This paper is intended to help TOF engineers using the calculation sheet AN02.2 to get an approximation of the optical power budget of a TOF system. It advises how to enter the input parameters and how to interpret the calculated results. In addition, this paper also provides some useful hints to help the TOF design engineer to develop a successful TOF illumination system.

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1. Introduction

An important step in designing TOF systems is to quickly get an estimation of the optical power needed to illuminate the scenery. A TOF camera is “living” from enough modulated light reflected back from the objects in the scenery. Especially, dark objects far away being observed with a camera system with a large field of view (FOV) do not reflect much signal. The calculation sheet AN02.2 is a very helpful tool to estimate how much illumination power is needed to detect any object. The calculations are based on the optical axis only. The real values can deviate significantly due to receiver lens distortion, aberration and illumination density distribution. This guide provides a step-by-step tool how to use the calculation sheet AN02.2. It is not an explanation why and how the parameters are calculated. For such explanations, refer to the application note AN02.0 which is the main reference document.

2. Reference documents

This application note makes references to or is based on following base documents

- Application note AN02.0, Reflected power calculation, ESPROS
- Application note AN02.2, Enhanced optical power calculation (form sheet), ESPROS
- Datasheet epc660-V2.01, ESPROS
- Datasheet DME 660-V1.04, ESPROS
- LED Datasheet SFH 4715S-V1.3, OSRAM
- VCSEL Datasheet PCW-SMV-2-W0850-D60-45, Princeton
- VCSEL Angular Beam Profile for PCW-SMV-2-W0850-D60-45, Princeton

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3. Data Input

3.1 Emitter datasheet data

The first step is to enter the relevant parameters of the illumination source (LED, VCSEL, laser diode) from its datasheet into the section Emitter / Datasheet.

IMPORTANT NOTE:

The illumination source has to be fast enough to be modulated with the target frequency. Typically, IR-LED's are relatively slow devices and they are available in two categories: General IR-Illumination for scenery illumination of security cameras. These IR-LED's have rise/fall time in the range of micro-seconds and cannot be used for TOF applications. A TOF illumination device should have a rise/fall time of less than 20ns for modulation frequencies up to 12MHz. If the modulation frequency is up to 24MHz, 12ns rise/fall time is fine. If the modulation frequency is 40MHz, 5-6ns rise/fall time is necessary to obtain good illumination modulation contrast.

3.1.1 Example with OSRAM LED 4715S

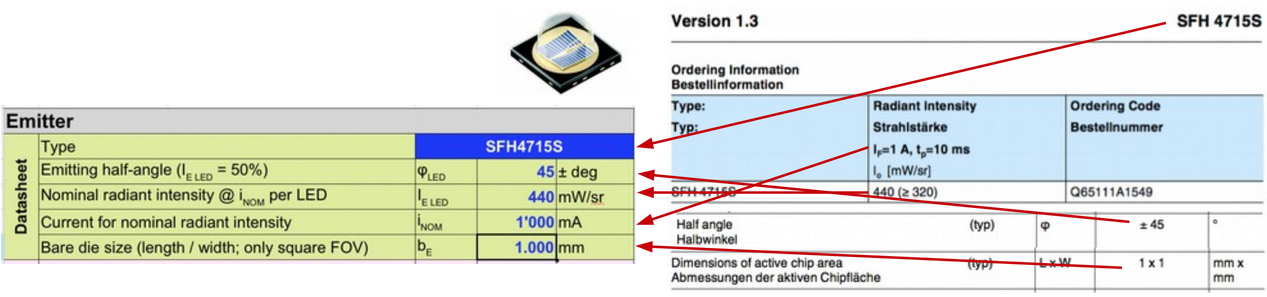

Figure 1: Input of the emitter data according the LED data sheet

IMPORTANT NOTE: Radiant intensity must be defined in mW/sr!

Source www.osram.com

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3.1.2 Example with VCSEL Princeton PCW-SMV-2-W0850-D60-45

Figure 2: Setup VCSEL parameters correctly

Source www.princetonoptronics.com/wp-content/uploads/PCW-SMV-2-W0850-1-D86-56.pdf

Datasheet parameter definitions:

Type	This is a documentation field only
Emitting half-angle ($I_{E\ LED}$ = 50%)	Use the value according to the datasheet. If there is no value available in case of a VCSEL, choose a number between 4.5° … 7.5°. This value affects only the “total radiant intensity” as long as the “opt. Power DC” value matches the datasheet value.
Nominal radiant intensity @ i_{NOM} per LED	Data sheet value in mW/sr
Current for nominal radiant intensity	Nominal current to get the nominal irradiance according to the data sheet
Bare die size (length / width; only square FOV)	Used to calculate the focal length

Table 1: Datasheet parameter definitions

NOTES:
For further calculation, do not change anymore values in this section. Adjust only values in this section to align to the expected camera design.

