Is Growing Beyond Earth Eye Safe?

23 April 2023 by Dr Scott T Shipley

You may be wondering if the Growing Beyond Earth (GBE) light source is eye safe. This is an independent analysis for GBE eye safety using the standards NASA employs for the International Space Station (ISS). The author (me) has no contractual relationship to MARSfarm Corporation (the manufacturer). This is also not my first eye safety analysis.[1]

1. GBE Light Levels

Figure 1 photo of GBE solid core board with all emitters at very low light shows the locations of the RGBW LEDs. A faithful geometric model of the GBE system was formed using Zemax Optic Studio™ to estimate light levels and demonstrate the features of reflecting growth chamber walls. Figure 2 shows incoherent irradiance [W cm^{-2}] for a model detector layer in the near field at 5 mm from the LED plane when each of the 157 LEDs theoretically emits 0.5 W optical power. The optical shaded model is shown in Figure 3, where rectangular detector layers are used to form the four vertical walls and three key horizontal layers within the growth chamber volume. Model results for both absorbing and reflecting walls are shown in Figures 4, 5 and 6 for the key horizontal layers, and in Figure 7 for the front wall surface.

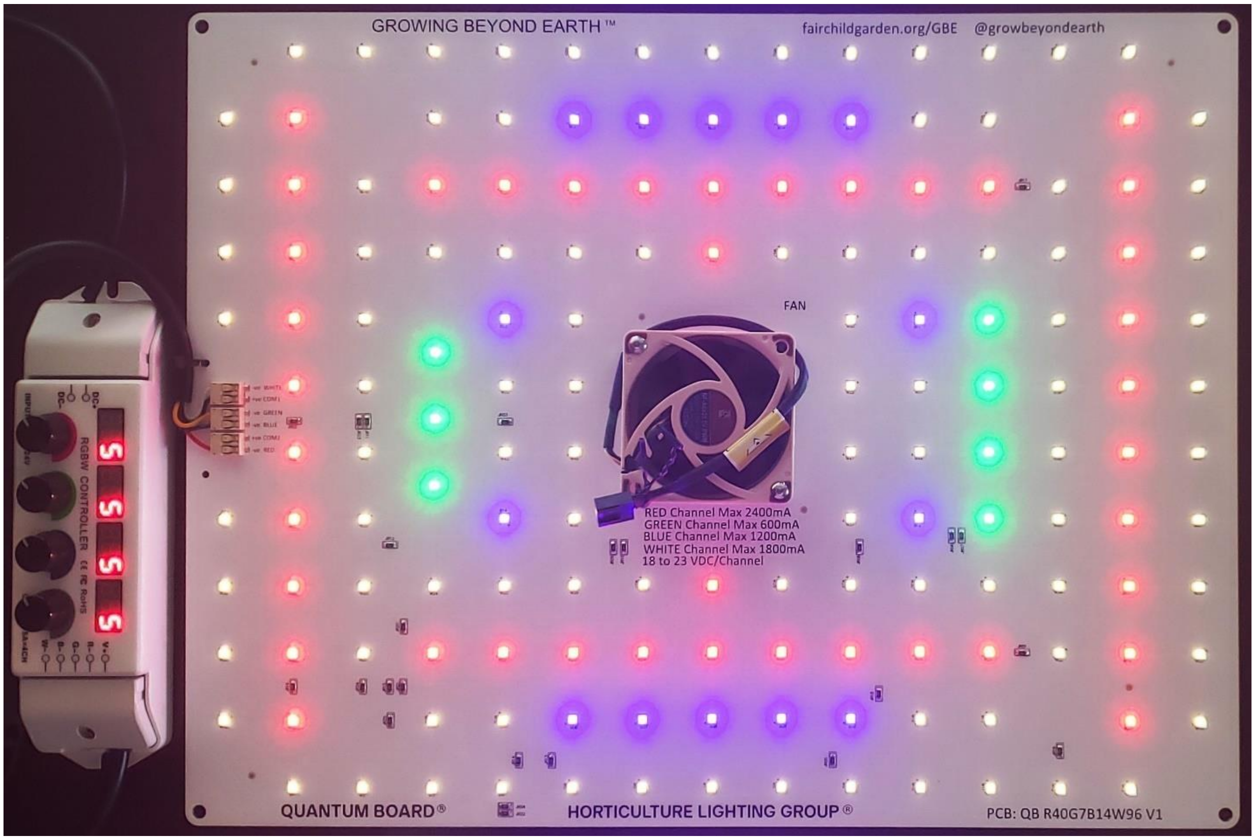
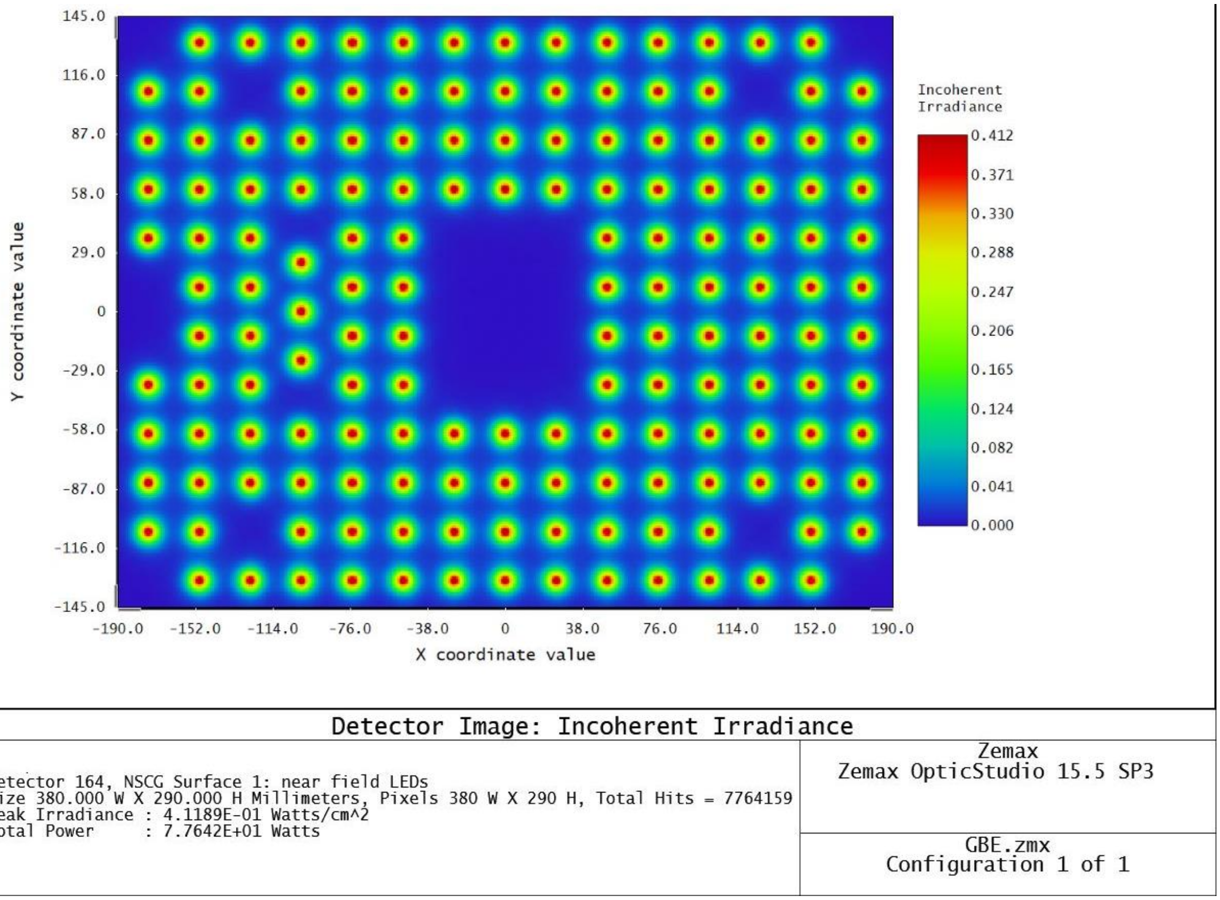


Figure 1 – GBE Quantum Board ® by Horticulture Lighting Group ® comprised of 40 red (R), 7 green (G), 14 blue (B) and 96 white (W) LEDs.



```
Detector Image: Incoherent Irradiance

Detector 164, NSCG Surface 1: near field LEDs
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 7764159
Peak Irradiance : 4.1189E-01 Watts/cm^2
Total Power     : 7.7642E+01 Watts

Zemax
Zemax OpticStudio 15.5 SP3

GBE.zmx
Configuration 1 of 1
```

Figure 2 – Near field irradiance [W cm^{-2}] with every LED at 0.5 W output power. Total power through the near field is just under the 78.5 W simulated output.

