Optical Design with Zemax for PhD

Lecture 11: Illumination

2016-03-02

Herbert Gross
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- Lambertian radiator
- Flux calculation
- Non-sequential raytrace
- Light sources
- Classical illumination systems
- Beam homogeneization by integrator rods
- Beam homogeneization by fly eye condensors
- Miscellaneous
- Illumination in Zemax
# Radiometric vs Photometric Units

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<th>Photometric</th>
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<td>Term</td>
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<tr>
<td>Energy</td>
<td>Energy</td>
<td>Radiometric Energy</td>
<td>Ws</td>
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<tr>
<td>Power</td>
<td>Radiation flux</td>
<td>$\Phi$</td>
<td>$W$</td>
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<tr>
<td>Radiation flux</td>
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<td>Radiometric Flux</td>
<td>$W$</td>
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<td>Power per area and solid angle</td>
<td>$L = \frac{d^2 \Phi}{\cos \theta d\Omega dA}$</td>
<td>Radiance</td>
<td>$W / \text{sr} / \text{m}^2$</td>
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<td>Power per solid angle</td>
<td>$I = \frac{d\Phi}{d\Omega} = \int L , dA_\perp$</td>
<td>Radiant Intensity</td>
<td>$W / \text{sr}$</td>
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<td>Emitted power per area</td>
<td>$E = \frac{d\Phi}{dA} = \int L \cos \theta , d\Omega$</td>
<td>Radiant Excitance</td>
<td>$W / \text{m}^2$</td>
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<td>Incident power per area</td>
<td>$E = \frac{d\Phi}{dA} = \int L \cos \theta , d\Omega$</td>
<td>Irradiance</td>
<td>$W / \text{m}^2$</td>
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<td>Time integral of the power per area</td>
<td>$H = \int E , dt$</td>
<td>Radiant Exposure</td>
<td>Ws / m$^2$</td>
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Solid Angle

- 2D extension of the definition of an angle:
  area perpendicular to the direction over square of distance

- Area element $dA$ in the distance $r$ with inclination $\theta$

$$ d\Omega = \frac{\cos \theta \cdot dA}{r^2} = \frac{dA_{\perp}}{r^2} $$

- Units: steradian sr

- Full space: $\Omega = 4\pi$
  half space: $\Omega = 2\pi$

- Definition can be considered as cartesian product of conventional angles

$$ d\Omega = \frac{dA}{r^2} = \frac{dx}{r} \cdot \frac{dy}{r} = \alpha_x \cdot \alpha_y $$
Solid Angle: Special Cases

- Cone with half angle $\varphi$
  
  $$\Omega = 2\pi \cdot (1 - \cos \varphi)$$

- Thin circular ring on spherical surface
  
  $$d\Omega = \frac{2\pi r \cdot \sin \varphi \cdot r \cdot d\varphi}{r^2} = 2\pi \cdot \sin \varphi \cdot d\varphi$$
Irradiance

- Irradiance: power density on a surface
  Conventional notation: intensity
  Unit: watt/m²

\[ E = \frac{d\Phi}{dA} = \int L \cdot \cos \theta \, d\Omega \]

- Integration over all incident directions
- Only the projection of a collimated beam perpendicular to the surface is effective

\[ E(\theta) = E_0 \cdot \cos \theta \]
Differential Flux

- Differential flux of power from a small area element $dA_s$ with normal direction $n$ in a small solid angle $d\Omega$ along the direction $s$ of detection

$$d^2\Phi = L \cdot d\Omega \cdot dA_{s\perp}$$

$$= L \cdot \cos \theta_s \cdot d\Omega \cdot dA_s$$

$$= L \cdot d\Omega \left( s \cdot dA_s \right)$$

- Integration of the radiance over the area and the solid angle gives a power
Fundamental Law of Radiometry

- Differential flux of power from a small area element \(dA_S\) on a small receiver area \(dA_R\) in the distance \(r\), the inclination angles of the two area elements are \(\theta_S\) and \(\theta_R\) respectively.

Fundamental law of radiometric energy transfer

\[
d^2\Phi = \frac{L}{r^2} \cdot dA_{S\perp} \cdot dA_{E\perp}
\]

\[
= \frac{L}{r^2} \cdot \cos \theta_S \cos \theta_E \cdot dA_S \cdot dA_E
\]

- The integration over the geometry gives the total flux.
Radiance independent of space coordinate and angle

The irradiance varies with the cosine of the incidence angle

Integration over half space

Integration of cone

Real sources with Lambertian behavior: black body, sun, LED

\[ L(\vec{r}, \vec{s}) = L = \text{const} \]

\[ E(\theta) = L \cdot A \cdot \cos \theta = E_o \cdot \cos \theta \]

\[ \Phi_{\text{Lam}}^{H} = \int E(\theta) \cdot d\Omega = \pi \cdot A \cdot L \]

\[ \Phi_{\text{Lam}}(\phi) = \pi AL \cdot \sin^2 \phi \]
Radiation Transfer

- Basic task of radiation transfer problems:
  integration of the differential flux transfer law

\[ d^2 \Phi = \frac{L}{r^2} \cdot dA_{S\perp} dA_{E\perp} = \frac{L}{r^2} \cdot \cos \theta_s \cos \theta_E dA_s dA_E \]

