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# Increased resolution using polarization filters in optical tomography

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**Abstract:** We demonstrate numerically the increased resolution of the image of a pure absorber as recorded by a scanning system composed of aligned source-detector when only polarization-preserving photons are selected.

**OCIS codes:** 110.6960, 290.5855, 110.5405

## 1. Introduction

The inverse problem of diffuse optical tomography is severely ill-posed due to the strong multiple scattering inside the medium. It has long been known that one potential approach to reduce this adverse effect is to employ polarization-selective illumination and detection. However, to quantify the advantages of polarization-selective imaging in an optically-thick or mesoscopic medium, one needs to resort to simulations. In this paper, we study the problem of light transmission through a multiply-scattering slab with an absorptive contrast. We use Monte Carlo simulations for polarized light to compute the sensitivity kernel of diffuse optical tomography (technique described in [1]). This result is used to model the data function, which is consequently displayed as an image. We show that the information contained in the state of polarization of the transmitted light allows one to reduce the ill-posedness. However, we do not solve explicitly the inverse problem. Rather, we show that the target can be resolved (in the lateral direction, without any depth resolution) by simply visualizing the data function recorded using the measurement scheme with a collimated and on-axis source-detector pair that is scanned over the surface of the slab. Depth resolution can potentially be obtained by rotating the device around the target and thus accumulating multiple projections. However, we note that polarization selectivity is more useful in media composed of relatively small particles and characterizable by the Rayleigh phase function. In such media polarization sensitivity is useful up to  $20\ell^*$  optical depth, where  $\ell^*$  is the transport mean free path. In media with large particles and strongly forward-peaked scattering, the polarization sensitivity is useful up to only  $\sim 1\ell^*$  optical depth.

## 2. The sensitivity function for polarized radiative transfer

We consider imaging of a scattering medium in the shape of a slab. The scattering coefficient and the scattering phase function are constant inside the medium but the absorption coefficient can vary. Propagation of light is assumed to obey the vector radiative transfer equation (vRTE), which describes the propagation of the vector specific intensity  $\mathbf{I} = (I, Q, U, V)$  composed of the four Stokes components. The source is a continuous-wave, collimated, polarized laser beam incident at some location  $\mathbf{r}_a$  on the surface of the slab and in the direction of the unit vector  $\hat{\mathbf{s}}_a$ . The detector measures the intensity (including the state of polarization) of light exiting on the medium at a different point  $\mathbf{r}_b$  and in the direction  $\hat{\mathbf{s}}_b$ . This measurement scheme encompasses both the transmission and the reflection geometries.

The presence of absorptive heterogeneities inside the slab will result in a detectable variation of the measured specific intensity. In fact, all four Stokes components of the specific intensity will be affected. We can define the data function as the difference between the registered intensity exiting a homogeneous (reference) and heterogeneous media. We can refer to this difference, denoted here by  $\Phi(\mathbf{r}_b, \hat{\mathbf{s}}_b; \mathbf{r}_a, \hat{\mathbf{s}}_a)$ , as to the shadow created by the absorptive heterogeneities. Within the accuracy of the first Born approximation, the equation that relates the fluctuations of the absorption coefficient  $\delta\mu_a(\mathbf{r})$  to the data function can be written as

$$\Phi(\mathbf{r}_b, \hat{\mathbf{s}}_b; \mathbf{r}_a, \hat{\mathbf{s}}_a) = \int [\mathbf{S}_{\text{out}} \cdot K(\mathbf{r}_b, \hat{\mathbf{s}}_b, \mathbf{r}_a, \hat{\mathbf{s}}_a; \mathbf{r}) \mathbf{S}_{\text{in}}] \delta\mu_a(\mathbf{r}) d^3r, \quad (1)$$

where the sensitivity matrix  $K(\mathbf{r}_b, \hat{\mathbf{s}}_b, \mathbf{r}_a, \hat{\mathbf{s}}_a; \mathbf{r})$  is an integral of two vRTE Green's functions  $G(\mathbf{r}, \hat{\mathbf{s}}; \mathbf{r}', \hat{\mathbf{s}}')$ , namely,

$$K(\mathbf{r}_b, \hat{\mathbf{s}}_b, \mathbf{r}_a, \hat{\mathbf{s}}_a; \mathbf{r}) = \int G(\mathbf{r}_b, \hat{\mathbf{s}}_b; \mathbf{r}, \hat{\mathbf{s}}) G(\mathbf{r}, \hat{\mathbf{s}}; \mathbf{r}_a, \hat{\mathbf{s}}_a) d^2s. \quad (2)$$

Note that  $K$  is a  $4 \times 4$  matrix. In any given measurement, this matrix acts on the initial state of polarization  $\mathbf{S}_{\text{in}}$  and the measured specific intensity is projected onto a given polarization state  $\mathbf{S}_{\text{out}}$ , which yields a scalar quantity [1]. It is worth noting that, in the scalar case, the sensitivity kernel is positive because addition of an absorber at some location can only reduce the measured intensity. In contrast, the elements of  $K$  are not required to be positive due to the fact that the Stokes components  $Q, U, V$  can change sign. In fact, the components of the vector  $K\mathbf{S}_{\text{in}}$  can have positive or negative signs.