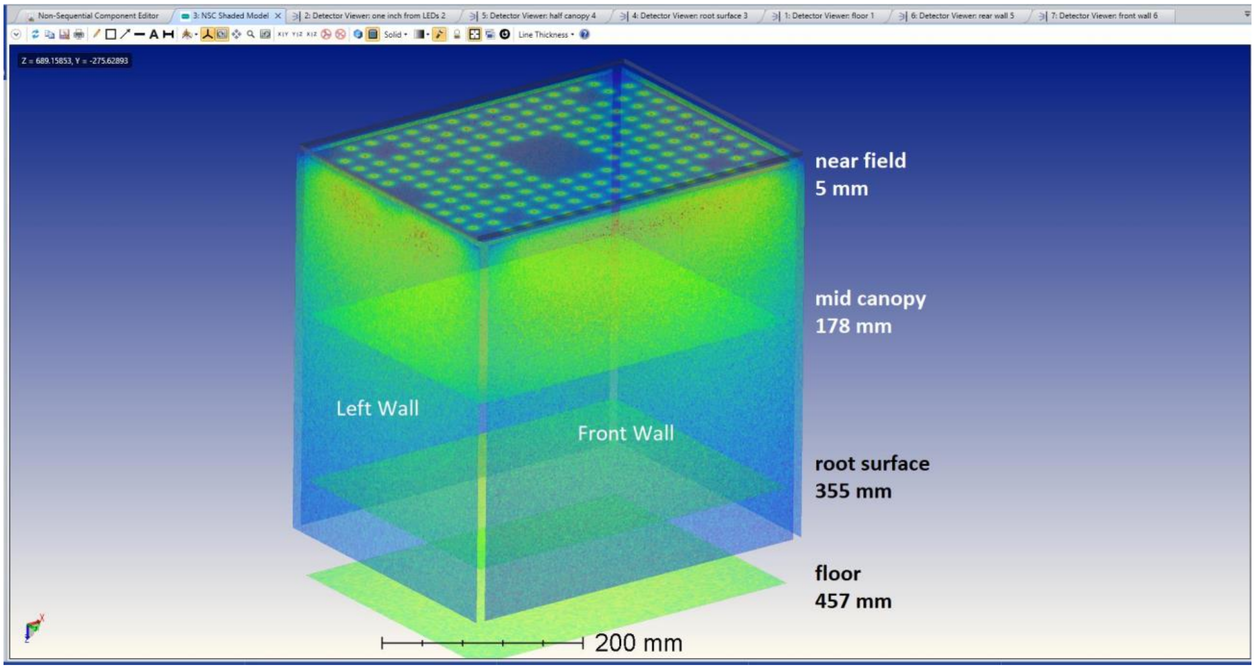
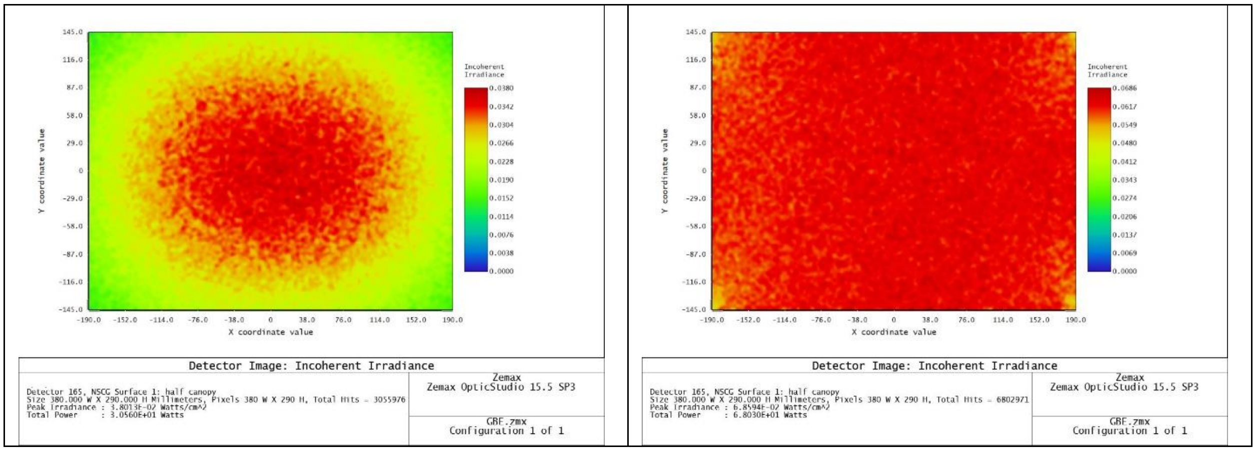


Figure 3 – Zemax shaded model for all LEDs ON and absorbing walls, which is also the case for no walls.

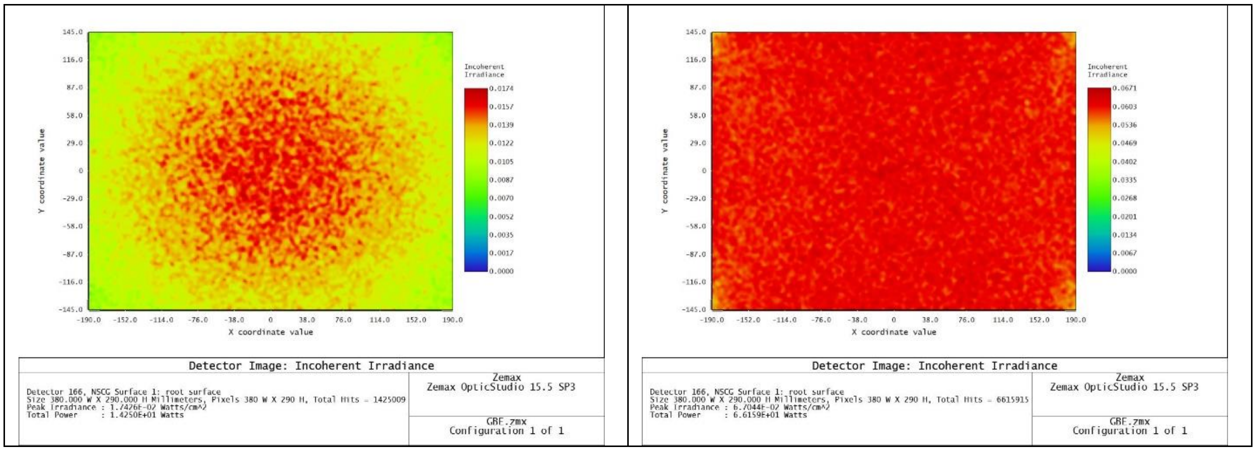
Reflecting walls provide superior light uniformity compared to absorbing walls. The absorbing wall case is identical to operations with the walls removed when all light escaping to the room is lost. Also note that light levels for reflecting walls are nearly constant with depth into an empty chamber. The absorbing/no wall case reduces light levels at the root surface by a factor of four (0.017 W cm^{-2} ÷ 0.067 W cm^{-2} ~ 25%).



```
Detector Image: Incoherent Irradiance
Detector 165, NSCG Surface 1: half canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 3055976
Peak Irradiance : 3.8013E-02 Watts/cm^2
Total Power     : 3.0560E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

```
Detector Image: Incoherent Irradiance
Detector 165, NSCG Surface 1: half canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 6802971
Peak Irradiance : 6.8594E-02 Watts/cm^2
Total Power     : 6.8030E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

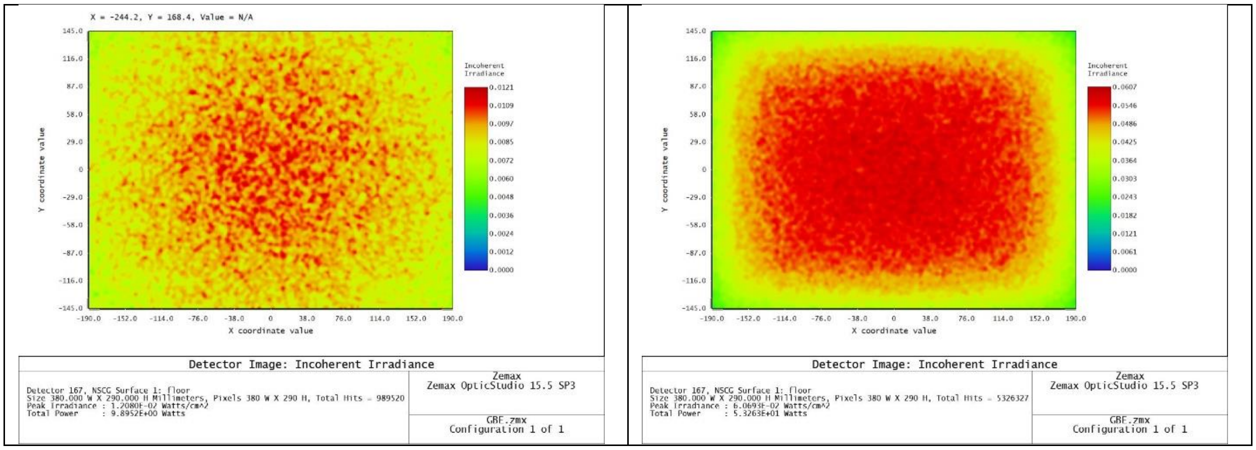
Figure 4 – Irradiance at mid canopy for absorbing (left) and reflecting (right) walls.



```
Detector Image: Incoherent Irradiance
Detector 166, NSCG Surface 1: root surface
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 1425009
Peak Irradiance : 1.7426E-02 Watts/cm^2
Total Power     : 1.4250E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

