



Tests non-destructifs (NDT) pour structures en matériaux composites

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Techniques de mesure sans contact

Mesures dimensionnelles

- Projection de franges
- ~~Corrélation numérique d'images~~

Mesures des champs de déplacement

- Interférométrie holographique-speckle (1D-2D-3D)
- Interférométrie différentielle (shearographie)

Thermographie

Ultrasons sans contact par laser

Applications aux composites

Comportement thermo-mécanique

- Dilatation
- Déformation sous contraintes thermiques
- ...

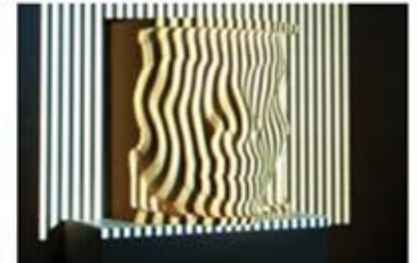
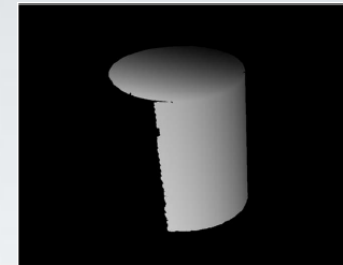
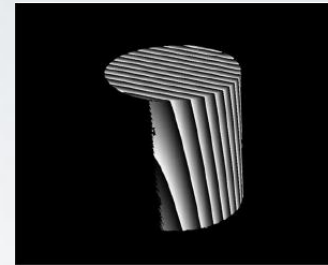
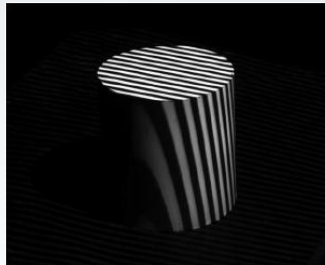
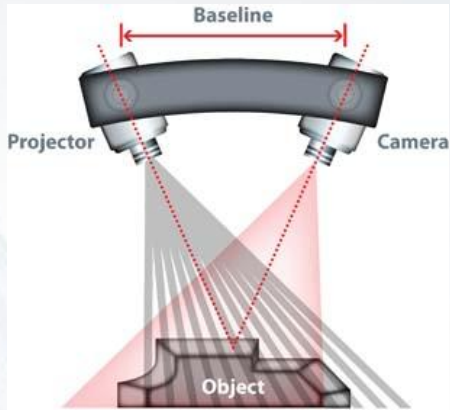
Détection de défauts internes

- Détection indirecte en surface
- Cartographie en profondeur

Résultats obtenus dans des projets divers
Développements actuels et futurs

Mesures thermo-mécaniques

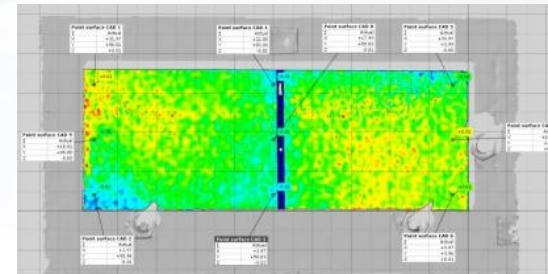
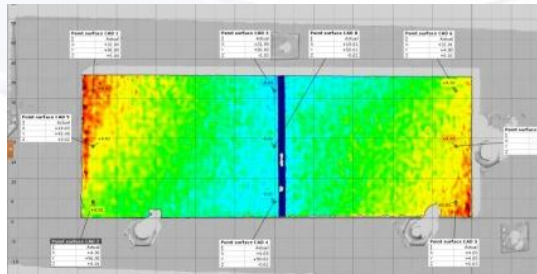
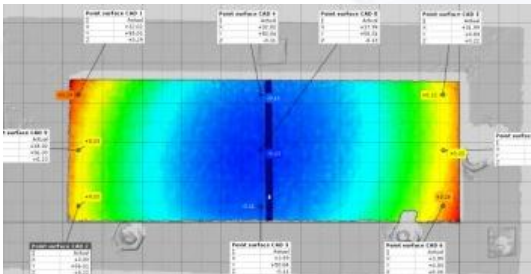
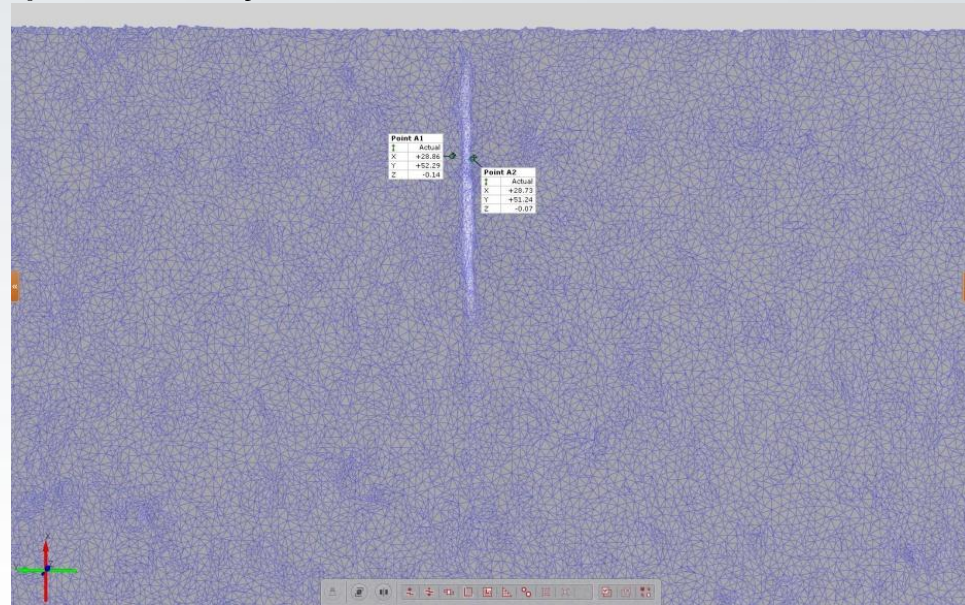
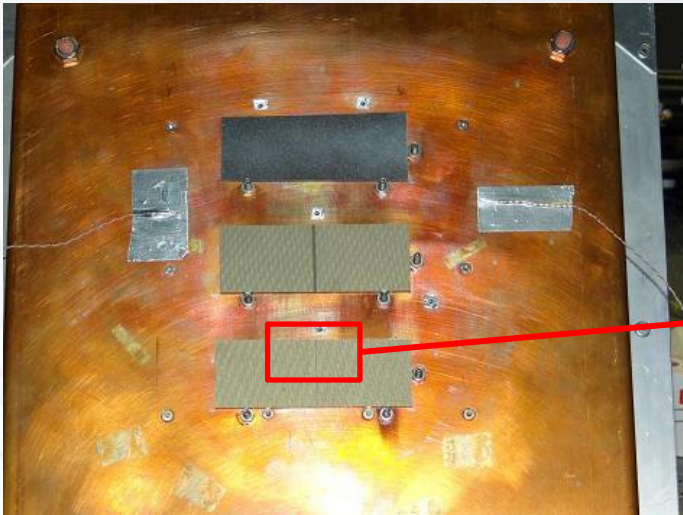
- Projection de franges
 - Mesures des coordonnées des points d'un objet



- Instrument commercial GOM ATOS

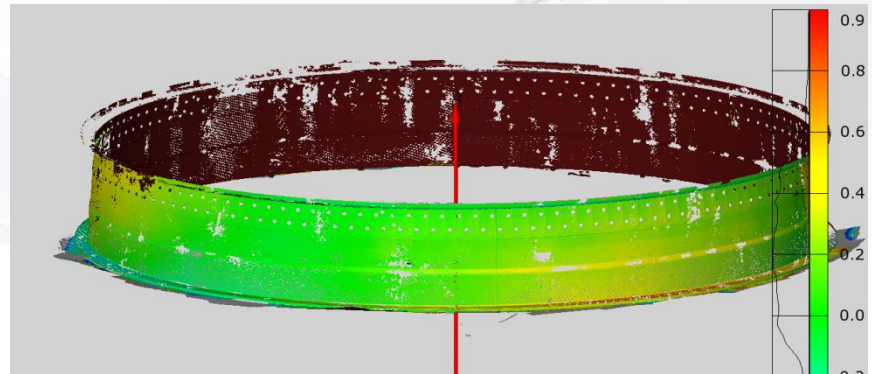
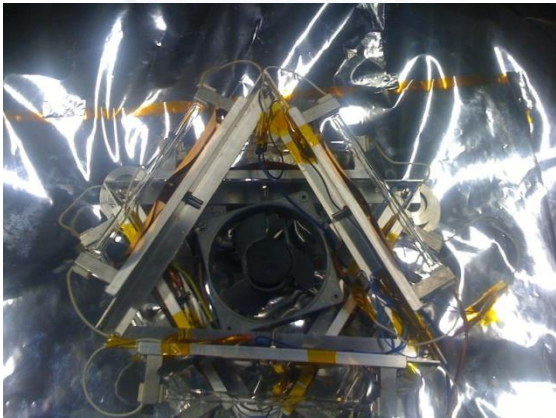
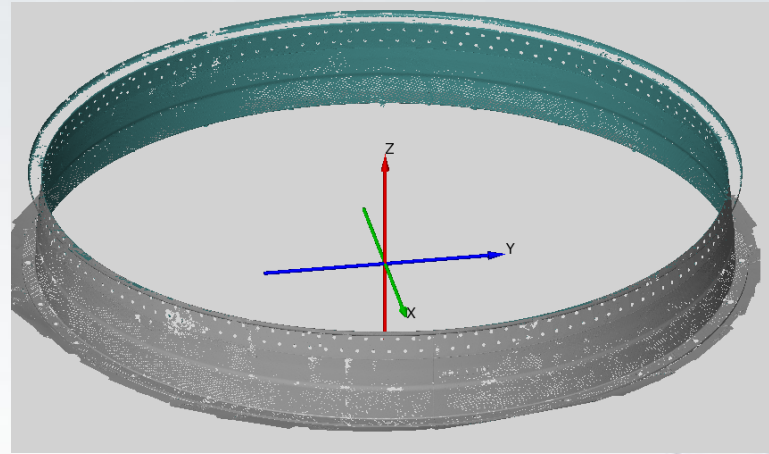
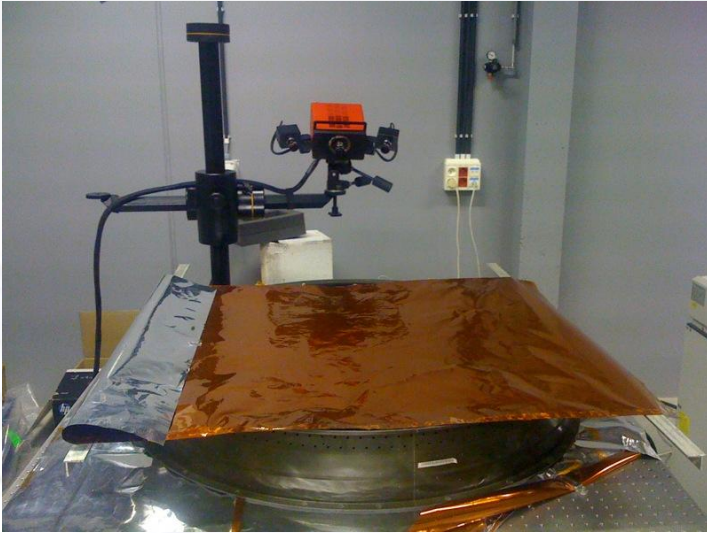
- Volume mesurable 1 : $130 \times 100 \times 80 \text{ mm}^3$ (résolution $10 \mu\text{m}$)
- Volume mesurable 2 : $500 \times 400 \times 320 \text{ mm}^3$ (résolution $50 \mu\text{m}$)

- Projet Engine Composite (E_COM) : Plan Marshall 2009-2013
- Caractérisation de coupons composites-hybrides



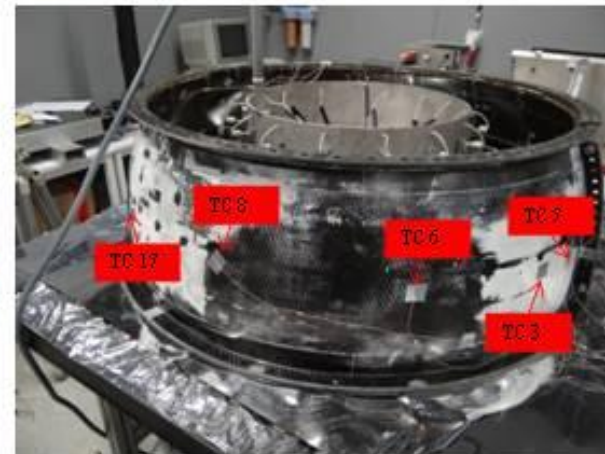
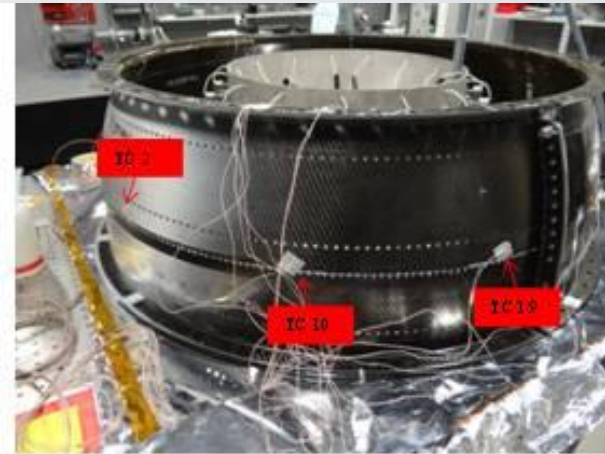
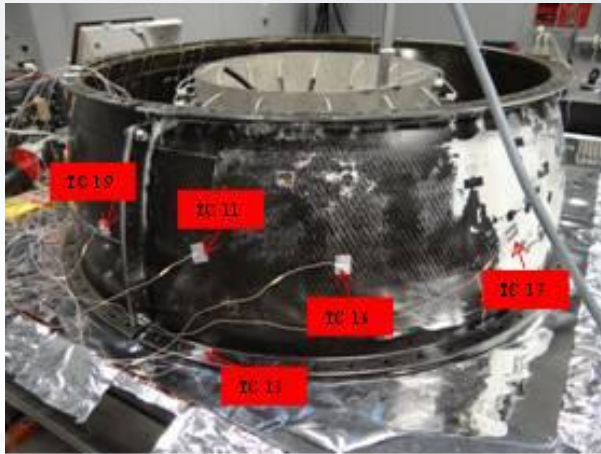
Mesures dimensionnelles

