Matrix approach of optical imaging through strongly scattering media

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The propagation of light in inhomogeneous media is a fundamental problem with important applications, ranging from astronomical observations through a turbulent atmosphere to deep tissue imaging in microscopy. Conventional focusing and imaging techniques based on the Born approximation generally fail in strongly scattering media due to the aberrations and multiple scattering (MS) events undergone by optical waves. Recent advances in light manipulation techniques have allowed great progresses in optical focusing through complex media [1]. Subsequently, a matrix approach of light propagation through complex media was developed [2]. The experimental access to the transmission matrix allows to take advantage of MS for optimal light focusing across a diffusive layer. However, MS is a much more difficult challenge with regards to imaging. Conventional reflection imaging methods usually rely on a single scattering assumption. In turbid media, MS starts to predominate beyond a few scattering mean free paths \( l_s \) [3](Fig.1A). Here we propose a matrix approach of optical imaging to push back the fundamental MS limit. Experimentally, this approach, referred to as smart-OCT, relies on the measurement of a time-gated reflection matrix from the scattering medium [4]. An input-output analysis of the reflection matrix allows to get rid of most of the MS contribution. Iterative time-reversal [5] is then applied to overcome the residual MS contribution as well as the aberration effects induced by the turbid medium itself. A proof-of-concept experiment demonstrates imaging through a strongly scattering paper layer from which only one reflected photon over 1000 billion is associated to a SS event from the object hidden behind it (see Fig.1C). In a second experiment, our approach is successfully applied to optical imaging through a thick layer of biological tissues (see Fig.1D). Compared to OCT, we show both theoretically and experimentally an extension of the imaging-depth limit by a factor two [3,4] (see Fig.1B).

![Image](image_url)

**FIG. 1:** (A) Single-to-Multiple scattering ratio vs optical depth \( F/l_s \) for several optical imaging techniques. (B) Penetration depth vs numerical aperture. (C) OCT and smart-OCT images of three magnetite beads hidden behind a strongly scattering layer of paper (thickness of 12.25\( l_s \)). (D) OCT and smart-OCT images of a positive resolution target USAF 1951 with a 800 \( \mu \)m thick layer of rat intestine on top of it.