```
Detector Image: Incoherent Irradiance
Detector 166, NSCG Surface 1: root surface
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 6615915
Peak Irradiance : 6.7044E-02 Watts/cm^2
Total Power     : 6.6159E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

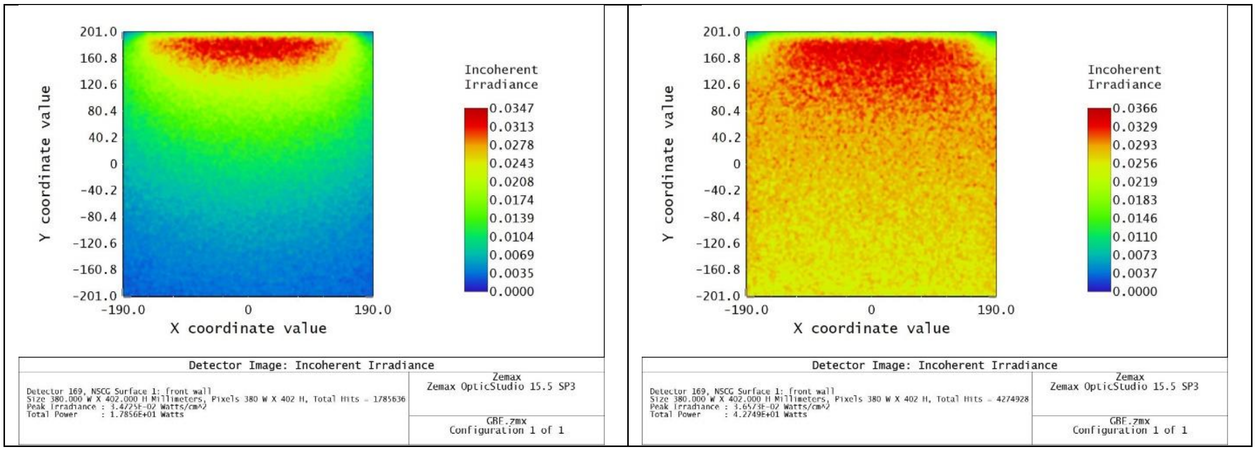
Figure 5 – Irradiance at root surface for absorbing (left) and reflecting (right) walls. The root surface is modeled at 4 inches (106.4 mm) above the floor of the GBE chamber.



```
Detector Image: Incoherent Irradiance
Detector 167, NSCG Surface 1: floor
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 989520
Peak Irradiance : 1.2080E-02 Watts/cm^2
Total Power     : 9.8952E+00 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

```
Detector Image: Incoherent Irradiance
Detector 167, NSCG Surface 1: floor
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 5326327
Peak Irradiance : 6.0693E-02 Watts/cm^2
Total Power     : 5.3263E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.zmx
Configuration 1 of 1
```

Figure 6 – Irradiance at the floor of the GBE chamber for absorbing (left) and reflecting (right) walls.

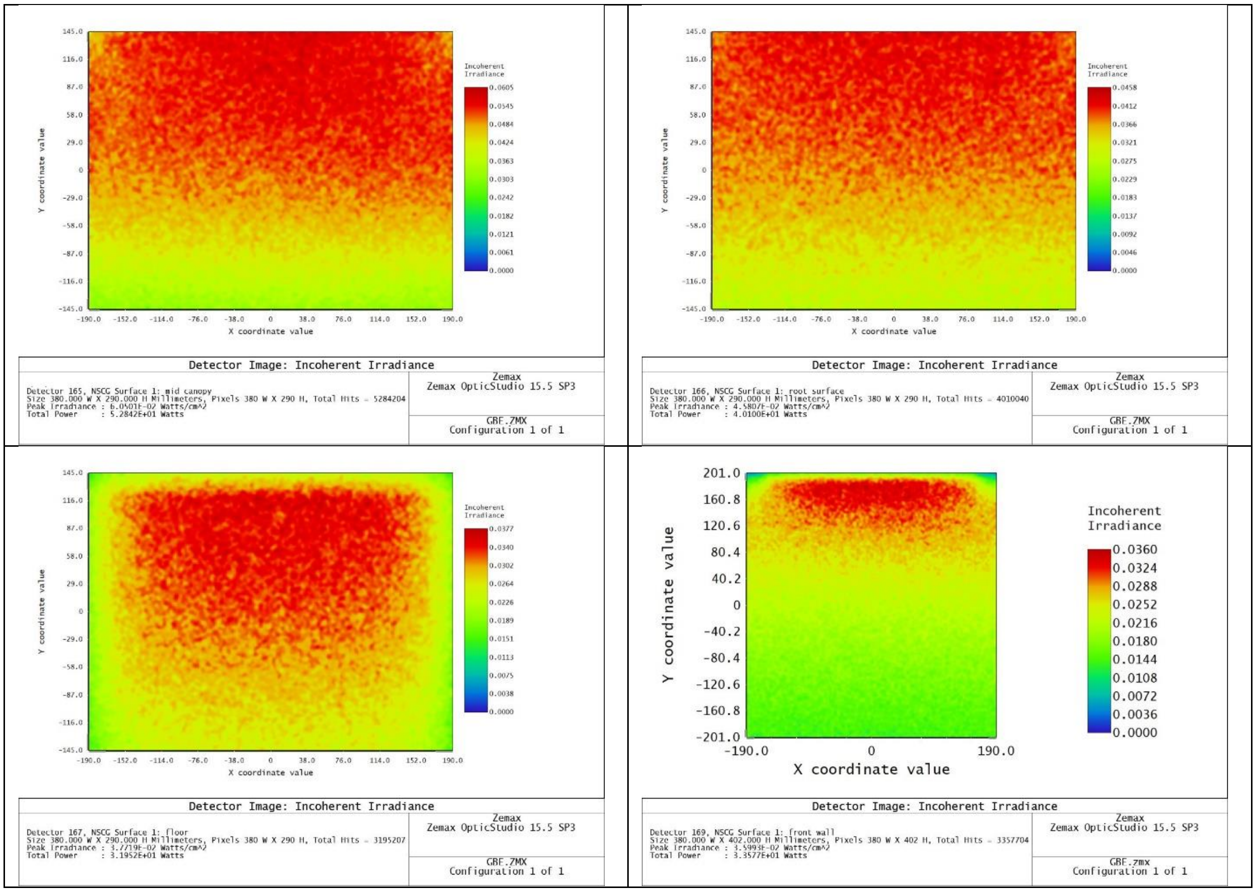


```
Detector 169, NSCG Surface 1: front wall
Size 380.000 W X 402.000 H Millimeters, Pixels 380 W X 402 H, Total Hits = 1785636
Peak Irradiance : 3.4725E-02 Watts/cm^2
Total Power     : 1.7856E+01 Watts
```

```
Detector 169, NSCG Surface 1: front wall
Size 380.000 W X 402.000 H Millimeters, Pixels 380 W X 402 H, Total Hits = 4274928
Peak Irradiance : 3.6573E-02 Watts/cm^2
Total Power     : 4.2749E+01 Watts
```

Figure 7 – Irradiance at front wall plane of GBE chamber for absorbing (left) and reflecting (right) walls.

The greatest optical hazards will occur when the GBE is operated at high power and with the front panel removed. This case is shown in Figure 8. We assume that no one willingly inserts their head into the chamber to stare at the lights,[2] so the most likely potential for optical injury may occur when the front wall panel is removed for chamber access and your unaided eye is located at the plane of the front wall. The mid canopy simulations for all four colors with the front wall installed are provided in Appendix A.



