Feasibility study of new metrology for x-ray capillary development

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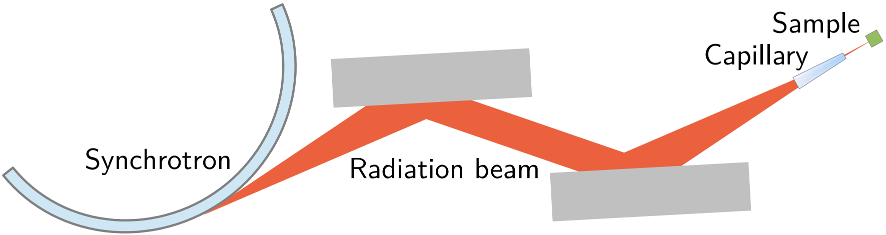
Outline

The role of x-ray capillaries at CHESS

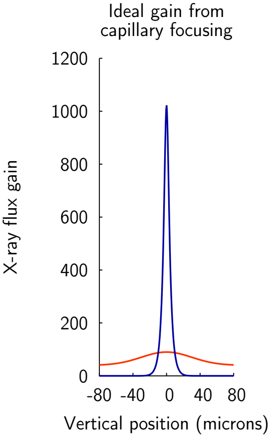
- Synchrotron radiation emerges in a relatively collimated narrow cone tangent to the beam path
- Upstream beamline optics can be used to select a bandwidth or perform initial focusing
- Capillaries are designed to perform the final microfocusing before the x-ray beam reaches a sample



Capillary design

What properties are we looking for?

- High intensity gain
- Low focal spot size
- High optical efficiency
- Effective over a wide energy range

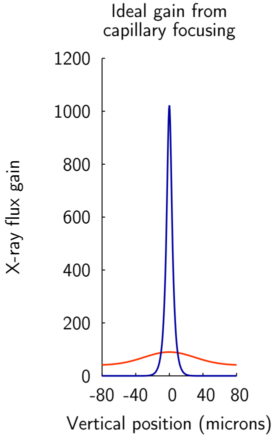


Capillary design

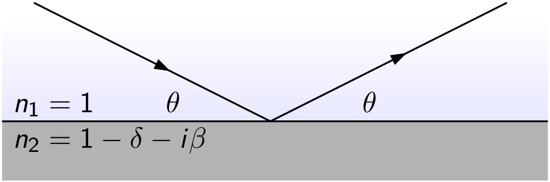
What properties are we looking for?

- High intensity gain
- Low focal spot size
- High optical efficiency
- Effective over a wide energy range

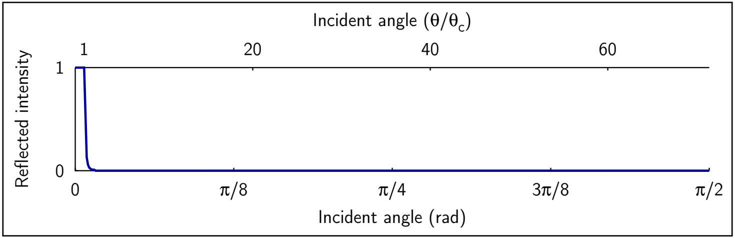
What tradeoffs can we make? The answer is dependent on the type of experiment the x-rays are being used to perform.



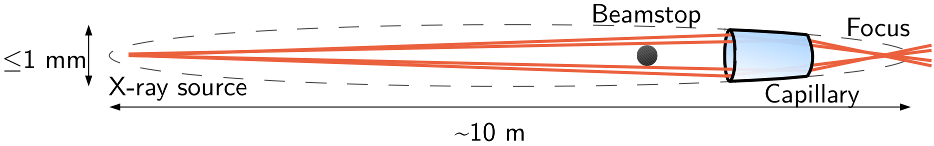
Total external reflection of x-rays



Because n_2 for glass is less than 1 by δ ($\sim$1 part in 10^5), any reflection below the critical angle (3 mrad at 10 keV) is referred to as *total external reflection* and preserves almost all ray intensity.