- Projet Engine Composite (E_COM) : Plan Marshall 2009-2013
- Mesure de dilatation radiale d'une virole en composites

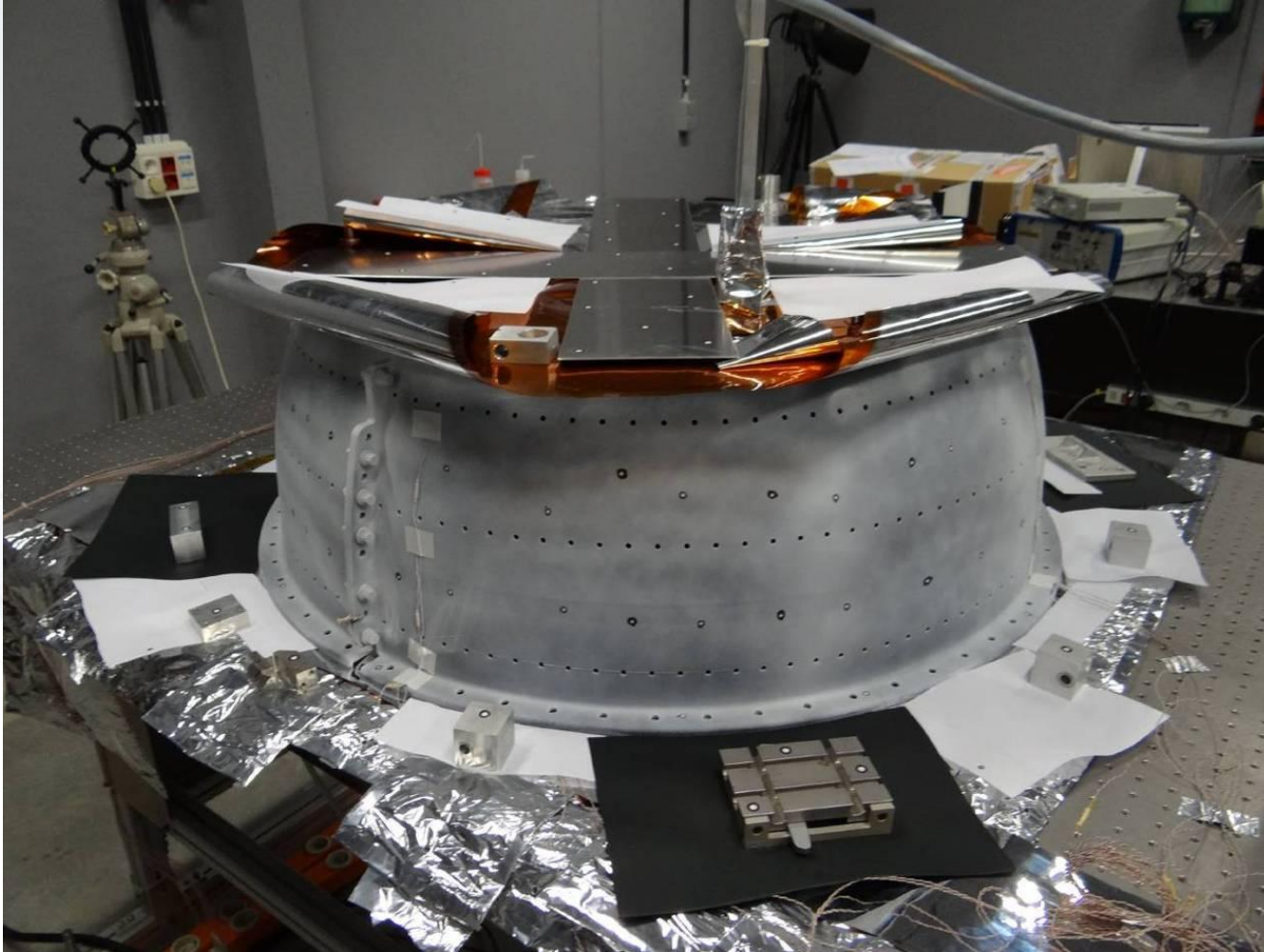


Mesures dimensionnelles

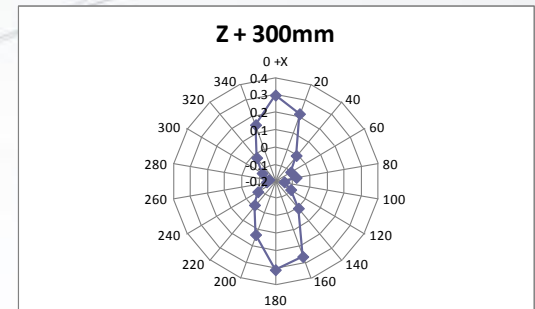
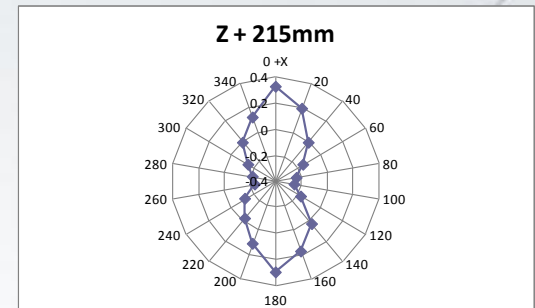
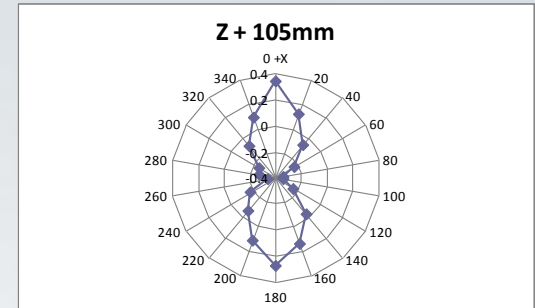
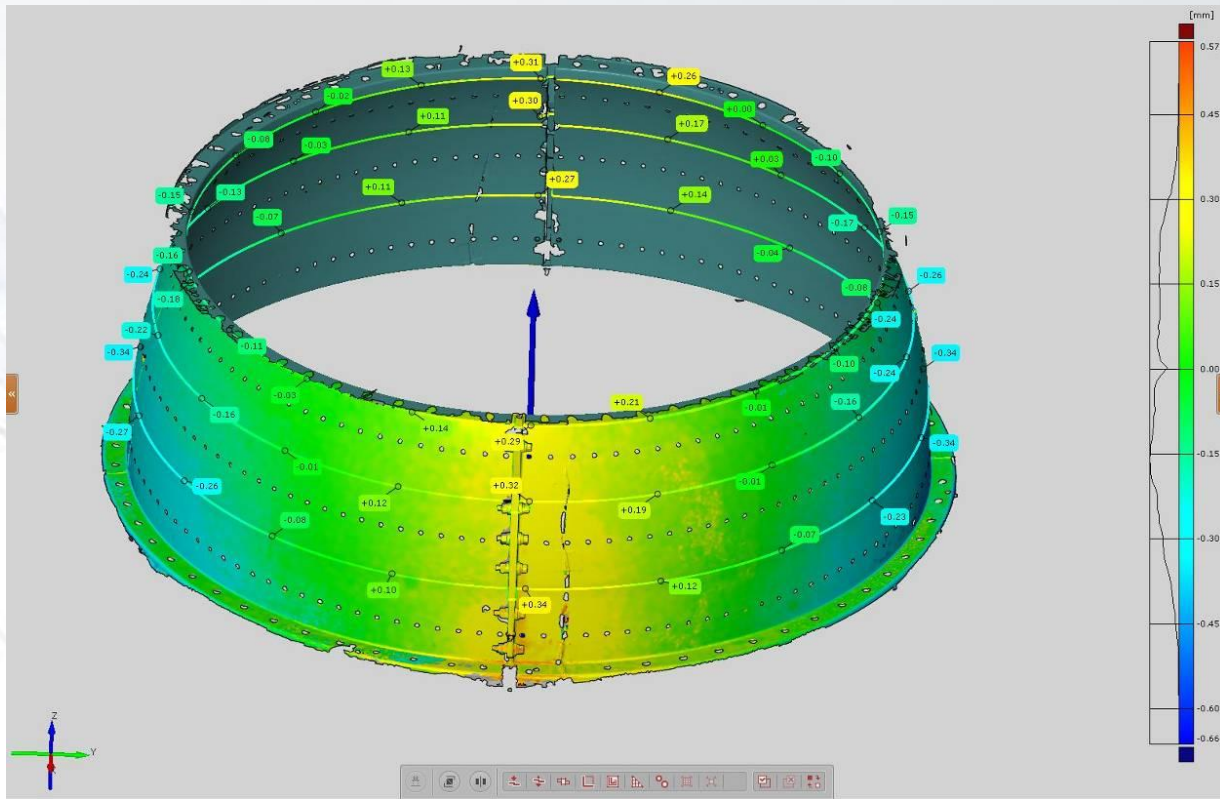
- Projet Engine Composite (E_COM) : Plan Marshall 2009-2013
- Mesure de dilatation radiale d'un carter en composites



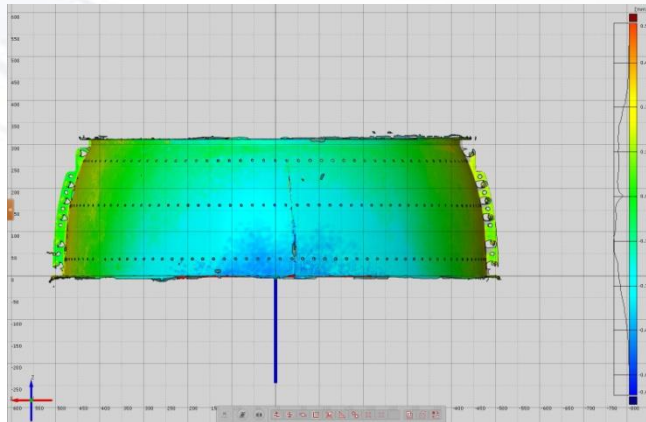
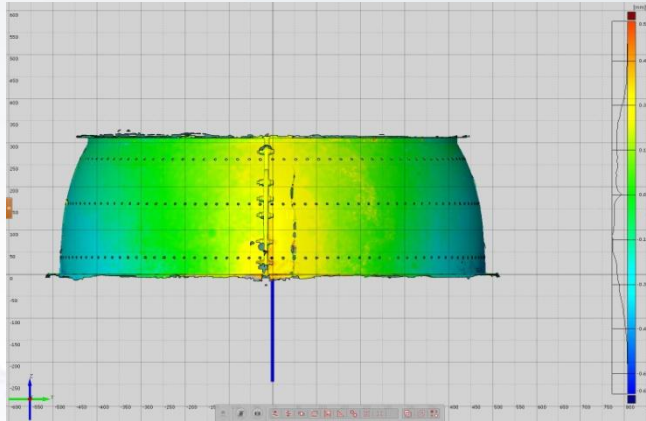
Mesures dimensionnelles



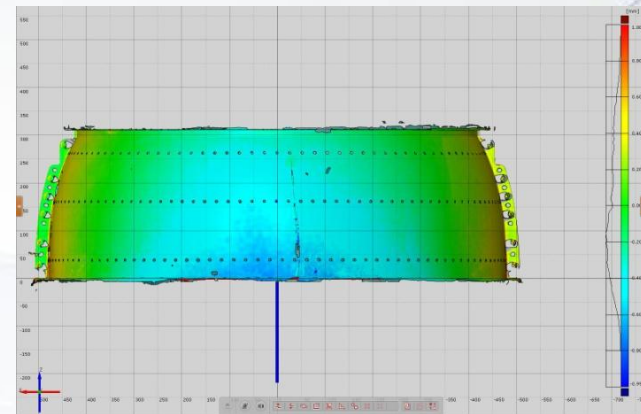
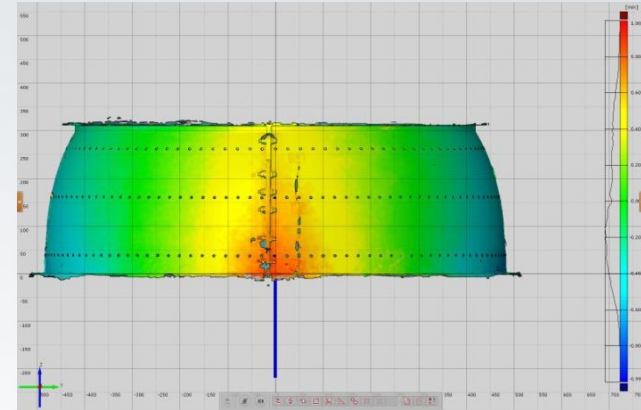
Carter #1: 20°-60°