```
Detector 165, NSCG Surface 1: mid canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 5284204
Peak Irradiance : 6.0501E-02 Watts/cm^2
Total Power     : 5.2842E+01 Watts
```

```
Detector 166, NSCG Surface 1: root surface
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 4010040
Peak Irradiance : 4.5807E-02 Watts/cm^2
Total Power     : 4.0100E+01 Watts
```

```
Detector 167, NSCG Surface 1: floor
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 3195207
Peak Irradiance : 3.7719E-02 Watts/cm^2
Total Power     : 3.1952E+01 Watts
```

```
Detector 169, NSCG Surface 1: front wall
Size 380.000 W X 402.000 H Millimeters, Pixels 380 W X 402 H, Total Hits = 3357704
Peak Irradiance : 3.5993E-02 Watts/cm^2
Total Power     : 3.3577E+01 Watts
```

Figure 8 – Irradiance at the key surfaces for reflecting walls when the front wall panel is removed for chamber access. Figure panels show irradiance at mid canopy (upper left), root surface (upper right), floor (lower left) and front wall (lower right).

2. Calibrating Optical Irradiance

The spectra for GBE LEDs were obtained using an Ocean Insight FLAME-S-UV-VIS-ES spectrometer from NASA KSC (by permission) and are shown in Figure 9. These data are available in spreadsheet formats and are plotted using Excel™. The absolute value for incoherent irradiance [mW cm^{-2}] is needed to evaluate eye safety. This spectrometer provides relative uncalibrated light intensity as a function of wavelength.

Equipment on hand for measuring light levels is usually limited to “illuminance” [Lux] and/or Photosynthetically Active Radiation (PAR) [µmol m^{-2} s^{-1}]. Lux and PAR data for GBE light levels measured at the chamber floor are provided in Table 1. A LiCOR 250A with LI-190R Quantum sensor was provided by NASA KSC and used (with permission) as a standard reference. A low-cost Quantum Sun brand ($170 US) PAR meter is based upon the Focus International Inc. device, see Wang (2019). PAR meters should generally agree for sunlight/white sources within 10%, see Barnes et al. (1993), Blonquist and Bugbee (2023). PAR measurements for monochromatic light sources should be used with caution. PAR comparisons in Table 1 show blue (445 nm) PAR from LiCOR and Quantum Sun differing by 40%.

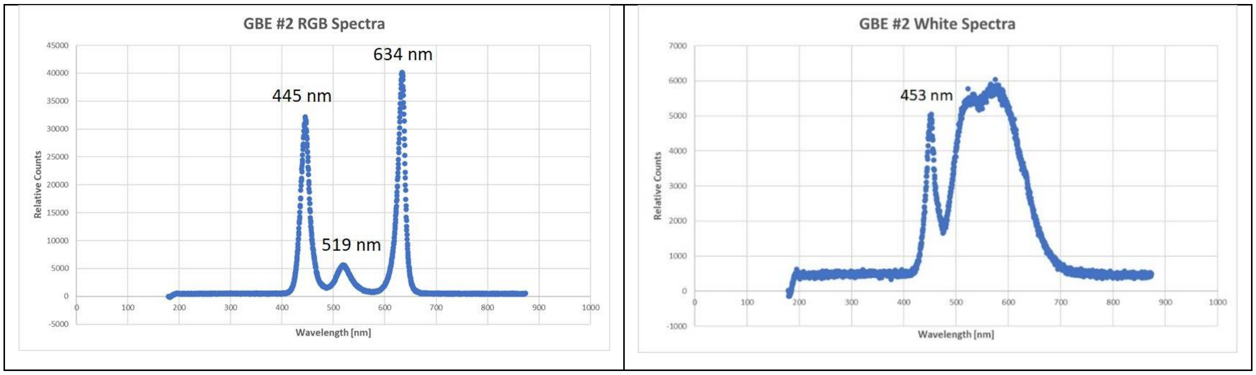


Figure 9 – Spectra for GBE Unit #2 using an Ocean Insight USB spectrometer.

The variation of PAR for each LED color as a function of RGBW digital setting is shown in Figure 10 for the center floor position of the GBE Unit #1 with all four reflective wall panels in place. Similar data for GBE Unit #2 are not significantly different. A low-cost Dr Meter Model LX1332B Lux Sensor ($35 US) was used in tandem to measure “illuminance” and these measurements are included in Figure 10.

Table 1 – GBE PAR Comparison for LiCOR 250A vs Quantum Sun

R	G	B	W	LiCOR	Quantum	LiCOR/Quantum	R only	G only	B only	W only
44	x	60	130	152	132	1.15				
44	x	x	x	19.8	19.3	1.03	1.03			
x	x	60	x	31.2	22.4	1.39			1.39	
x	x	x	130	120	108	1.11				1.11
x	x	x	200	269	248	1.08				1.08
x	x	120	x	108	78	1.38			1.38	
120	x	x	x	116	110	1.05	1.05			
x	100	x	x	15.6	14.6	1.07		1.07		
x	200	x	x	48.8	46	1.06		1.06		
x	200	x	x	47.9	44.5	1.08		1.08		
switch sensor places							634 nm	519 nm	445 nm	white
x	200	x	x	47.9	44.5	1.08		1.08		
44	x	x	x	19.8	18.8	1.05	1.05			
x	x	60	x	31.3	22.2	1.41			1.41	
x	x	x	130	120	108	1.11				1.11
					Average	1.15	1.04	1.07	1.40	1.10

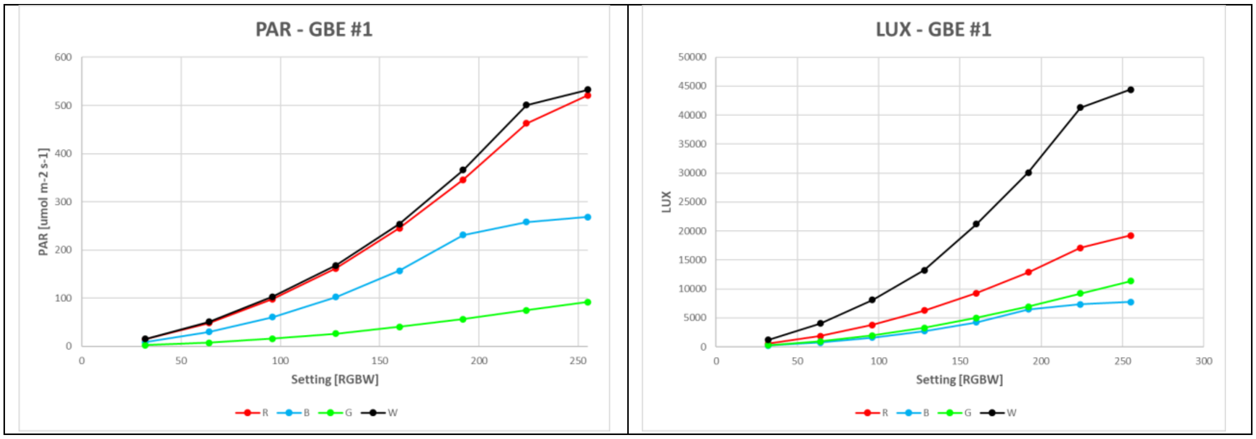


Figure 10 – Photosynthetically Active Radiation (PAR) at floor center position for GBE Unit #1 using the Quantum Sun (left), and illuminance (Lux) near floor center position using a Digital LED Lux Meter (right).

Definitions

Photosynthetically Active Radiation (PAR) is the integrated number of photons incident per unit area and per unit time [μmol m^{-2} s^{-1}] for the "visible" wavelength λ [nm} interval from 400 nm to 700 nm:

$$\text{PAR} = \sum_{400}^{700} I_\lambda N(\lambda)\ \delta\lambda \qquad [\mu\text{mol m}^{-2}\ \text{s}^{-1}]$$

where

I_λ	spectral irradiance	[W m^{-2} nm^{-1}]	
$N(\lambda)$	#photons per Joule	[μmol J^{-1}]	= 8.379E-3 μmol J^{-1} nm^{-1} * λ [nm]

Illuminance (Lx) is spectral irradiance weighted by the human photopic response luminosity function:

$$\text{Lx} = \text{K}_{555} \sum_{400}^{700} I_\lambda y(\lambda)\ \delta\lambda \qquad [\text{Lux}]$$

where

$y(\lambda)$	photopic luminosity function	[ ]	= 1.0 at 555 nm
K_{555}	conversion constant	[Lux m^2 W^{-1}]	= 683 Lux m^2 W^{-1}

Table 2 provides the EXEMPT levels for PAR and Lx when luminance is about 1 cd cm^{-2}, which is considered to be eye safe for incoherent visible radiation. The photopic luminosity function $y(\lambda)$ is included in Table 2 and shown below in Figure 12. Table 2 favors LiCOR over Quantum Sun for blue calibration.

Table 2 – Irradiance and illuminance for monochromatic source PAR = 10 μmol m^{-2} s^{-1}

Wavelength [nm]	Irradiance [mW cm^{-2}]	$y(\lambda)$ [ ]	Illuminance[a] [Lux]	PAR for 1 cd cm^{-2} [μmol m^{-2} s^{-1}]	Lx for 1 cd cm^{-2} [Lux]
400	0.282	2.8e-3	5.7	1750	998
445	0.265	0.042	76.9	130	1000
500	0.239	0.323	526	19	1000
519	0.227	0.691	1085	9.2	1000
555	0.215	1.000	1468	6.8	1000
600	0.199	0.631	857	11.7	1000
634	0.181	0.023	290	34.4	1000
700	0.170	4.1e-3	4.8	2095	142

Note a: (Definitions) 1 cd = 1 lm sr^{-1} = (1/683) W sr^{-1} at 555 nm; 1 Lux = 1 lm m^{-2} = 1 sr cd cm^{-2}

The Zemax model is compared with the measured spatial distribution for Green monochromatic light at mid canopy in Figure 11. The Quantum Sun PAR measurements are obtained with the front wall removed and generally reproduce the angular distribution of LED light at mid canopy.

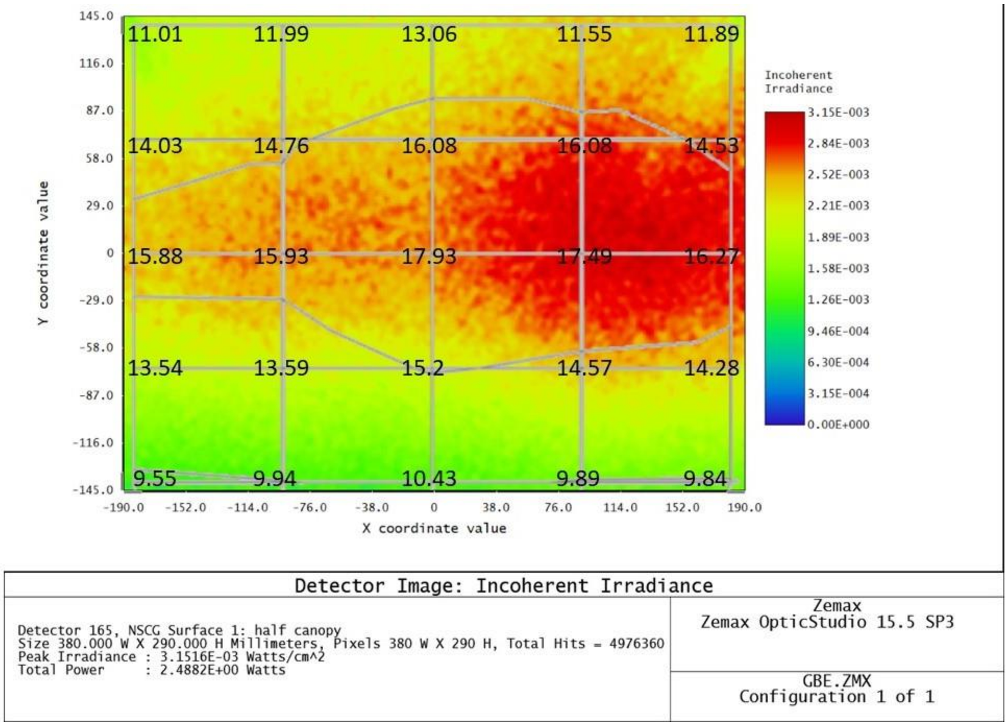


Figure 11 – GBE mid canopy with Green LEDs at half power (G = 64), overlaid on Zemax simulation for incoherent irradiance with front wall removed. Front wall is located at Y coordinate = -145 mm.

We now have enough information to estimate the output optical power of each LED, as follows:

Red, R = 64		
max PAR measured	48.3 µmol m^{-2} s^{-1} at floor	Quantum Sun
I_λ at 634 nm	0.181 mW cm^{-2} per 10 µmol ~ 0.874 mW cm^{-2}	Table 2
I_λ modeled	14.8 mW cm^{-2} for 0.5 W at floor	Zemax
optical power, R = 64	29 mW per LED	front door open
Green, G = 64		
max PAR measured	17.9 µmol m^{-2} s^{-1} at mid canopy	Quantum Sun
I_λ at 519 nm	0.227 mW cm^{-2} per 10 µmol ~ 0.406 mW cm^{-2}	Table 2
I_λ modeled	3.15 mW cm^{-2} for 0.5 W at mid canopy	Zemax, Fig. 11
optical power, G = 64	64 mW per LED	front door open
Blue, B = 60		
max PAR measured	31.2 µmol m^{-2} s^{-1} at floor	LiCOR
I_λ at 519 nm	0.265 mW cm^{-2} per 10 µmol ~ 0.827 mW cm^{-2}	Table 2
I_λ modeled	5.5 mW cm^{-2} for 0.5 W at floor	Zemax
optical power, B = 60	75 mW per LED	front door open
White, W = 64		
max PAR measured	51.1 µmol m^{-2} s^{-1} at floor	Quantum Sun
$\langle I_\lambda \rangle$ at 555 nm	0.215 mW cm^{-2} per 10 µmol ~ 1.1 mW cm^{-2}	Table 2
I_λ modeled	36.1 mW cm^{-2} for 0.5 W at floor	Zemax
optical power, W = 64	15 mW per LED	front door open