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3.2 Emitter application data

The second step is to enter the application parameters of the emitter. For example, the light output power is defined in the datasheet at a specific forward current, typically for DC conditions (100% duty cycle). Since we use a modulated signal, the duty cycle is lower than 100%. Thus, the peak current of the modulated signal can be higher than the rated DC current. The data sheet has a section with a curve that shows the maximum forward peak current at a certain duty cycle. This current is typically much higher than the DC current. Table 1 gives an overview about the parameters. A more detailed description can be found in the next sections.

FOV horizontal (round)	Horizontal field of view angle. If the field of view is round, this parameter is used to define the field of view
FOV vertical	Vertical field of view angle. Not used if a round field of view is selected.
FOV: 1: rectangular, 2: round	If the illumination lens forms a rectangular spot, choose “1”. This is the case typically with a diffuser on a VCSEL. If the illumination lens forms a round spot, choose “2”.
Effective current per emitter @ application	Enter the intended peak current. This current can be much higher than the max. DC current according to the data sheet.
Number of emitters @ application	Several emitters can be used in parallel to increase the irradiance of the illumination. Enter the number of emitters here. However, make sure that all emitters are in perfect phase. A time delay of just 100ps will have a negative impact on the modulation contrast and lead to distance errors in the near field.
Forward voltage @ effective current	Use the forward voltage drop at the used forward current. This parameter is used to calculate the power dissipation.
Frame rate	The frame rate has an influence on the power dissipation. The higher the frame rate the higher the power dissipation.
Number of DCS	This field defines the number of DCS' until the next distance value can be calculated. It is “4” in a standard 4-DCS scheme, “2”, if only two DCS' are used (with increased distance error) or “1” in rolling mode.
Lens efficiency	If there is a lens in front of the emitter, losses on the surfaces will reduce the transmission efficiency. Covers all optical power losses of the emitting system parts, like lens transmission, filters, front cover window, etc. If an LED is used without a lens or a VCSEL with a diffuser, enter 100% efficiency.

Table 2: Application parameter definitions

3.2.1 FOV without emitting optics e.g. DME 660

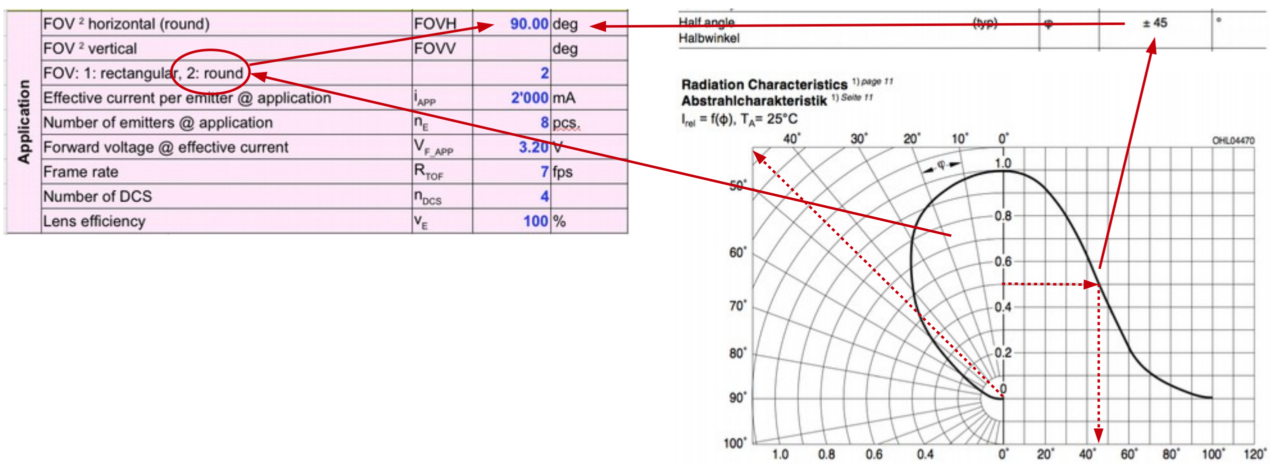

Figure 3: Select emitting FOV without emitting optics e.g. according LED datasheet