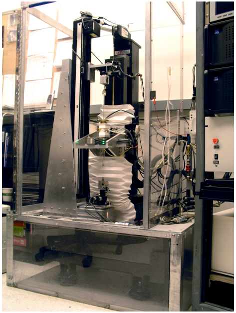


Capillary techniques



Cornell's pulling process:

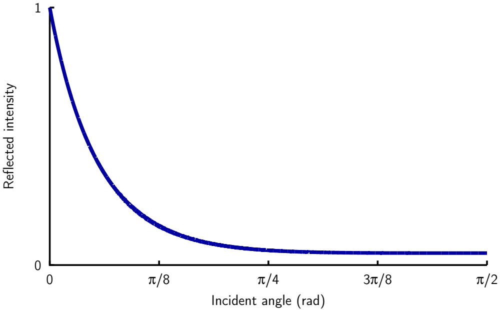
1. Program used describing a parabolic shape
2. Glass tube is loaded into the puller
3. Mobile furnace heats part of the glass
4. Tension is applied to the tube's ends
5. Capillary inner radius is locally reduced via conservation of mass
6. Furnace moves to new location, based on the stretched length

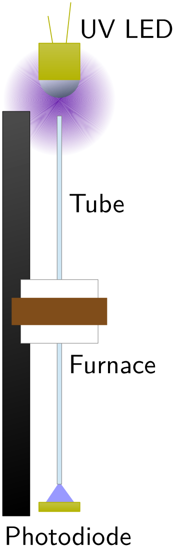


Capillary techniques

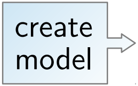
Is there a way to know the capillary ID as it's in the process of being stretched?

Use a UV light and a filtered photodiode to measure light transmission. Why UV?





Program structure flowchart



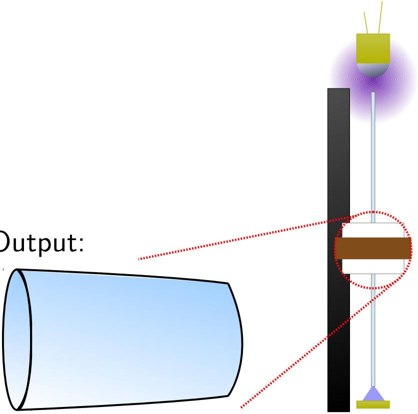
Program structure flowchart

create model →

Input (experimental):

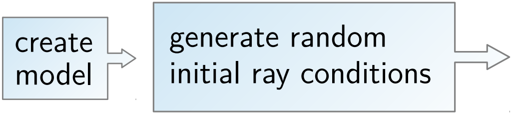
- Maximum divergence
- X-ray focal length
- X-ray source distance
- etc.

Output:



Includes both random scattering (Gauss-Markov process) *and preset centerline deflection error*

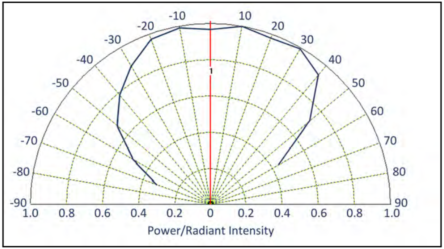
Program structure flowchart



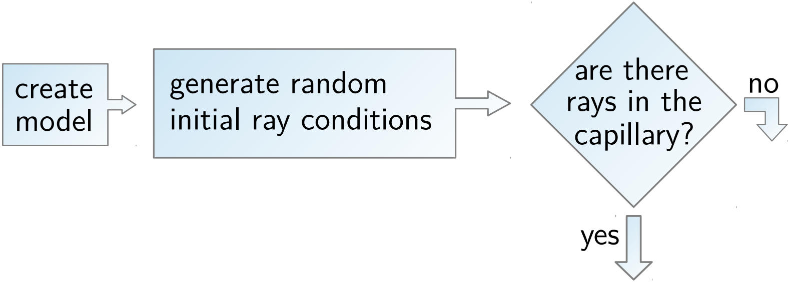
Program structure flowchart

create model → generate random initial ray conditions →

Monte Carlo: uniform distribution within extended source; specific angular distribution



