Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

CADIPT

Dynamic Frequency-Domain Photothermal Imaging Methodologies for Non-Destructive Evaluation of Industrial Materials: A Review of the State-of-the-Art

Pantea Tavakolian
Andreas Mandelis

CINDE
CANADIAN INSTITUTE FOR NON-DESTRUCTIVE EVALUATION

NDT in Canada
NDTiC 2018
Canada's NDT Conference

June 19 - 21
Halifax Convention Centre
Halifax, Nova Scotia

Outline

1. Introduction about thermography systems
2. Lock-in thermography
3. Match Filtering thermography
4. Pulsed photothermal radar
5. Enhanced truncated correlation photothermal coherence tomography (ETC-PCT)
6. Conclusions
7. Future Work

CADIPT

Active thermography system

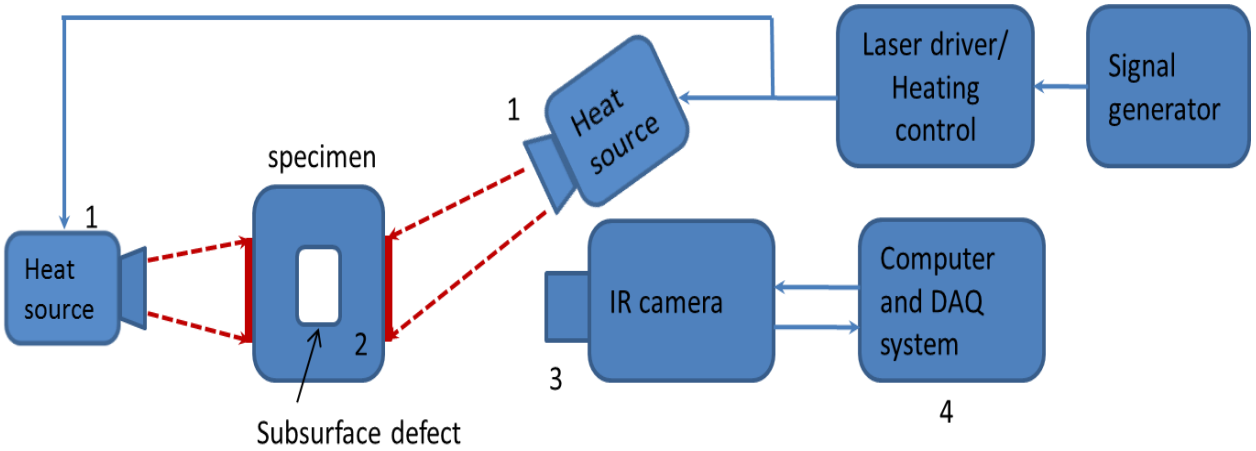
Step 1: Heating; In some cases a heating source controller is connected to a signal generator to receive the modulating signal.

Step 2: thermal diffusion through the material bulk following the heat deposition cut-off at the surface.

Step 3: Infrared camera detection.

Step 4: The thermogram sequence is processed with the reconstruction algorithm on a computer.

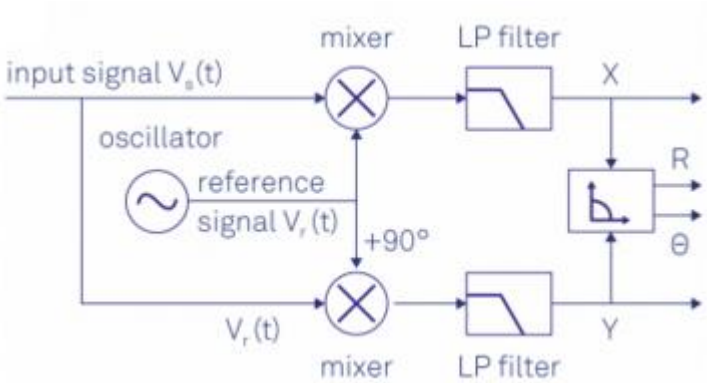
A generic active thermography instrumentation



Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

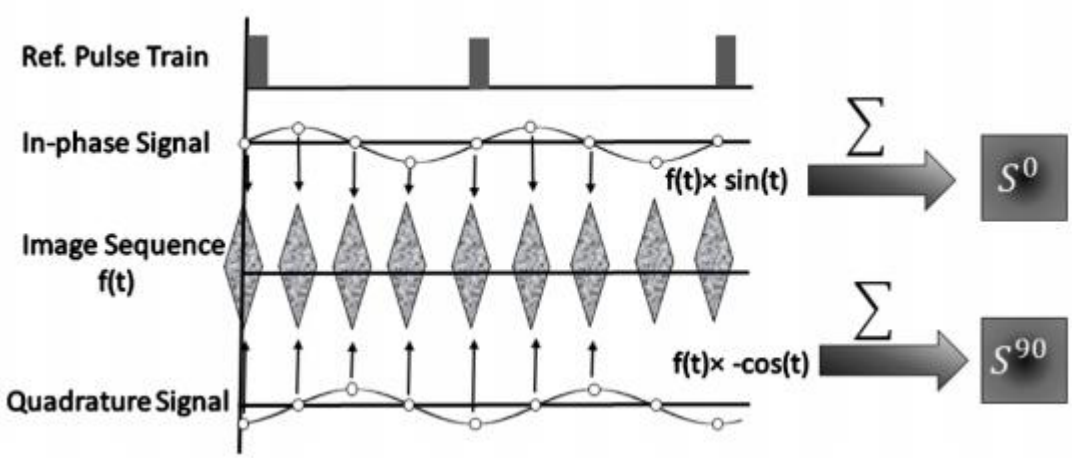
CADIPT

Lock-In thermography



$$= \sqrt{(S^0)^2 + (S^{90})^2}$$

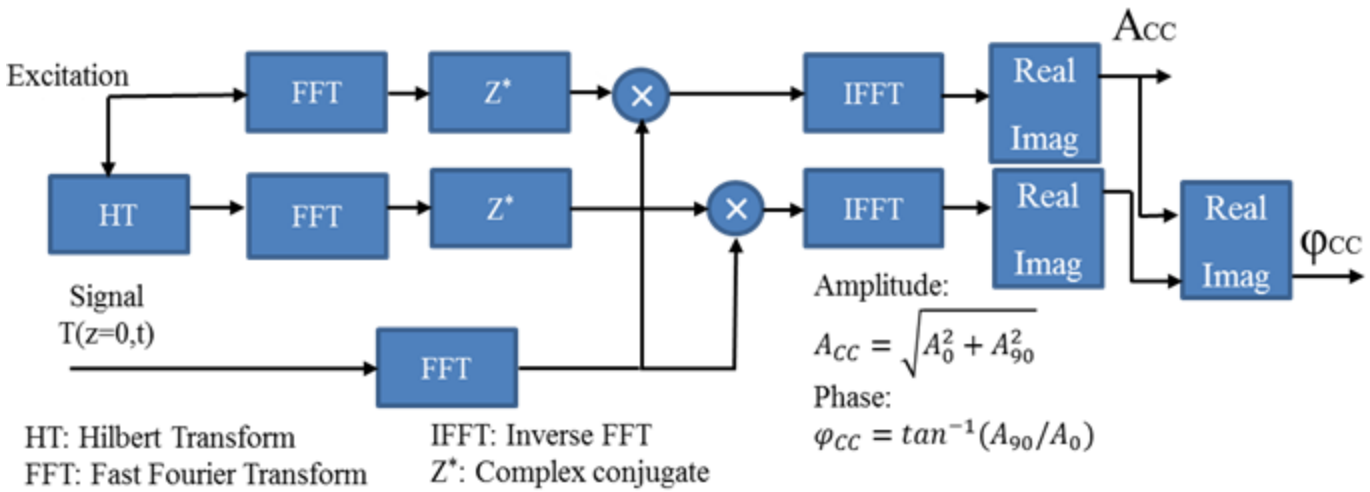
$$= \arctan\left(S^{90}/S^0\right)$$



Ashkan Ojaghi, Artur Parkhimchyk, and Nima Tabatabaei, "First step toward translation of thermophotonic lock-in imaging to dentistry as an early caries detection technology" (2016)

