# Efficient full-wave simulation of wavefront shaping to focus light through biological tissue

**Jake A. J. Bewick,[1] Peter R. T. Munro,[1] Simon R. Arridge,[2] and James A. Guggenheim,[1,3,4]**

[1]*Department of Medical Physics and Biomedical Imaging, UCL, London, UK*
[2]*Department of Computer Science, UCL, London, UK*
[3]*Institute of Cardiovascular Sciences, University of Birmingham, Birmingham, UK*
[4]*School of Computer Science, University of Birmingham, Birmingham, UK*

**Abstract:** We simulate wavefront shaping through a $TiO_2$ phantom and a discrete particle representation of biological tissue using the T-matrix and angular spectrum methods. Our method is $10\times$ faster to compute than the pseudospectral time-domain method.


## Introduction

Biological tissue strongly scatters visible and near-infrared light, resulting in a significant reduction in intensity at depth. As a result, imaging modalities such as optical coherence tomography or photoacoustic microscopy are constrained to image superficial tissues. One method to extend the penetration depth of light in these modalities is wavefront shaping (WFS) [1] - a technique in which the incident light is spatially modulated to control its propagation through scattering media, potentially allowing light to be focused at arbitrary locations within tissue.

Computational methods for simulating WFS could complement experimental investigation, which is often constrained by a lack of control. For example, with computational approaches it becomes possible to evaluate the field inside a given medium, resolve both amplitude and phase information, and fully manipulate the optical properties and geometry of said medium. Unfortunately, current approaches to simulate light propagation through biological tissue are either too computationally intensive to model volumes large enough to significantly benefit from WFS, or too incomplete to model underlying deterministic scattering and interference processes accurately.

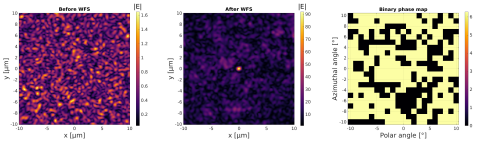
We propose coupling the T-matrix method with the discrete particle model to create an efficient but rigorous simulation of light propagation through biological tissue. The T-matrix method works by propagating light through a medium of scattering particles such that the total field is a superposition of the scattered fields associated with each sphere, creating a solvable matrix system [2]. By controlling the density, radii, and refractive indices of these spheres we are able to design bespoke domains with desired optical properties potentially matching those of tissue. To simulate the complex beams found in WFS we apply the angular spectrum method whereby arbitrary beams can be decomposed into a spectrum of plane waves incident at varying angles which can be simulated sequentially.

In this manuscript we demonstrate how our T-matrix discrete particle approach coupled with an angular spectrum decomposition of the incident field can be used to efficiently simulate optical foci generation through turbid media. We begin by replicating the original Vellekoop and Mosk WFS experiment [1] by simulating the generation of an optical focus through a titanium dioxide scattering layer. We then simulate focus generation through a *tissue-like* $100\mu m^3$ sample volume.

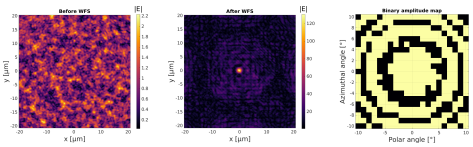
## Simulated wavefront shaping in optically scattering layers and biological tissues

A $10x30x30\mu m^3$ domain was constructed from titanium dioxide spheres with a radius of 1μm and refractive index of 2.6 at a concentration of 0.26. The background refractive index was set to 1.33 and 441 different plane waves ($\lambda$=633nm) were simulated propagating through the medium, with the polar and azimuthal angles of the incident waves varying from -10 to 10°. A transport mean free path of $\sim$5μm ensures that there is no correlation between the input and output fields. We evaluate the amplitude and phase on a $20x20\mu m^2$ plane just behind the medium. Using a simple stepwise sequential algorithm we iterate through the speckle patterns generated for each incident angle, modulating either the phase or amplitude and recording the change in intensity in a target region relative to a reference beam. By calculating the superposition of all the modulated waves that maximise the intensity in the target we are able to generate the strong optical foci seen in Figure 1a and Figure 1c.