Program structure flowchart



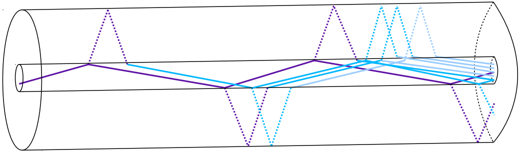
Program structure flowchart

create model → generate random initial ray conditions → are there rays in the capillary?

no ↓

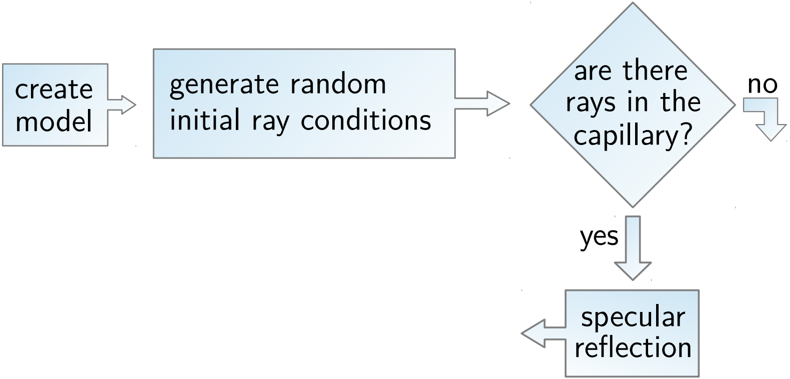
yes ↓

Assumption: photons do not refract through the capillary wall and reenter the inner space.

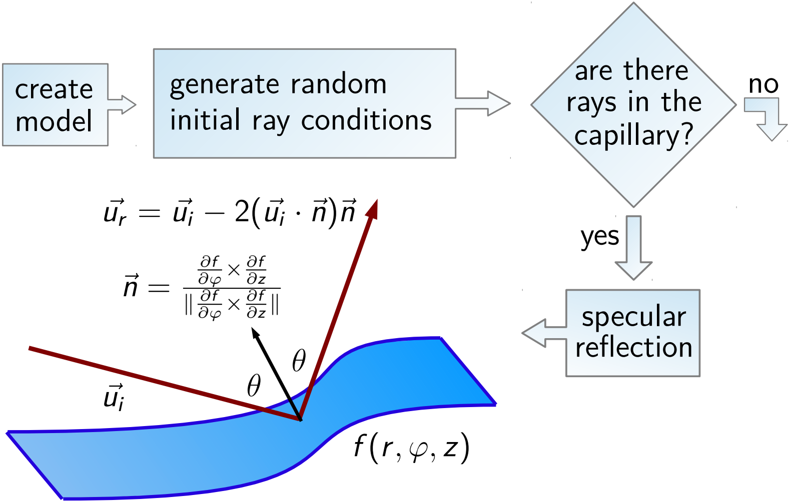


A separate, recursive 3D algorithm tracked all refracted rays and showed that they contributed <1% of total intensity, even in ideal cases like the one pictured