CADIPT

Match-filter thermography algorithm

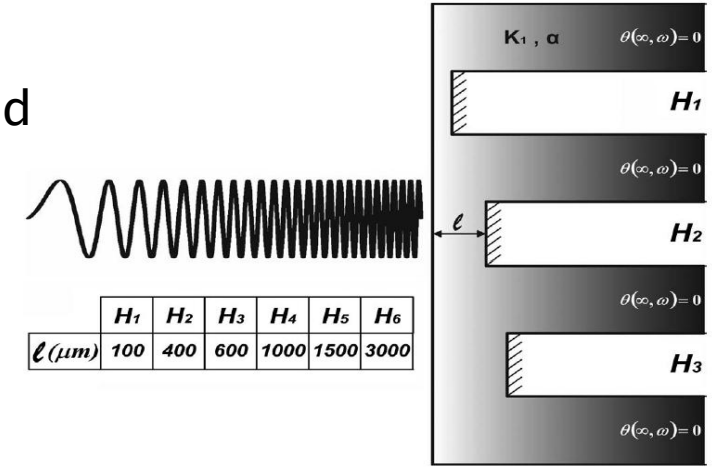


Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

CADIPT

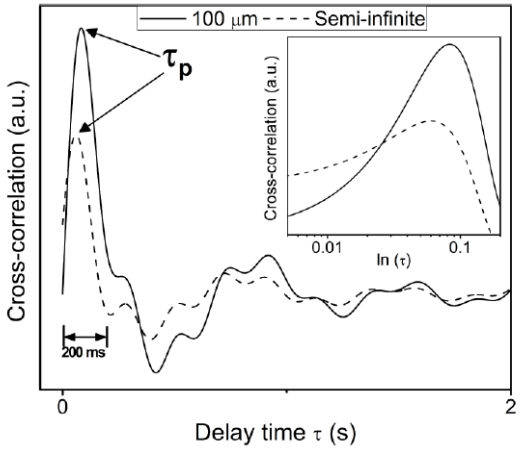
Thermal wave-radar

A steel sample containing several blind holes with steel overlayer of various thicknesses.

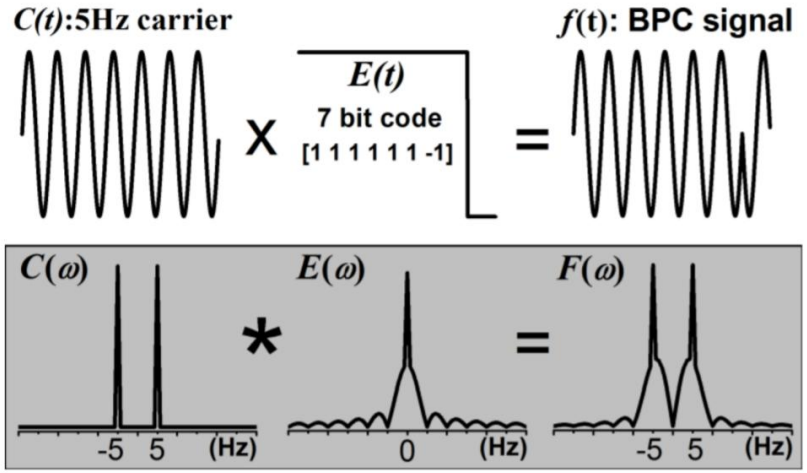


	H_1	H_2	H_3	H_4	H_5	H_6
ℓ (μm)	100	400	600	1000	1500	3000

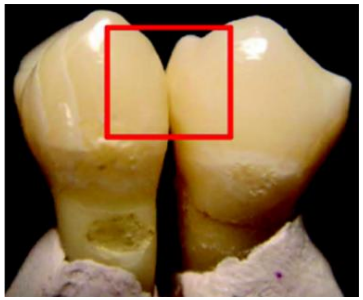
Theoretical TWR signals for 100-µm thick and semi-infinite steel samples. The inset magnifies the time interval checked in the main plot

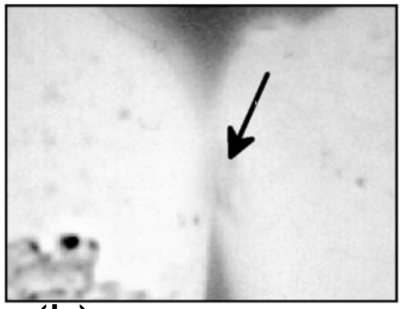


Binary Phase Coding Thermal Coherence thermography

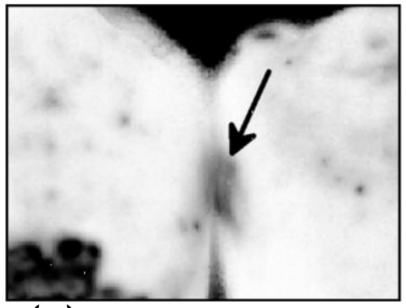


- Binary Phase Coding (BPC) signal construction in time (top) and frequency (bottom) domains for a 7-bit code and 5 Hz carrier





(b)

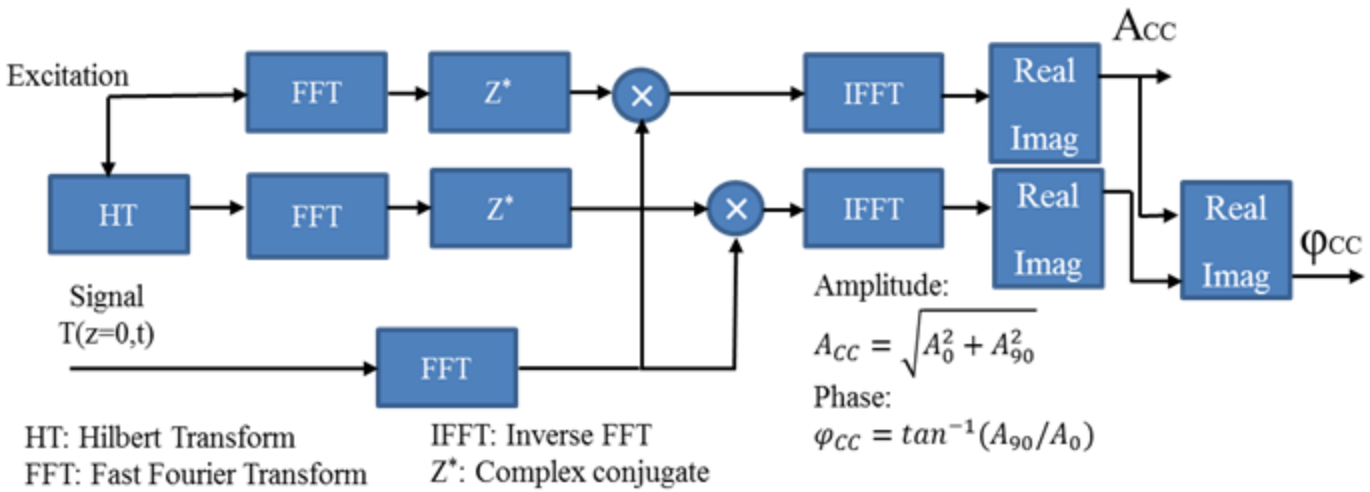


(c)