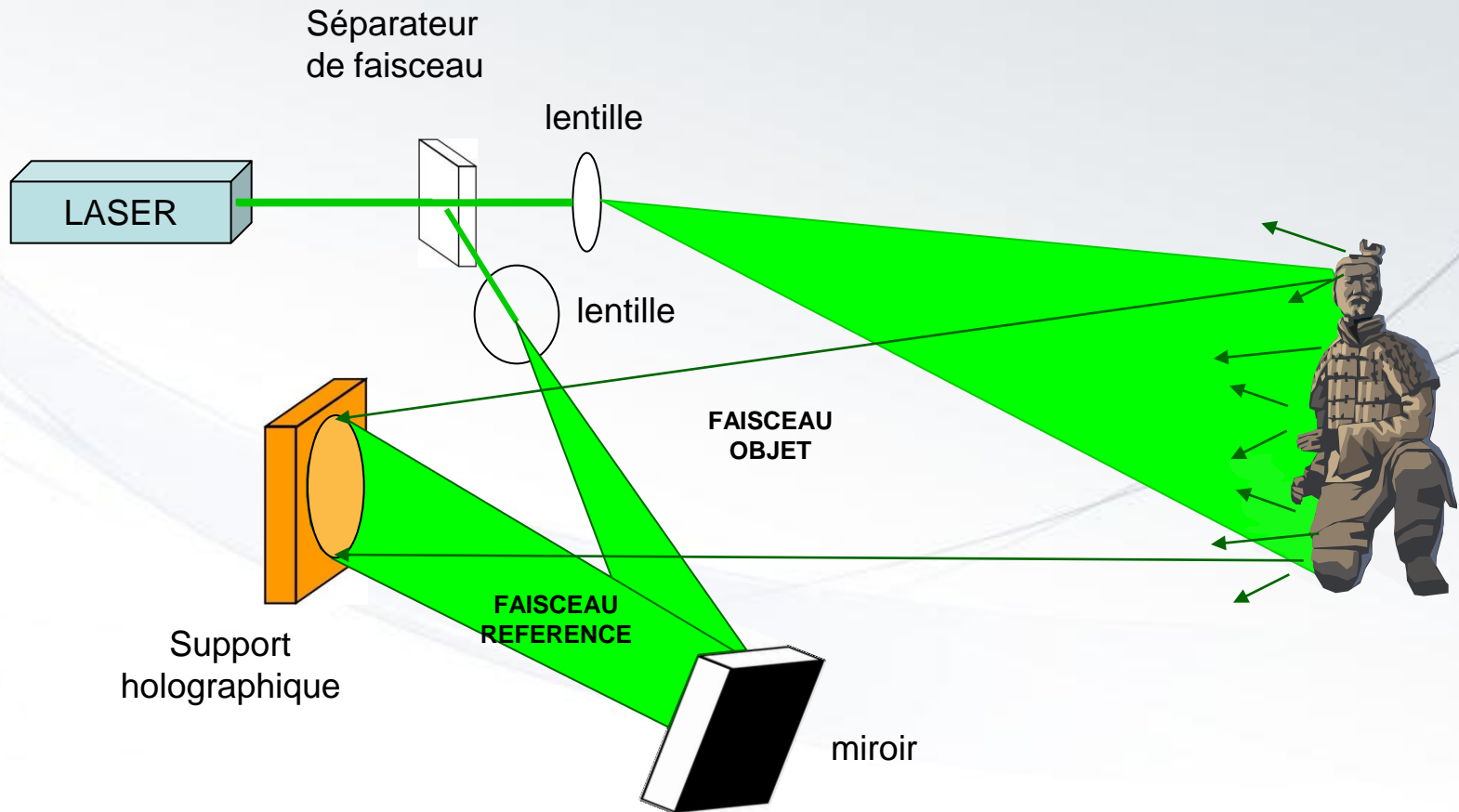
Carter #1 : 20°C - 60°C



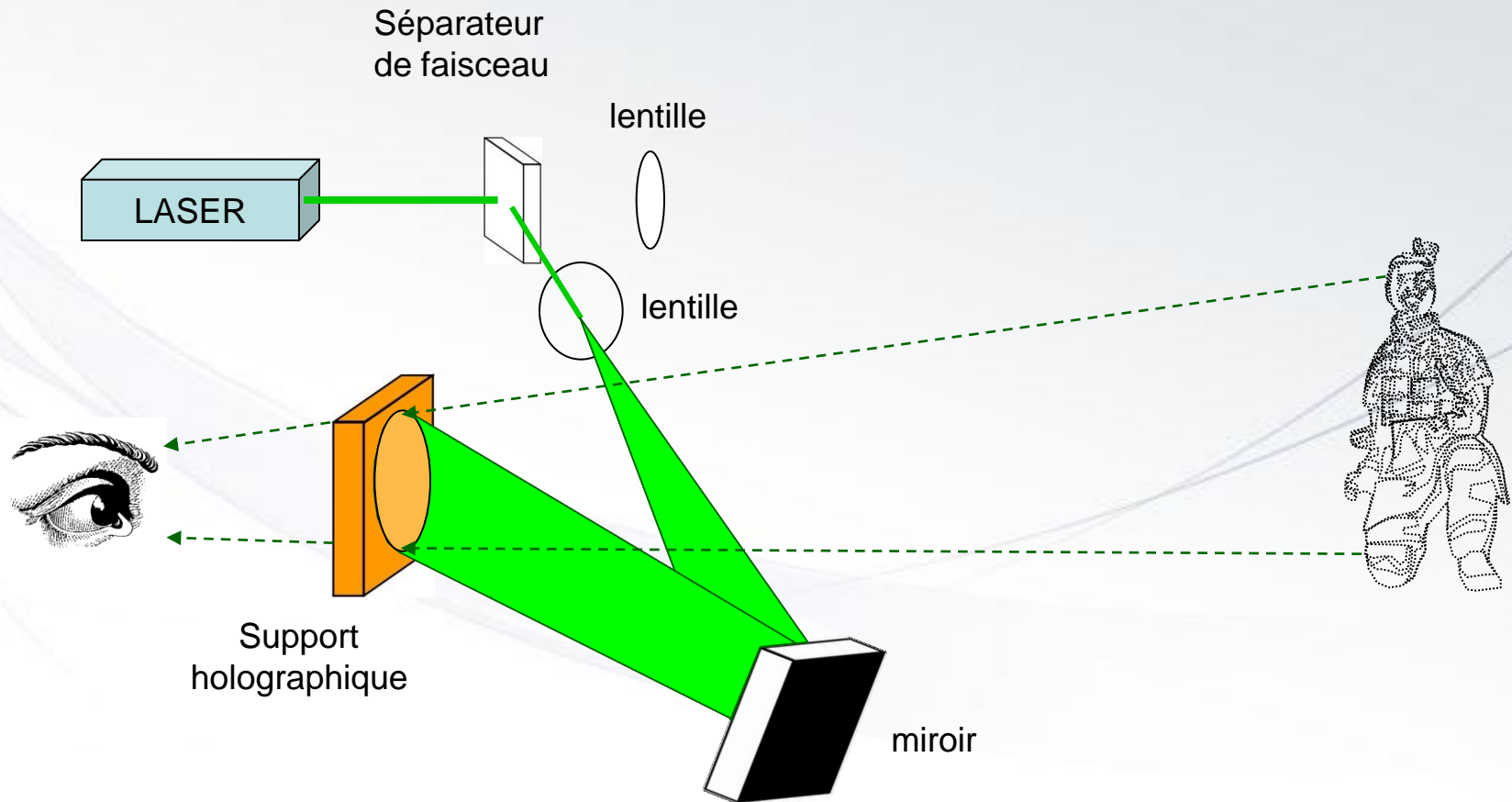
Carter #1 : 60°C - 100°C



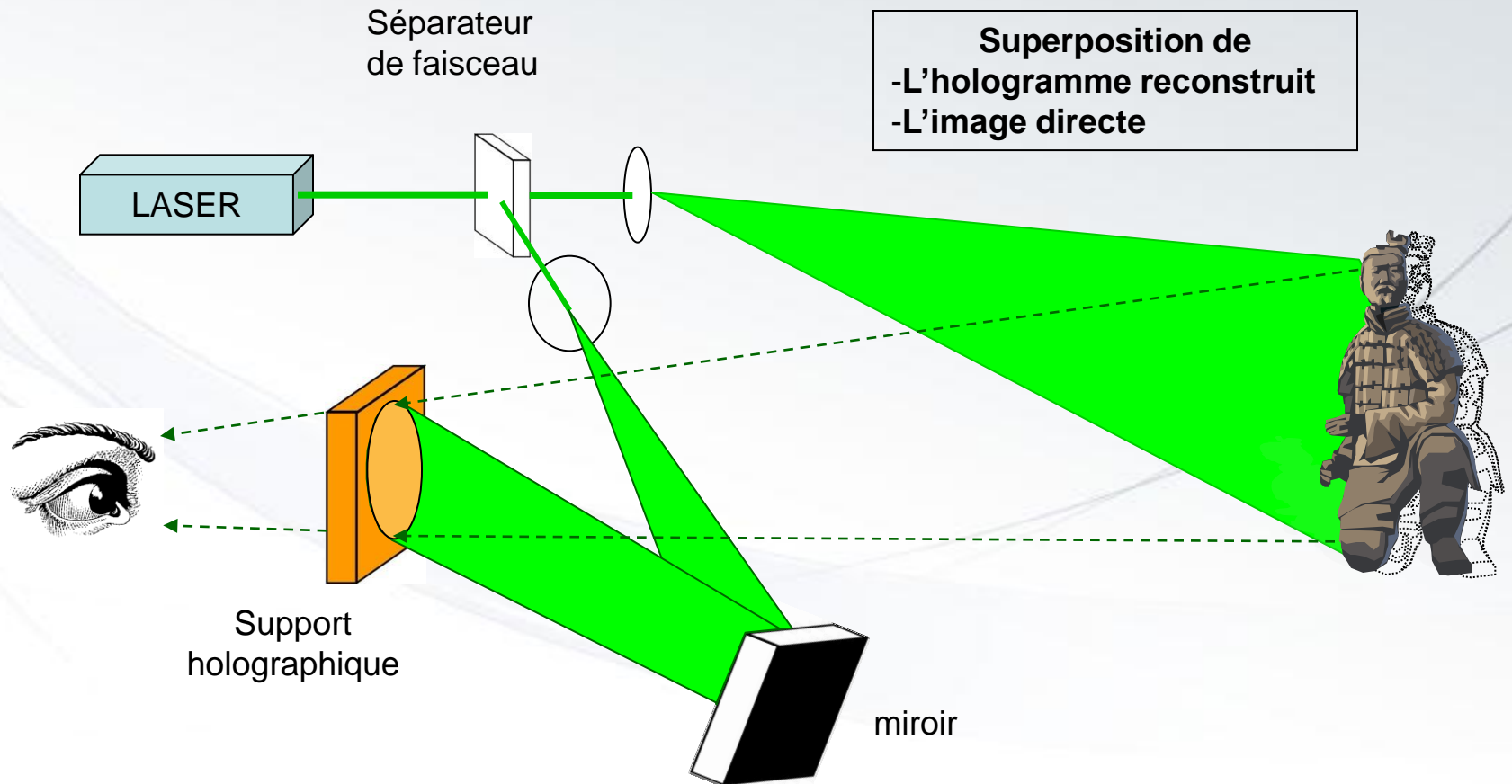
Holographie – 1 : Principe d'écriture



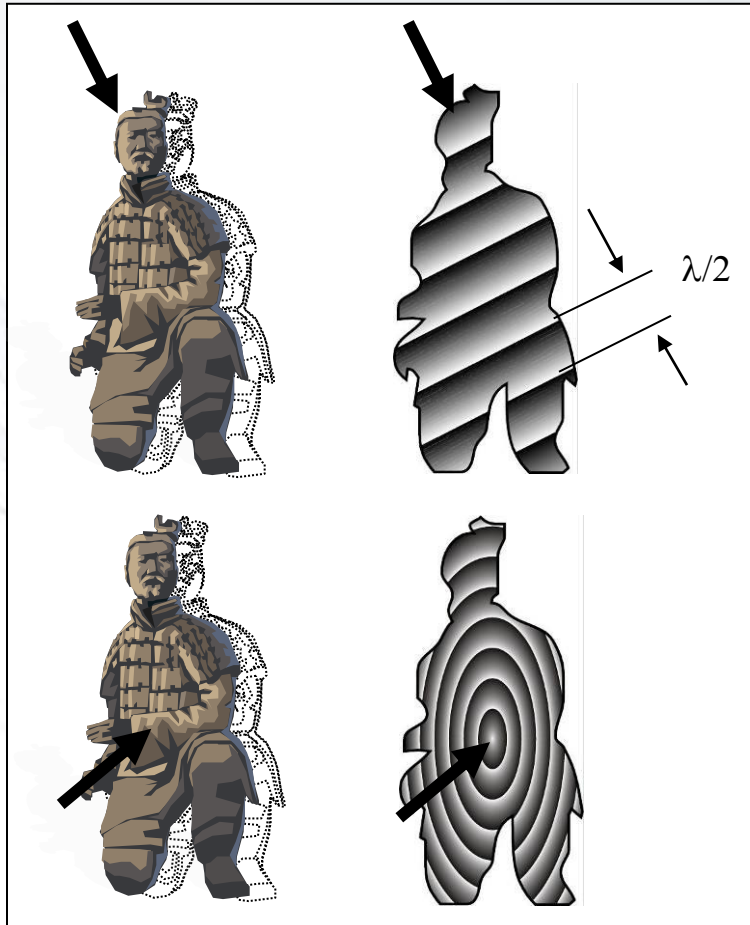
Holographie – 2 : Principe de lecture



Holographie – 3 : Lecture avec objet



Interférométrie holographique :