3.2.2 FOV with emitting optics e.g. with a VCSEL illumination

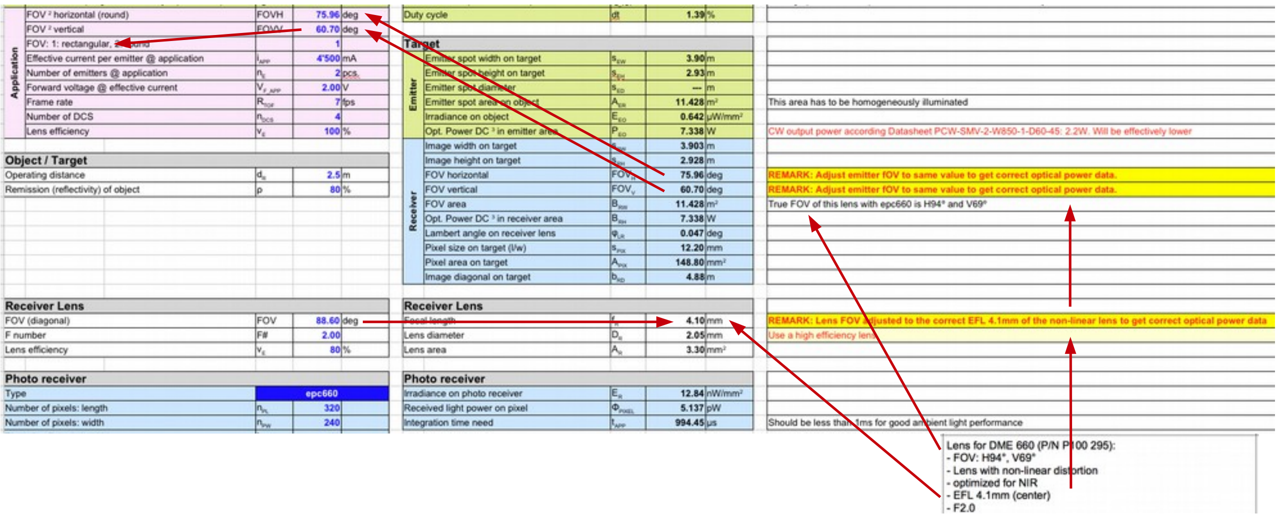

Figure 4: Select emitting FOV with emitting optics for a VCSEL

3.2.3 Optical power adjustment to match the application e.g. DME 660

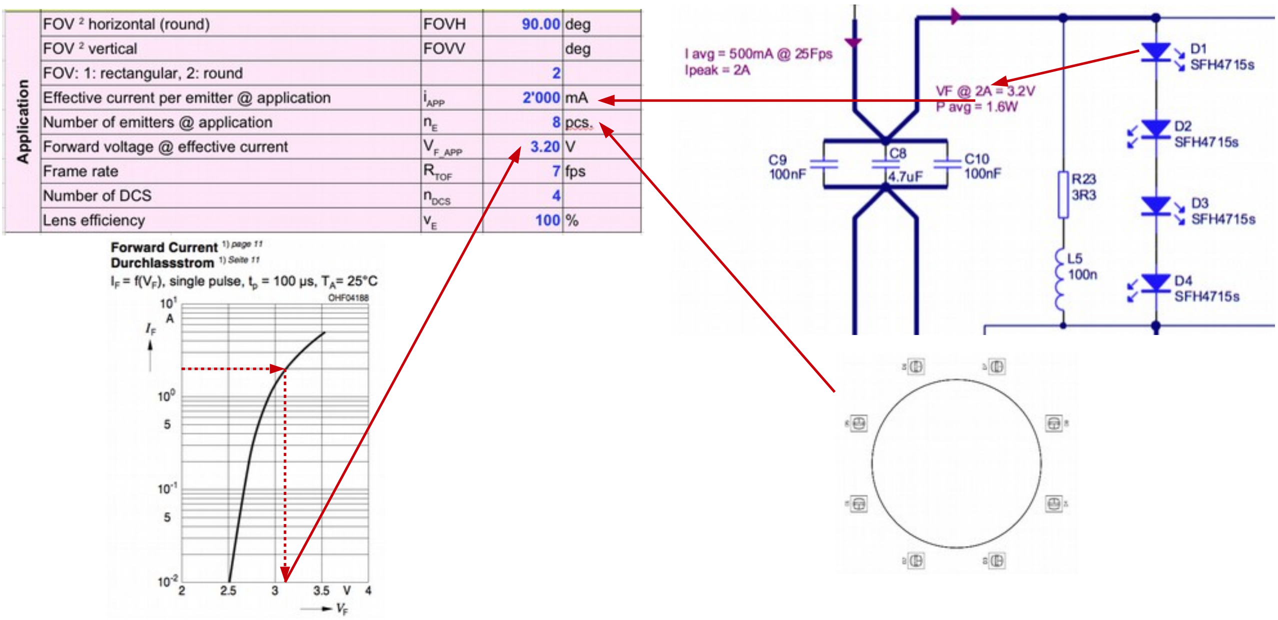

Figure 5: Select emitting LED / VCSEL parameters for the application

NOTES:

- Use these parameters to adjust the optical power for the expected / necessary integration time e.g. < 1ms.
- Take care that the emitting FOV and receiving FOV are matching.
- Take care not to exceed the maximum parameters of the LED/VCSEL datasheet.
- Take care that the electrical parameters are feasible.

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3.3 Object data

In this section of the calculation sheet, the object data are entered. There are just two parameters: the distance to the object and the object reflectivity (remission). Please note that the distance has a power of two impact whereas the object reflectivity is linear. For example if the remission of the object is e.g. 40%, the received signal is half of an object with 80% reflection. If the distance is doubled, then the received signal is one quarter only. Or in other words, the distance ratio from the closest to the farthest object location has a much higher impact on the received signal than the object reflectivity.

Object / Target			
Operating distance	d_R	6.0	m
Remission (reflectivity) of object	ρ	90	%

*Table 3: **Object data input***

- Operating distance: Distance from lens surface to the object/target
- Remission: Reflectivity of the object/target. Table 4 Shows some numbers of real objects:

Surface	Reflective index
Testcard Kodak WHITE	90%
Testcard Kodak Gray	18%
White (paper)	75 – 85 %
Light yellow	60 – 70 %
Light grey, light green	40 – 60 %