- Two classes of problems:
  1. Constant radiance, the integration is a purely geometrical task
  2. Arbitrary radiance, a density function has to be integrated over the geometrical light tube

- Special cases:
  Simple geometries, mostly high symmetric, analytical formulas

- General cases: numerical solutions
  - Integration of the geometry by raytracing
  - Considering physical-optical effects in the raytracing:
    1. absorption
    2. reflection
    3. scattering
• Decomposition of the light cone into small infinitesimal ray tubes

• The irradiance scales with the area change

\[
\Delta A' = \left(1 + \frac{r}{R_x}\right) \cdot \left(1 + \frac{r}{R_y}\right) \cdot \Delta A
\]
Raytube-Modell

- Optical power flux

- General transfer: Jacobian matrix of differential area transform

\[ \Delta^2 \Phi = \frac{L_j}{r_{j,j+1}^2} \cdot \cos \theta_j \cdot \cos \theta_{j+1} \cdot \Delta A_j \cdot \Delta A_{j+1} \]
Non-Sequential Raytrace

- Conventional raytrace:
  - the sequence of surface hits of a ray is pre-given and is defined by the index vector
  - simple and fast programming of the surface-loop of the raytrace
- Non-sequential raytrace:
  - the sequence of surface hits is not fixed
  - every ray gets its individual path
  - the logic of the raytrace algorithm determines the next surface hit at run-time
  - surface with several new directions of the ray are allowed:
    1. partial reflection, especially Fresnel-formulas
    2. statistical scattering surfaces
    3. diffraction with several grating orders or ranges of deviation angles
- Many generalizations possible:
  - several light sources, segmented surfaces, absorption, …
- Applications:
  1. illumination modelling
  2. statistical components (scatter plates)
  3. straylight calculation
Nonsequential Raytrace: Examples

1. Prism with total internal reflection

2. Ghost images in optical systems with imperfect coatings
3. Illumination systems, here:
   - cylindrical pump-tube of a solid state laser
   - two flash lamps (A, B) with cooling flow tubes (C, D)
   - laser rod (E) with flow tube (F, G)
   - double-elliptical mirror
     for refocussing (H)
Different ray paths possible
Illumination Simulation

- Simple raytrace: S/N depends on the number of rays $N$

- Improved SNR: raytube propagation, transport of energy density

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<td>$N = 100.000$</td>
<td>$N = 10.000$</td>
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RXI Collimator

- Collimating highly divergent radiation of a LED
- Separation of the beam path into two channels
- Good performance of collimation only for axis point
- Good collection efficiency
Special problems in the layout of illumination systems:
1. complex components: segmented, multi-path
2. special criteria for optimization:
   - homogeneity
   - efficiency
3. incoherent illumination: non-unique solution
Complex Geometries

- Lighthouse optics
- Fresnel lenses with height 3 m
- Separated segments
Realistic Light Source Models

CAD model of light sources:
  1. Real geometry and materials
  2. Real radiance distributions

Bulb lamp

XBO-lamp
Angle Indicatrix Hg-Lamp high Pressure

- Polar diagram of angle-dependent intensity
- Vertical line: Axis Anode - Cathode
Illumination LED lighting
Principle of Köhler illumination:

- Alternating beam paths of field and pupil
- No source structure in image
- Light source conjugated to system pupil
- Differences between ideal and real ray paths
2. Epi-illumination
Complicated ring-shaped components around objective lens
Principles of Beam Profiling

- Basic problem:
  Generation of a desired intensity distribution in space/angle domain

- Coherent beams:
  - appropriate phase element
  - free space propagation delivers re-distribution of intensity
  - optional phase correcting element
  - components: 1. smooth aspheres
    2. diffractive elements
    3. holograms

- Incoherent beams:
  - superposition of folded beams with subapertures
  - basic principle of energy conservation
  - components: 1. segmented mirrors
    2. lenslet arrays
    3. light pipes
    4. fibers
    5. axicons

- Partial coherent beams:
  problems with residual speckle
Axicon Component

- Axicon: component with cone surface
- Refractive or reflective versions possible
- Refractive:
  - small angle approximation \( \beta = (n-1) \cdot \alpha \)

- Fresnel principle not fulfilled
- Benefit: extended line along axis but nonuniform peak height
Axicon Lens Combination

- Generation of a ring profile
- Axicon: cone surface with peak on axis
- Ringradius in the focal plane of the lens

\[ R = (n - 1) \cdot f \cdot \alpha \]