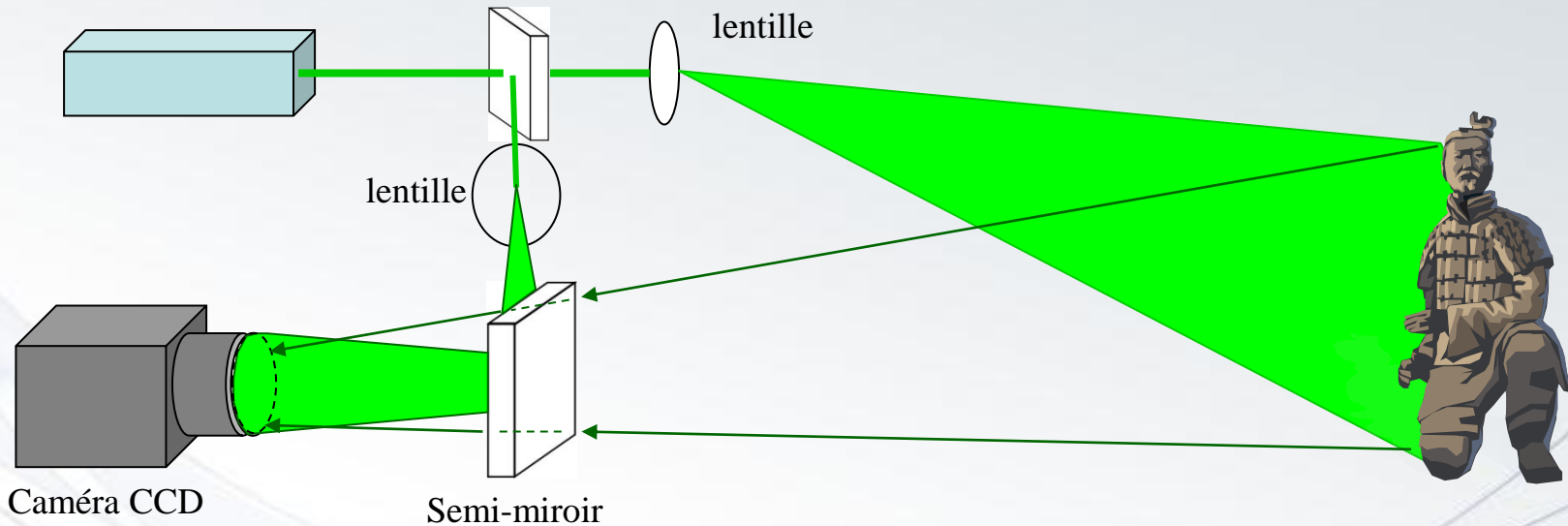


$$I(x,y) = I_0(x,y) \cdot [1 + m(x,y) \cos \Delta\phi(x,y)]$$

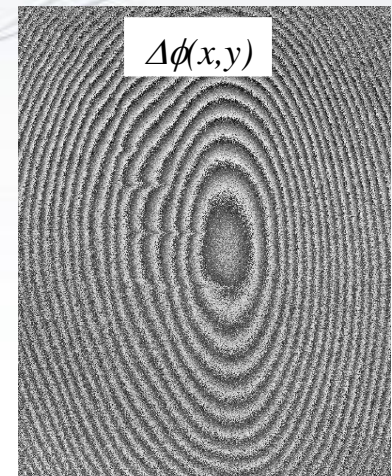
$$\Delta\phi(x,y) = \mathbf{S}(x,y) \cdot \mathbf{L}(x,y)$$

- Changement de position entre 2 instants
- Mesure du champ des déplacements
- Distance entre 2 franges reliée à la longueur d'onde du laser λ
- $\lambda / 2$: 250-300 nm

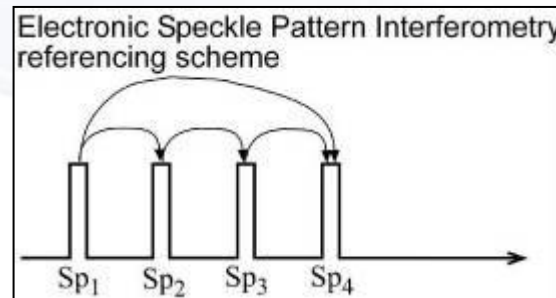
Interférométrie de speckle (ESPI : Electronic Speckle Pattern Interferometry)



- Acquisition de specklegrammes Sp_i à différents instants
- Interférogrammes sont obtenus par différences numériques entre 2 specklegrammes

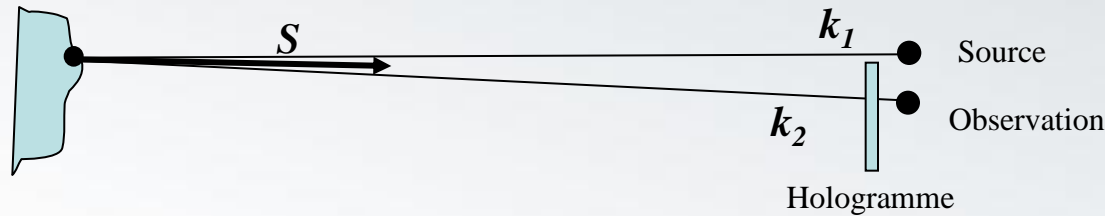


$$|Sp_i - Sp_j|(x, y) \div \sin\left(\frac{\Delta\phi(x, y)}{2}\right)$$



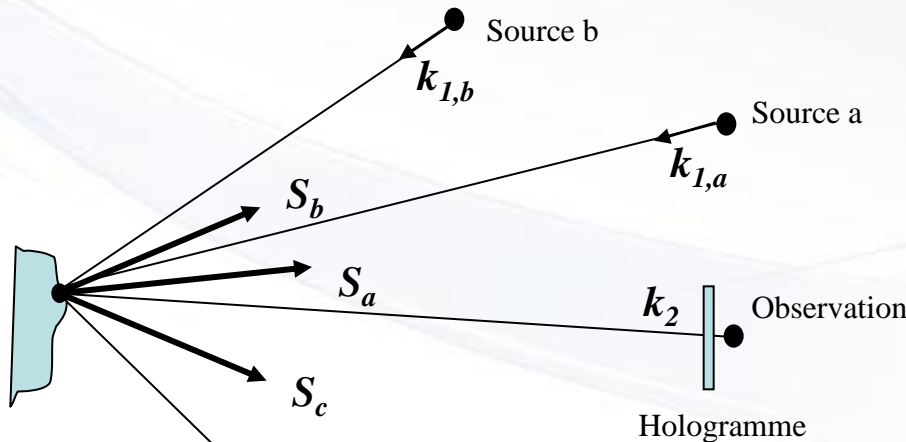
- Interprétation des mesures en terme de déplacements
 - Déplacement Hors-Plan (1D)

$$\Delta\phi(x,y) = \mathbf{S}(x,y) \cdot \mathbf{L}(x,y)$$



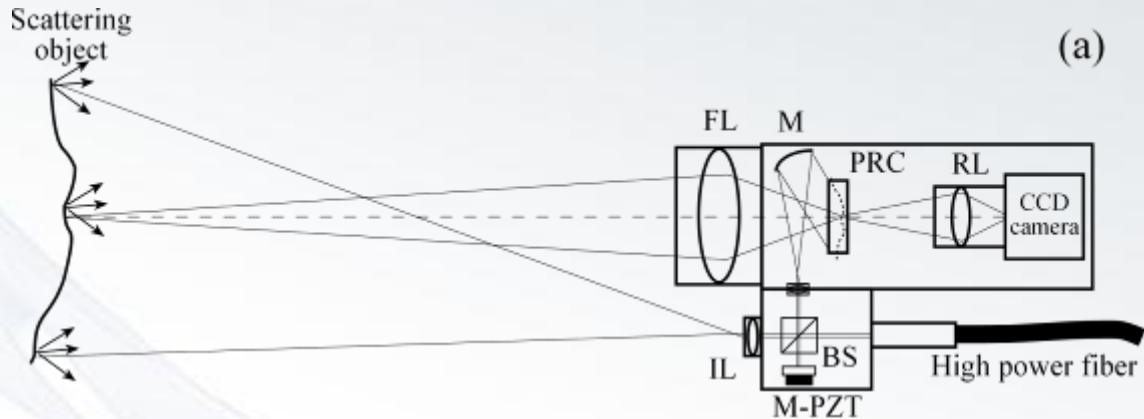
$$\Delta\phi = \frac{4\pi}{\lambda} L_{OP}$$

- Déplacement 3 directions (3D)

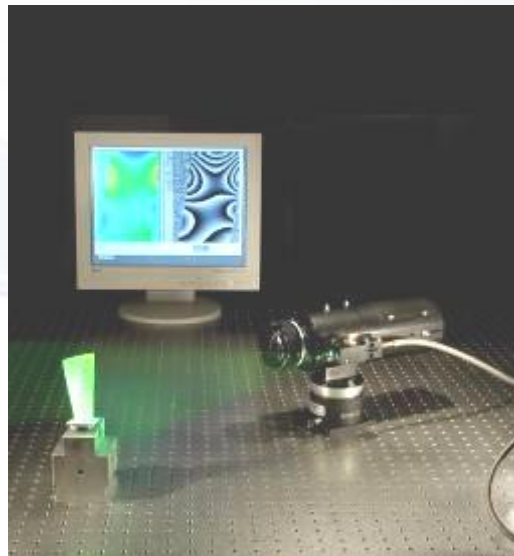


$$\begin{aligned} \Delta\phi_a &= S_a \cdot L \\ \Delta\phi_b &= S_b \cdot L \\ \Delta\phi_c &= S_c \cdot L \end{aligned}$$

- Système commercial basé sur des cristaux photoréfractifs
- Développé au CSL – commercialisé par Optrion



M : Mirror
 M-PZT : Mirror on piezotranslator
 BS : Beamsplitter
 FL : Frontal lens
 RL : Relay lens
 IL : Illumination lens
 PRC : Photorefractive crystal



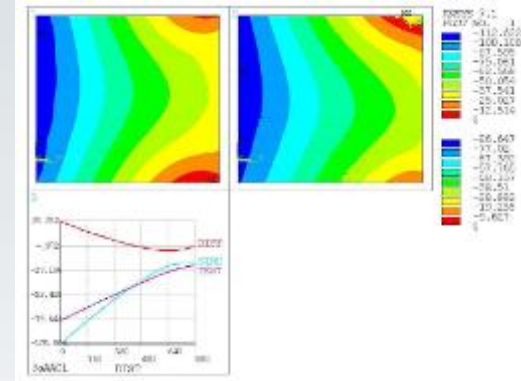
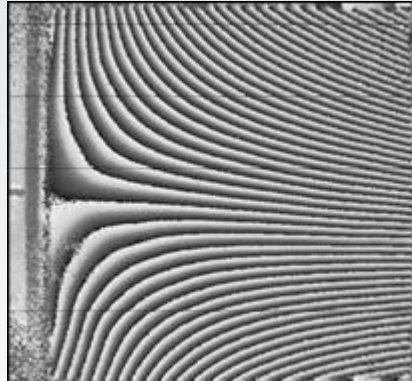
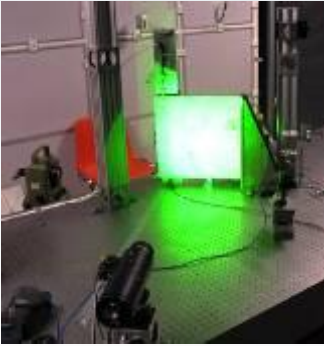
Laser YAG DPSS
 $\lambda = 532 \text{ nm}$

Gamme de mesure :
 15 nm – 25 μm

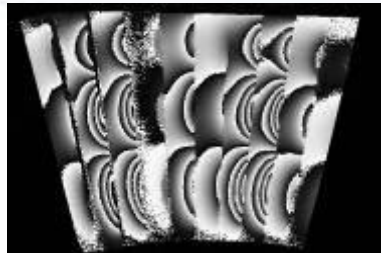
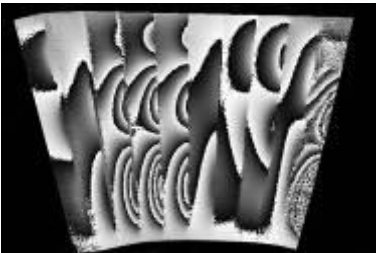
Temps de réponse :
 Qqs secondes - nanosecondes

- Applications

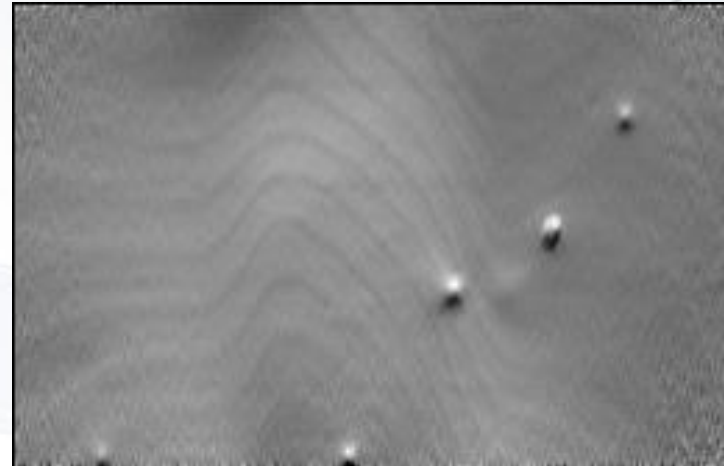
Métrie



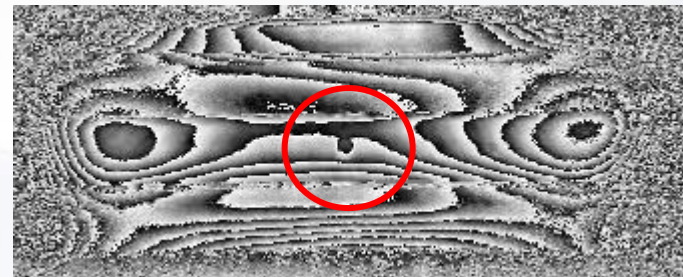
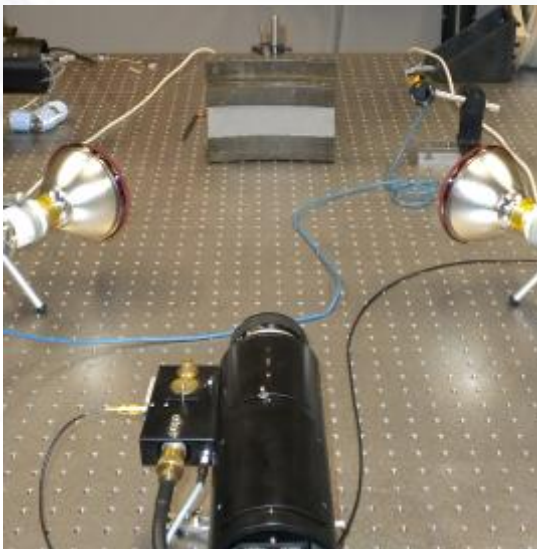
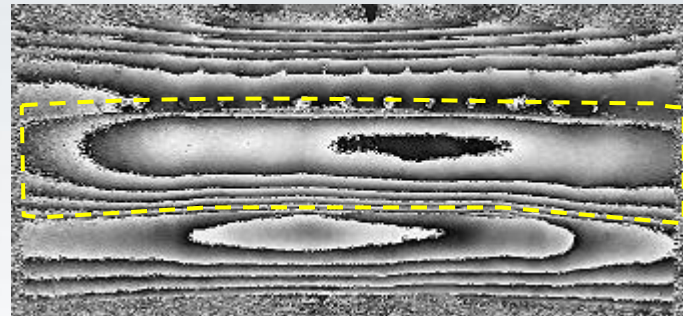
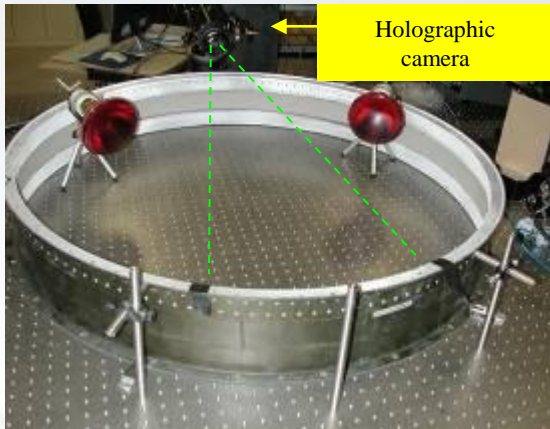
Modes de Vibration