3. SSP 57121 precedence: ACGIH TLV and KNPR 1860.2

SSP 51721 (2019) specifies that instruments on ISS follow the ACGIH TLV for permissible exposure. The general approach for unlimited use of optical devices is to cap luminance below 1 cd cm^{-2} as recommended by NASA KSC KNPR 1860.2 (Exempted Items, Section 3.4.2, b4). KNPR 1860.2 also exempts InfraRed (IR) sources with irradiance less than 10 mW/cm^2 (Section 3.4.2, b3), where "IR" is generally understood to indicate wavelengths > 700 nm. Earlier versions of ACGIH (2016) stated:

> *"If the luminance is greater than 1 candela per square centimeter (cd/cm2), then the TLVs in Section 1 [Chronic Blue], 2 [IR Corneal & Lens] and 4 [Visible Retinal] apply. With a low luminance <1 cd/cm2 and no special sources involved, there may not be a significant risk and the TLV would not be exceeded."*

This statement does not appear in ACGIH TLV (2023). The 1 cd cm^{-2} exemption remains prescribed by KNPR 1860.2 but should be revisited, especially for retinal hazards in the red and near IR. The photopic response curve (CIE086-1990, Corrected 2005) has also been abandoned by ACGIH in favor of the Retinal Hazard Function R(l), which shows much greater retinal sensitivity for red LEDs and wavelengths above 700 nm. The 1 cd cm^{-2} exemption may not provide sufficient protection for red and near-IR sources.

Since GBE does not produce significant irradiance above 630 nm, this caution should not be of concern.

4. Retinal Thermal Hazard function R(λ)

Optical safety analyses should be updated to include the Retinal Thermal Hazard function R(λ), which is shown in Figure 12. The average human retinal response is identified in Figure 12 for both photopic (color daytime) and scotopic (grey dark) vision. Luminance calculations and measurement devices (Lux meters) assume the photopic response function. Luminance calculations and measurements should also consider the Scotopic response function for exposures to the dark-adapted eye. There exists a mid-range level for illumination where photopic (cones) and scotopic (rods) are both active, which is known as mesopic vision. In addition, pupillary adaptation to red light is a well-known strategy to maintain the dark-adapted eye.

Note that R(λ) = 1.0 in range from 435 nm to 700 nm, which applies at this time to all GBE LEDs. We estimate the incoherent irradiance in mW cm^{-2} using Zemax Optics Studio™ by analysis. Best practice is to verify exposure using calibrated optical sensors, such as the LiCOR 250A for wavelengths in range 400 nm to 700 nm.

Figure 12 – "Photopic" and "Scotopic" Luminous Efficiency function, with Retinal Thermal Hazard Function R(λ) from ACGIH (2023).

5. Considerations for Eye Safety: Formula and calculations

ACGIH TLV (2023) is a protected proprietary document. Researchers who want to verify the following equations and statements should acquire their own copy.

ACGIH identifies four (4) optical hazards related to visible and infrared radiation. ACGIG TLV (2023) recommends that each optical hazard be evaluated independently, as follows:

Section 1, Blue Light, ACGIH TLV pp 149-155

ACGIH Eqs. (1) through (5)
ACGIH Figure 2 – Blue light hazard function B(λ)
ACGIH Table 2 – Hazard Weighting Functions
Wavelength range 305 nm to 700 nm

Inputs:

Spectral radiance L_λ [W cm^{-2} sr^{-1} nm^{-1}] for each wavelength in range 305 nm < λ < 700 nm
Spectral bandwidth δλ for each LED type, use Full Width Half Maximum (FWHM)

Estimates:

The effective radiance for the blue light hazard at the GBE chamber floor for maximum possible illumination (Figure 10) using ACGIH Eq. (1) is provided in ACGIH Table 3. We assume uniform lighting at the sprouting surface with uniform angular spread over 2π steradians. Estimated exposure would apply to a human observer at sprouting surface looking up into the light board, either by direct viewing or specular reflection.[2] The blue light hazard for White LED is estimated using the measured spectrum from GBE Unit #2 shown in Figure 9. This white LED spectrum is repeated in Figure 13, including a convolution of the White LED spectrum with the blue light hazard function B(λ). This White LED sample has an average weighted wavelength of 556 nm, and approximately 12% of the White LED light is operating as a Blue LED. It follows that the blue light hazard for White LEDs can be extrapolated from results for a Blue LED.

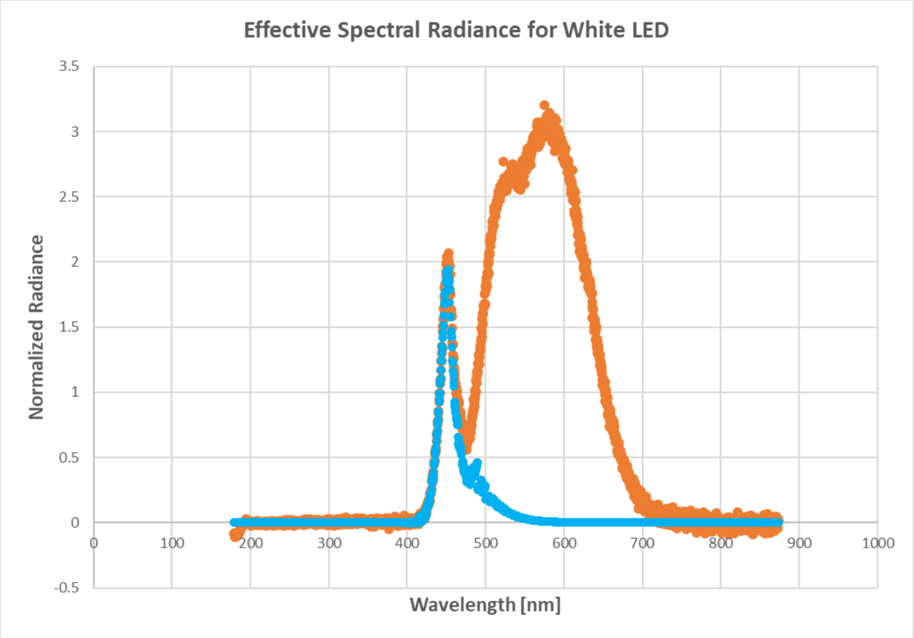


Figure 13 – Measured White LED spectrum (orange line). The blue line is the White LED spectrum convoluted with the blue light hazard function B(λ).

Table 3 – Blue Light Hazard Exposure Limits for Maximum Light Levels at Root Surface

Color	**Wavelength**	**µmol $m^{-2}s^{-1}$**	**mW $cm^{-2}sr^{-1}$**	**B(λ)**	**L_B (Eq.1)**	**t_{max} (Eq.2b)**
White	556 nm (average)	532 (max)	11.4	tbd	2.28e-2	73 min
Blue	445 nm	267 (max)	7.08	0.970	6.86e-2	24 min
Green	519 nm	92 (max)	2.09	0.040	1.16e-2	2.4 hr
Red	634 nm	521 (max)	9.43	0.001	9.43e-5	12 day

Section 2, Infrared Hazard to Cornea & Lens, ACGIH TLV pp 153

ACGIH Eqs. (6), (7)
Wavelength range 770 nm to 3000 nm
Spectral irradiance in this wavelength range is expected to be near zero.

Section 3, Infrared Hazard to Retina, ACGIH TLV pp 153-155

ACGIH Eqs. (8), (9)
ACGIH Figure 3 – Retinal thermal hazard function.
ACGIH Table 2, R(λ)
Wavelength range 770 nm to 1400 nm
Spectral irradiance in this wavelength range is expected to be near zero.

Section 4, Visible Radiation, ACGIH TLV pp 154-159

ACGIH Eqs. (10) through (13)
ACGIH Table 2, R(λ)
Wavelength range 380 nm to 1400 nm

Inputs:

Spectral radiance L_λ [W cm^{-2} sr^{-1} nm^{-1}] for each wavelength in range 305 nm < λ < 1400 nm
Spectral bandwidth $\delta\lambda$ for each LED type, use Full Width Half Maximum (FWHM)

Threshold Limit Values (TLV):

The effective radiance $L_R(\lambda)$ is the convolution of radiance and R(λ) with wavelength (ACGIH Eq. 10). ACGIH requires that effective radiance L_R must not exceed 45 W cm^{-2} sr^{-1} (ACGIH Eq. 12c), which applies to extended sources with subtense greater than 0.1 radian (5.7 degrees). When red LED is dominant and direct viewing is considered, ACGIH Eq. (13c) provides for the special case where the human pupil remains dilated, $\alpha < \alpha_{MAX}$, and exposures extend beyond 0.25 sec. Since *this is the more conservative limitation* and direct viewing may be allowed, worst case strategy elects ACGIH Eq. (13c) to apply to all GBE light sources, so that

$$L_R\ [\mathrm{W\ cm^{-2}\ sr^{-1}}] < 3.2\ [\mathrm{rad\ s^{1/4}}]\ \alpha^{-1}\ t^{-1/4} \qquad \text{ACGIH (2023) Eq. (13c)}$$

where α [rad] is the subtense angle of the incoherent light source and t [s] is stare time. Using Solar subtense angle α = 8.7e-3 radian (one-half degree), then

L_R < 366 W cm^{-2} sr^{-1}	$t^{-1/4} \sim 1$	1 sec stare time
L_R < 205 W cm^{-2} sr^{-1}	$t^{-1/4} \sim 0.56$	10 sec stare time
L_R < 48 W cm^{-2} sr^{-1}	$t^{-1/4} \sim 0.13$	1 hr stare time

Formula and Estimates:

Given PAR [µmol m^{-2} s^{-1}] for a monochromatic source at wavelength λ, use spectrometer to extend calibration to non-visible wavelengths:

PAR_λ	[µmol m^{-2} s^{-1}]	Photosynthetic Active Radiation
$E_{photon} = h\ c\ /\lambda$	[J photon^{-1}]	photon energy
$I_\lambda = PAR_\lambda\ /\ E_{photon}$	[W m^{-2}]	irradiance
$L_\lambda = {}_\lambda\ /\ \omega$	[W cm^{-2} sr^{-1}]	radiance, solid angle ω
$L_B = \sum_{380}^{1400} I_\lambda R(\lambda)\ \delta\lambda$	[W cm^{-2} sr^{-1}]	effective radiance
$L_v = K_{555}\ \sum_{380}^{830} I_\lambda y(\lambda)\ \delta\lambda$	[cd cm^{-2}]	luminance

where K_{555} = 683 lm/W is the maximum spectral luminous efficacy, a constant defined at 555 nm.

LED sources in GBE are broad angle with FWHM ~ 120 degrees. *ACGIH eye-safe radiance for long-term viewing of visible LEDs with Solar solid angle should correspond to* ***PAR measurements below 120 µmol m^{-2} s^{-1}***. Irradiance and luminance estimates are provided in Table 2 (above) for a 10 µmol m^{-2} s^{-1} monochromatic source as a function of wavelength. Convolution of the photopic luminosity function with a white LED spectrum is shown in Figure 14. Approximately half (56%) of the white LED irradiance contributes to luminance in the visible spectrum.

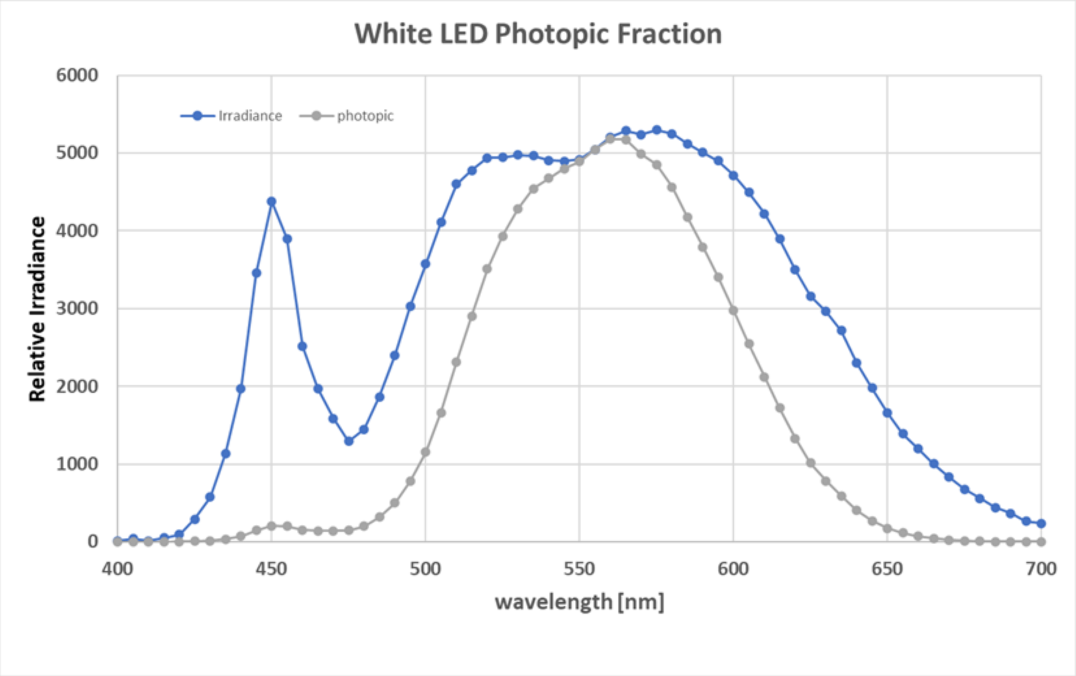


Figure 14 – Convolution of white LED spectrum from Figure 13 (blue line) with the CIE 086-1990 photopic luminosity function.

6. Solar Exposure Comparison:

It is useful to compare these stare time allowances to intentional ocular exposure to the Sun (aka "Sun gazing"). The Solar Constant S_o at Top of Atmosphere (TOA) is 1368 ± 7 W m^{-2} measured at average orbital radius $<R_\oplus>$ = 149.6 Gm (92.8E+06 miles). Using the Black Body formula for 5780 K Solar Photosphere and 2.167e-5 factor for range squared reduction (Stull, 2000), Solar radiance at ISS in wavelength interval from 400 nm to 1200 nm is about 1334 W cm-2 sr-1 with 56% of the radiance in the visible spectrum. PAR (400 nm to 700 nm) at ISS should be about 2500 µmol m^{-2} s^{-1}. PAR on Earth surface is reduced due to atmospheric attenuation (USNA, 2022) and solar elevation angle. LiCOR measurements of direct Sun at NASA KSC run about 2000 µmol m^{-2} s^{-1} under clear sky conditions.

Note that ACGIH TLV provides a factor of two safety margin for Solar radiance exposures of one second. NASA TP 2001-209990: Eye Safety (Chou, 2001) recommends neutral density filters which transmit less than 0.003% visible light (Neutral Density ~4.5), which provides a safety factor of 333, or 20 times the ACGIH long-term TLV. Ewald and Ritchey (1970) cite case studies for intentional foveomacular retinopathy associated with Sun gazing to establish the time interval (minutes) for retinal damage and some experience with retinal recovery. That is, people intentionally stared at the Sun for various reasons and sustained retinal damage resulting in visual impairment.

7. Summary Conclusion (The Bottom Line)

ACGIH eye-safe radiance for long-term viewing of White LEDs with Solar solid angle correspond to ***PAR measurements below 120 µmol*** $m^{-2}\,s^{-1}$.

PAR meter measurements of the Sun on a clear day run about 2000 µmol $m^{-2}\,s^{-1}$ and are reduced by 85% to about 300 µmol $m^{-2}\,s^{-1}$ when viewed through a GBE wall.

Light levels inside the GBE chamber will exceed EXEMPT eye safe limits when each color is operated separately above the following light settings:

Red	R > 48
Green	G > 64
Blue	B > 128
White	W > 96

With GBE walls in place (85% reduction), viewing GBE lights through the walls is eye safe (EXEMPT) when each color is operated separately at any power level.

When multiple colors are used at the same time, the optical power can be estimated by summing up the contributions for each color.

An increase in one color will reduce the output of the other colors (WxAzygy, 2022). Therefore, the summation of independent contributions will be a worst case.

Acknowledgments

This effort was supported independently by WxAnalyst LTD. Thanks to NASA KSC for access and permission to calibrated optical equipment. Two Growing Beyond Earth (GBE) test units were purchased by WxAnalyst LTD directly from MARSfarm.

Note 1: Dr Scott T Shipley (*aka Dr Scotty*) is the Director for WxAnalyst LTD Inc, a Florida R&D Corporation located in Satellite Beach, Florida. He performed eye safety analyses for Shuttle Lidar, the Spectrum optical fluorescence instrument currently on ISS, and the Ohalo III growth chamber currently planned for ISS.

Note 2: EP 172 Plants in Space Podcast, “NASA astronaut and Expedition 66 Flight Engineer Thomas Marshburn checks out chile peppers growing inside the International Space Station's Advanced Plant Habitat” (*do not do this*):

https://www.wbur.org/hereandnow/2021/12/24/astronauts-christmas-space

References

ACGIH (2023) Threshold Limit Values (TLV) and Biological Exposure indices (BEI),

ISBN: 978-1-607261-52-0.

Barnes, C., Tibbitts, T., Sager, J., Deitzer, G., Bubenheim, D., Koerner, G., and B Bugbee (1993) Accuracy of Quantum Sensors Measuring Yield Photon Flux and Photosynthetic Photon Flux. HORTSCIENCE 28(12):1197–1200. https://journals.ashs.org/hortsci/view/journals/hortsci/28/12/article-p1197.xml

Blonquist, M. and B. Bugbee (2023, not dated) Spectral Errors from Four Commercial Quantum Sensors Under LEDs and Other Electric Lights. https://www.apogeeinstruments.com/content/Quantum%20Sensors-LEDs.pdf

Chou, B.R. (2001) Eye Safety and Solar Eclipses. NASA TP 2001-209990 eye safety. https://umbra.nascom.nasa.gov/eclipse/021204/text/eye-safety.html

CIE086-1990 (October 2005) CIE 1988 2-degree Spectral Luminous Efficiency Function for Photopic Vision, Cor.1:2005, ISBN 978 3 900 734 23 7.

Ewald, R.A. and C.L. Ritchey (1970) Sun Gazing as the Cause of Foveomacular Retinitis. American Journal of Opthamology, **70**, pp 491-497.

KNPR 1860.2 Rev. C (2019) Kennedy Space Center Nonionizing Radiation Protection Program, Kennedy NASA Procedural Requirements, Effective Date: August 20, 2019, Expiration Date: August 20, 2024.

NASA (September 2019) SSP 51721 Baseline, ISS Safety Requirements Document.

Stull, R.B. (2000) Meteorology for Scientists and Engineers, Second Edition, Brooks/Cole, Pacific Grove, CA.

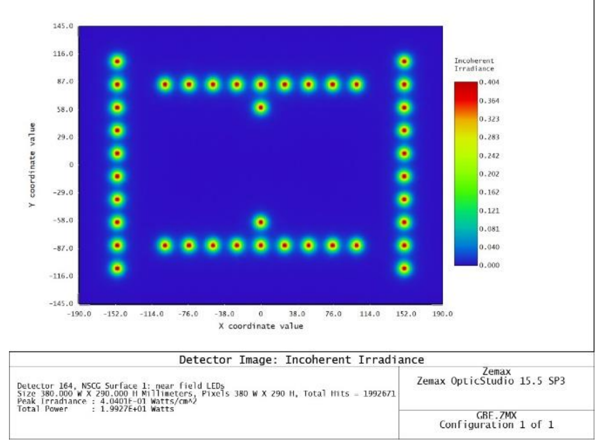
USNA (2022) Atmospheric Transmittance. US Naval Academy. https://www.usna.edu/Users/oceano/pguth/md_help/remote_sensing_course/atmos_transmit.htm

Wang, D. (2019) Systems and methods for improving a spectral response curve of a photo sensor. Focus Universal Inc., US Patent 10,217,779 B2. https://patents.google.com/patent/US10217779B2

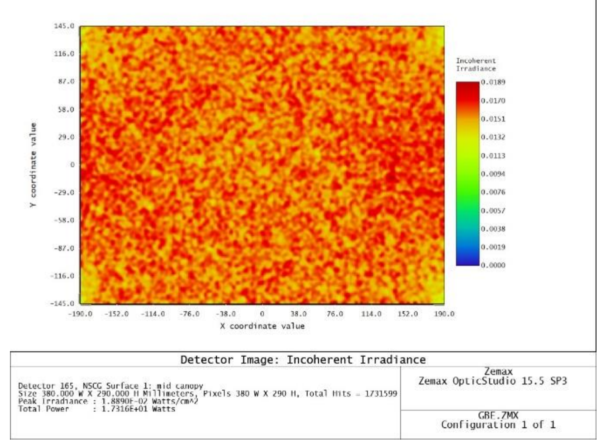
WxAzygy® (2022) n-PAR Zero Sum Game. MARSfarm Community Forum, https://wxanalyst.com/20220512_nPAR_Zero_Sum.pdf

Appendix A

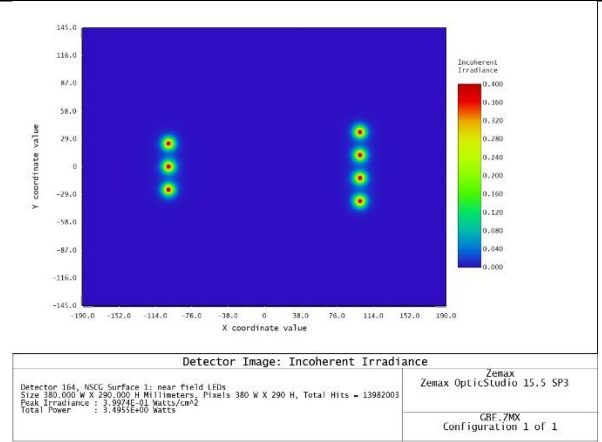
Uniformity at mid canopy



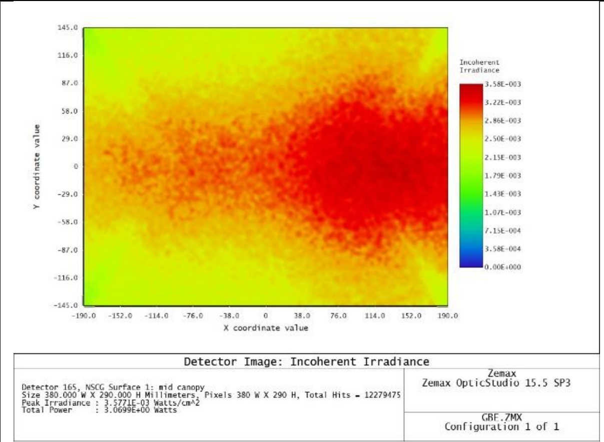
```
Detector Image: Incoherent Irradiance
Detector 164, NSCG Surface 1: near field LEDs
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 1992671
Peak Irradiance : 4.0401E-01 Watts/cm^2
Total Power     : 1.9927E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```