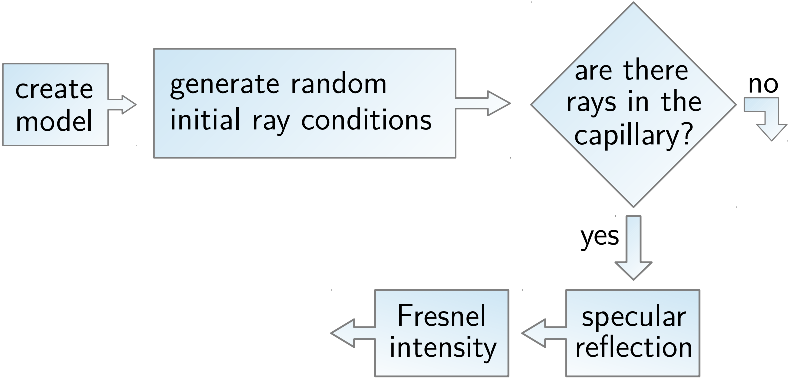
Program structure flowchart



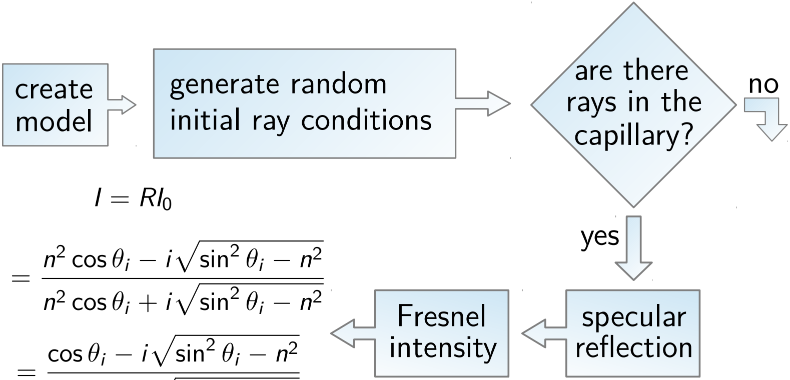
Program structure flowchart



Program structure flowchart



Program structure flowchart



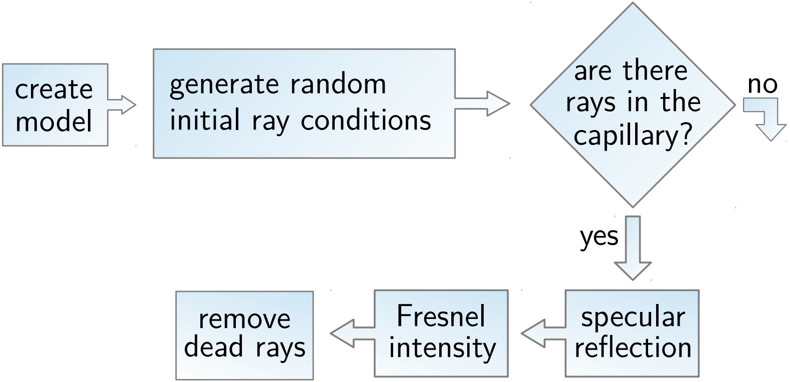
$$I = RI_0$$

$$R_{\parallel} = \frac{n^2 \cos\theta_i - i\sqrt{\sin^2\theta_i - n^2}}{n^2 \cos\theta_i + i\sqrt{\sin^2\theta_i - n^2}}$$

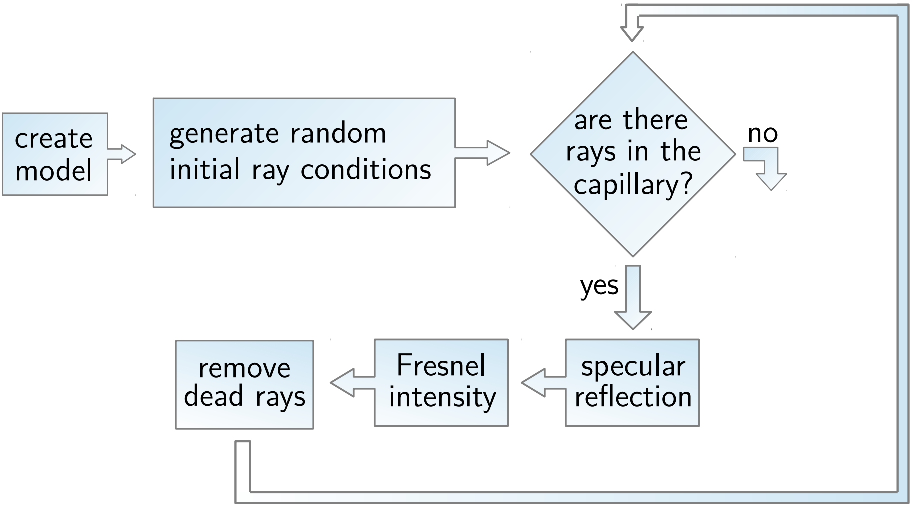
$$R_{\perp} = \frac{\cos\theta_i - i\sqrt{\sin^2\theta_i - n^2}}{\cos\theta_i + i\sqrt{\sin^2\theta_i - n^2}}$$

$$R = \frac{R_{\parallel} + R_{\perp}}{2}$$

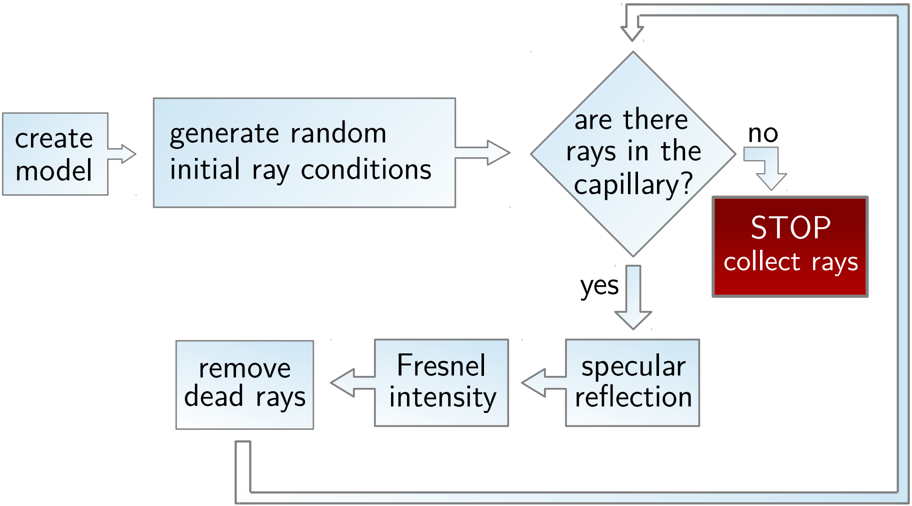
Program structure flowchart



Program structure flowchart



Program structure flowchart

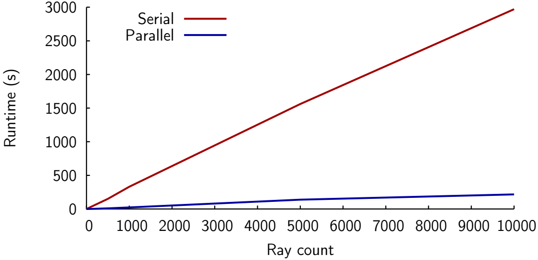


Why is this important?

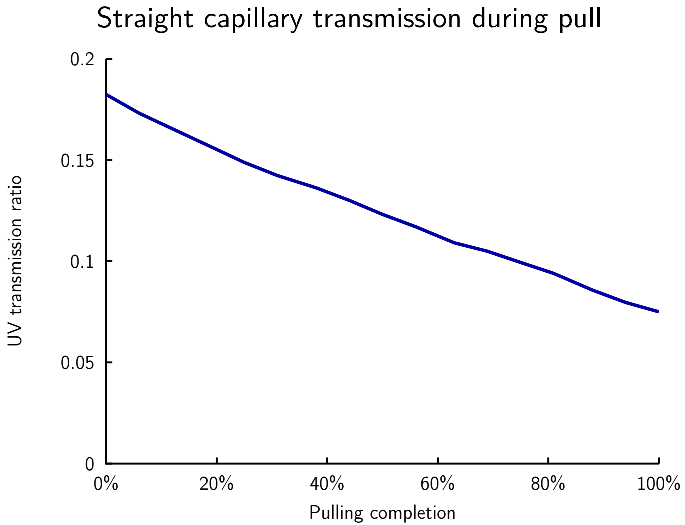
Similar programs have been written by Dr. Huang and previous REU students, but

- This is the first truly 3-dimensional capillary raytracer at Cornell, and accounts for non-ideal profiles (bending & scattering)
- This program employs parallel raytracing strategy rather than serial
- My method is more difficult to implement but much quicker

Both parallel and serial tracing methods run in $\Theta(n)$ time. However the coefficient on the parallel tracer is orders of magnitude smaller.



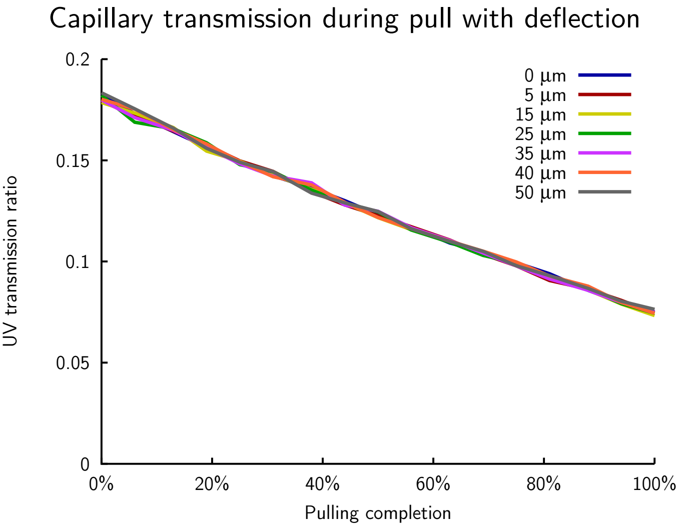
Primary simulation results



Shape:

- Max. radius 0.4 mm
- Min. radius 0.12 mm
- Init. length 20 cm

Primary simulation results



Shape:

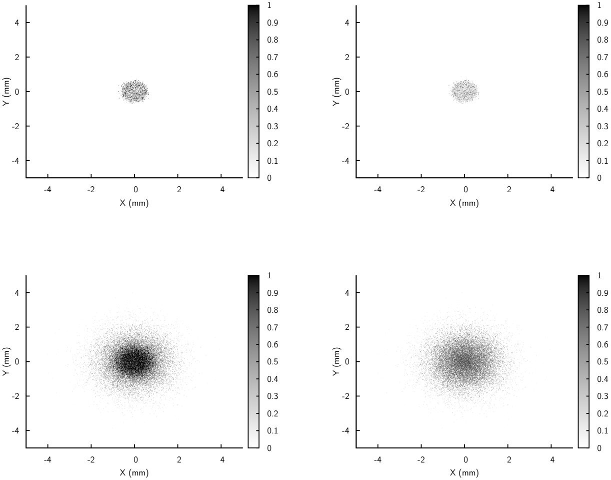
- Max. radius 0.4 mm
- Min. radius 0.12 mm
- Init. length 20 cm

Spatial intensity distributions

All rays | Only indirect

1 mm

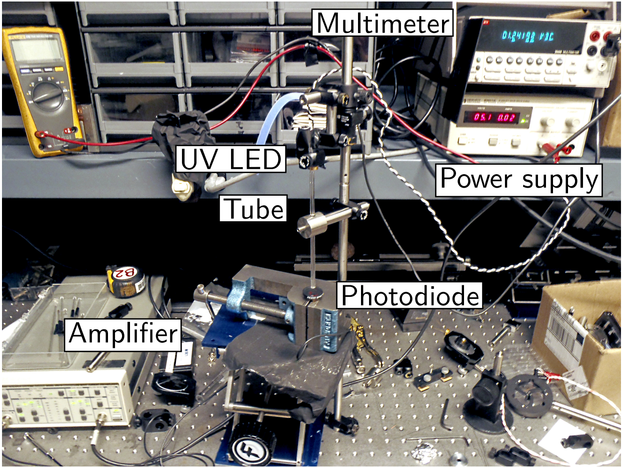
10 mm

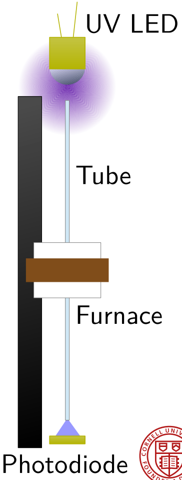


Total intensity:
54.0% indirect

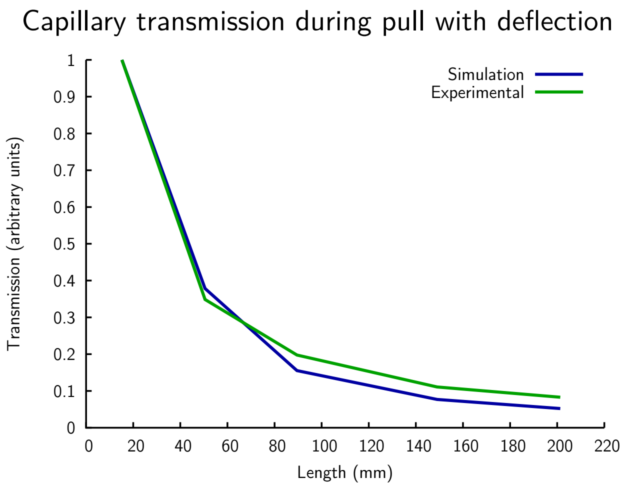
Experimental setup

For the experimental verification, instead of using pre-drawn capillaries, I used straight (unmodified) glass tubes.





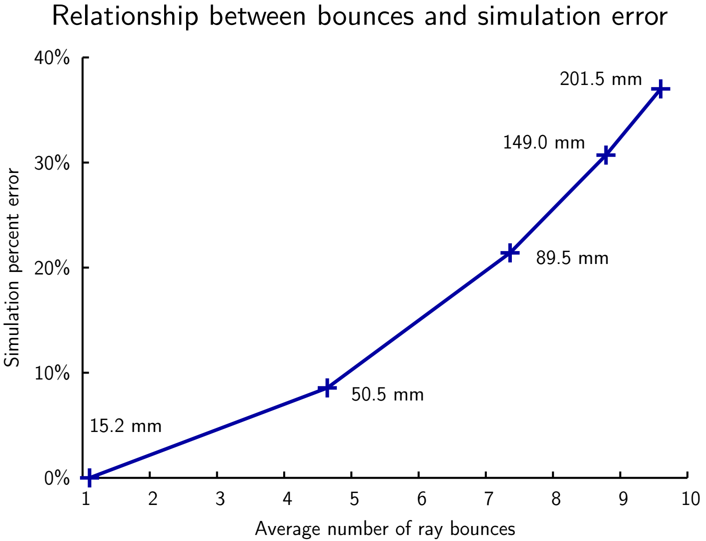
Normalized transmitted light



Justification:

- Ray reflection counts and error are likely to be correlated
- Longer tubes will result in more bounces
- The UV filter is not 100% opaque to visible light

Reflection count vs. raytracer accuracy



Summary

Conclusions

- Cornell now has a working, versatile 3D capillary raytracer.
- The fundamental idea behind the methodology works. A linear trend exists in UV intensity as a capillary is being pulled, so we can monitor the ID in realtime.
- This trend is unaffected by up to moderate profile imperfections.
- Preliminary experiment indicates that the simulation matches real data well but will tend to deviate for long capillary lengths.

Acknowledgments

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