



Optimization in Optical Design

When you tell a code like Zemax to optimize your design, it launches into a computationally intensive process of changing variables and assessing whether the system is improved or not. Each assessment potentially involves a lot of calculations, so efficient procedures are important.

Previously we looked at these patterns of rays launched into the pupil from a given object point for generating spot diagrams.



Uniform

random

square

triangular

polar

Now we consider how to launch **FEWER** rays into the pupil from a given object point during the more computationally intensive optimization process ...



Why not use uniform sampling for optimization?

Here's an illustration of why uniform sampling is simply not practical in the computationally intensive procedure of optimizing even a simple lens system.

Optimizing a simple triplet lens...

- 8 variables (4 curvatures, 4 thicknesses), 1000 choices per variable $\rightarrow \sim 10^{24}$ permutations
- If 10 sfcs, 100 wavelengths, 100 field pts, 1000 rays per wl & field pt $\rightarrow 10^8$ rays per system
- Need to trace 10^{24} systems $\times 10^8$ rays/system = 10^{32} ray-surfaces

If your computer can compute 10^9 ray-surfaces/second, you need 10^{23} seconds...

3×10^{15} Years!!!





Gaussian Quadrature

Efficient optimization requires an efficient way to integrate over a range of pupil locations, wavelengths, field angles, etc. Optical design uses the Gaussian quadrature numerical method to efficiently calculate integrals as a weighted sum at just a few carefully chosen points (“nodes”).

$$I = \int_{-1}^1 \omega(x)f(x)dx \approx \sum_{i=1}^n \omega_i f(x_i)$$

- $\omega(x)$ is a weighting function and $f(x)$ is function being integrated
- Uses knowledge of maximum order of integrand
- Exact result for polynomial integrand of order $(2n - 1)$ using n nodes
- Orders of magnitude fewer evaluation points than uniform sampling

Actual interval converted to $[-1, 1]$ using “change of interval” equations
See, e.g. http://en.wikipedia.org/wiki/Gaussian_quadrature

Key papers:

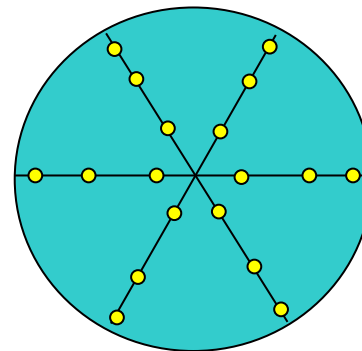
1. G. W. Forbes, “Optical system assessment for design: numerical ray tracing in the Gaussian pupil,” J. Opt. Soc. Am. A 5(11), 1943-1956 (1988).
2. B. J. Bauman and H. Xiao, “Gaussian Quadrature for optical design with non-circular pupils and fields, and broad wavelength ranges,” Proc. SPIE 7652, 76522S (2010).



Gaussian Quadrature on circular pupil

Gaussian quadrature applied to the variable ρ^2 over the interval $[0,1]$ yields the radii that are used in the Zemax default merit function.

$$\rho = \sqrt{L_i'} = \boxed{0.3357, 0.7071, 0.9420}$$



Type	Wave	Hx	Hy	Px	Py	Target	Weight	Value	% Contrib
1 DMFS									
2 BLNK	Sequential merit function: RMS spot radius centroid GQ 3 rings 6 arms								
3 BLNK	No default air thickness boundary constraints.								
4 BLNK	No default glass thickness boundary constraints.								
5 BLNK	Operands for field 1.								
6 TRAC	1	0.000	0.000	0.336	0.000	0.000	0.873	0.000	0.000
7 TRAC	1	0.000	0.000	0.707	0.000	0.000	1.396	0.000	0.000
8 TRAC	1	0.000	0.000	0.942	0.000		0.000	0.873	0.000

Merit Function Editor

Wizards and Operands Merit Function: 0

Optimization Wizard

Current Operand (1)