While the elements of  $K$  can have arbitrary sign, the scalar sensitivity kernel  $\mathbf{S}_{\text{out}} \cdot K\mathbf{S}_{\text{in}}$  is always positive (if  $\mathbf{S}_{\text{out}}$  is a physical state). Experimentally, this corresponds to a sensitivity measurement of the intensity of the radiation that reaches the detector after passing through a polarization filter. Thus, we can define the co-polarized channel as the one obtained for  $\mathbf{S}_{\text{out}} \parallel \mathbf{S}_{\text{in}}$  and the cross-polarized channel as the one obtained for  $\mathbf{S}_{\text{out}} \perp \mathbf{S}_{\text{in}}$  (which is physically attainable). The channels themselves can be interpreted as the probabilities for the radiation to leave at the incidence point with some polarization  $\mathbf{S}_{\text{in}}$  and to be detected with some polarization  $\mathbf{S}_{\text{out}}$  after passing through a given voxel centered at  $\mathbf{r}$ . Thus, the scalar sensitivity kernel  $\mathbf{S}_{\text{out}} \cdot K\mathbf{S}_{\text{in}}$  can be considered as a probability density function modulo an appropriate normalization. As noted in [2] it is possible to make use of photons that preserve their initial polarization in order to increase imaging contrast. In particular, it was demonstrated numerically [2] that the photons that preserve circular polarization tend to stay very close to the straight line connecting the source and detector if these are aligned (especially for Rayleigh-like medium).

We can select the polarization preserving photons by subtraction of channels (co-polarized minus cross-polarized). In our approach, this turns out to be equivalent to the calculation of the components of the vector  $K\mathbf{S}_{\text{in}} = [\Delta I, \Delta Q, \Delta U, \Delta V]$ . As an example, for circular polarization this is  $\Delta V = K_{41} + K_{44}$ .

Note that the sensitivity matrix elements  $K_{ij}$  can be calculated efficiently with the Monte Carlo method by exploiting the vRTE symmetry and reciprocity relations [1].

### 3. Scanning with aligned source and detector

We can simulate the data function for an arbitrary target absorber by performing the volume integration in (1). The "inverse crime" simulated reconstruction would then use this data function to reconstruct the shape of the target pretending that the latter is unknown. However, even the "inverse crime" reconstructions can be numerically unstable and yield images of poor quality due to the intrinsic ill-posedness of the inverse problem. In a sense, however, we can quantify the expected quality of the images by observing the dependence of the data function on the shape and position of a small absorber. In the best-case scenario no reconstruction is required at all: the data function can be directly visualized and the generated image coincides with the target. This is the case, for example, in an unscattering medium. In this work, we show that the same effect can be obtained by displaying the dependence of the sensitivity kernel on the position of an axially-aligned source-detector pair and utilizing polarization-selective measurements.

Recall that we are interested in the polarization-preserving photons. Hence, only channel subtraction will be considered. This corresponds to an integration of a component of the sensitivity vector  $(K\mathbf{S}_{\text{in}})_i$ , e.g.,  $\Delta V$  for  $i = 4$ , over the volume occupied by the absorber. We work in the transmission geometry and assume that the source and detector are aligned and on-axis; the source-detector pair is then scanned over the surface of the slab and the data function thus generated is directly visualized. Note that this simulation can be performed very efficiently. In transmission, only two Monte Carlo processes must be completed to calculate the kernel independently from the source-detector position. We then utilize the linearity of equation (1) and the translational invariance of the kernel with respect to a lateral shift of all three arguments  $\mathbf{r}_a, \mathbf{r}_b$  and  $\mathbf{r}$  to simulate the scanning pattern. In other words, once the kernel is calculated it is only needed to sum over its elements that are localized on the absorber with no need of new Monte Carlo simulations for every position of the source-detector relative to the absorber. In Fig. 1, we present the results in transmission geometry obtained for a scattering medium with an absorbing target shaped as the letter F and located in the mid-horizontal plane of the slab. We study a medium with the Rayleigh phase function and the optical depth equal to  $20\ell^*$  and a medium with large particles (characterized by Mie scattering) of the optical depth of  $1\ell^*$ . In the latter case, the scattering asymmetry parameter is  $g = 0.95$  and the size-parameter of the scatterers is  $x = 15$ . The images allow one to visualize the data function obtained as described above. For the Rayleigh-like medium, the unpolarized ( $\Delta I$ , first plot) and circularly-polarized channel subtractions ( $\Delta V$ , second plot) are used. For the Mie-like medium, the unpolarized ( $\Delta I$ , third plot) and linearly-polarized channel subtractions ( $\Delta Q$ , fourth plot) are used. The absorber's sharp shadow is clearly visible when polarization is employed. We emphasize that the images shown in