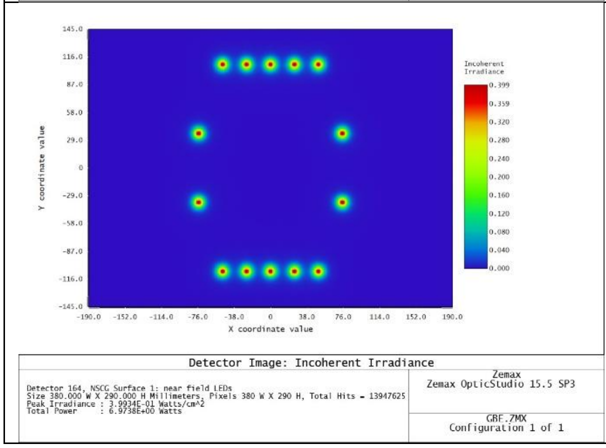
```
Detector Image: Incoherent Irradiance
Detector 165, NSCG Surface 1: mid canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 1731599
Peak Irradiance : 1.8890E-02 Watts/cm^2
Total Power     : 1.7316E+01 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```



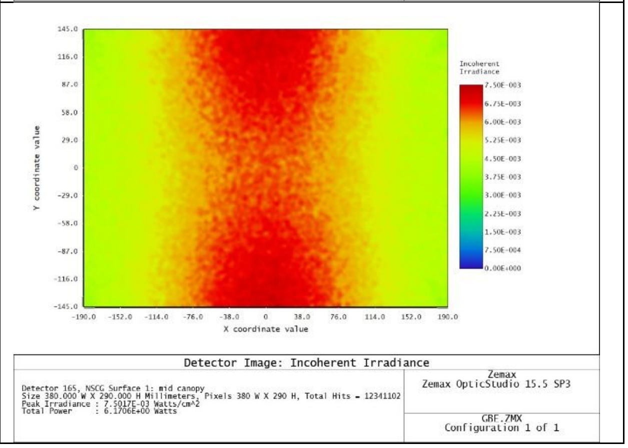
```
Detector Image: Incoherent Irradiance
Detector 164, NSCG Surface 1: near field LEDs
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 13982003
Peak Irradiance : 3.9974E-01 Watts/cm^2
Total Power     : 3.4955E+00 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```