Optimization Function

Type: RMS

Criteria: Spot Radius

Reference: Centroid

Pupil Integration

Gaussian Quadrature

Rectangular Array

Rings: 3

Arms: 6

Obscuration: 0

Boundary Values

Glass Min: 0 Max: 1000 Edge Thickness: 0

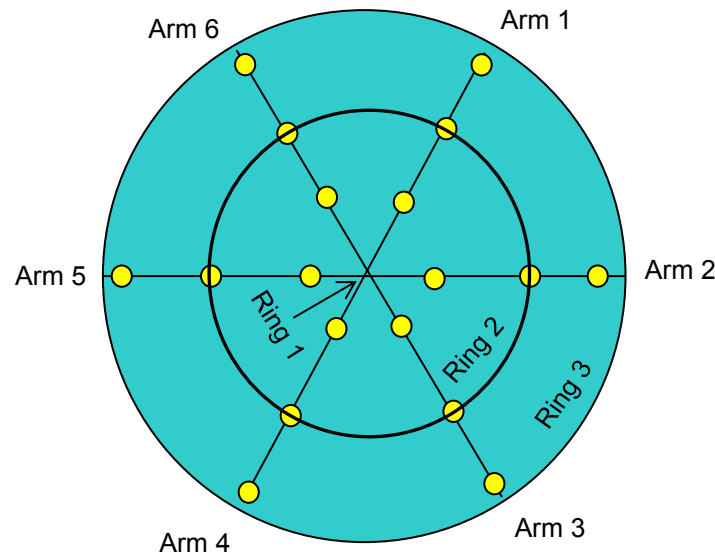
Air Min: 0 Max: 1000 Edge Thickness: 0

OK Apply Save Settings



Rings and Arms

Zemax refers to the pupil Gaussian quadrature nodes as intersection points of rings and arms. The intersection points of these rings and arms mark the pupil points through which rays are traced for optimization calculations.

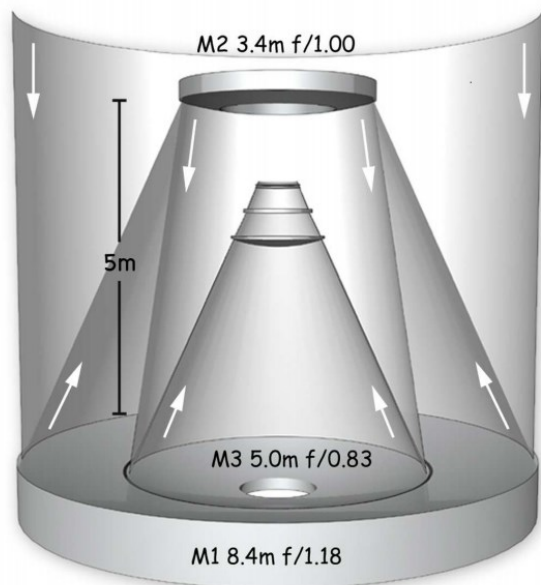
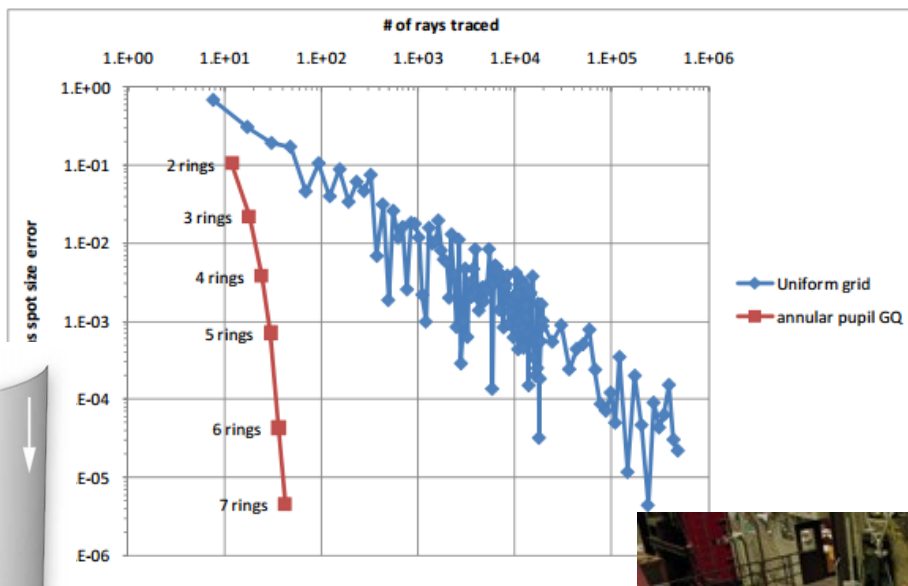


How many rings should you use? ... It depends on the order of your significant aberrations. Using $(2n-1)$ rings will provide optimal results for ray aberrations of order n . If in doubt, you can increase the number of rings until the result stops changing by more than $\sim 1\%$.