Middle brown, middle gray	20 – 30 %
Dark grey, other dark colors	10 – 20 %
Mirror, highly polished, retro-reflectors	140 – 30'000 %
Silver mirror, behind glass	80 – 90 %
Clear glass, PMMA	6 – 8 %
Stainless steel, micro-finished	400%
Stainless steel, brushed	120%
Stainless steel, dull	50 – 60 %
Aluminum, polished	140%
Aluminum, high-gloss	80 – 90 %
Aluminum, dull	55 – 75 %
Aluminum, anodized, black	75 – 85 %
Plaster, white	70 – 80 %
Opaque white plastic	87%
Black plastic	14%
Concrete, sandstone, gray	15 – 50 %
Brick, red	10 – 20 %
Carbon, black	2 – 10 %
Clean pine wood	75%
Wood, light	40 – 60 %
Wood, dark	10 – 15 %

Surface	Reflective index
Snow	80 – 90 %
Cloud	60 – 90 %
Desert	30%
Green field, lawn, vegetation	6 – 25 %
Forest	5 -18 %
Soil	7%
Water surface	5 – 22 %
Roadway, asphalt	15%
Roadway, concrete	8 – 15 %
Roadway, macadam	6 – 13 %
Roadway, dirty and gravel	3 – 7 %
Automobile tire, black (new)	1.5%
Caucasian face, male, front	30 – 50 %
Negroid face male, front	10 – 30 %
Light grey suit	11%
Neoprene, black	4%
Dark blue suit, overcoat	2 – 3 %
Black velvet	0.4%
Transparent brown plastic bottle	60%
Clear plastic bottle	40%
Beer foam	70%
Cork	35%
Wooden pallets, clean	20%
Carpet, light	30 – 35 %
Carpet, dark	2 – 20 %
Black foam	0.2%

Table 4: Reflection index of various surfaces

IMPORTANT NOTE:

- Values in Table 4. The reflectivity can vary significantly from the value stated in the table. Thy are also wavelength dependent.
- Pixel size on target: Basic condition for reliable TOF distance reading:
  Ideally at the target distance, the object should be larger than tree times the pixel size on the target. This guarantees not seeing two different objects or a big reflectivity transition (e.g. black to white having pixel cross-talk) with one pixel.