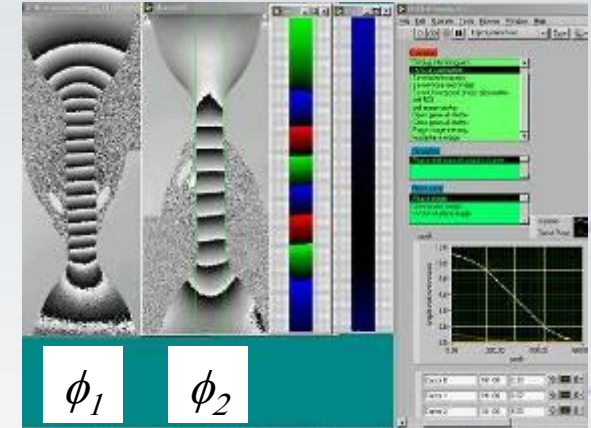
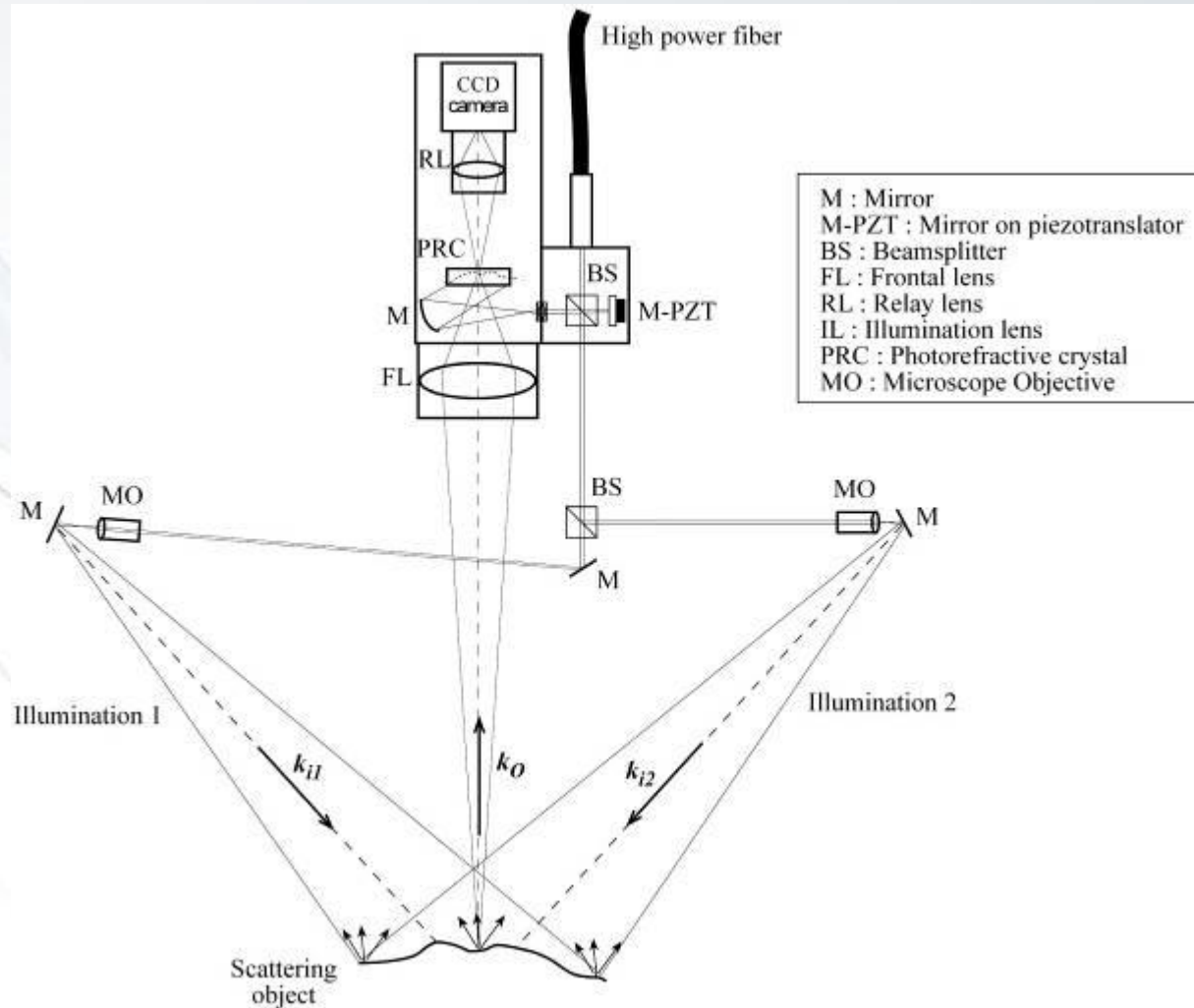
Détection de défauts



- Applications : Détection de défauts (Plan Marshall E_COM)



- Extension à la mesure 2D



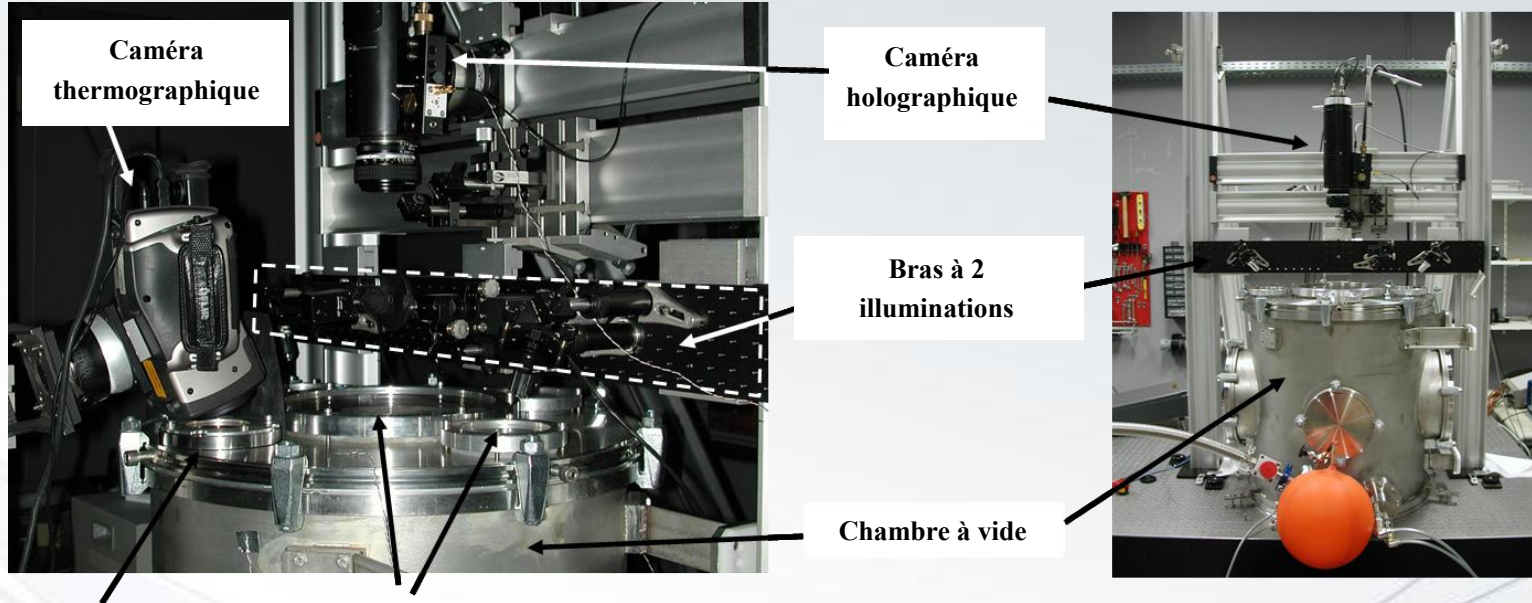
$$L_{IP} = \frac{\phi_1 - \phi_2}{2\pi} \frac{\lambda}{2\sin 2\theta_1}$$

In plane
Displacement

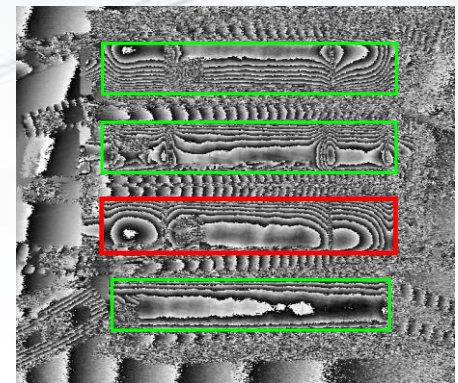
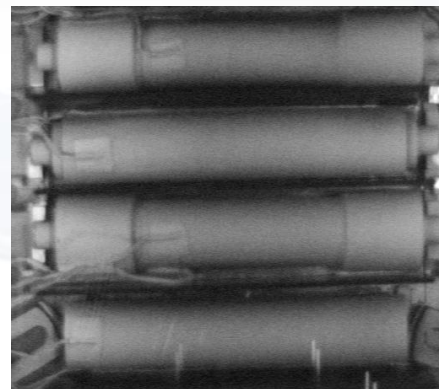
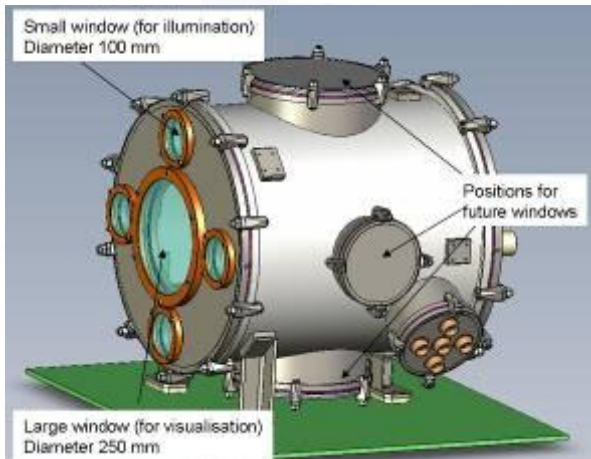
$$L_{OP} = \frac{\phi_1 + \phi_2}{2\pi} \frac{\lambda}{4\cos^2 \theta_1}$$

Out of plane
Displacement

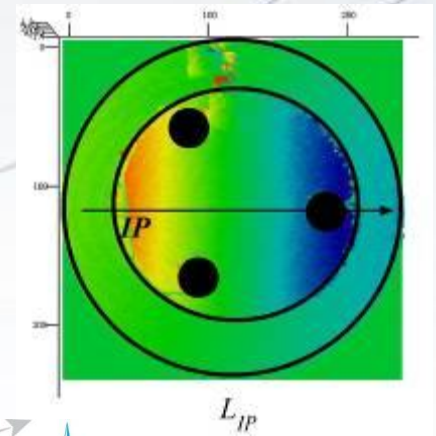
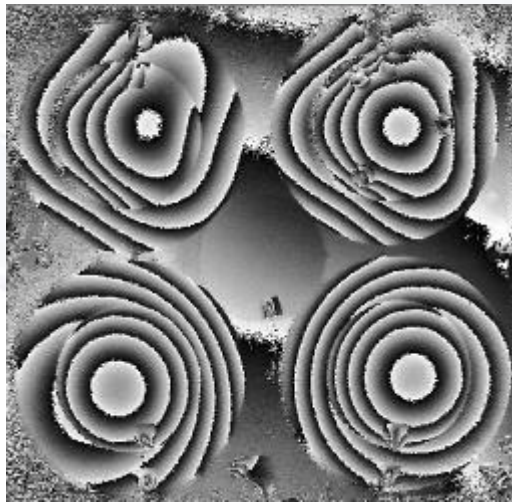
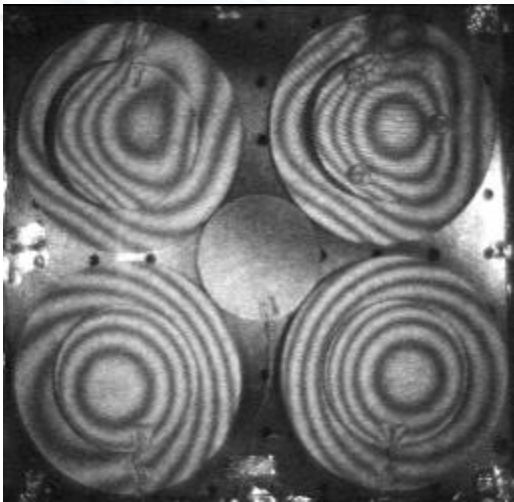
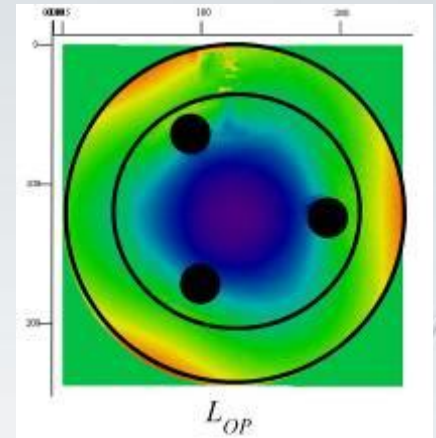
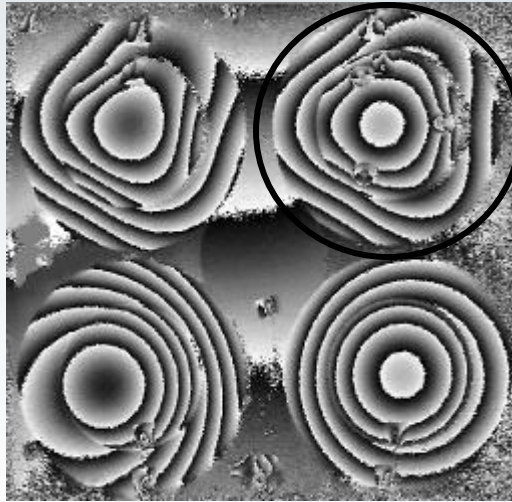
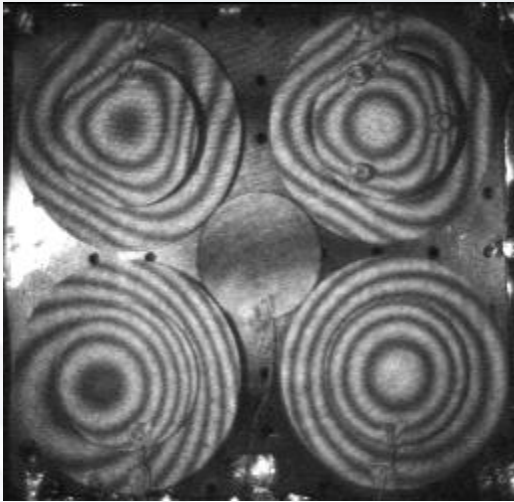
- Applications – Mesures de dilatation (projet ESA)



