MASTER 2 INTERNSHIP AND PHD THESIS PROPOSAL (ACADEMIC YEAR 2026–2027)

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Collaboration with ONERA - The French Aerospace Lab - Centre de Châtillon where experiments are planned as well.
Thesis possibility after internship: YES

INFRARED TOMOGRAPHY FOR THE INVESTIGATION OF STRATEGIC MATERIALS FOR THE AVIATION AND SPACE INDUSTRIES

TOMOGRAPHIE INFRAROUGE POUR LE CONTROLE DE MATERIAUX STRATEGIQUES DE L'AVIATION ET DE L'ESPACE

Keywords: *Optical coherent tomography, Infrared imaging, Deep subsurface imaging, Scattering materials for aviation and space industry, Non-destructive testing, Cultural heritage*

Description of the work: *100% Experimental (optical bench development, performance characterization and measurements, possibility of materials fabrication and characterization and of optical simulations) (to be discussed)*

To probe optically the subsurface of a scattering medium using an external illumination of intensity I_0, the effect of multiple scattering is such that the quantity of ballistic photons, i.e. photons that pass through the medium without undergoing multiple scattering events, decreases exponentially with the distance traveled by light in the medium. Indeed, for a layer of thickness L of a medium showing both absorption and scattering, the intensity of ballistic photons is $I_b = I_0 \exp(-L/l_s).\exp(-L/l_a)$, $l_{s,a}$ being the scattering and the absorption mean free path, respectively. An object located within a few scattering mean free paths below the surface produces a blurred image on a camera; deeper objects become invisible as the few remaining ballistic photons are overwhelmed by multiply scattered ones reaching the detector.

High-resolution, depth-resolved imaging beneath scattering media is nevertheless possible using **Optical Coherence Tomography (OCT)**, based on low-coherence interferometry [Huang1991]. Broadband sources allow optical "slicing" into 3D samples: interference occurs only at depths where the optical path difference between reference and sample beams is zero (Figure 1). This selectively detects singly backscattered (ballistic) photons while rejecting the diffuse background, yielding clear tomographic images.

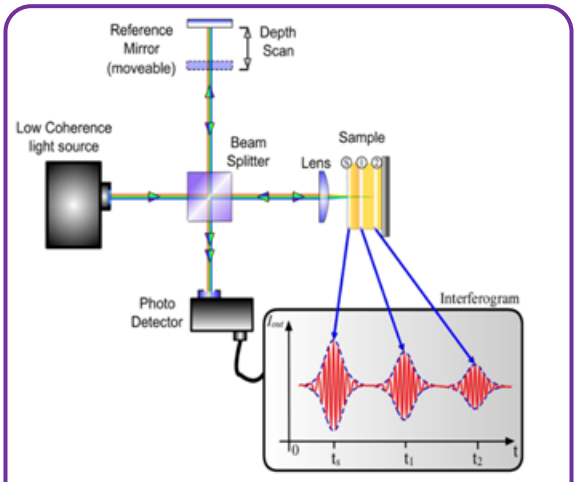


Figure 1: Schematic graph of an early time-domain optical coherence tomography (TD-OCT)

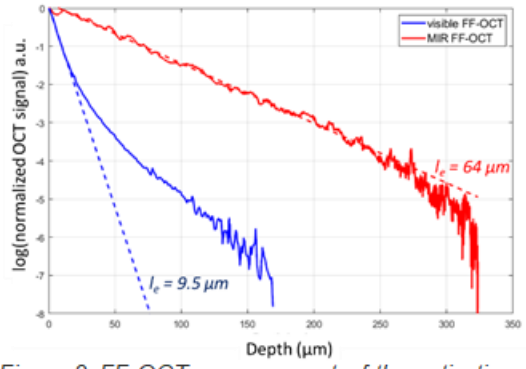


Figure 2: FF-OCT measurement of the extinction mean-free-path l_e of white acrylic paint in the MIR spectral range (MWIR, 3-5 µm) compared to the same measurement at visible wavelengths.