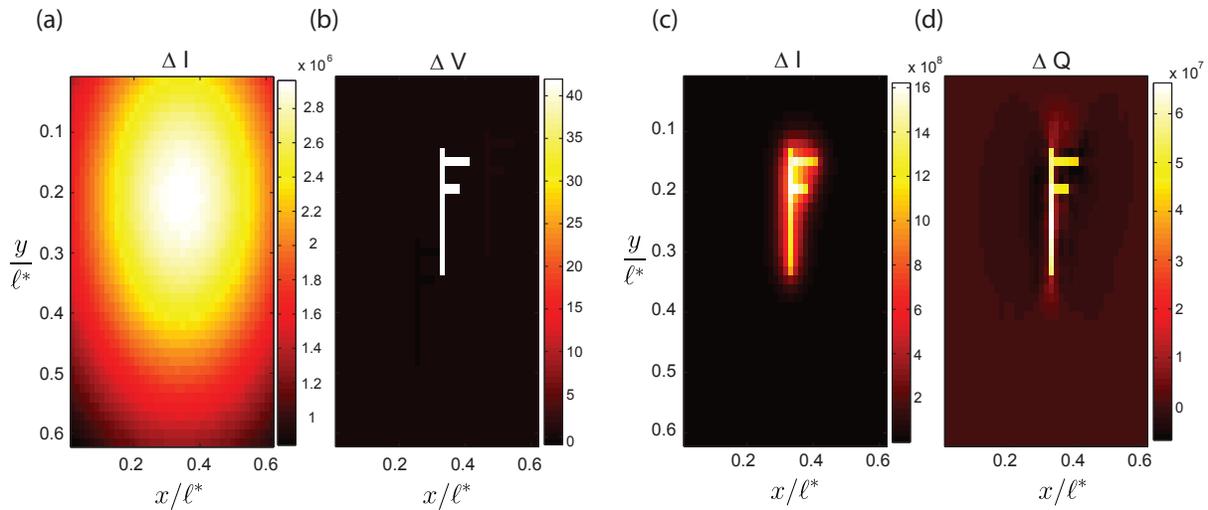


Fig. 1. Images in transmission geometry of an absorber shaped as the letter F surrounded by a Rayleigh scattering medium of  $20\ell^*$  depth (a,b) and a Mie scattering medium of  $1\ell^*$  depth (c,d). Plot (a):  $\Delta I$  (unpolarized). Plot (b):  $\Delta V$  (circular polarization). Plot (c):  $\Delta I$  (unpolarized). Plot (d):  $\Delta Q$  (linear polarization). The lengths are expressed in units of transport mean free path  $\ell^*$ .

Fig. 1 are not the shadows that would be physically obtained with a wide-front illumination. The result is not as trivial. It requires, in an experimental realization, scanning of an axially-aligned and collimated source-detector pair over the surface of the slab. Moreover, even in the case of polarized channel subtraction, there are many scattering events that result in the detected signal.

#### 4. Conclusions

The usefulness of polarization-sensitive measurements for imaging or vision through a scattering medium has long been established. In this contribution, we have shown how the selection of the portion of the signal composed of only polarization-preserving photons can be used to resolve a blurred object. In the case of a Rayleigh-like medium, we can resolve an object in a very optically thick medium using circular polarization. While for Mie-like media, we find that the usefulness of linear polarization is evident for visualizing shallow absorbers buried at depths on the order of  $1\ell^*$ . The effect can be related to the existence of negative components of the sensitivity matrix. Correspondingly, there are regions within the sample such that placing an absorbing inhomogeneity in those regions actually results in an increased measured signal (when channel subtraction as described above is utilized). As a result, an increased sensitivity of the measured signal to the location of the absorber is obtained and the inverse problem becomes less ill posed to the extent that merely visualizing the raw data function yields the correct shape of the target.

Our results and conclusions are closely related to and were in part motivated by the experimental results of [2] involving similar one-dimensional scans. In line with [2], we found that in transmission mode the circular polarization is useful when a Rayleigh-like medium is considered while for a Mie-like medium, the linear polarizations are better suited.

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