Fenêtre ZnSe Fenêtre verre

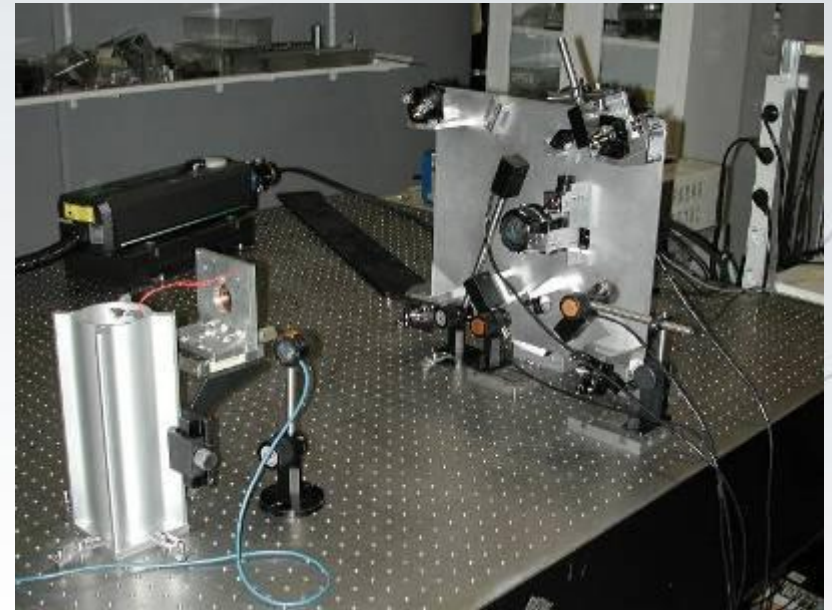
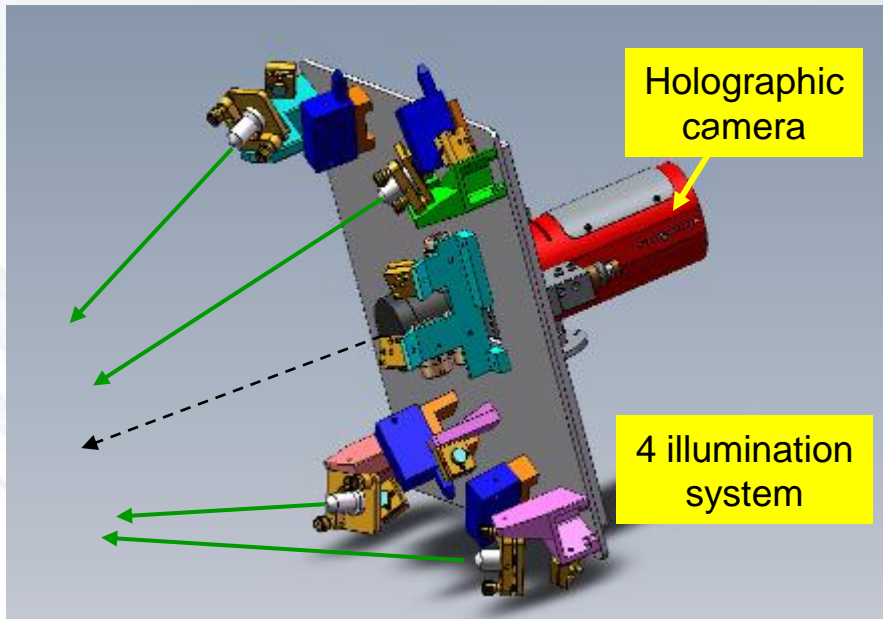


- Applications – Mesures de dilatation (projet ESA)

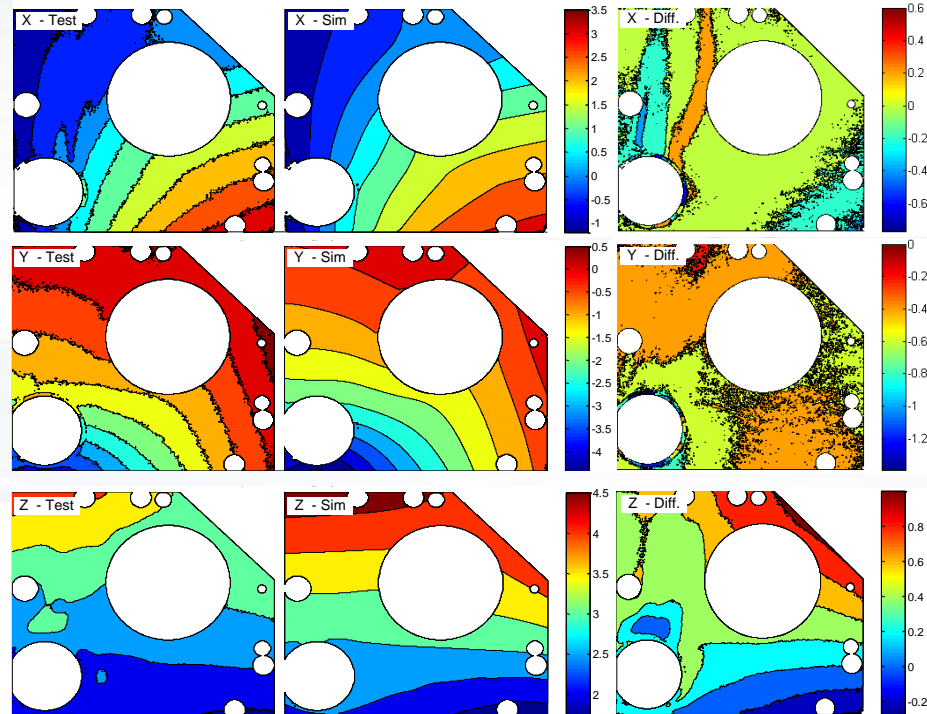
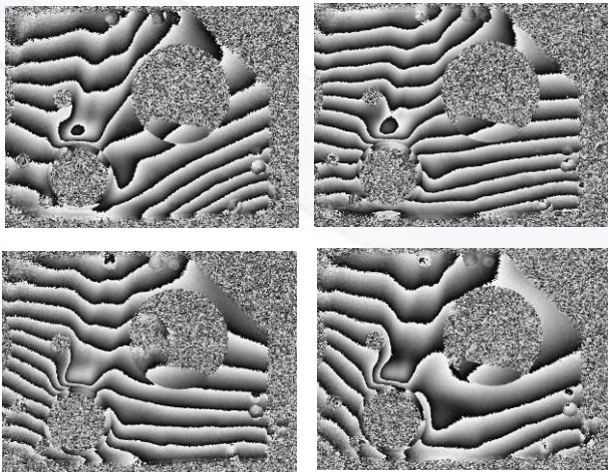
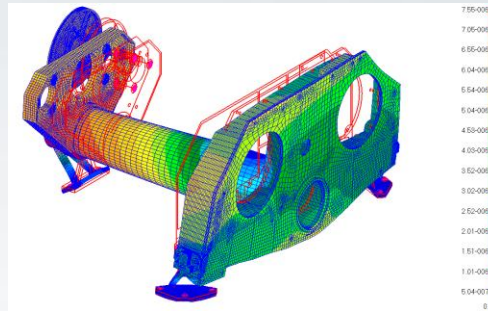
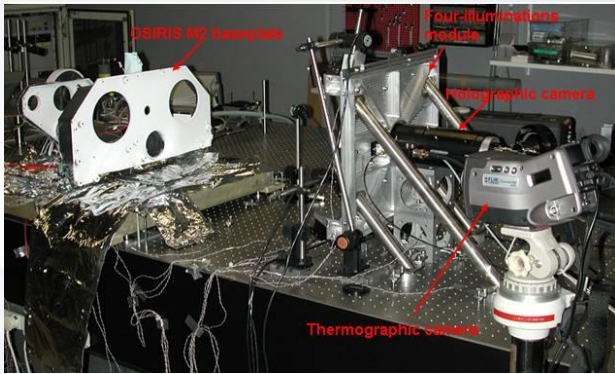


Interférométrie holographique 3D

- Extension à la mesure 3D (Projets RW + ESA)



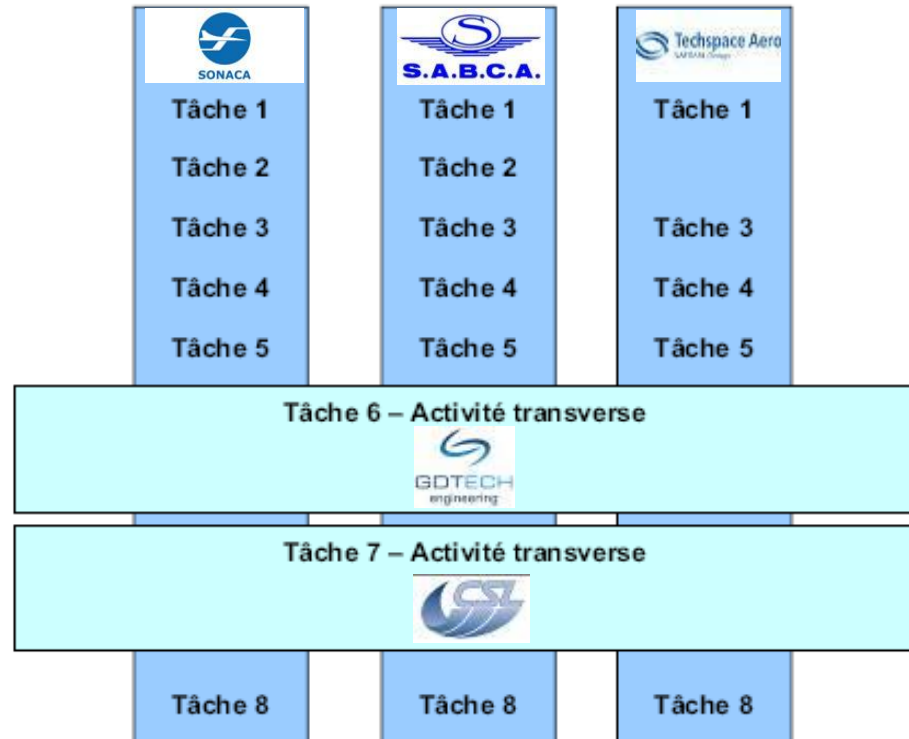
- Applications : Mesures thermoélastiques sur structures spatiales en SiC (projet ESA)