- Teeth matrix with hidden interproximal early caries. The red rectangle shows the imaged area. (b) Conventional LIT and (c) TCT phase images of the teeth matrix

CADIPT

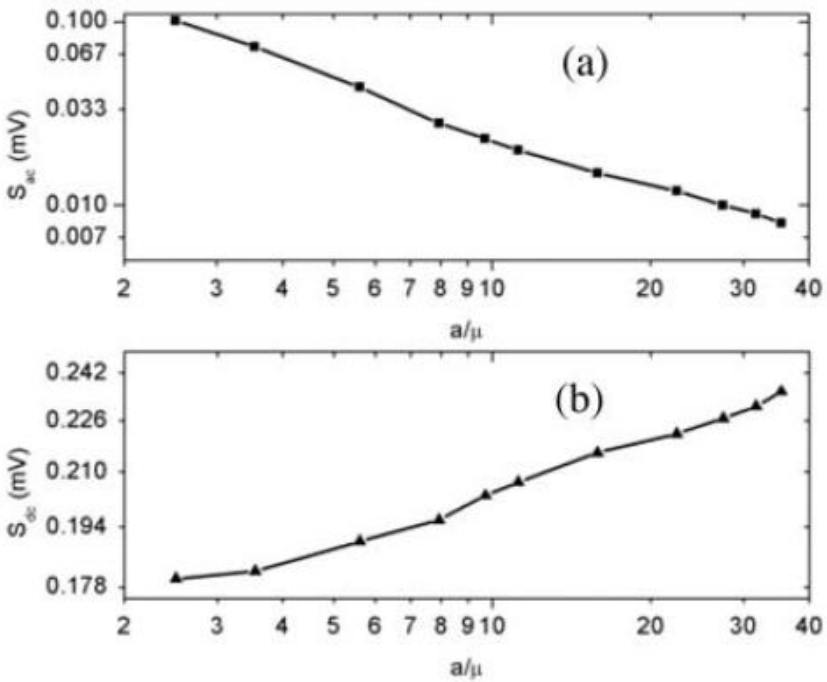
Pulsed chirp photothermal radar algorithm

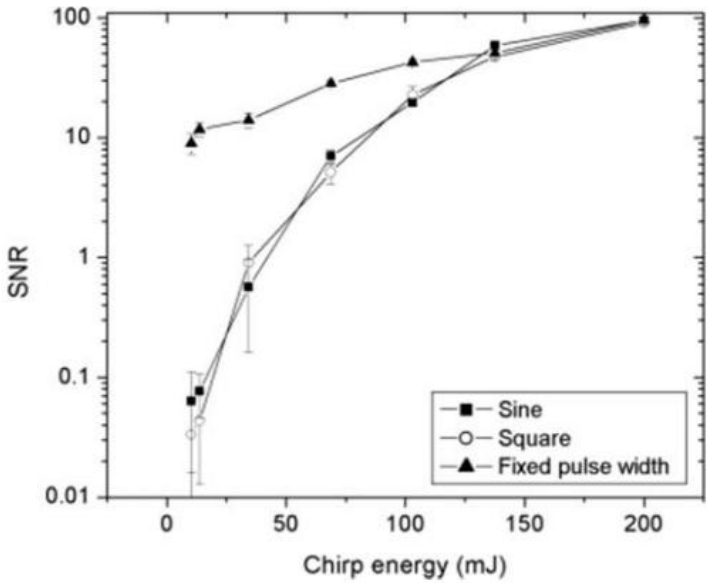


CADIPT

Pulsed chirp photothermal radar

$$T(\vec{r}, t; \omega) = T_0 + T_{dc}(\vec{r}, t; \omega) + T_{ac}(\vec{r}, t; \omega)$$



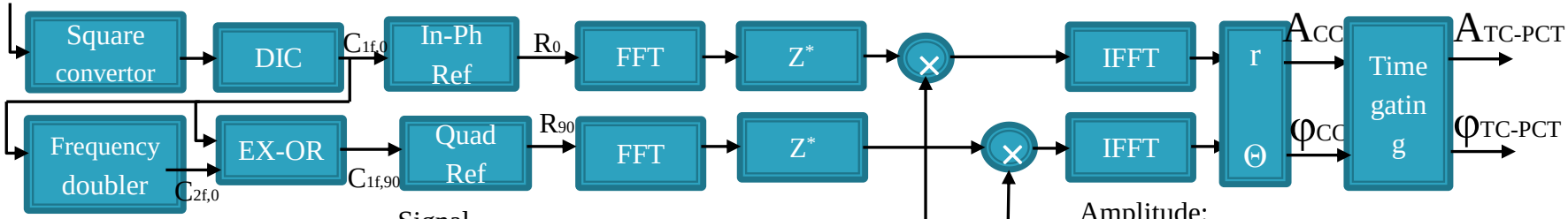


where *a* is the laser beam spotsize and u is the thermal diffusion length

Enhanced Truncated Correlation-Photothermal Coherence Tomography (E-TC-PCT) reconstruction algorithm

CADIPT

- **E-TC-PCT** cross-correlates the in-phase and the quadrature of a delay-incremented reference chirp ($R_{n,0}$ and $R_{n,90}$) with the thermal images (S) captured by the camera in a pixel-by-pixel format.



DIC: Delay incremented unit
EX-OR: Exclusive-OR
FFT: Fast Fourier Transform
IFFT: Inverse FFT
Z^*: Complex conjugate

Amplitude:

$$A_{CC} = \sqrt{A_0^2 + A_{90}^2}$$

Phase:

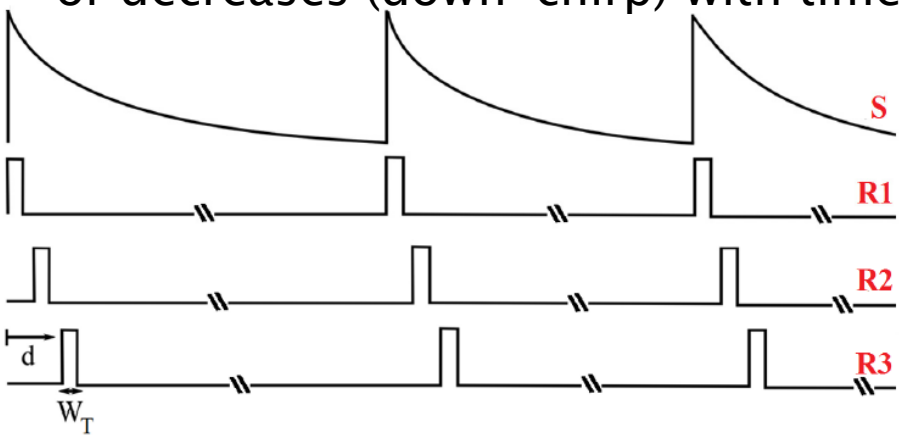
$$\varphi_{CC} = tan^{-1}(A_{90}/A_0)$$

Enhanced TC-PCT reconstruction algorithm, and amplitude and phase measurements

CADIPT

Excitation and thermal signal generation

- Excitation pulses: short duration pulses under thermal confinement (much less than the thermal relaxation time) with high peak power.
- Reference chirp: Phase incrementing (d in ms)
- A chirp is a signal in which the frequency increases (up-chirp) or decreases (down-chirp) with time.