Conventional OCT acquires such slices point by point, requiring mechanical scanning. At the **Institut Langevin**, Claude Boccara's group pioneered an alternative **Full-Field OCT (FF-OCT)** approach, where a camera simultaneously detects multiple pixels under wide-field illumination [Dubois2002] [Vabre2002]. Each depth scan yields an *en-face* image with superior lateral resolution, and the use of spatially incoherent light makes the technique far less sensitive to optical aberrations [Barolle2021]. Since OCT imaging relies on ballistic photons, its penetration depth is limited by the **extinction mean free path** l_e, defined as $1/l_e = 1/l_s + 1/l_a$. Consequently, the technique has been mainly applied to **biological tissues**, where $l_s \approx 100\,\mu\text{m}$ or more in the **visible–near-infrared range** (the so-called biological transparency window). In contrast, OCT becomes ineffective for subsurface imaging of **opaque, highly scattering materials**, where l_s is only a few μm in the same spectral range.

By integrating a mid-wave or long-wave infrared (MWIR/LWIR) camera, similar to those used in thermal imaging, into an interferometric setup combined with a broadband infrared source, we aim to achieve deep imaging through diffusive and/or opaque layers such as paints, coatings, plastics, ceramics, or aged varnishes.

Full-Field OCT (FF-OCT) remains largely unexplored in the mid-IR range. This project will therefore address both fundamental questions on infrared light propagation in complex scattering media and applied challenges in several

fields. This internship/PhD thesis offers an opportunity to contribute to the development of a new generation of infrared interferometric imaging tools, expanding the reach of OCT beyond its traditional spectral limits. Anticipated applications include:

- Non-destructive testing, particularly for detecting subsurface defects in industrial coatings used in aerospace and advanced manufacturing.

- Cultural heritage analysis, enabling visualization beneath painted surfaces and ceramic glazes.

Importantly, we have already validated the proposed concept by constructing a **basic interferometric mid-IR prototype** combined with a **MWIR camera**. As shown in Figure 2, using acrylic paint as a scattering test sample, the **mean OCT signal intensity** decays exponentially with depth below the surface. From this decay, we determine an extinction mean free path $l_e = 64\ \mu\mathrm{m}$. For comparison, the same measurement performed at visible wavelengths yields $l_e = 9.5\ \mu\mathrm{m}$, clearly demonstrating the **advantage of mid-infrared FF-OCT** for **deep subsurface imaging**.

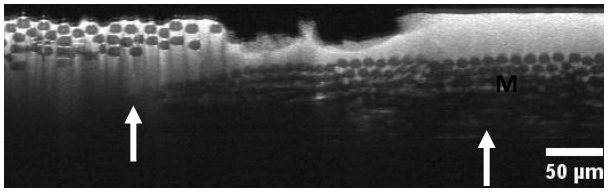


Figure 3: FF-OCT cross-section of an Oxide/Oxide composite in the visible range, showing alumina fibers (arrows) in an alumina matrix (M). In this wavelength range, the imaging depth is limited to ~100 µm.

This work will be conducted within a collaboration between the Institut Langevin and ONERA. It will focus primarily on imaging and characterizing the oxide/oxide ceramic matrix composite (CMC) materials developed for the aviation and space industries in order to increase combustion temperature. These CMC, consisting of fabrics of oxide fibers embedded in an oxide matrix, are based on the weak matrix principle and exhibit a high level of porosity (Figure 3). The goal will be to test FF-OCT on these materials across the three wavelength ranges (visible, MWIR, and SWIR) and to evaluate its performance in detecting defects (such as plies stacking or waviness) and in measuring the matrix porosity. This porosity can occur on macro-, micro-, and nanoscale levels. At the latter two scales, which are too small to allow for direct imaging, we will investigate the relationship between the porosity and the scattering mean free path measured by FF-OCT, from both experimental and theoretical perspectives (physical modeling).

The development of the OCT instruments and sample characterization using these techniques will be carried out at Institut Langevin. The fabrication and characterization of the materials using non-optical methods will be conducted at ONERA – The French Aerospace Lab, Centre de Châtillon, depending on the experimental requirements and the candidate's profile.

References:

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