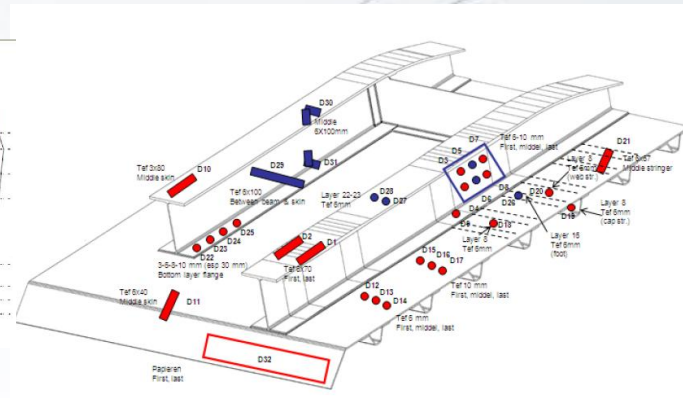
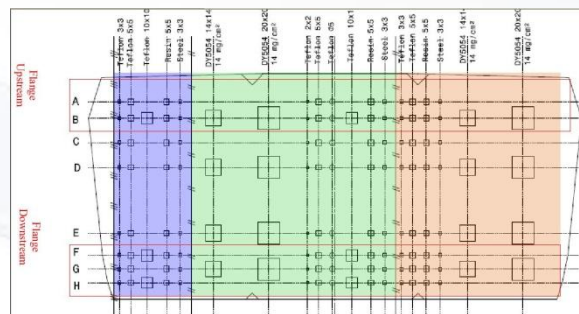
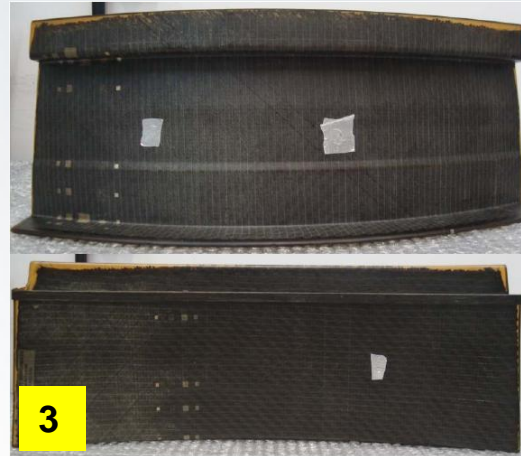
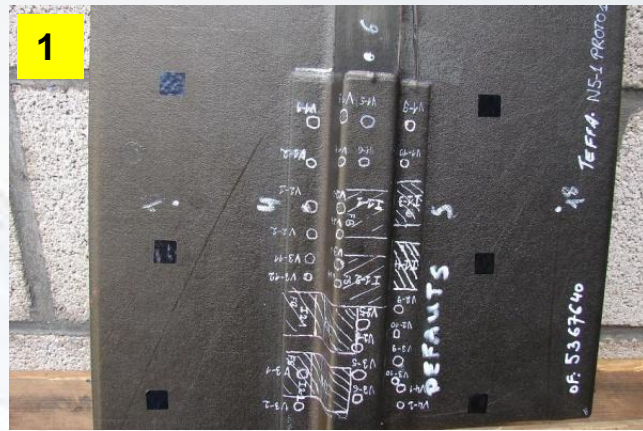
Détection de défauts

- Efficient Composite Technologies for Aircraft Components (ECOTAC)
 - Plan Marshall
 - 2011-2014

NDT inspection ←

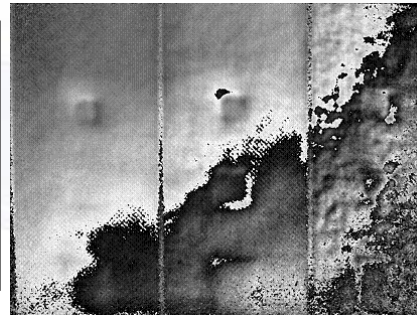
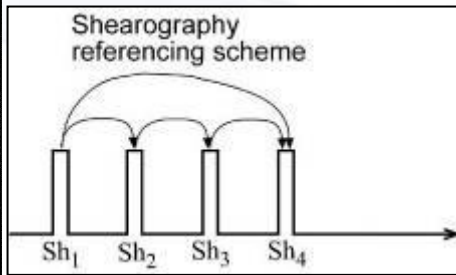
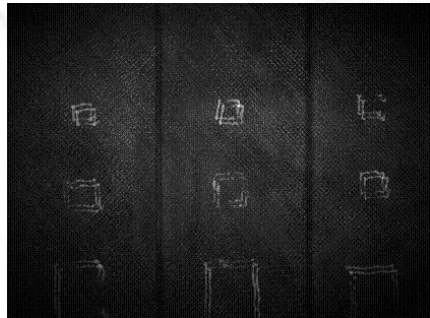
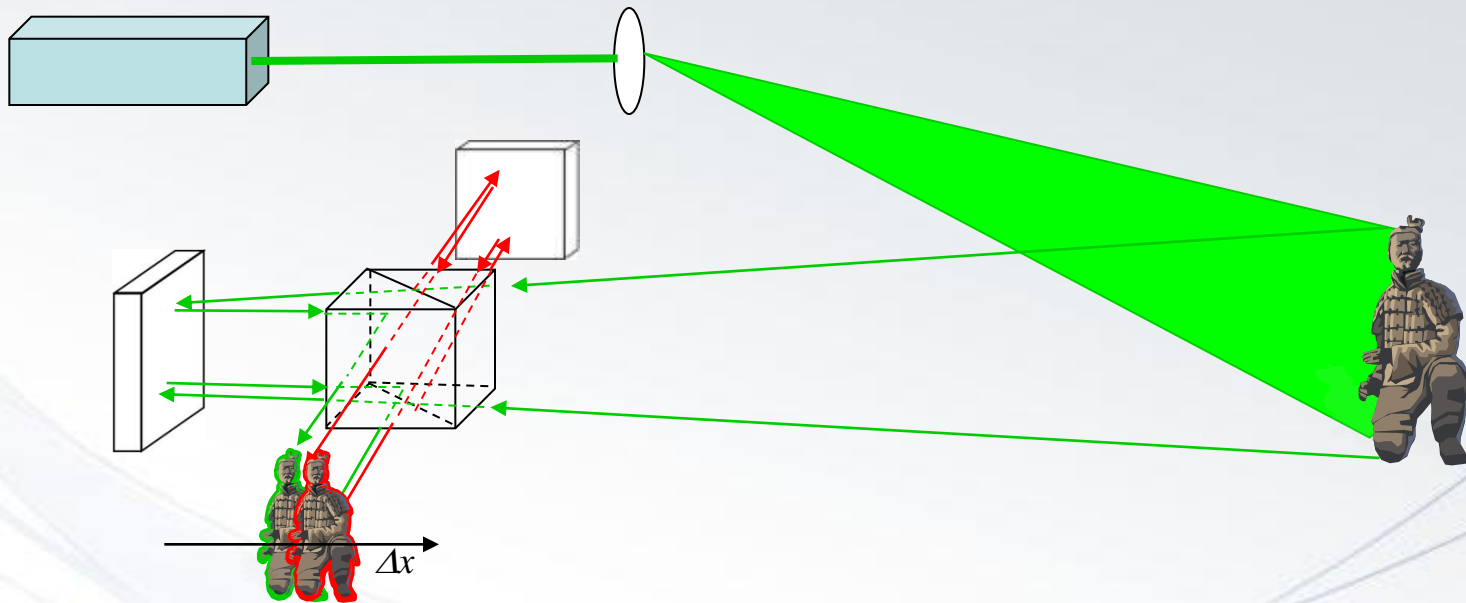


- Inspection des composites
 - Détection de défauts
 - Structures complexes
- Phase 1: Comparaison de techniques CND émergentes:
 - Shearographie
 - Thermographie
 - Ultrasons par laser (sans contact)
- Phase 2:
 - Développement d'une technique (ou combinaison de techniques)
 - Inspection des composites développés dans ECOTAC
- Echantillons de tests pour Phase 1
 - Proviennent du projet APC (Avion Plus Composites) : Marshall 07-10
 - Structures complexes
 - Défauts répertoriés



Description des techniques : La Shearographie

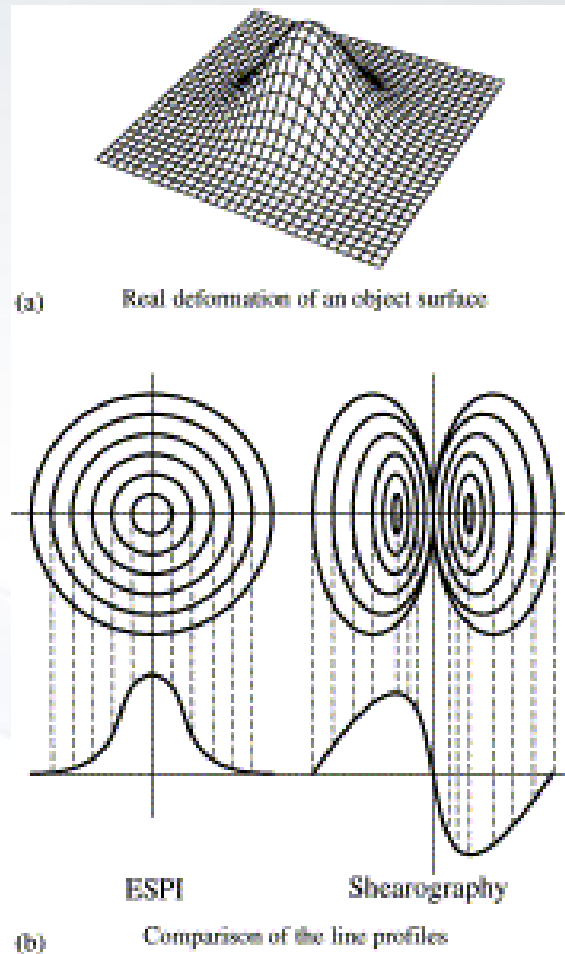
- Shearographie de speckle



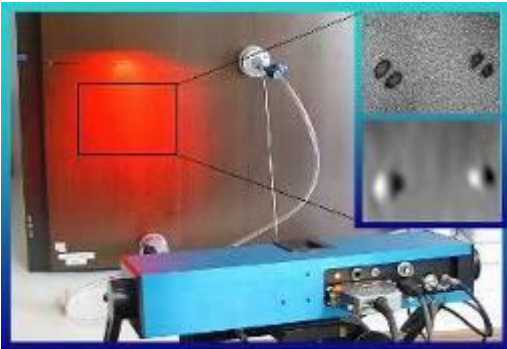
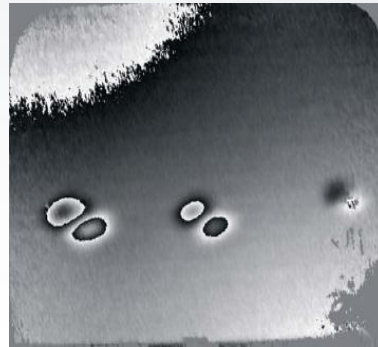
$$|Sh_i - Sh_j|(x, y) \div \sin\left(\partial \frac{\Delta\phi(x, y)}{\partial x} \Delta x\right)$$

$$\partial \frac{\Delta\phi(x, y)}{\partial x} \rightarrow \partial \frac{L(x, y)}{\partial x}$$

- Holographie-ESPI vs. Shearographie



- Shearographie de speckle
 - Avantages :
 - Technique auto-référencée : pas de faisceau référence extérieur
 - Peu sensible aux perturbations de l'environnement
 - Application principale : détection de défauts



Sollicitations :

- Thermique
 - Lampes halogènes
 - Lampes quartz
 - Flash ou continu
- Vibratoire
- (Dé)Pression
- Mécanique

www.dantecdynamics.com

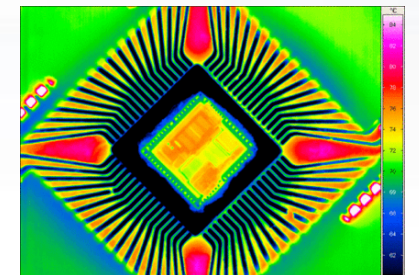
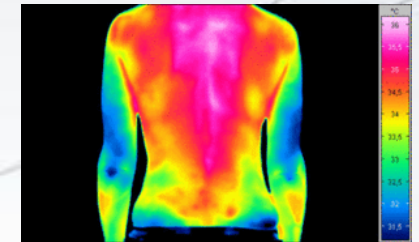
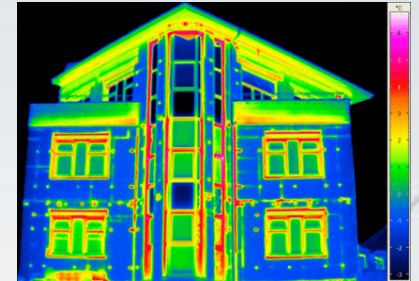
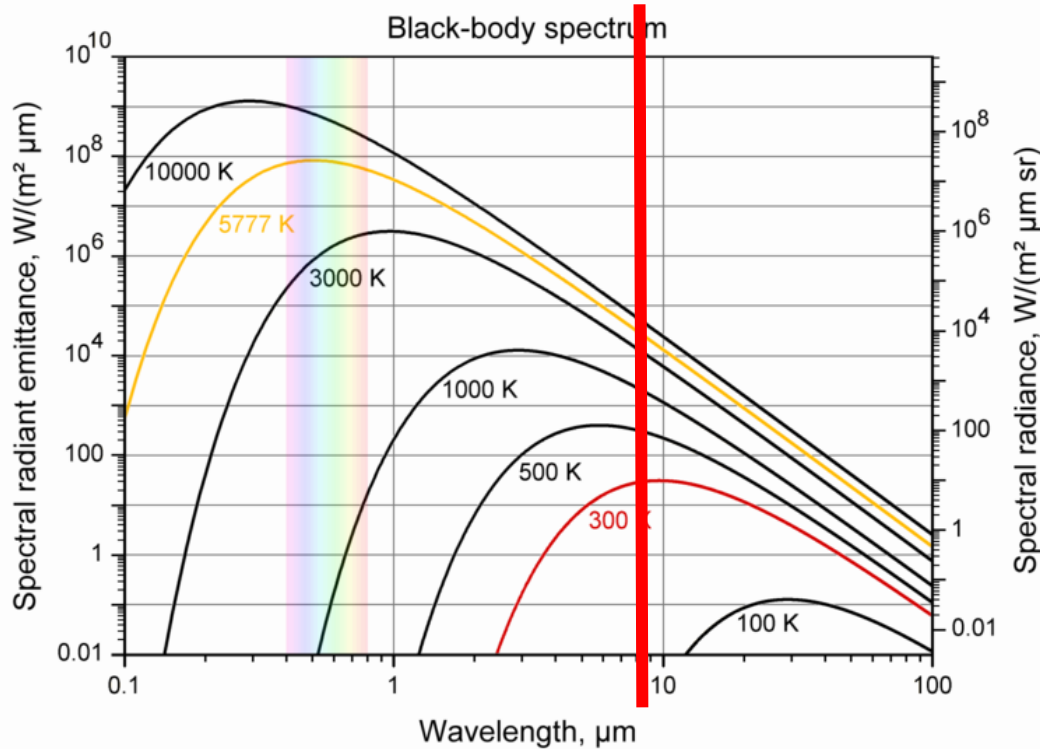
www.steinbichler.de

www.isi-sys.com

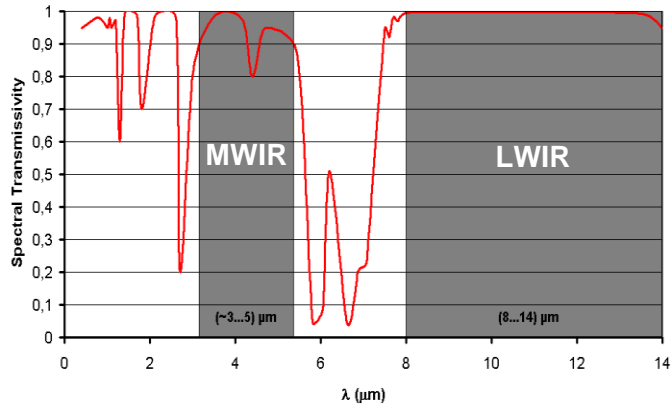
www.laserndt.com

Description des techniques : La Thermographie

- Thermographie : mesure de la température
 - Loi de Planck d'émission du « corps noir »
 - Tout corps porté à une certaine température émet un rayonnement



