Terahertz Time-Domain Imaging Framework for Cultural Heritage Studies

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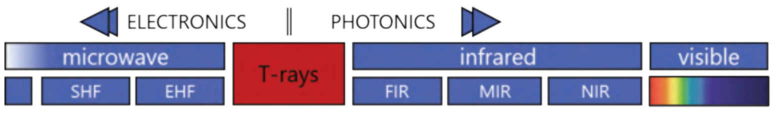
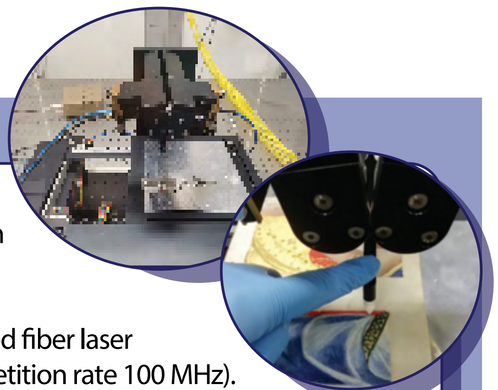
Background



Terahertz time-domain (THz-TD) imaging plays an increasingly significant role in the study of solid-state materials by enabling the simultaneous extraction of spectroscopic composition and surface topography in the far-infrared region (3–300 cm^{-1}). However, when applied to works of art in reflection configuration, significant challenges arise, including weak signal intensity, multiple signal losses, and surface distortion. Our study proposes a practical solution to overcome these limitations and conducts an integrated imaging and spectroscopic analysis on Cultural Heritage surfaces, allowing for the retrieval of surface thicknesses, material distribution, and pigment spectroscopic signals.

Methods

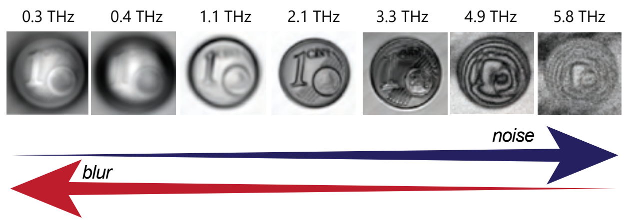


Device:
Commercial THz-TD system (TOPTICA Photonics)
Source:
Mode-locking Erbium-doped fiber laser (λ= 1560 nm, Δt=50 fs, repetition rate 100 MHz).
Imaging Acquisition:
Reflection configuration in nitrogen atmosphere.

$$\underbrace{E(t)}_{\mathbb{R}} \xrightarrow{FT} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} E(t) e^{-i\omega t} dt = \underbrace{E(\omega)}_{\mathbb{C}} = A(\omega) e^{i\phi(\omega)}$$

Intrinsic Limitations of Terahertz Time-Domain imaging

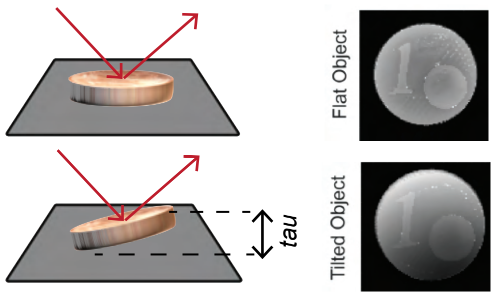
Frequency-Dependent Image Quality



The beam radius depends on the beam weist (w_0) and on the Reyleigh length (z):

$$w(z) = w_o \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

Axial Misalignement of the Object



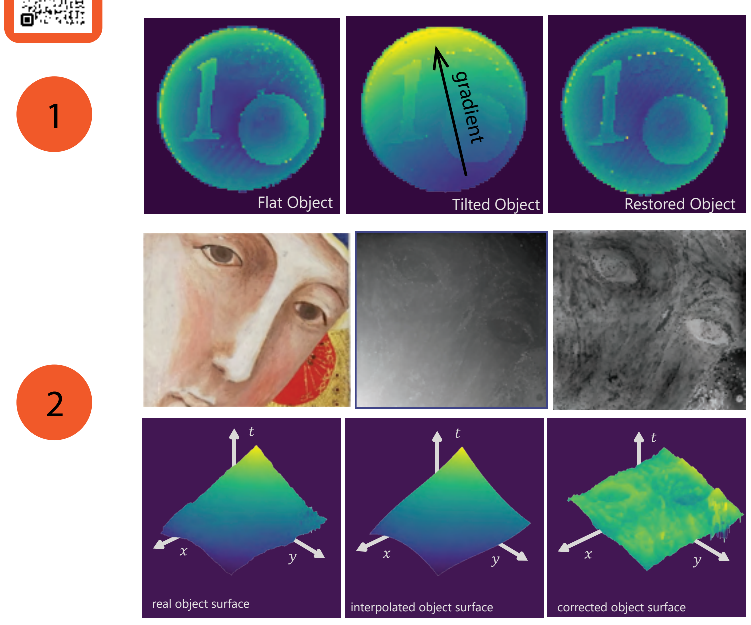
The axial de-focusing causes an error in the phase determination. This is known as *phase-variance issue* and affets the determination of refrax index value.

$$\Phi'(\omega) = \Phi(\omega) + \Delta\Phi(\omega, \tau)$$
$$\Phi'(\omega) = \Phi(\omega) + \omega\tau$$

Results

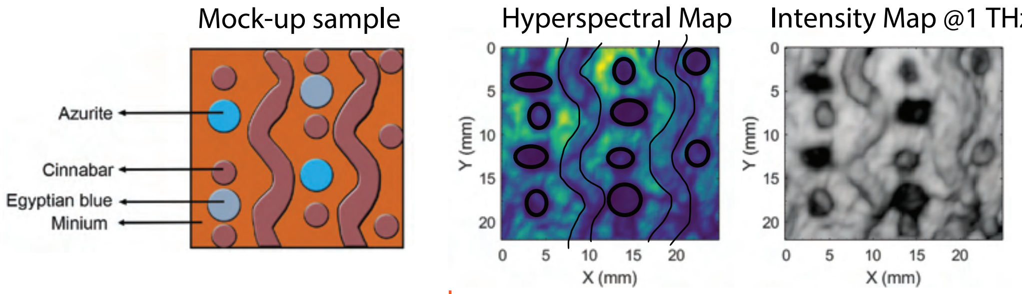
We developed a two-step computational method to remove the instrinsic limitations of THz-TD:
(1) self-referenced method for geometrical distortion removal;
(2) computer vision method for beam-shape effects and noise removal.

Examples:

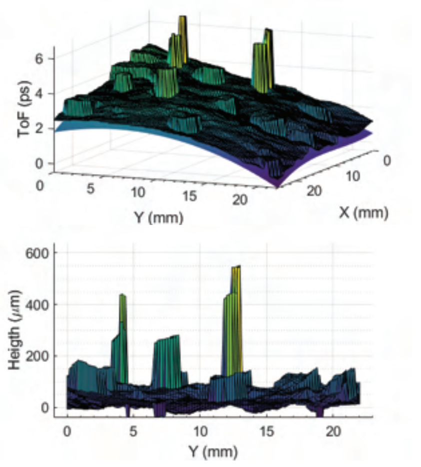


THz-TD for pigment identification and hyperspectral mapping

Mock-up sample | Hyperspectral Map | Intensity Map @1 THz

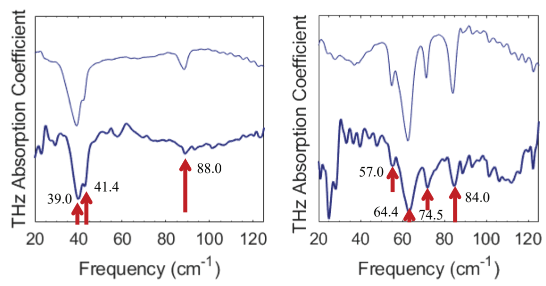


Geometrical Distortion Correction



Absorption Coefficient Determination

$$\alpha(\omega) = \frac{2\omega}{c} \frac{2\phi(\omega)}{(1 - |A(\omega)|)^2 + \phi^2(\omega)}$$



Cinnabar (HgS) | Minium (Pb_3O_4)

Conclusion

In our study, a laboratory-designed approach that combines imaging acquisition and spectroscopic analysis was proposed to explore the potential advantages and limitations of THz-TD on real artworks. To achieve this, we addressed issues related to axial misalignments and electric field drift, and subsequently determined the absorption coefficient map between 20 and 120 cm^{-1}. Undoubtedly, the utilization of far-infrared electromagnetic radiation can offer significant advantages when considering hyperspectral imaging at scale of sub-millimeter resolution. The integration of THz-TD and the different working modality of THz-TD (i.e., imaging and spectroscopy) further advances the capabilities of this technique, making it highly beneficial for routine analysis of cultural heritage.

References

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