Example of GQ used for annular pupils

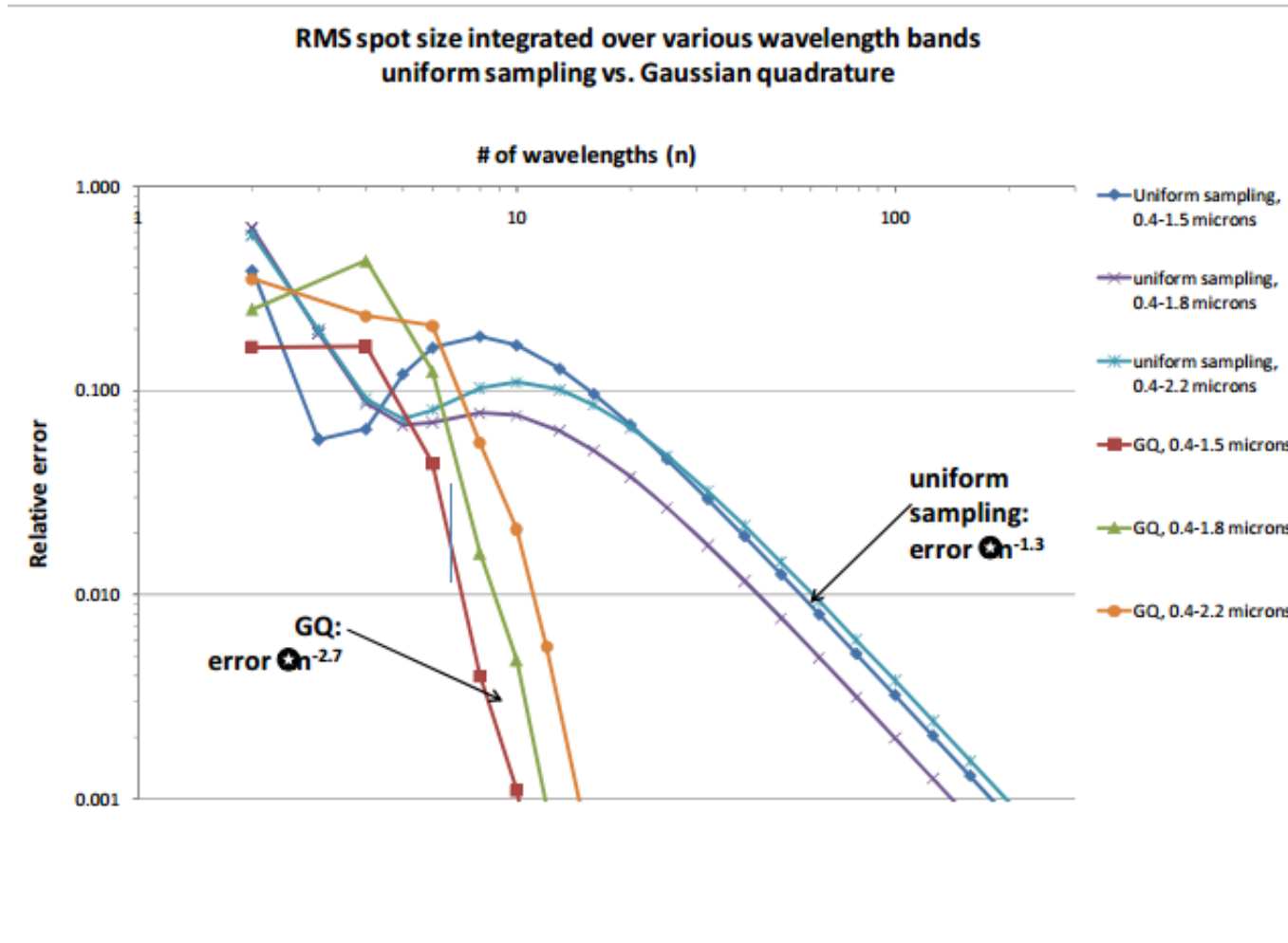
Here is an example of using GQ to speed up optimization for optical systems with annular pupils. This shows that several orders of magnitude fewer rays are required to achieve comparable rms spot size error for the Large Synoptic Survey Telescope (8.4 m primary mirror!)...





Example of GQ used for wide wavelength range

Three-glass apochromatic lens designed for visible through short-wave infrared





Merit Function

The merit function in Zemax is defined as a weighted sum of the differences between target values and current values of design parameters that are designated as variables.

$$(\text{MF})^2 = \frac{\sum_i W_i (V_i - T_i)^2}{\sum_i W_i},$$

where W_i is the weight, V_i is the current value, and T_i is the target value.



Remember: Many Possible Solutions

If you consider your design space as a surface, there can be many local maxima and minima. This means that an optimization algorithm rarely finds the best solution at first. Sometimes it is necessary to “beat on” the design to force it into a new local minimum.

