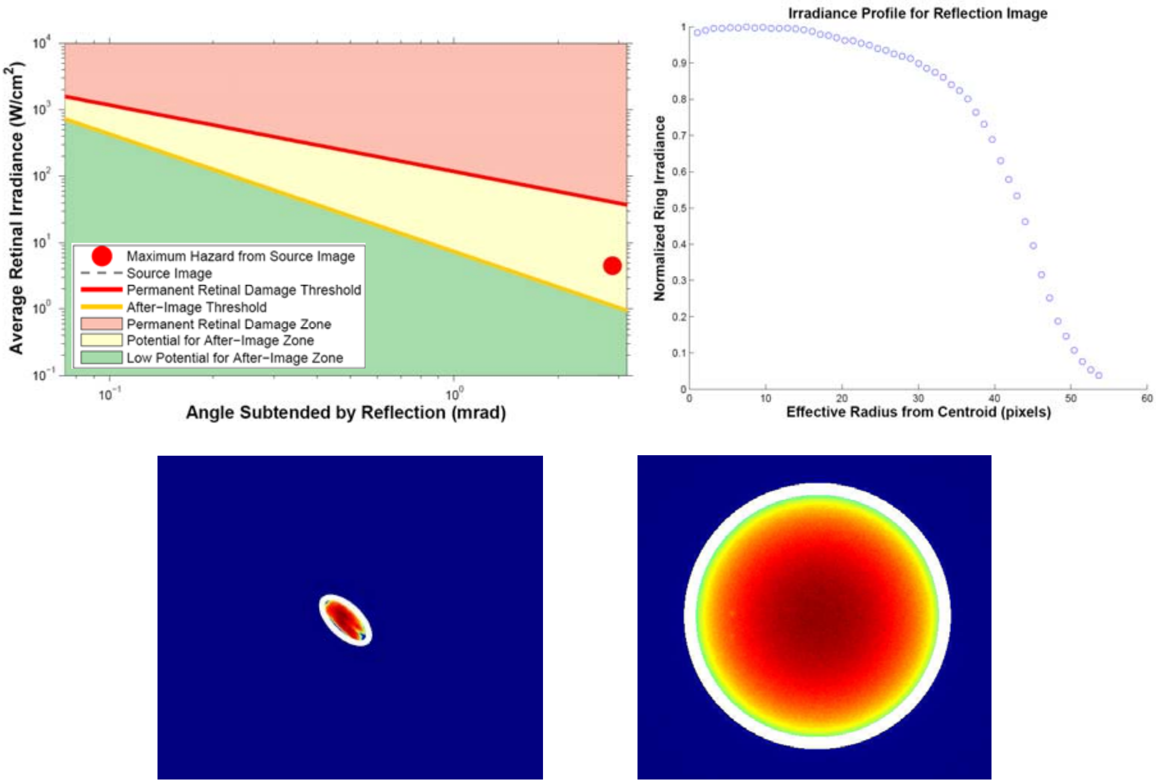

Figure 6. Output from web-based glare evaluation: hazard analysis of dish glare located 29 m from observer (top left), normalized irradiance profile of reflected image (top right), normalized flux map of reflected image (bottom left), and normalized flux map of sun image (bottom right).

4. Conclusions

This paper has derived analytical equations that estimate the range of distances that can cause permanent eye damage (retinal burn) or temporary flash blindness (after-image) from specular reflections as a function of collector optical characteristics (e.g., focal length, reflectivity, slope error, size), environmental conditions (e.g., direct normal insolation), and observer conditions (e.g., ocular properties, distance to collector). At sufficiently far distances, the potential for ocular impacts diminishes due to a decreasing subtended angle of the glare source for a given retinal irradiance. The retinal irradiance is calculated assuming no atmospheric attenuation and depends on the direct normal insolation, mirror reflectivity, slope error (beam divergence angle), and ocular properties (pupil diameter, transmission coefficient, and eye focal length).

A web-based tool has also been developed to evaluate glint and glare hazards both analytically and empirically. The empirical evaluation requires that the user upload digital images in RAW format of the glare source and of the sun (for scaling). Outputs from the web-based tool include a hazard analysis that indicates if a high potential exists for either permanent eye damage or temporary after-image (flash blindness) from the glare source, normalized irradiance profiles of the glare and sun images, and normalized flux maps.

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Nomenclature

b	Collector focal length (m)
d_p	Pupil diameter (m) (~0.002 m for typical daylight adjusted eye)
D	Aperture size of the collector (m)
E_r	Retinal irradiance (W/cm^2)
$E_{r,burn}$	Retinal irradiance threshold for retinal burn (W/cm^2)
$E_{r,flash}$	Retinal irradiance threshold for temporary flash blindness (W/cm^2)
f	Eye focal length (m) (~0.017 m for typical human eye)
I	Corneal irradiance (at front of eye) (W/cm^2)
Q	Direct normal insolation (W/cm^2)
x	Distance between observer and collector (m)
$x_{burn,min}$	Minimum distance from the collector that can cause retinal burn (m)
$x_{burn,max}$	Maximum distance from the collector that can cause retinal burn (m)
$x_{flash,min}$	Minimum distance from the collector that can cause temporary flash blindness (m)
$x_{flash,max}$	Maximum distance from the collector that can cause temporary flash blindness (m)
β	Total beam divergence angle (sun shape (~0.0094 rad) + 2(slope error)) (rad)
ρ	Reflectivity (-)
τ	Ocular transmission coefficient (-) (~0.5 for typical human eye)
ω	Subtended source angle of the glare source as viewed by an observer (rad)

References

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