Photothermal chirp

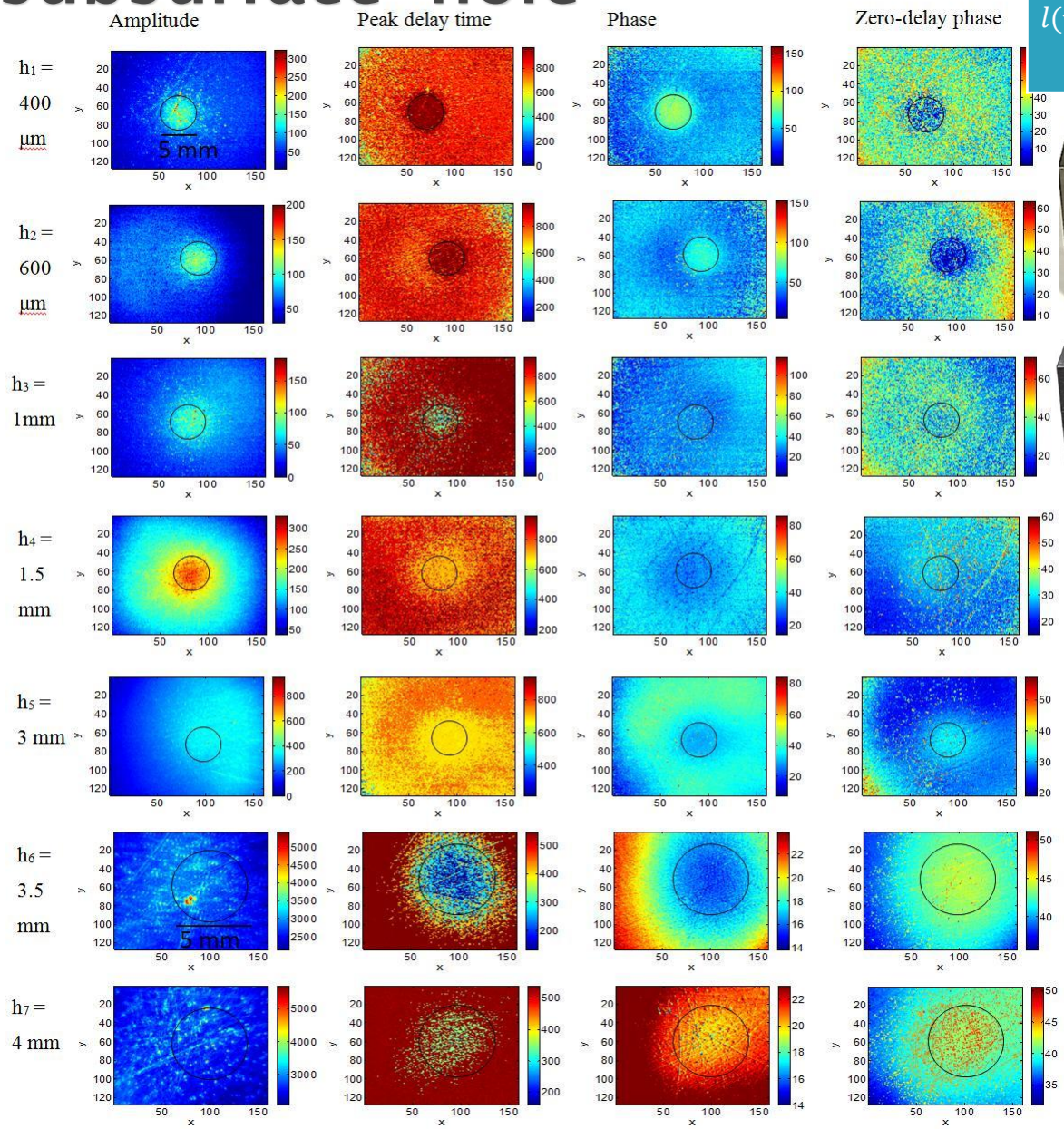
1st reference chirp

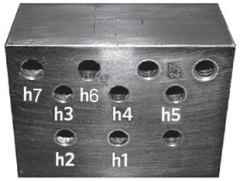
2nd reference chirp

3rd reference chirp

Steel sample with several subsurface hole

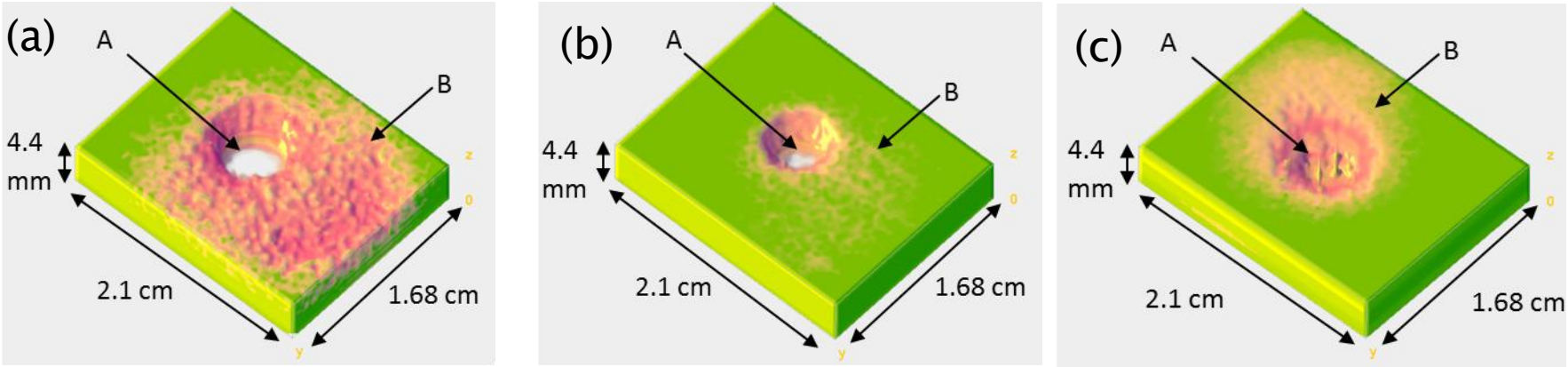
	h_1	h_2	h_3	h_4	h_5	h_6	h_7
$l(mm)$	0.4	0.6	1	1.5	3	3.5	4



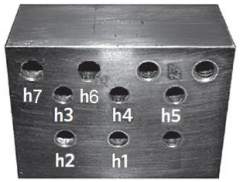


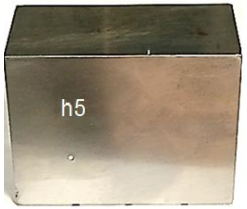
E-TC-PCT images of the holes in the steel sample. Each row displays four E-TC-PCT output channels (amplitude, peak delay time, phase, and zero-delay phase) for one of the holes.

3D images of holes ≤ 1.5 mm deep



	h_1	h_2	h_3	h_4	h_5	h_6	h_7
$l(mm)$	0.4	0.6	1	1.5	3	3.5	4





3-D visualization of the invisible subsurface holes in a steel block sample using TC-PCT imaging. Amplitude tomograms of the enhanced TC-PCT of hole h_1 (a), h_2 (b), and h_3 (c) with truncation time gate of 40 ms. Each image covers an area of 2.1 cm × 1.68 cm on the sample, and the image delay time range is 1.2 s which corresponds to depth of 4.39 mm. A and B on these images display the holes, and the energy accumulation at the back surface, respectively. The laser beam illuminating the sample from the bottom is a pulsed chirped signal with sweep range of 0.2 Hz-0.6 Hz, duration 12 s, and pulse duration 10 ms. Diameter of the illumination beam is 3 cm, and the laser fluence per pulse is 7 mJ/cm^2.

Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

Lock-in thermography

CADIPT

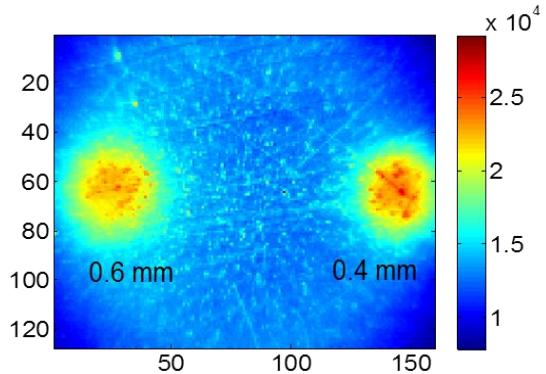
Amplitude

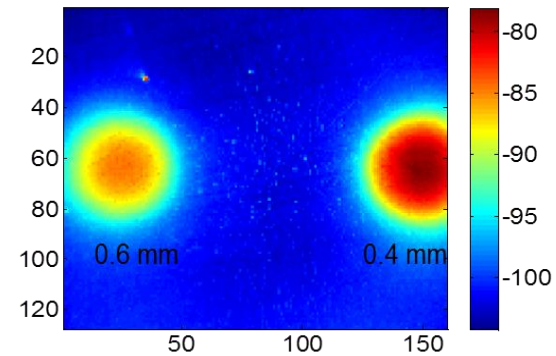
Phase

$h_1 = 0.4$ mm

&

$h_2 = 0.6$ mm

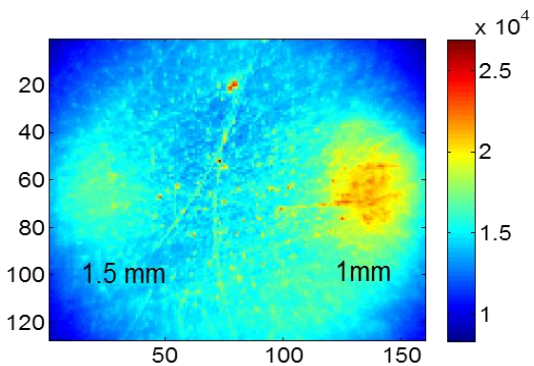


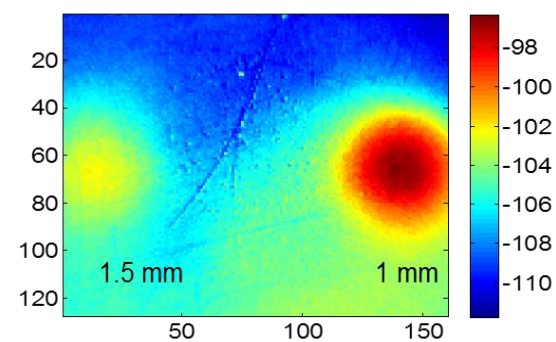


$h_1 = 1$ mm

&

$h_2 = 1.5$ mm





Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

Thermal wave radar

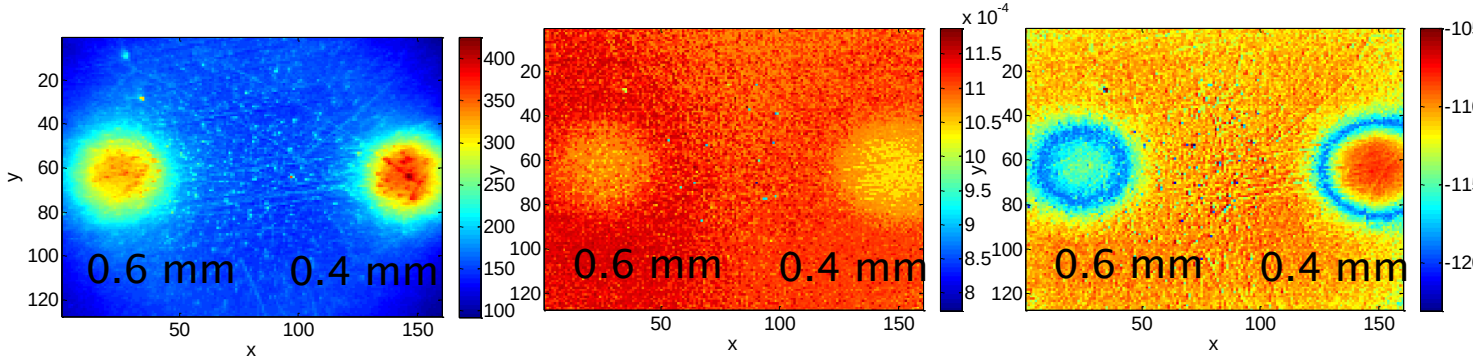
CADIPT

Amplitude | Amplitude Delay | Phase

$h_1 = 0.4$ mm

&

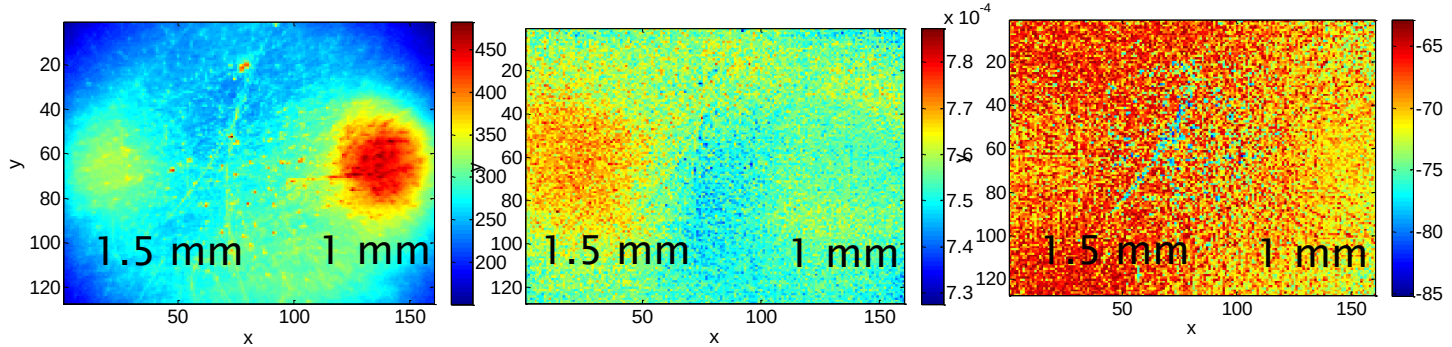
$h_2 = 0.6$ mm



$h_1 = 1$ mm

&

$h_2 = 1.5$ mm

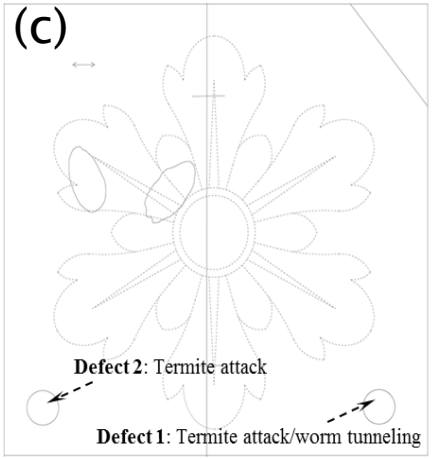


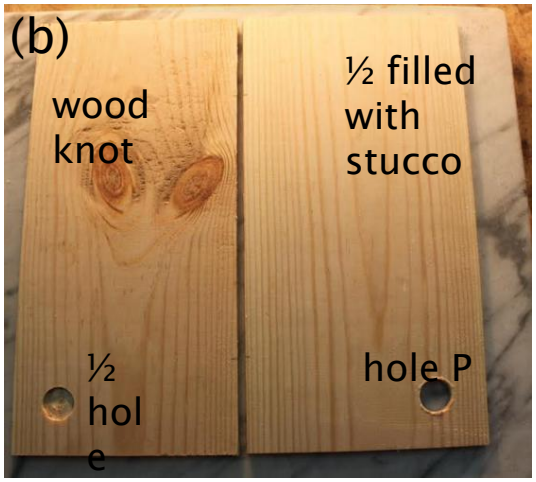
Defects in the inlay sample

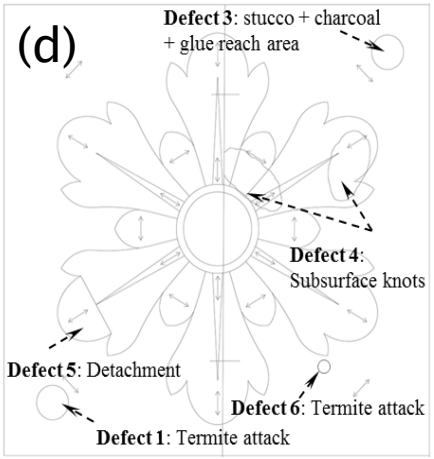
A photograph of the front side (recto) of the final sample is shown in (a) and a middle layer underneath (a) is shown in (b).

The positions, names and sizes of the defects in the inlay sample: c) recto, and d) verso.

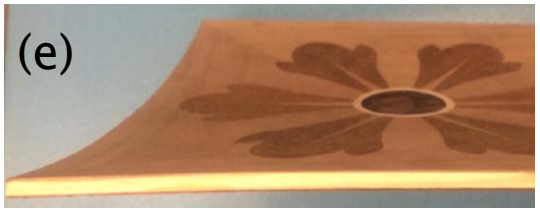
It should be noted that defect 1 affects the entire middle layer, while defect 2 affects only one half of it.







Cross-sectional image of the sample (e)

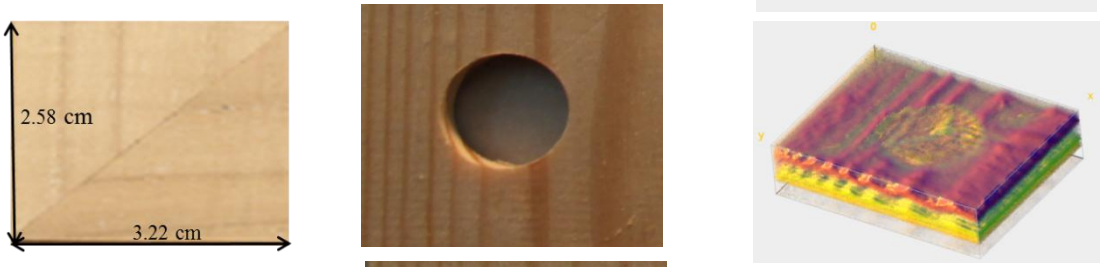


Defectoscopy in an art object

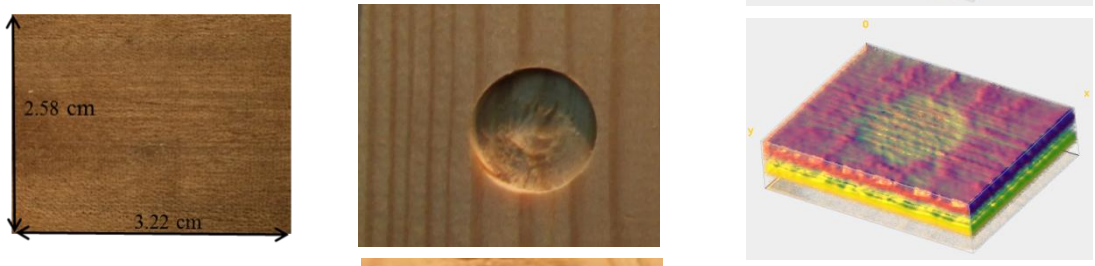
Imaging area: 3.22 cm × 2.58 cm

TC-PCT images of a delamination of a top layer

TC-PCT images of drilled hole in the middle

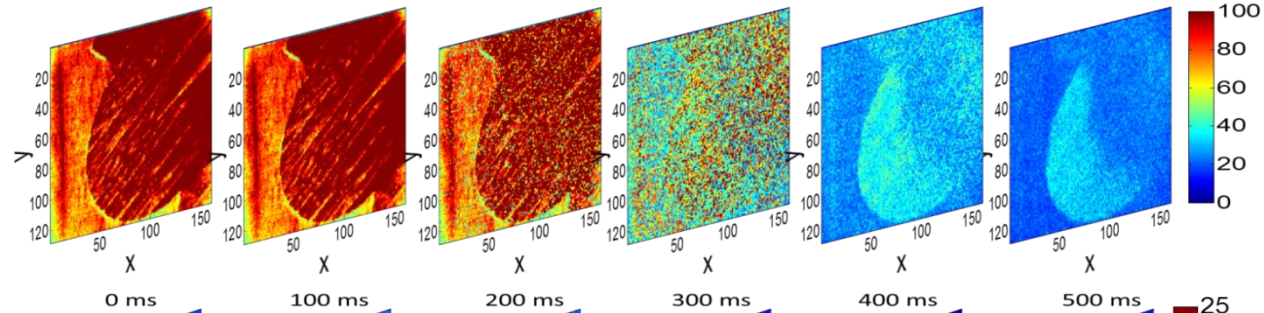


TC-PCT images of ½ drilled hole in the middle

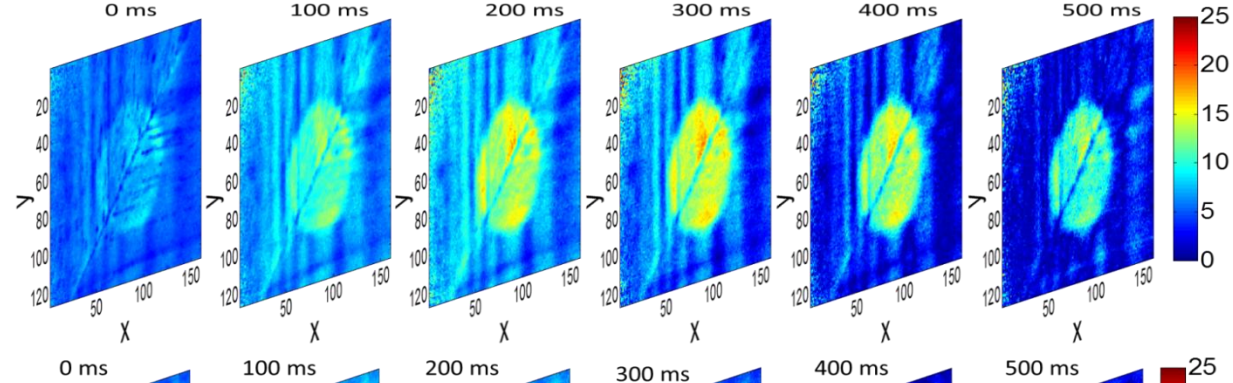


TC-PCT images of a wood knot in the middle layer

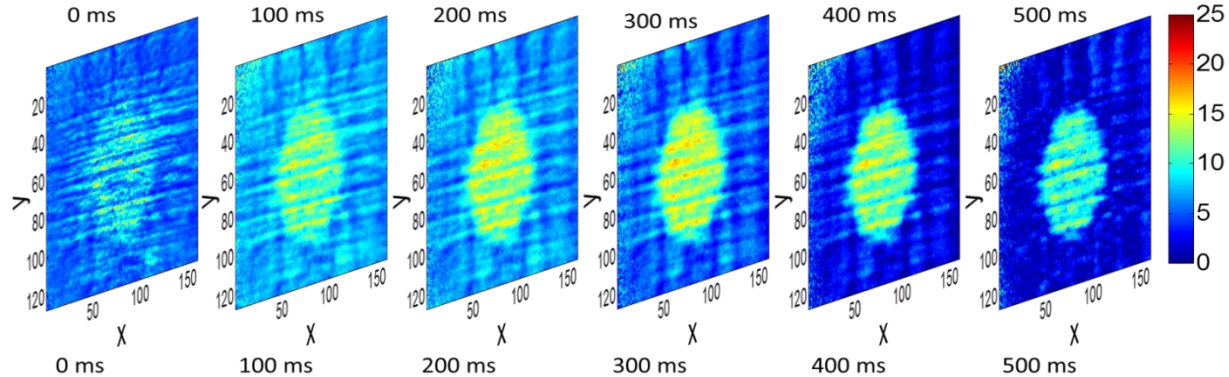
E-TC-PCT images of a delamination of a top layer



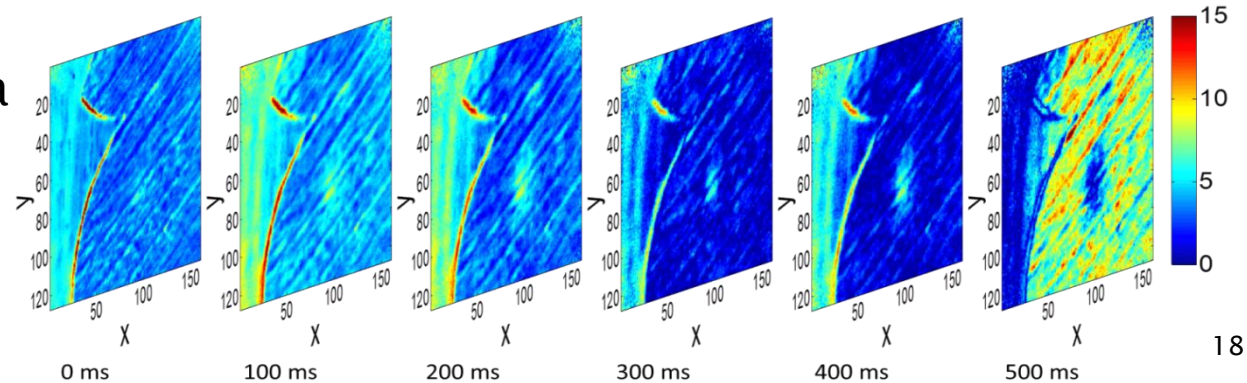
E-TC-PCT images of drilled hole in the middle



E-TC-PCT images of ½ drilled hole in the middle

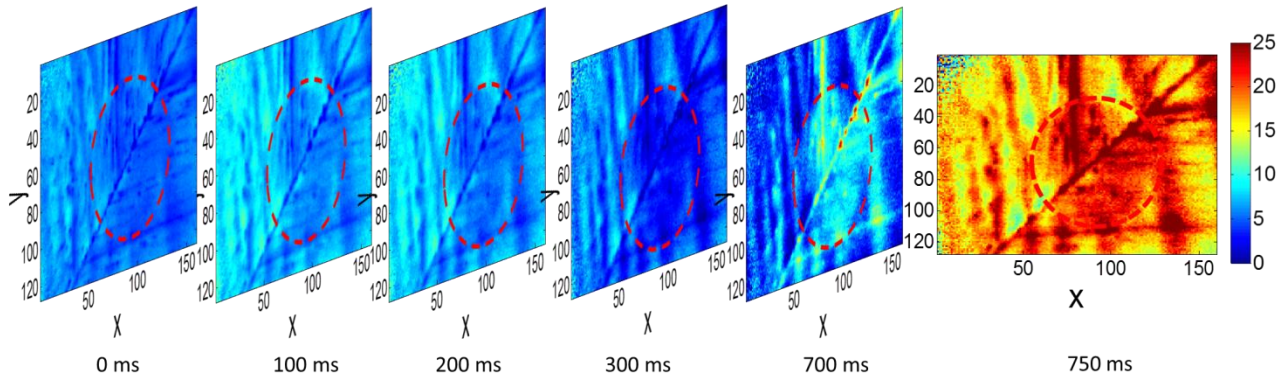


E-TC-PCT images of a wood knot in the middle layer

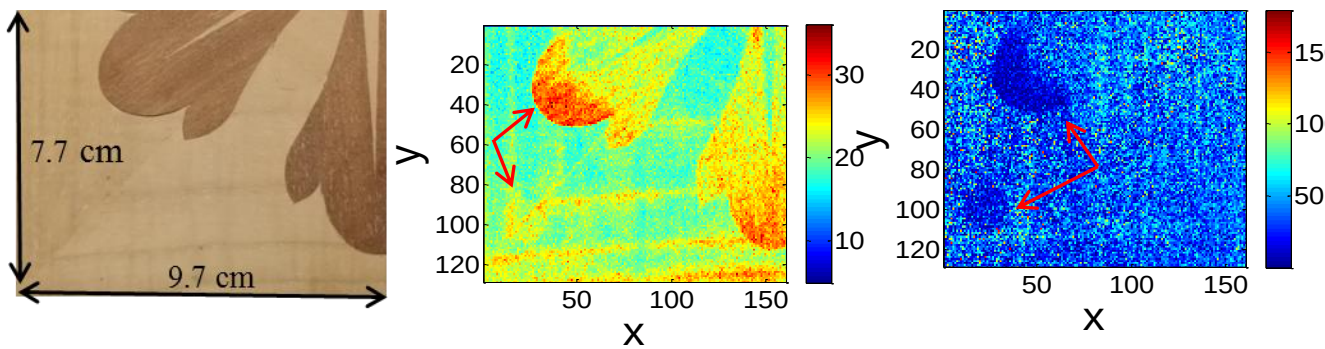


Defectoscopy in an art object

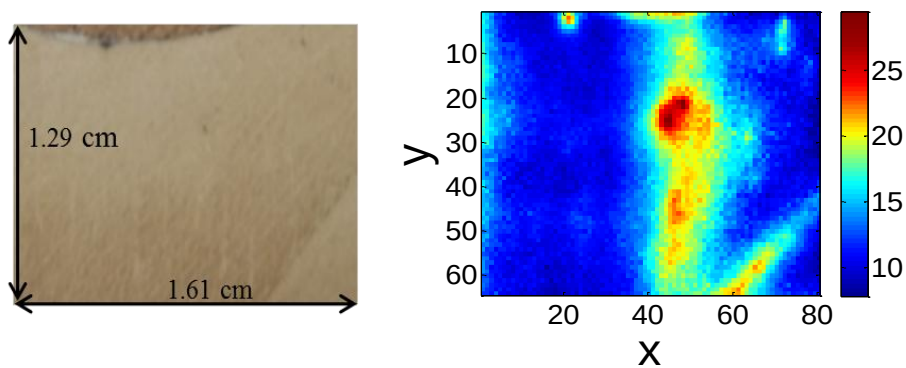
TC-PCT images of filled hole with stucco and charcoal in the middle



TC-PCT images of a larger area showing two defects in one image experiment



TC-PCT images of a deep hole in the middle layer

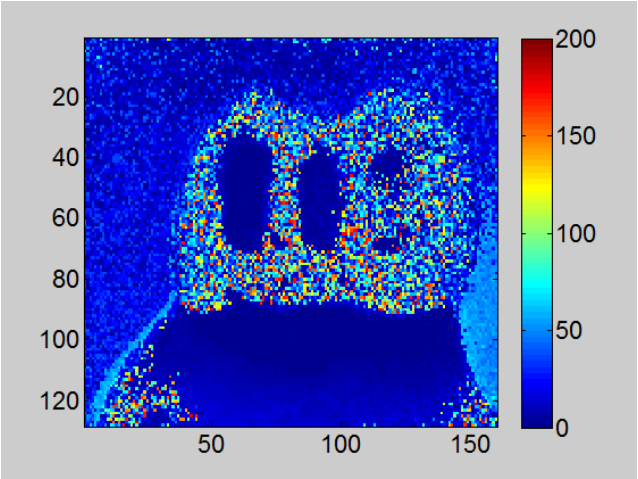


Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

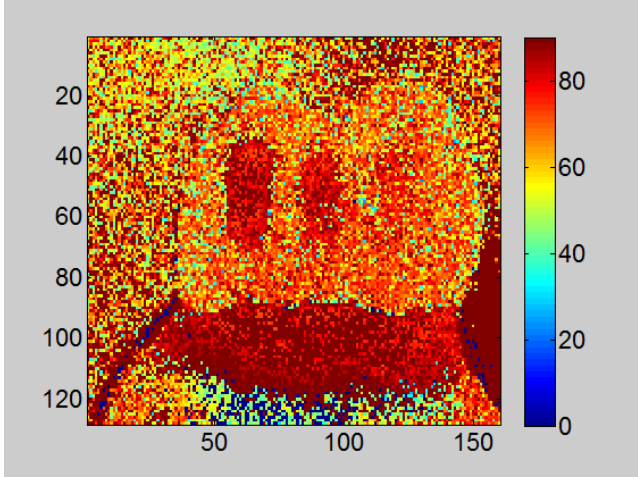
Dental imaging

CADIPT

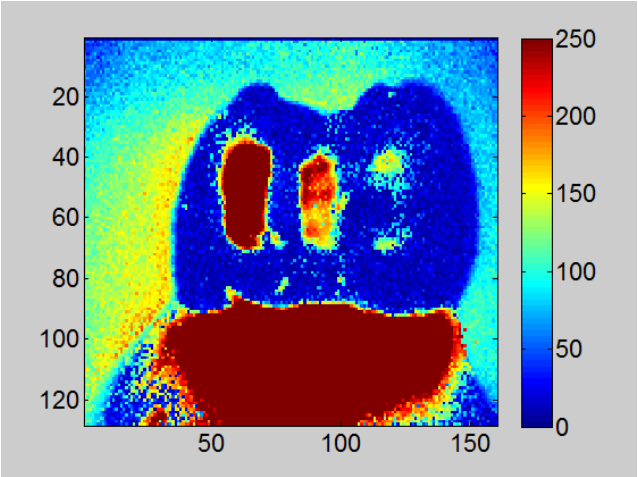
Phase



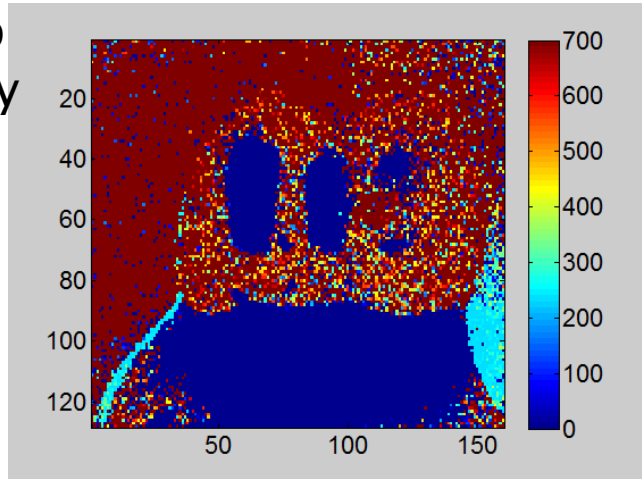
Phase delay



Amp

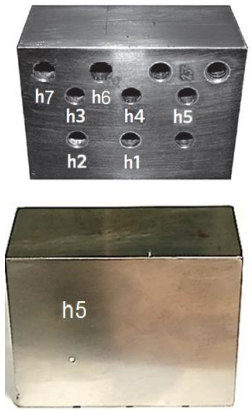


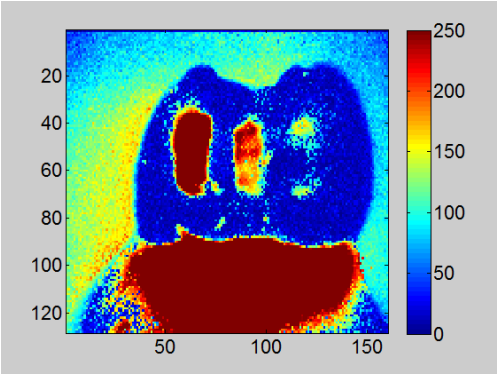
Amp delay



Conclusions

- Enhanced TC-PCT
  - is a new thermal imaging modality that can provide high resolution 3D images of different specimen
  - has higher axial resolution and depth range compared to all other modalities
  - can be applied for non-destructive testing of industrial materials and art objects
  - is able to be used for biomedical applications





Future work

- Signal analysis for each application to realize an image enhancement method for different case studies.
- New applications such as diagnosis of Osteoporosis

Thank you!