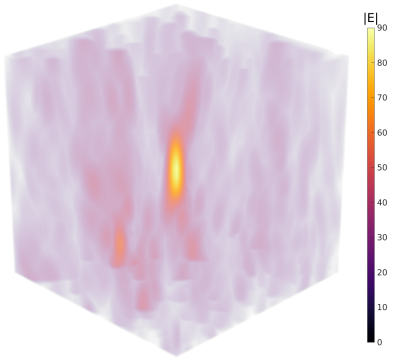
To demonstrate how WFS can generate a focus through biological tissue, a $100\mu m^3$ discrete particle domain was generated with Mie theory. Embedding particles with a radius of 1.72μm and a refractive index of 1.6 in a medium with a refractive index of 1.33 at a concentration of 0.0077 produces a *tissue-like* domain with a scattering coefficient of $10mm^{-1}$ and an anisotropy of 0.9 when the wavelength of incident light is 1064nm. Once again, a stepwise sequential algorithm is used to shape the incident light and generate the focus seen in Figure 1b.




(a) Binary phase WFS is able to generate a strong optical focus through a highly scattering titanium dioxide slab.




(b) Binary amplitude WFS can also generate a focus, now through our *tissue-like* sample domain. The light has only propagated 100μm through a medium with a transport mean free path of 1mm, and as such the scattering is much weaker.




(c) Focus generated through a titanium dioxide slam using binary phase modulation. As phase and amplitude can be evaluated at arbitrary locations 3D visualisations of the focus can be created.

Fig. 1: We can use amplitude and phase modulation to generate optical foci through scattering media.

Figure 2 shows how incident light is scattered by the titanium dioxide domain. However, when the phase map found in Figure 1a is applied a strong focus is generated in our desired target region. Simulating each incident plane wave took $<$1 hour, while a pseudospectral time-domain simulation was found to take $\sim$12 hours - the T-matrix method is significantly more efficient as the space between scatterers does not need to be discretized.

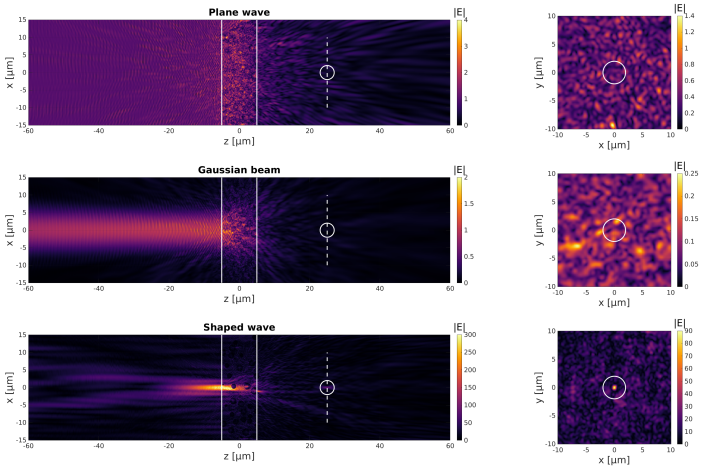



Fig. 2: The turbid titanium dioxide domain (deliminated by the solid white lines) scatters an incident plane wave and Gaussian beam, but a properly shaped wavefront is able to generate a focus in the target region (highlighted by the white circle). This focus can be clearly seen on the right by imaging the xy plane at the dashed lines.

## Summary and outlook

We simulated WFS and the propagation of shaped light through bespoke scattering domains by coupling the T-matrix and discrete particle methods. As compared to ansatz approaches like Monte Carlo or random phase screens, the T-matrix method is a direct solution to Maxwell's equations - an important consideration as it is essential to simulate scattering rigorously when studying novel phenomena (like WFS) that relies on multiple scattering and interference processes. WFS specifically has significant potential to enhance modalities that rely on targeted or deep delivery of light into tissue, and our computational method would have a number of applications, including: generating training data for deep learning, validating the existence of open channels, providing a framework to evaluate shaping algorithms, and augmenting experimental investigation by allowing for direct visualisation of light inside *tissue-like* domains with bespoke optical properties and geometries.

## References

1. I. M. Vellekoop and A. Mosk, "Focusing coherent light through opaque strongly scattering media," *Optics letters*, vol. 32, no. 16, 2007.
2. P. Waterman, "Matrix formulation of electromagnetic scattering," *Proceedings of the IEEE*, vol. 53, no. 8, pp. 805–812, 1965.