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3.4 Receiver lens data

3.4.1 Option 1: Design with lens data FOV and F-number

Receiver Lens					
Datasheet	FOV 4 (diagonal)	FOV	88.60	deg
	F-number	F#	1.40	
	Lens efficiency	V_E	80	%

Table 5: Linear lens: Fill in the lens data according the datasheet

- FOV (diagonal): Round (or diagonal) field of view of the lens system.
  NOTE: If the FOV for the used imager type is not known, set the FOV according chapter 3.4.2.
- F-number: F-number of the aperture of the lens system. The lower the number, the higher the gain of the lens.
- Lens efficiency: Covers all optical power losses of the emitting system part, e.g. lens transmission, filters, front cover window, etc.

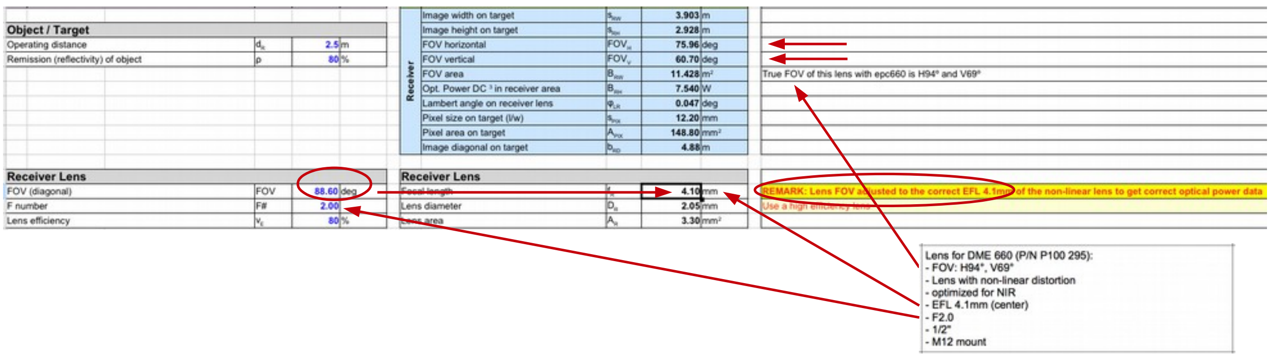

Figure 6: Non-linear lens: Adjust FOV to get correct focal length on the optical axis

3.4.2 Option 2: Design with focal length and lens diameter

- FOV (diagonal): Adjust the FOV number until focal length shows the correct value.
  NOTE: This can be done only after setting the correct photo-receiver data.
- F-number: Adjust the F-number until the lens diameter (aperture) shows the correct value.
- Lens efficiency: Covers all optical power losses of the emitting system part, e.g. lens transmission, filters, front cover window, etc.

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3.5 Photo-receiver datasheet data

Photo-receiver				
Datasheet	Type	epc660		
	Number of pixels: length	n_{PL}	320	
	Number of pixels: width	n_{PW}	240	
	Pixel size (length / width)	b_{PIXEL}	20	µm
	Integration time for irradiance 1 LSB	t_{NOM}	103.00	µs
	Irradiance for 1 LSB @ t_{NOM}	$E_{R\text{-}LSB}$	0.620	nW/mm^2
	Irradiance level expected in LSB	E_R	50	LSB

Table 6: Photo-receiver data input

- Type: Imager type
- Number of pixels: length: Horizontal pixel-field size. Defines the FOV on the object.
- Number of pixels: width: Vertical pixel-field size. Defines the FOV on the object.
- Pixel size: Pixel dimension for a square pixel. Defines the FOV on object.
- Integration time for irradiance 1 LSB: Integration time for the nominal sensitivity/irradiance definition according to the datasheet.
- Irradiance for 1 LSB: TOF imager sensitivity according to the datasheet. This value is wavelength dependent because the quantum efficiency of the imager is a function of wavelength.
- Irradiance level expected in LSB: Set the TOF amplitude value which is expected for the application.
  Proposal: Choose e.g. minimum TOF amplitude for maximum acceptable distance noise.
  Refer to the distance noise chart of the imager datasheet.