- Ring width due to diffraction

\[ \Delta R = \frac{1.22 \cdot f \cdot \lambda}{a} \]
- Superposition of subapertures with different profiles
- Flip of orientation due to reflection
- Simple example:
- Towards tophat from gaussian profile by only one reflection
- Ideal homogenization:
incoherent light without interference
- Parameter:
  Length $L$, diameter $d$, numerical aperture angle $\theta$, reflectivity $R$
- Partial or full coherence:
speckle and fine structure disturbs uniformity
- Simulation with point source and lambert indicatrix or supergaussian profile
Principle of a light pipe / slab integrator:
Mixing of flipped profiles by overlapping of sub-apertures
Spatial multiplexing, angles are preserved
Number of internal reflexions determine the quality of homogeneity
- Number of reflection depends on length and incident angle

\[ m = \frac{2L \cdot \tan u'}{a} \]

- Kontrast V as a function of length
Rectangular Slab Integrator

- Full slab integrator:
  - total internal reflection, small loss
  - small limiting aperture
  - problems high quality of end faces
  - also usable in the UV

- Hollow mirror slab:
  - cheaper
  - loss of 1-2% per reflection
  - large angles possible
  - no problems with high energy densities
  - not useful in the UV
Conical Light Taper

- Waveguide with conical boundary
- Lagrange invariant: decrease in diameter causes increase in angle:
  Aperture transformed
  \[ D_{in} \cdot \sin u = D_{out} \cdot \sin u' \]
- Number of reflections:
  - depends on diameter/length ratio
  - defines change of aperture angle
Flyeye Array Homogenizer

- Array of lenslets divides the pupil in supabertures
- Every subaperture is imaged into the field plane
- Overlay of all contributions gives uniformity
- Problems with coherence: speckle
- Different geometries: square, hexagonal, triangles
- Simple setup with one array
- Improved solution with double array and additional imaging of the pupil

![Diagram of Flyeye Array Homogenizer]
Flyeye Array Homogenizer

- Simple model:
  Secondary source of a pattern of point sources
Flyeye Array Homogenizer

- Example illumination fields of a homogenized gaussian profile
  a) single array
  b) double array
    - sharper imaging of field edges
    - no remaining diffraction structures
Partial Coherent Illumination
Flys Eye Condenser

- Partial coherent radiation out of a fiber
  Single step flys eye condenser
- Residual speckle (green, mean) depends on
  focal length of collimator and divergence of the beam
- Modern mode decomposition: localized shifted modes
  - Non-orthogonal basis mode decomposition
  - Optimized basis to fulfill sampling theorem
  - Mode support localized corresponding
    to coherence cells
Fly Eyes Condensor in the Phase Space

- before array
- after array
- after condenser
- in array focal plane
- in receiver plane

I(u)
I(x)
- Lenses of constant focal length
- Size of refractive lenses large: diffraction negligible
- Improved mixing effect due to statistical variation of location and size of lenses
- Geometry: Voronoi distribution
Statistical Array of Micro Lenses

- Phase of mask
- Far field coherent
- Micro speckle
Statistical Scatter Plate: Coherence

- Speckle in far field due to residual coherence
  
  1. coherent

  2. partial coherent divergence 0.5 mrad

  3. partial coherent divergence 1.0 mrad
Reflection based array:
Facetted mirror
Principle:
Change of lateral intensity profile during propagation for non-flat phase

Setup:
1. first asphere introduces phase for desired redistribution
2. propagation over z
3. second asphere corrects the phase

Usually the profile exists only over a short distance
Simple options:
Relative illumination / vignetting for systems with rotational symmetry

Advanced possibility:
- non-sequential component
- embedded into sequential optical systems
- examples: lightguide, arrays together with focussing optics, beam guiding,...

General illumination calculation:
- non-sequential raytrace with complete different philosophy of handling
- object oriented handling: definition of source, components and detectors
- Relative illumination or vignetting plot
- Transmission as a function of the field size
- Natural and artificial vignetting are seen
Partly non-sequential raytrace:

- Choice of surface type 'non-sequential'
- Non-sequential component editor with many control parameters is used to describe the element:
  - type of component
  - reference position
  - material
  - geometrical parameters
- Some parameters are used from the lens data editor too:
  entrance/exit ports as interface planes to the sequential system parts
Example:

Lens focusses into a rectangular lightpipe
Illumination in Zemax

Complete non-sequential raytrace

- Switch into a different control mode in File-menu
- Defining the system in the non-sequential editor, separated into
  1. sources
  2. light guiding components
  3. detectors
- Various help functions are available to constitute the system
- It is an object (component) oriented philosophy
- Due to the variety of permutations, the raytrace is slow!
Illumination in Zemax

- Many types of components and options are available
- For every component, several parameters can be fixed:
  - drawing options
  - coating, scatter surface
  - diffraction
  - ray splitting
  - ...
Illumination in Zemax

- Starting a run requires several control parameters
- Rays can be accumulated
Illumination in Zemax

Typical output of a run: