

# Polarization-sensitive scattering in OpticStudio

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## Abstract

This article describes how you can use a custom DLL named MSP to simulate polarization-sensitive bulk scattering in non-sequential mode in OpticStudio. Modelling scattering evaluates how the polarization of rays affect their new directions of propagation on scattering, and then updates their polarization at each scattering event. This article describes the MSP DLL, which was created for polarization-sensitive scattering and is available for download in this article. The article also summarizes seven experiments that explore this capability. With OpticStudio, you can simulate fluorescence in combination with Mie scattering. Both aspects (the combination of fluorescence and scattering, and polarization-sensitive scattering) are important for modelling biological imaging.

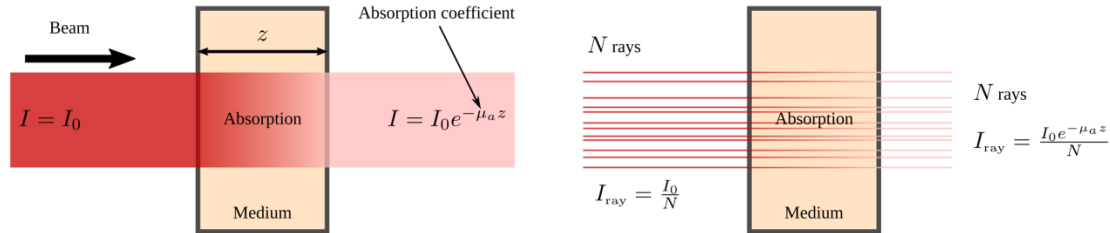
## Introduction

The modelling of light diffusion as it propagates through turbid media is important for a range of fields, including remote sensing, underwater imaging, and imaging through atmospheric turbulence. Biological imaging receives great attention in particular. In this field, system design involves modelling both the imaging system and light propagation in turbid media and scattering samples. Using non-sequential mode in OpticStudio is very convenient for such modelling, provided accurate models of the imaging system are known and valid, and rigorous models for volumetric scattering are available [1]. This article reviews the use of the MSP DLL, a custom DLL that can be used in OpticStudio to accurately model polarization of rays that undergo bulk scattering using the Mie phase model. For more details on its implementation, see [1].

## Modelling scattering

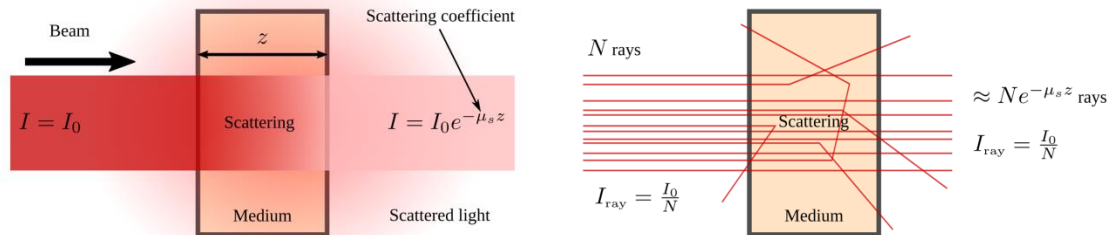
When a beam of light enters a turbid medium, it suffers extinction mainly due to two factors: absorption and scattering [2]. A Monte Carlo analysis samples the beam using light rays and then propagates the rays through the medium. Each ray can be absorbed or scattered according to defined probabilities, which depend on the optical parameters of the medium. One option for modelling absorption, which is used in OpticStudio, is to decrease the intensity associated with the ray according to the Beer-Lambert

law as  $\exp(-z\mu_a)$ , where  $z$  is the distance travelled inside the medium and  $\mu_a$  is the absorption coefficient. The following figure illustrates this. On the left is a macroscopic view of the beam; on the right is a Monte Carlo simulation using traced rays:



Notice how the beam is sampled by  $N$  rays (in this case, the rays are randomly distributed in the cross-section of the beam), and how each ray is assigned an intensity that is equivalent to the intensity of the beam divided by  $N$ . Each ray undergoes absorption, such that the output beam suffers commensurate extinction, which is  $\exp(-\mu_a z)$ .

When beam extinction occurs due to scattering, the intensity of each ray is preserved but the direction of propagation is changed during a scattering event. As a result, rays are removed from the beam, also causing extinction. In this case, the scattering coefficient  $\mu_s$  (the inverse of the mean-free path, which determines the probability of the occurrence of scattering events) determines the extinction rate at  $\exp(-\mu_s z)$ . This can be illustrated as follows:



Because scattering changes the direction of light propagation, light is propagated to other directions than the direction of the incident beam propagation. The properties of the scattering medium produce a far-field intensity distribution. (Note: For this model to be valid, the assumption that scattering events are mutually independent needs to hold.) Rays preserve the intensity if there is no absorption. Beam extinction is the consequence of the reduced number of rays that preserve the direction at output. The properties of the medium (such as particle size, index of refraction, and particle density) determine the mean-free path, the angular dependence of the scattering, and the polarization.

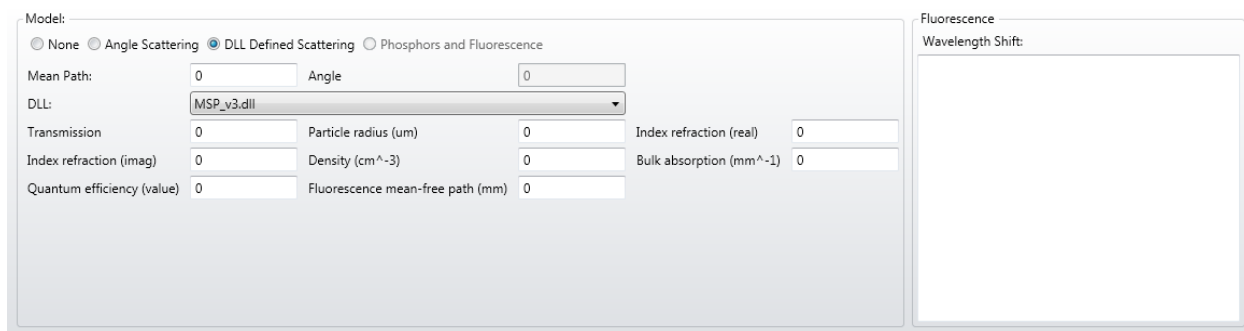
On a scattering event, the new direction is determined using a probability distribution function that is set to match the far-field intensity distribution. For historic reasons, it is called the *phase function*. This means that tracing enough rays reproduces the far-field distribution. Examples of common phase

functions are the Henyey-Greenstein phase function, the Mie phase function, and the Rayleigh phase function.

## Polarization-sensitive scattering

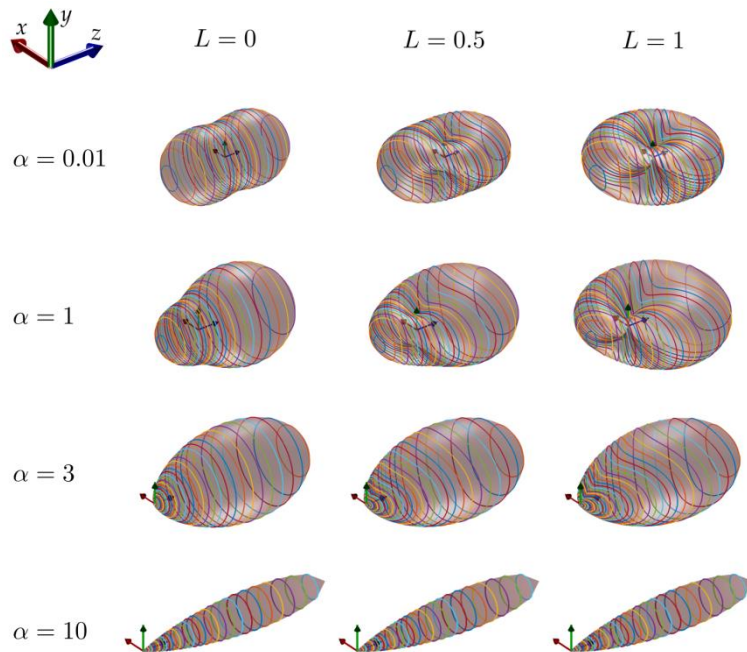
Phase functions are dependent on the state of polarization of the incident ray [2]. The practical and widely used Henyey-Greenstein phase function has very convenient properties, although some simulation problems might require a more accurate physical model, such as Mie scattering. However, the Henyey-Greenstein phase function suffers from a key limitation: It cannot validly treat polarization.

The MSP DLL can be used to model Mie scattering with correct tracking of polarization (that is, the correct electric field associated with each ray). After installing the DLL, access it in OpticStudio (Object Properties > Volume Physics tab > DLL drop-down menu > MSP.dll).



Plots of the phase function are known as scattering diagrams. The following diagrams show examples of Mie scattering for different particle sizes (parameter  $\alpha$ ) and different polarization states (parameter  $L$ ;  $L=0$  unpolarized and  $L=1$  linearly polarized).

In the following diagrams, a ray is initially propagating along the  $z$  axis. Its polarization (whether linear or elliptical) is oriented towards the  $y$  axis. The surface denotes the probability of scattering at each direction. Note how the phase function and therefore the direction of ray's propagation after a scattering event are dependent on the polarization of the incident ray,  $L$ , just before it scatters.



Scattering events that occur on a scattering Mie solution also modify the polarization of the ray deterministically, so it is important to update the electric field of the ray as it is being scattered.

Correct treatment and tracking of polarization at a scattering event requires three steps:

1. Calculate the degree of linear polarization of the incident ray,  $L$
2. Calculate the new direction of propagation using the polarization-sensitive phase function
3. Update the electric field (polarization) of the ray after the scattering event

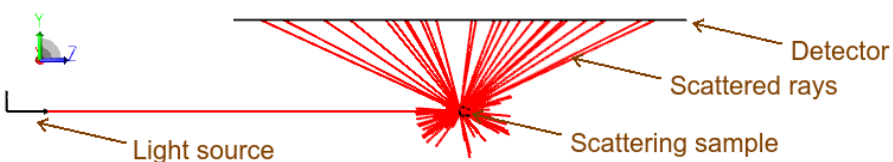
If a model for bulk scattering does not treat polarization, OpticStudio assumes random polarization for the scattered ray. The electric field is correctly perpendicular to the new direction of propagation that satisfies  $\mathbf{k} \cdot \mathbf{E} = 0$ , but actual polarization is lost.

## Experiments

We performed some simulations to explore the scattering dependency on polarization. OpticStudio can perform these simulations using the MSP DLL.

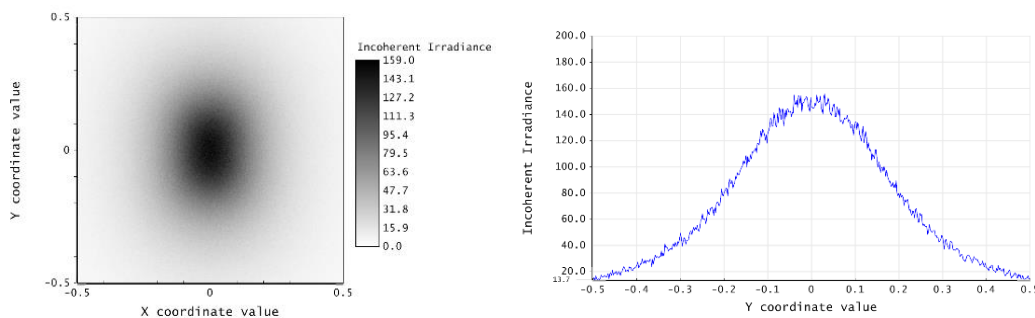
### Experiment 1

In the first experiment, we configured a setup such that rays from a point source are launched toward a scattering sample, and a detector is placed above the sample, as shown in the following image.



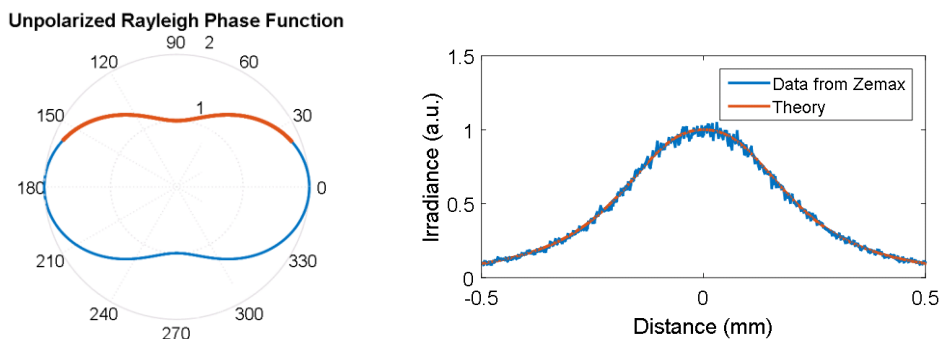
We set the source to allow only one scattering event (in OpticStudio > on the Properties tab of the source), and we set the mean-free path to a very small number ( $mfp=0.001\text{mm}$ ). This configuration ensures that rays scatter only once and do so very closely to the surface of the sample. The sample material has a refractive index of 1, so its shape and size do not affect the experiment. Therefore, the intensity distribution that is recorded at the detector directly depends on the phase function of the scattering properties of the sample material.

The particle size is set to a very small number, such that scattering is in the Rayleigh regime (we do this for convenience; because a simple closed-form solution is known for Rayleigh scattering, the results can be compared with the theory). The following diagram shows the intensity at the detector for incident unpolarized or circularly polarized rays ( the raw data is on the left; the central column intensity profile is on the right).



Notice how the vertical direction of the detector, which is labeled Y coordinate value in the graph on the right, corresponds with the propagation direction of the incident rays because the detector is placed parallel to the incoming rays (see the experimental layout above). With this geometry, each pixel of the detector subtends a different solid angle and the signal is reduced toward the edges, as expected.

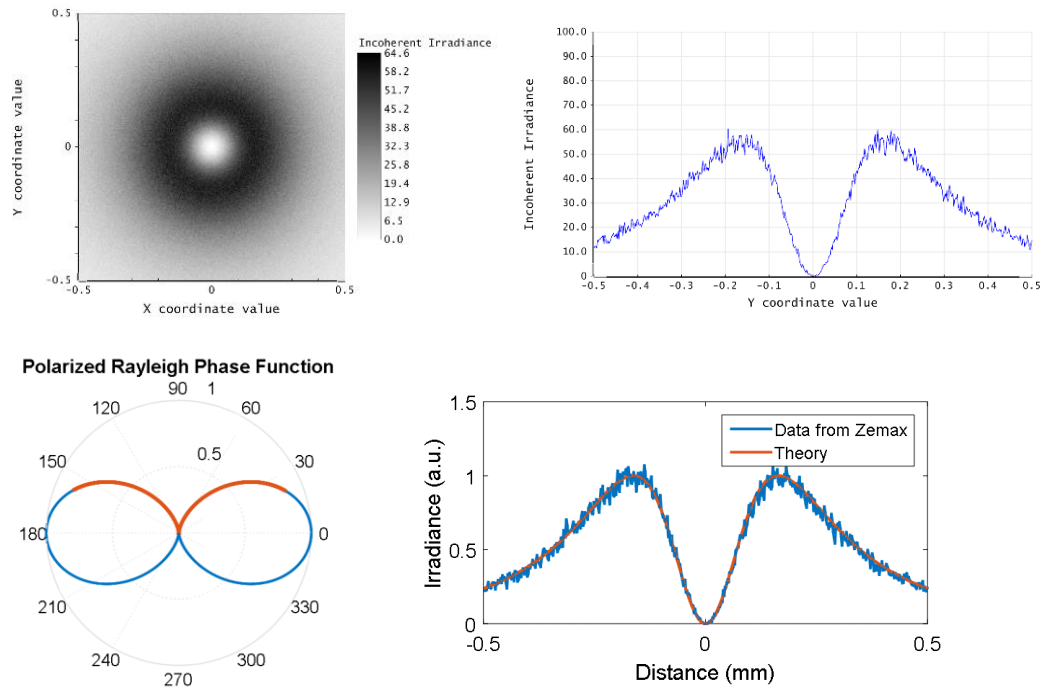
If we compute the theoretical Rayleigh phase function for unpolarized light, we observe a perfect match:



The left graph above is the theoretical phase function for Rayleigh scattering of unpolarized light. The red-colored portion represents the range of angles that the detector spans in this setup. These angles are therefore captured by the detector (detector length is 1mm and the sample is placed at 0.2mm from the detector). Results projected on the detector are shown in the graph above on the right.

## Experiment 2

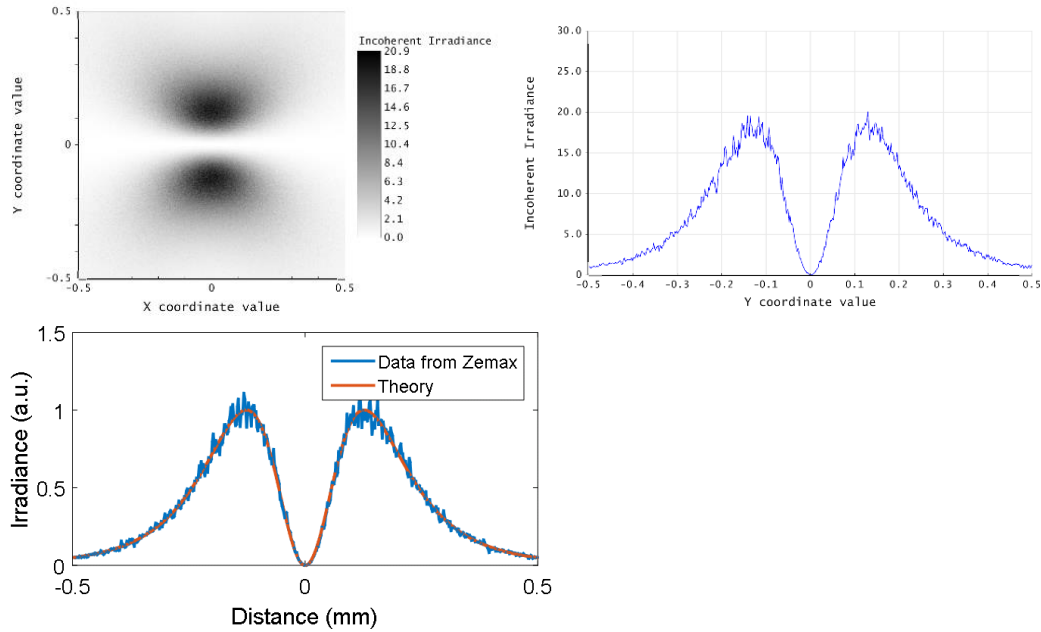
Setting the polarization of the incident rays to be linear and vertical (in OpticStudio, on the Source tab of the object properties of a source object) produces entirely different results:



In the lower-right graph above, using the Mie scattering model and accounting for polarization by using the MSP DLL produced the expected theoretical results.

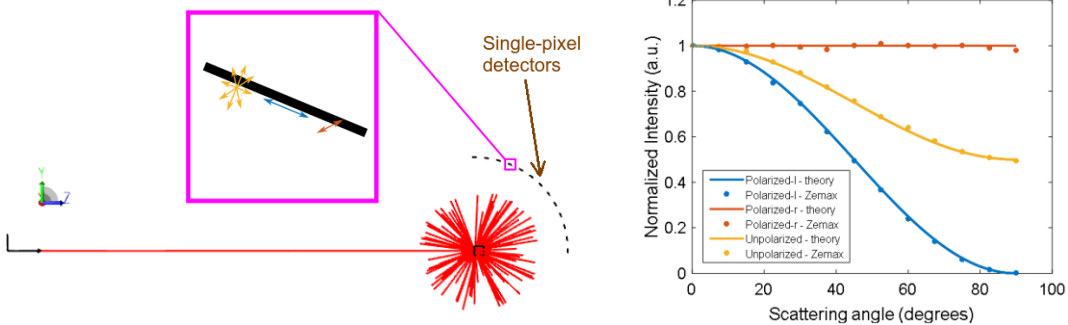
## Experiment 3

We can perform a further experiment: Consider the same setup as above, consider unpolarized incident light, but now we perform polarized detection. We place an analyzer in front of the detector (in OpticStudio, set the detector to Use Polarization). We configure rectangular detectors to detect only polarized light at a given direction. The following results again show a perfect agreement with the theoretical expectation:



#### Experiment 4

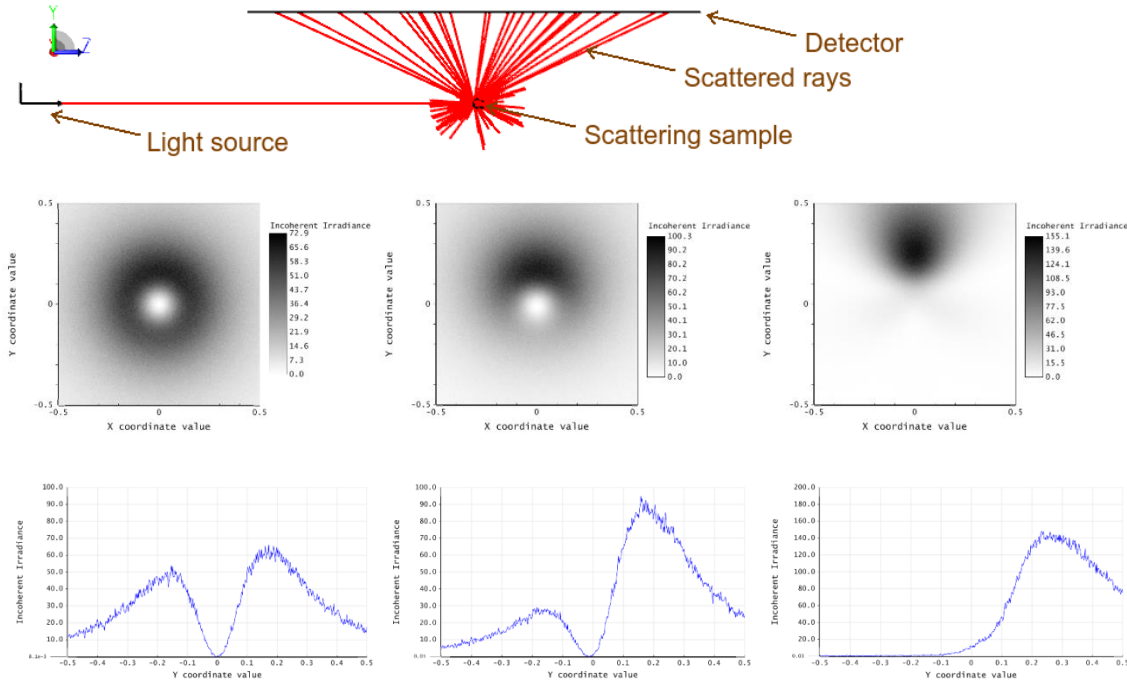
Another way to explore the dependency of the phase function for various states of polarization is to perform direct measurements in OpticStudio using single-pixel detectors placed at a range of scattering angles, and to plot the intensity of each detector:



In the graph on the right above, each detector represents a measurement point. The expected theoretical results for Rayleigh scattering are also plotted for reference. In the graph, blue, red, and yellow correspond to linear polarization in the x direction, linear polarization in the y direction, and unpolarized, respectively.

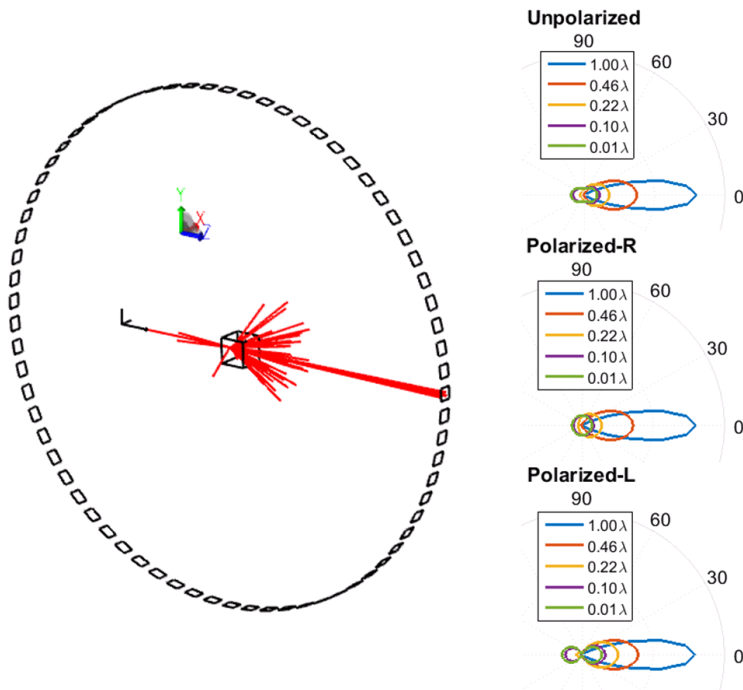
#### Experiment 5

So far, we've explored the polarization dependency in the Rayleigh regime. The MSP DLL is also valid for general Mie scattering. In this experiment, we achieve the same results by using the same setup but different sizes of the scattering particles, specifically, (left)  $0.1\lambda$ , (center)  $0.2\lambda$ , and (right)  $0.5\lambda$ :



## Experiment 6

Similarly, we can measure the phase function using a setup with a range of single-pixel detectors that are placed 360° around the sample:

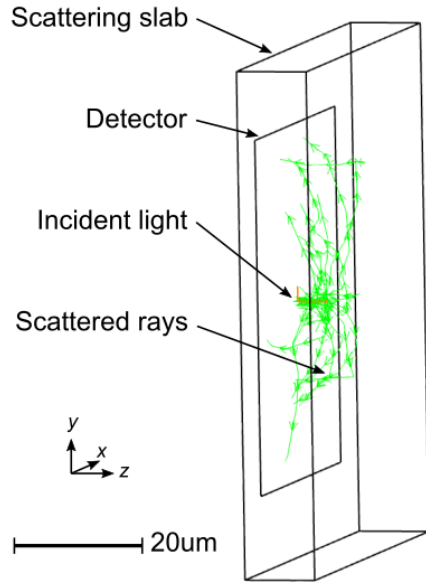


The polar plots on the right were constructed using the intensity values that were measured by each detector. These plots resemble perfectly the known scattering diagrams for general Mie scattering.



### Experiment 7

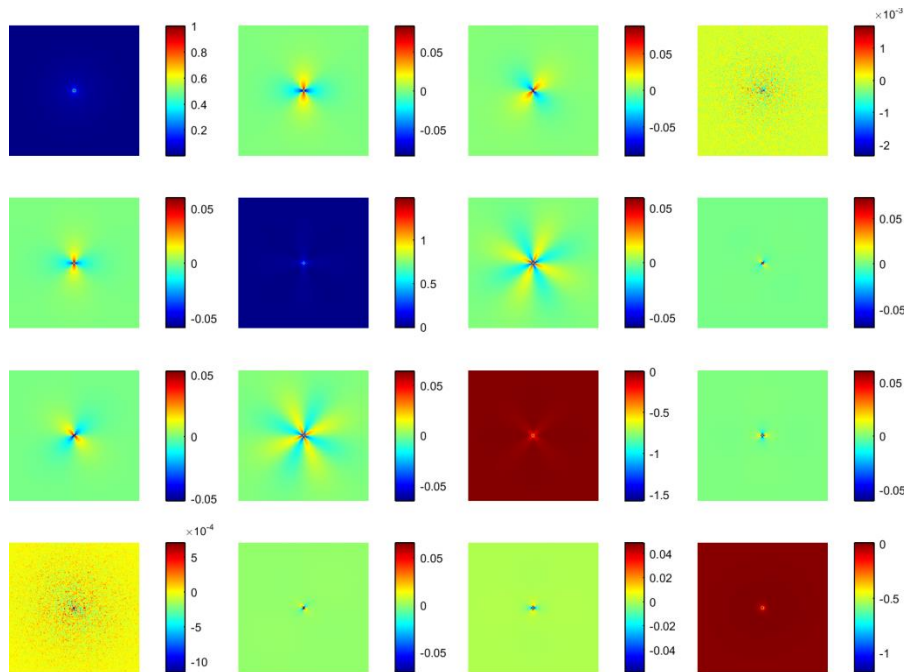
Finally, we perform a more generic polarimetric experiment. We calculate the Mueller matrices (one is associated with each detector pixel) as spatial maps by measuring backscattering coming from a slab of turbid material. A beam of light is launched toward the slab of turbid material. Upon entering the scattering material, light rays scatter several times. Some rays eventually propagate back out of the object and are detected. A detector is placed close to the face of the slab and only detects back-scattered rays:



Using the MSP DLL, you can calculate the polarization-sensitive scattering and relate the polarization of the output rays to the polarization of the input rays. The Stokes vector is a standard way to describe polarization. This vector of four components defines any general state of polarization. Thus, the effect of any polarimetric optical component that modifies polarization of a light beam can be completely defined by the so-called Mueller matrix, which relates the input and output polarization states expressed as a four-component vector, which is therefore a 4x4 matrix:

$$\vec{S}_b = \mathbf{M} \vec{S}_i \quad \Longleftrightarrow \quad \begin{pmatrix} I_b \\ Q_b \\ U_b \\ V_b \end{pmatrix} = \mathbf{M} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

For this experiment, the slab of turbid material can be considered an optical component that modifies the polarization state of the backscattered rays. The location of the rays on the detector is relative to the point of injection, which is the center. Therefore, it is possible to calculate its associated Mueller matrix. However, this 4x4 matrix depends on the point of exit of the backscattered rays, which is why the Mueller matrix is calculated as a spatial map. Results are plotted as follows:



These results are a general case for polarimetric sensing, because they conform to a measurement of full polarization of (in this case) the backscattering from a slab of turbid material.

## Simulation of fluorescence

In addition to calculating polarization-sensitive Mie scattering, the MSP DLL can also incorporate the simulation of fluorescence combined with scattering.

To simulate fluorescence, the MSP DLL uses the wavelength shift capability that OpticStudio offers for bulk scattering. (In OpticStudio, > the Volume Physics tab of the properties of the scattering object > Fluorescence box.) By entering text strings “wave1, wave2,prob” it is possible to set the probability that on a scattering event the incident wavelength number “wave1” is shifted to wavelength “wave2” with probability “prob.”

Using the MSP DLL, you can input a Fluorescence-associated mean-free path, which determines the mean distance a ray propagates before it fluoresces (with probability as defined). This distance can be set lower than the scattering mean-free path, but not higher.

If fluorescence occurs, the ray undergoes a wavelength shift, a change in direction of propagation, and polarization. The direction of propagation is selected isotropically, the polarization is set linear at random direction, and the phase is randomized. These properties simulate incoherent fluorescence emission after they are averaged over many rays. This happens only if fluorescence occurs. If the ray is bulk scattered, the scattering mean-free path applies, the new direction of propagation is calculated based on the material properties and the phase function for Mie scattering, and polarization is updated according to Mie theory. Scattering and fluorescence can therefore be simulated simultaneously. This

might serve to simulate both samples and imaging through a scattering material that expresses auto-fluorescence [1].

## Conclusion

This article reviewed the polarization sensitivity of bulk scattering of rays in non-sequential mode. The MSP DLL accounts for polarization effects in Mie scattering. Several experiments explored this sensitivity to polarization. The ability to combine simulation of fluorescence and Mie scattering is also possible and illustrated. Both (a) the possibility of combining fluorescence and scattering simultaneously, and (b) the performance of polarization-sensitive Mie scattering are important in biological imaging, which involves both the modelling of imaging systems and light diffusion in scattering (and/or fluorescing) samples and turbid media.

## References

1. G. Carles, P. Zammit, and A. R. Harvey, "Holistic modeling of optical systems and photon transport in turbid media using a commercial ray-tracer," *in preparation*.
2. H. C. van de Hulst, *Light scattering by small particles* (John Wiley & Sons, 1957).