4. Result interpretation

The most important results are marked with a red cell border. The first result to check is the integration time needed t_{APP} to achieve the intended signal in the receiver (LSB) with the given application parameters. It is at the bottom of the Results section of the table. If this value is below 1ms, the application will work well in outdoor conditions, provided that the ambient light is filtered with an efficient optical bandpass filter with a filter bandwidth of less than 60nm. If the integration time is higher than 1ms, ambient light requirements have to be relaxed.

Results

Emitter			
Total radiant intensity @ i_{NOM}	$I_{E\ TOT}$	**3.96**	W/sr
Focal length for bare die (only square FOV)	f_R	**---**	mm
Electrical peak power	P_{PP}	**31.50**	W
Electrical energy per DCS	I_{E_DCS}	**10.007**	mWs
Total electrical power consumption (average)	I_{E_TOT}	**0.801**	W
Duty cycle of emitter	dt	**2.54**	%

Target				
Emitter	Emitter spot width on target	s_{EW}	**---**	m
	Emitter spot height on target	s_{EH}	**---**	m
	Emitter spot diameter	s_{ED}	**9.21**	m
	Emitter spot area on object	A_{ER}	**66.591**	m²
	Irradiance on object	E_{EO}	**0.109**	µW/mm²
	Opt. DC power in emitter area	P_{EO}	**7.288**	W
Receiver	Image width on target	s_{RW}	**9.368**	m
	Image height on target	s_{RH}	**7.026**	m
	FOV horizontal	FOV_H	**75.96**	deg
	FOV vertical	FOV_V	**60.70**	deg
	FOV area	B_{RW}	**65.823**	m²
	Opt. DC power in receiver area	B_{RH}	**7.204**	W
	Lambert angle on receiver lens	φ_{LR}	**0.028**	deg
	Pixel size on target (l/w)	s_{PIX}	**29.28**	mm
	Pixel area on target	A_{PIX}	**857.07**	mm²
	Image diagonal on target	b_{RD}	**11.71**	m

Receiver Lens			
Focal length [3]	f_R	**4.10**	mm
Lens diameter	D_R	**2.93**	mm
Lens area	A_R	**6.73**	mm²

Photo-receiver			
Irradiance on photo-receiver	E_R	**5.03**	nW/mm²
Received light power on pixel	Φ_{PIXEL}	**2.010**	pW
Integration time need	t_{APP}	**635.39**	µs

Table 7: Results section of the optical power budget calculation

The next result to be checked is the total electrical power needed for the illumination I_{E_TOT}. Does it match with the power I have available for the application? If not, one or all of the the following application parameters have to be relaxed:

- Frame rate
- Field of view
- Operating range
- An option is also to decrease the receiver lens F-number.

Finally, the duty cycle result has to be evaluated in order not to exceed the optical power limits of the LED or the VCSEL.

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5. Ambient-light conditions

The integration time is, among others, an important value to evaluate, how much ambient light can be tolerated to operate the TOF camera. It is important that the light to the imager has been filtered with an efficient bandpass filter, matching with the used emitter wave-length.

Office, business area	Luminance [Lux]
Traffic area, corridor	20 – 50
Lobby, reception, restroom, staircase	150 – 200
Conference room, reception room	200 – 750
Office work	700 – 1'500
Writing table	1'000 – 2'000
Production area	
Warehouse, reception room	150 – 300
Regular production	300 – 750
Inspection area	750 – 1'500
Electronic production	1'500 – 3'000
Hotel area	
Reception, cashier's section	200 – 1'000
Shop area	
Shopwindow, packing table	200 – 1'000
Shopwindow, outside	1'500 – 3'000
Hospital, doctor's surgery	
Patient's room, storage space	100 – 200
Diagnostic room	300 – 750
Surgery room, emergency room	750 – 1'500
Education, school area, library	
Auditorium, indoor in general	100 – 200
Classroom	300 – 750
Laboratory, library, painting and art	750 – 1'500
Outdoor	
Dark night	< 0.001
Starlight	0.001 – 0.01
Full moon	0.01 – 0.1
Street illumination, worse	0.1
Street illumination, good	20
Sunset	1 – 100
Cloudy, heavily	100 – 2'000
Cloudy	2k – 10k
Cloudy, lightly	10k – 25k
Hazy, transparent clouds	25k – 50k
Sunshine	50k – 100k

Table 8: Typical ambient-light condition

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