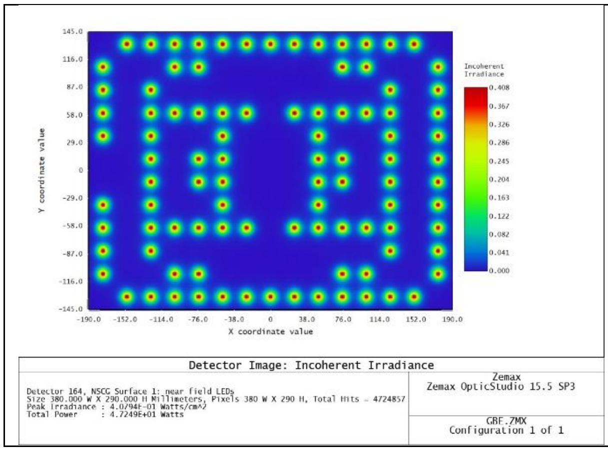
```
Detector Image: Incoherent Irradiance
Detector 165, NSCG Surface 1: mid canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 12279475
Peak Irradiance : 3.5771E-03 Watts/cm^2
Total Power     : 3.0699E+00 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```



```
Detector Image: Incoherent Irradiance
Detector 164, NSCG Surface 1: near field LEDs
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 13947625
Peak Irradiance : 3.9934E-01 Watts/cm^2
Total Power     : 6.9738E+00 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```



```
Detector Image: Incoherent Irradiance
Detector 165, NSCG Surface 1: mid canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 12341102
Peak Irradiance : 7.5017E-03 Watts/cm^2
Total Power     : 6.1706E+00 Watts
Zemax
Zemax OpticStudio 15.5 SP3
GBE.ZMX
Configuration 1 of 1
```

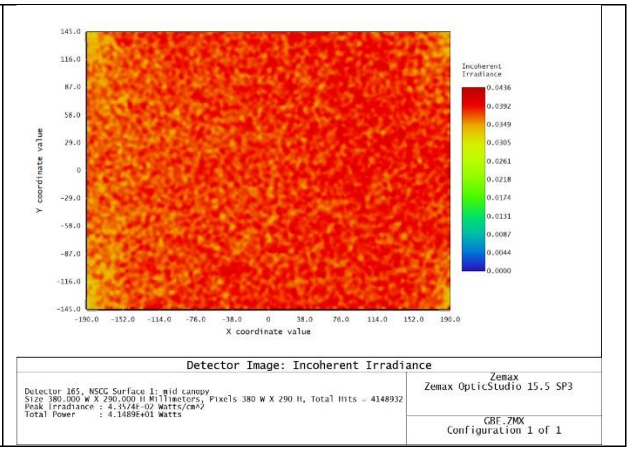


Detector Image: Incoherent Irradiance

```
Detector 164, NSCG Surface 1: near field LEDs
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 4724857
Peak Irradiance : 4.0794E-01 Watts/cm^2
Total Power     : 4.7249E+01 Watts
```

Zemax
Zemax OpticStudio 15.5 SP3

GBF.ZMX
Configuration 1 of 1



Detector Image: Incoherent Irradiance

```
Detector 165, NSCG Surface 1: mid canopy
Size 380.000 W X 290.000 H Millimeters, Pixels 380 W X 290 H, Total Hits = 4148932
Peak Irradiance : 4.3574E-02 Watts/cm^2
Total Power     : 4.1489E+01 Watts
```

Zemax
Zemax OpticStudio 15.5 SP3

GBF.ZMX
Configuration 1 of 1