

Synthetic X-Ray Radiograph Generation Using Ray Tracing in COMSOL Multiphysics®

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Abstract

X-ray imaging is widely used in nondestructive testing, industrial inspection, and medical diagnostics. Computational radiography provides a means of evaluating imaging geometries and generating controlled projection data without repeated physical experiments. This work presents a framework for generating synthetic two-dimensional X-ray radiographs in COMSOL Multiphysics® using the Ray Optics Module, deterministic ray tracing, and Beer–Lambert attenuation. X-rays are represented as rays emitted from a configurable source and propagated through three-dimensional single- and multi-material geometries toward a planar detector. Material-dependent attenuation is implemented using the Optical Attenuation model, with attenuation coefficients assigned according to the material traversed by each ray.

Two approaches for constructing radiographic images from the transmitted rays are investigated and compared: a boundary Accumulator and the Spot Diagram functionality. In both approaches, the transmitted ray intensity is mapped to detector position to form a two-dimensional X-ray projection. The resulting images demonstrate the expected dependence of transmitted intensity on material composition and X-ray path length. The model is evaluated using simple and multi-material geometries, and selected results are compared with Monte Carlo simulations. The framework also supports variation of source position, detector geometry, and object configuration. A sequence of projections can therefore be generated from multiple source positions and exported for subsequent processing by image reconstruction software, making the approach applicable to imaging configurations such as digital tomosynthesis.

The developed methodology demonstrates how the Ray Optics Module can be adapted for synthetic radiography within the COMSOL Multiphysics® environment. It provides an integrated approach for studying X-ray imaging geometry, material attenuation, and projection formation, with potential applications in radiographic system design, simulation of tomographic acquisition, and multiphysics-based imaging studies.

Keywords: Ray tracing, X-rays, optics, radiation transport, image generation, Beer–Lambert attenuation

Introduction

X-ray imaging systems are widely used in medical diagnostics and nondestructive evaluation. The experimental acquisition can require equipment, repeated exposures, physical samples, and time. Computational radiography can therefore be useful for studying imaging geometries and generating controlled images. Synthetic radiograph generation enables rapid testing of imaging configurations and provides controllable datasets without requiring physical experiments. This work investigates the use of the Ray Optics Module in COMSOL Multiphysics® [1] for generating two-dimensional X-ray projection images using ray tracing and Beer–Lambert attenuation.

In the proposed approach, X-rays are represented by rays emitted from a defined source and propagated through three-dimensional objects toward a planar detector. Material-dependent attenuation along the ray trajectories is incorporated using the Beer–Lambert law. The transmitted rays are subsequently used to construct two-dimensional radiographic images using two different approaches available within COMSOL Multiphysics®: the Spot Diagram and Accumulator methods. The influence of imaging geometry, including off-axis source configurations, is also investigated. The numerical implementation is evaluated using representative single- and multi-material geometries, and the resulting attenuation and image formation are compared with Monte Carlo simulations. The following sections describe the underlying attenuation model and imaging geometry, the implementation within the Ray Optics Module, the

two image-generation approaches, and their performance for the selected simulation cases.

Theory and X-Ray Imaging Geometry

A radiographic image is formed when X-rays pass through the object and reach the image receptor. In radiographic imaging, image formation is governed by the attenuation of X-rays as they pass through the patient.

Different tissues/materials absorb and transmit X-ray photons to varying degrees depending on their thickness, density, atomic composition, and the energy of the incident beam. These differences in attenuation produce the intensity variations recorded by the detector and ultimately form the radiographic image. This is called differential absorption, and is what creates the different shades seen on a radiograph. As the primary X-ray beam passes through the object, photons may be absorbed, scattered, or transmitted.

A ray-tracing-based X-ray simulation framework was developed in COMSOL Multiphysics® using the Ray Optics Module. Rays emitted from an X-ray source propagate through heterogeneous materials, where attenuation is modeled according to the Beer–Lambert law.

Beer–Lambert attenuation

The main principle behind image simulation is Beer–Lambert law [1] which empirically describes the attenuation in intensity of a radiation beam passing through homogeneous medium. Beer–Lambert Law is expressed mathematically as:

$$I = I_0 e^{-\mu x},$$

where I is transmitted intensity of radiation after passing through the material, I_0 is the initial intensity of the radiation, μ is linear attenuation coefficient of the material (cm^{-1}), x is thickness of the material (cm). This allows to simulate synthetic X-ray projection image by calculating the intensity value at each pixel of detector.

The transmitted intensity is accumulated on a detector plane to generate synthetic 2D radiographic projections. The model assumes following simplifications: monochromatic X-ray source, straight-line propagation, no scattering, no secondary radiation, attenuation only, idealized detector response.

Imaging geometry

The simulated radiographic system consists of an X-ray source (point source), a three-dimensional object and a planar detector. Rays are emitted isotopically in all directions from the source and

propagate through the object toward the detector. Applied collimation forms a divergent cone-beam geometry. The transmitted intensity recorded at the detector depends on both the material properties of the object and the path length traveled by each ray through the attenuating domains.

The relative positions of the source, object, and detector determine the geometric characteristics of the resulting radiographic projection. In the reference configuration, the source is positioned along the central imaging axis, defined as the line connecting the source position and the center of the detector. The object is positioned between the source and detector. The source-to-object distance (SOD) and source-to-image distance (SID) control the geometric magnification of the projected object (see Fig. 1). For a point-source approximation, the geometric magnification may be expressed as

$$M = \frac{SID}{SOD}$$

Both on-axis and off-axis source configurations were investigated. In the off-axis configuration, the source was laterally displaced relative to the detector centerline. The resulting rays therefore intersect the object and detector at oblique angles, producing a shifted and potentially geometrically distorted projection. This configuration is useful for demonstrating the flexibility of the ray-tracing approach and for investigating the influence of source position on radiographic image formation. The detector is modeled as a planar surface located downstream of the object. Individual ray intersections with this surface are subsequently used to construct a two-dimensional X-ray projection. Two approaches for generating the detector image are considered in this work: visualization of ray intersections using the *Spot Diagram* functionality and spatial accumulation of ray quantities using an *Accumulator*.

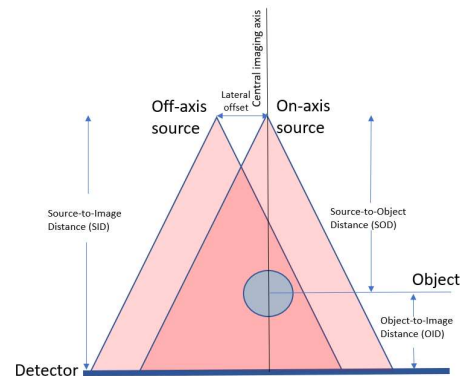


Figure 1. Schematic of the simulated X-ray imaging geometry showing the source, object, and detector.

Numerical Model in COMSOL

Multiphysics®

COMSOL Multiphysics® does not provide a dedicated built-in X-ray radiography imaging interface that directly maps X-ray transmission to a 2D detector images. Therefore, in this work, a radiographic simulation workflow was constructed using *Ray Optics* functionality.

Ray Optics Module handles high-frequency geometrical optics and ray tracing, but it is primarily designed for ultraviolet, visible, and infrared light interacting with refractive/reflective media. It does not natively model X-ray attenuation, photoelectric absorption, or Compton/Rayleigh scattering spectra out of the box, so current X-ray imaging work uses nontrivial setup. It overrides the default optics behavior and forces the software to calculate atomic-scale physics using custom variables.

X-rays were represented by geometrical rays, while material attenuation and detector image formation were implemented through additional model definitions and postprocessing procedures.

The numerical implementation consists of three main components: ray generation and propagation, attenuation of ray intensity through material domains, and reconstruction of the transmitted intensity distribution at the detector.

Ray Optics model

A three-dimensional model was created and the *Geometrical Optics* interface from the Ray Optics Module was added with *Ray Tracing* study. The source, object, and detector positions correspond to the imaging geometry described earlier.

In the *Ray Release and Propagation* the *Wavelength distribution* of release rays has been chosen monochromatic with zero number of secondary rays. It is assumed absolute vacuum as *Optical dispersion module* and the refractive index of domains n regardless of the material is set to 1 which reflects the fact that the refractive index for X-rays in matter is slightly less than 1. The intensity and power have been computed to facilitate image generation.

Rays can be released via several methods such as from Grid and from Data File, the use of the second will be discussed later. The simplest way to model point source is using Release from Grid: rays were

released from a point source and directed toward the detector plane. The ray direction vector is spherical, but as only the rays that will reach detector are of interest, the collimation can be simulated via *Cone Angle* and *Cone axes* in *Conical ray direction vector* as demonstrated in Fig. 2. The number and angular distribution of released rays were selected to provide sufficient sampling of the detector. The intensity has been initialized uniformly distributed with nominal values of total source power 1 W and initial intensity 1000 W/m².

Implementation of X-ray attenuation

The Geometrical Optics interface describes ray trajectories but does not by itself constitute a complete radiographic image-formation model. X-ray attenuation was therefore incorporated by associating an intensity quantity with each ray and reducing this quantity according to the path length traveled through attenuating materials.

Attenuation coefficient has been chosen as *Optical attenuation model*. The exponential decay formula used in COMSOL optical attenuation model [1] is mathematically identical to the Beer-Lambert law, where the linear attenuation coefficient μ corresponds to attenuation coefficient α in the COMSOL interface. This coefficient is retrieved from the material properties, which are assigned manually to specific geometric domains.

The linear attenuation coefficient μ measures the fractional reduction in intensity of an X-ray beam per unit thickness of a material. It is expressed in units of cm⁻¹ and is obtained by multiplying the mass attenuation coefficient μ/ρ by the material's bulk density ρ . The foundational mass attenuation data is sourced from the National Institute of Standards and Technology (NIST) X-ray mass attenuation databases [2]. Ray paths are computed within COMSOL automatically and their accuracy depends on meshing.

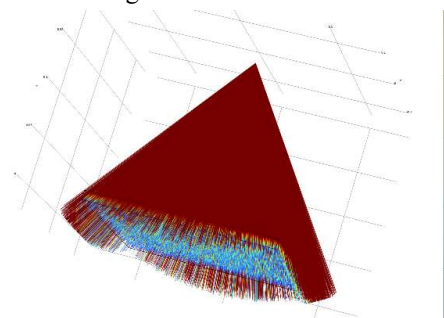


Figure 2. Ray trajectories visualization. Blue color represents lower intensity due to attenuation after passing through object.

Generation of the radiographic image: Spot Diagram and Accumulator methods

Two approaches were investigated for converting the transmitted ray data into a two-dimensional radiographic image: an *Accumulator*-based approach and the *Spot Diagram* functionality. Both methods use the same ray trajectories and attenuation model described above, but differ in how the detector is defined and how the transmitted ray information is spatially discretized into an image.

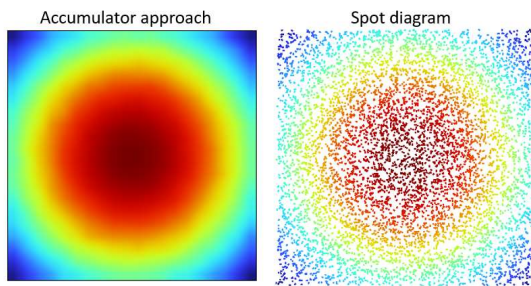


Figure 3. Generated X-ray image visualized within COMSOL interface using both methods: Accumulator and Spot diagram.

Accumulator:

In the Accumulator approach, the detector is explicitly represented within the ray-tracing model by a *Wall* boundary. The detector surface is therefore part of computational geometry and can be meshed independently according to the required detector resolution. In the present work, the wall was meshed using rectangular grid with element dimensions corresponding to the desired pixel size. Consequently, each surface element can be treated directly as an individual detector pixel.

Two quantities were evaluated on this detector wall. First, a boundary *Accumulator* was used to count the number of ray-wall interactions N_i within each detector element. This provides the number of rays contributing to a given detector pixel. Second, the *Deposited Ray Power* was evaluated on the same wall, providing the total ray power deposited within each detector element.

After completion of the ray-tracing study, the radiographic image was obtained from the expression

$$Image_i = \begin{cases} \frac{Q_i}{L_i}, & L_i \neq 0 \\ 0, & L_i = 0 \end{cases}$$

Or, in COMSOL syntax,

if(gop.wall1.bacc1.lnum != 0, gop.wall1.bsrc1.Qp / gop.wall1.bacc1.lnum, 0).

Here, *gop.wall1.bacc1.lnum* represents the number of ray interactions L_i recorded within a detector element, while *gop.wall1.bsrc1.Qp* represents the deposited ray power Q_i associated with that element. Dividing the deposited power by the number of contributing rays therefore provides a normalized detector value corresponding to the mean deposited ray power of the rays arriving within that detector pixel. The conditional expression assigns a value of zero to detector elements that are not intersected by any rays and additionally prevents division by zero.

An important advantage of this approach is that the spatial discretization of the final image is defined directly by the detector mesh. The detector can therefore be constructed with the same dimensions and rectangular pixel pitch as the physical detector that is being represented. No additional spatial binning of the ray positions is required after the COMSOL solution, since the ray contributions have already been accumulated according to the detector mesh during the simulation. The disadvantage is that the additional *Wall*, *Accumulator*, and deposited-power calculations are included in the ray-tracing computation and can consequently increase the computational cost.

Spot Diagram:

The Spot Diagram approach does not require either the detector *Wall* or an *Accumulator*. Instead, the detector is introduced during postprocessing using an *Intersection Point 3D* dataset. A plane corresponding to the desired detector position is specified, and COMSOL determines the points at which the previously calculated ray trajectories intersect this plane. In this sense, the detector is not represented as a meshed physical boundary during the ray-tracing calculation; rather, its location is defined subsequently from the stored ray trajectories.

A *2D Plot Group* containing a *Spot Diagram* is then created using the *Intersection Point 3D* dataset as the image surface. Each plotted point represents the intersection of an individual ray trajectory with the detector plane. The color expression of the Spot Diagram can be defined using either the ray intensity, I , or the ray power, Q , allowing the

transmitted quantity carried by each individual ray to be visualized at its corresponding detector position.

The Spot Diagram therefore produces a discrete ray-based representation of the detector signal rather than a pixel-based image directly. Each detector intersection retains its spatial coordinates together with the corresponding intensity or ray-power value. The complete Spot Diagram data can subsequently be exported from COMSOL as a spreadsheet, providing the detector-plane coordinates and associated ray quantities for all transmitted rays. These data can then be postprocessed externally, where the detector plane can be divided into pixels of arbitrary size and the individual ray contributions assigned, averaged, summed, or otherwise processed within those pixels according to the required image-formation procedure.

This provides considerably more flexibility in defining the detector resolution after the ray-tracing calculation. For example, the same ray-tracing solution can be rebinned using several different detector pixel sizes without repeating the COMSOL simulation. In contrast, changing the effective pixel size in the Accumulator-based approach generally requires changing the detector mesh and repeating the corresponding calculation if the accumulation is tied to that mesh.

The fundamental distinction between the two approaches is therefore the stage at which spatial discretization is introduced. In the Accumulator approach, the detector and its pixelization are incorporated directly into the COMSOL model through the meshed *Wall* boundary, and ray quantities are accumulated into these predefined detector elements during the solution. In the Spot Diagram approach, COMSOL retains the individual ray intersections with a virtual detector plane, while conversion of these discrete ray samples into detector pixels is performed afterwards during postprocessing. Thus, the Accumulator method provides a detector image directly on a prescribed physical pixel grid, whereas the Spot Diagram method provides the underlying ray-intersection data from which an image with an arbitrary pixelization can subsequently be constructed.

Simulation Cases and Results

Validation with Monte Carlo simulations

The box consisting solely of air was simulated in COMSOL and compared with an equivalent to Geant4-based GATE 10 model (see Fig. 4). Since

scattering effects are neglected in this work, only primary, unscattered photons were considered in the Geant4 analysis. The comparison was performed using the normalized X-ray transmission, I/I_0 , evaluated along the detector diagonal using on a 20×20 -pixel grid. In addition to the numerical comparison between COMSOL and Geant4, the results were compared with the analytical Beer-Lambert prediction $I/I_0 = \exp(-\mu x)$ using the same attenuation coefficient and material thickness.

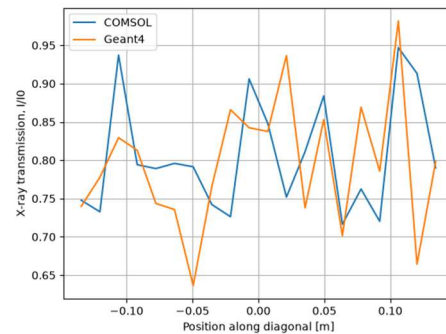


Figure 4. Diagonal cross-section of the simulated X-ray transmission profile across the detector for a spatial resolution of 20×20 pixels.

The COMSOL and Geant4 profiles show comparable transmission levels, with the remaining point-to-point variations mainly arising from the finite number of simulated rays/photons.

Agreement with the Beer-Lambert model provides an analytical benchmark for validating the attenuation predicted by both simulation frameworks.

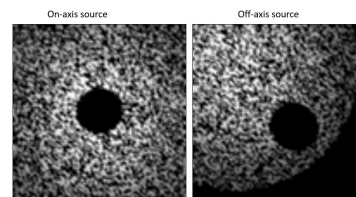


Figure 5. Simulated X-ray transmission images of a small spherical object for an on-axis source (left) and a laterally displaced off-axis source (right). The off-axis source produces a shifted and asymmetric projection on the detector.

Single-material spherical object

Figure 5 shows the simulated detector response for a small spherical object for two source positions. In the on-axis configuration, the X-ray source is aligned with the center of the detector, resulting in an approximately symmetric projection of the sphere. In the off-axis configuration, the source is laterally displaced from the detector axis. This changes the ray incidence geometry and causes a

corresponding displacement and asymmetry of the projected object and the surrounding intensity distribution on the detector.

More complex geometry / multiple materials

Figure 6 demonstrates the capability of the developed model to simulate more complex object geometries and overlapping attenuation features. The configuration contains objects of different sizes and positions, producing a spatially varying transmission pattern on the detector. The resulting image shows that the model can reproduce both broad attenuation regions and smaller localized features within the same projection.

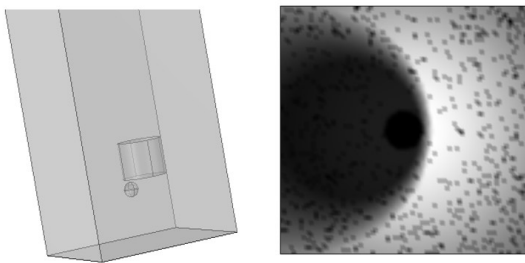


Figure 6. Demonstration of the model capability for simulating complex object configurations: simulation geometry (left) and corresponding X-ray transmission image (right), showing both extended and localized attenuation features.

Discussion

Ray-Sampling Strategy and Computational Considerations

An important consideration in the implementation of the proposed radiographic framework is the number and spatial distribution of rays required to generate a detector image. In conventional ray-release approaches, a large number of rays may be generated from the source and only a fraction of these rays intersect the detector at positions useful for image reconstruction. For the deterministic attenuation model considered in this work, such oversampling is not necessary.

Under the assumptions of a point X-ray source, straight-line ray propagation, Beer–Lambert attenuation, and neglect of scattered radiation, the primary intensity recorded at a given detector location is determined by the single geometrical path connecting the source to that detector location. Consequently, the detector itself can be used to define the required ray directions. A single ray directed toward each detector sampling position is sufficient to evaluate the transmitted primary intensity for that pixel.

To implement this approach in COMSOL Multiphysics®, the spatial coordinates corresponding to the detector grid were precalculated and used to determine the required ray release directions. These data were then supplied to the Ray Optics model using the Release from Data File functionality. This produces a deterministic correspondence between released rays and detector sampling positions and avoids generating large numbers of rays that do not contribute additional information to the primary-transmission image.

The present study does not provide a quantitative computational-performance comparison, and therefore no conclusions regarding execution-time improvement are made. Nevertheless, the ray-sampling strategy reduces the number of ray trajectories required by the model to approximate the number of detector sampling locations. The approach is particularly appropriate for the attenuation-only model used here. More advanced image-formation models incorporating a finite focal spot, scattered radiation, detector-area integration, or stochastic interactions may require multiple rays per detector pixel.

Generality of the Framework and CAD Integration

A further advantage of implementing the radiographic workflow within COMSOL Multiphysics® is that image generation can be applied directly to three-dimensional geometries used in other COMSOL models. In addition to parameterized geometries constructed within COMSOL, CAD geometries can be imported, assigned material properties and attenuation coefficients, and used directly as objects in the ray-tracing simulation. This makes it possible to generate synthetic X-ray projections of engineering components with substantially more complex geometries than the simple validation objects considered in this study.

The framework is therefore not restricted to a particular object geometry or imaging arrangement. Source position, detector position, object orientation, material assignment, and detector sampling can be parameterized within the same model. This is particularly relevant to imaging systems requiring projections from several source positions, such as digital tomosynthesis [3], where a sequence of simulated projection images can be exported for subsequent reconstruction.

An additional potential benefit of performing the simulation within COMSOL Multiphysics® is the

possibility of combining radiographic image generation with other physics interfaces. For example, a component could first be subjected to structural or thermal simulation and the resulting state subsequently used as the object for synthetic radiography. Such coupled applications were not investigated in the present work but represent a potential extension of the developed framework.

Limitations and Future Development

The current model represents primary X-ray transmission using geometrical ray tracing and Beer–Lambert attenuation. It therefore does not reproduce all physical processes contributing to a measured radiograph. In particular, scattered radiation, finite focal-spot effects, energy-dependent detector response, and other secondary interactions are not currently included. The suitability of the one-ray-per-pixel strategy is consequently tied to the deterministic primary-transmission approximation adopted in this study.

Future development may incorporate polychromatic X-ray spectra and energy-dependent attenuation coefficients, detector-response models, finite source dimensions, and additional radiation-interaction mechanisms. Quantitative investigation of computational performance and detector sampling requirements would also be valuable, particularly for high-resolution detector arrays and large series of projection images.

Conclusions

A framework for generating synthetic two-dimensional X-ray projection images in COMSOL Multiphysics® has been developed and demonstrated. COMSOL does not provide a dedicated out-of-the-box interface for X-ray radiographic image generation; therefore, existing functionality within the Ray Optics Module was adapted and combined to reproduce the principal stages of radiographic image formation. X-rays were represented using geometrical rays, material-dependent attenuation was incorporated through the Beer–Lambert law, and the transmitted ray intensity was mapped onto a planar detector to construct two-dimensional projections.

Two approaches to image generation were investigated using the Spot Diagram and boundary Accumulator functionalities. The developed workflow was demonstrated for simple and multi-material geometries and was compared with Monte Carlo simulations to assess the resulting attenuation behavior. The simulations showed that the adapted Ray Optics framework can reproduce the expected relationship between material attenuation, X-ray

path length, and detector intensity and can be used to generate projection images from different source positions.

A detector-driven ray-release strategy was also developed in which ray trajectories are predetermined from the required detector sampling locations. For the deterministic primary-transmission model considered here, this allows one ray to be associated with each detector pixel rather than relying on the release of a much larger population of rays. The framework can additionally be applied to imported CAD geometries and parameterized COMSOL models, allowing synthetic radiographs to be generated for complex engineering components.

The presented work demonstrates that existing COMSOL Multiphysics® tools can be combined beyond their standard applications to create a flexible virtual radiography workflow. The approach provides a basis for simulation of multi-view acquisition geometries such as digital tomosynthesis and also offers the potential for future integration of X-ray image generation with other COMSOL physics models. Further development will focus on energy-dependent attenuation, detector response, finite source effects, scattering, and quantitative evaluation of computational performance.

References

- [1] COMSOL AB, *Ray Optics Module User's Guide*, COMSOL Multiphysics®, Version [6.3], Stockholm, Sweden.
- [2] Hubbell, J. and Seltzer, S. (1995), Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients 1 keV to 20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest, <http://physics.nist.gov/PhysRefData/XrayMas sCoef/cover.html>, [online], <http://physics.nist.gov/PhysRefData/XrayMas sCoef/cover.html>.
- [3] Dobbins JT 3rd, Godfrey DJ. Digital x-ray tomosynthesis: current state of the art and clinical potential. *Phys Med Biol*. 2003 Oct 7;48(19):R65-106. doi: 10.1088/0031-9155/48/19/r01. PMID: 14579853.