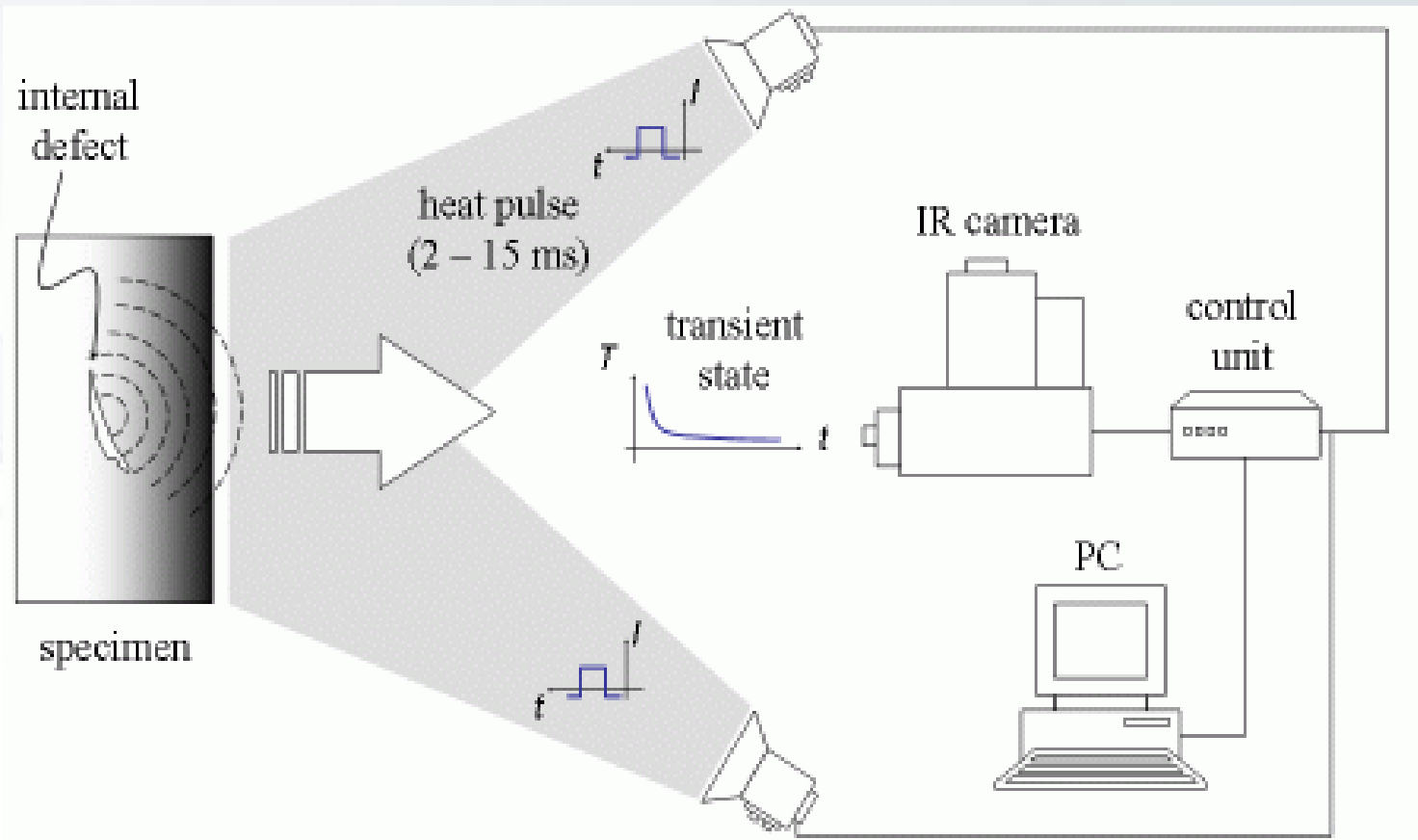
- Imagerie thermique
 - Différentes gammes infrarouges
 - Différentes technologies de caméras



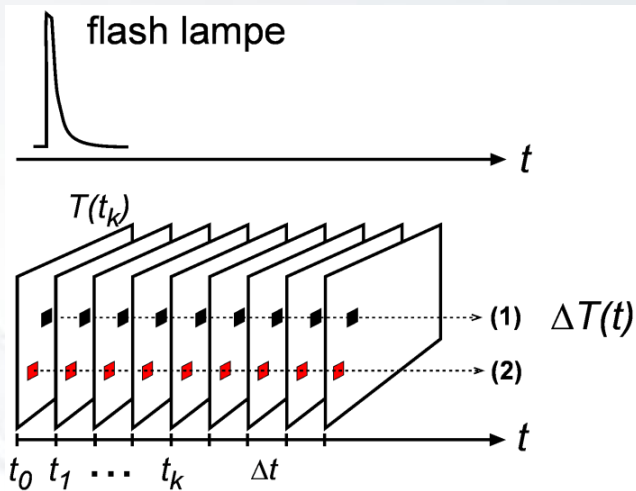
| Type | Detector Material | Spectral range | Maximum pixel numbers | Maximum frame rate | NETD @ 30°C |
|-----------------------------|-------------------|-------------------------|---------------------------------------|----------------------------|-------------------------|
| Uncooled Microbolometer FPA | a-Si VOx | 8 ... 14 μm | 1024 x 768 | 30 Hz | 85 mK |
| | | | 640 x 480 | 60 Hz | 50 mK |
| | | | 384 x 288 | 60 Hz | 40 mK |
| Cooled IR-Photodiode FPA | HgCdTe (MCT) | 8 ... 10 μm | 640 x 512 384 x 288 | 120 Hz 300 Hz | 20 mK |
| Cooled QWIP FPA | AlGaAs/GaAs | 8 ... 9 μm (small band) | 1024 x 1024 640 x 512 384 x 288 | 120 Hz 120 Hz 260 Hz | 35 mK 25 mK 25 mK |

- La thermographie pour le CND
 - Mesurer des différences de température entre différentes parties de la pièces
 - Permet de détecter des défauts
 - Caractéristiques thermiques différentes
 - « Thermographie Active »
 - On provoque des changements de température selon diverses modalités par des moyens contrôlés
 - Stimulation thermique
 - Stimulation mécanique-ultrasonore
 - Stimulation par induction
 - ...

- Thermographie : excitation lampe pulsée – Optical Pulse Thermography (OPT)



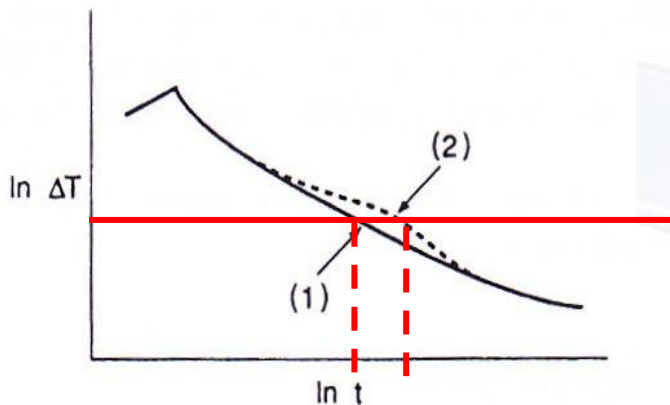
- Thermographie : excitation lampe pulsée – Optical Pulse Thermography (OPT)



Observation du passage d'une impulsion thermique et de son effet sur les défauts internes

$$t \approx \frac{z^2}{\alpha}$$

L'instant d'observation t donne une image à la profondeur z (α : diffusivité thermique du matériau)

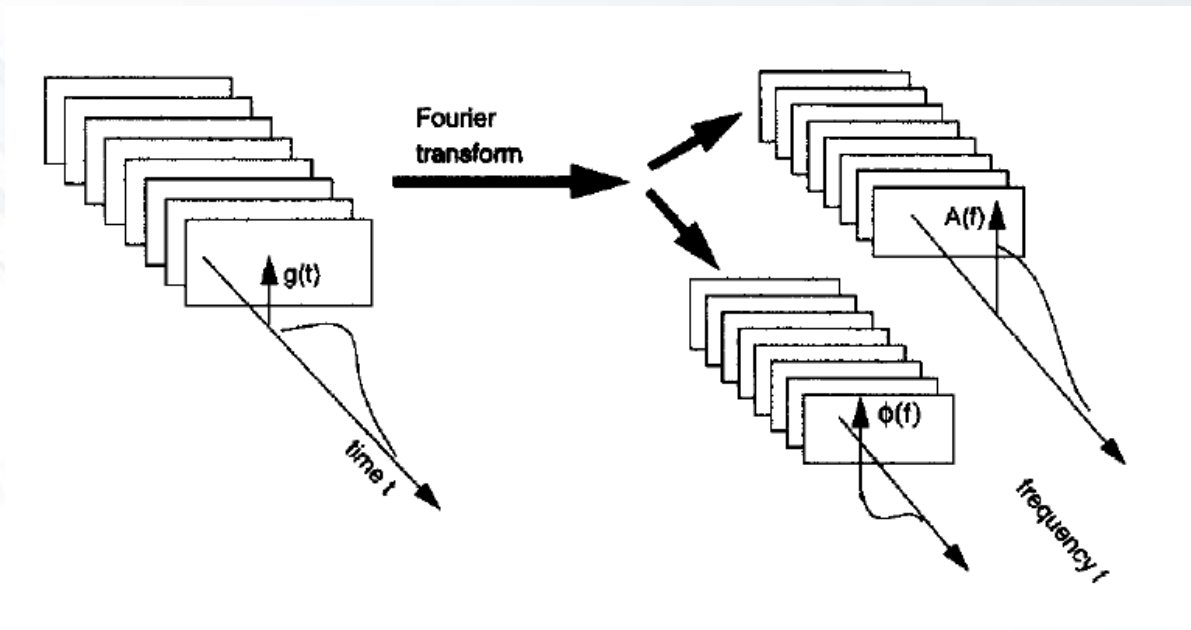


Le défaut a des caractéristiques thermiques différentes de celles du matériau environnant

- Thermographie : thermographie pulsée
 - Pulse Phase Thermography (PPT)

$$F(f_n) = \Delta t \sum_{k=0}^{N-1} \Delta T(\mathbf{k}\Delta t) \exp(-j 2\pi kn / N) = \text{Re}_n + j \text{Im}_n$$

$$f_n = \frac{n}{N \Delta t}$$



$$A_n = \sqrt{\text{Re}_n^2 + \text{Im}_n^2}$$

$$\phi_n = \tan^{-1} \left(\frac{\text{Im}_n}{\text{Re}_n} \right)$$

- Thermographie : thermographie pulsée
 - Pulse Phase Thermography (PPT)

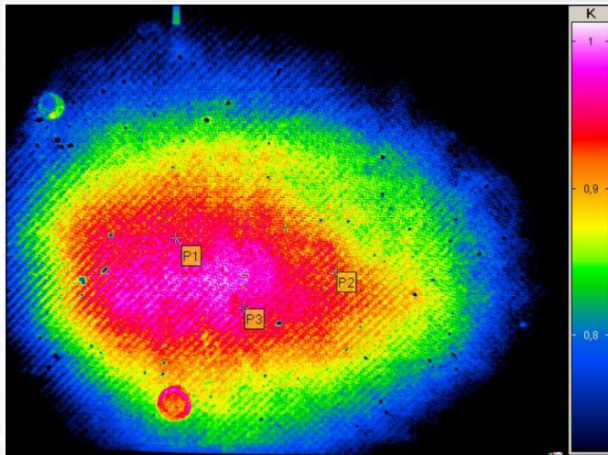


Figure 19: Amplitude image of the PPT analysis

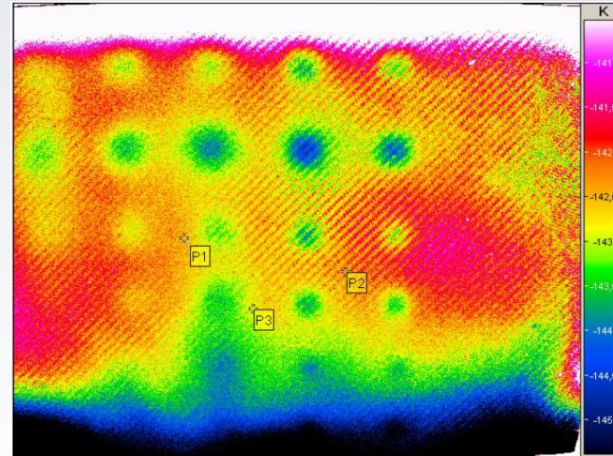
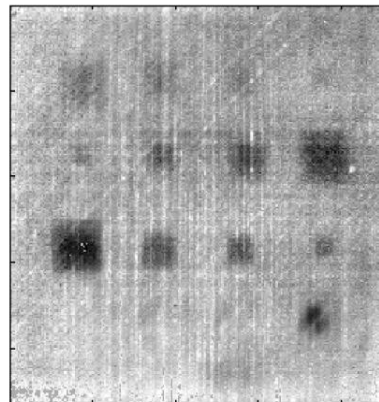
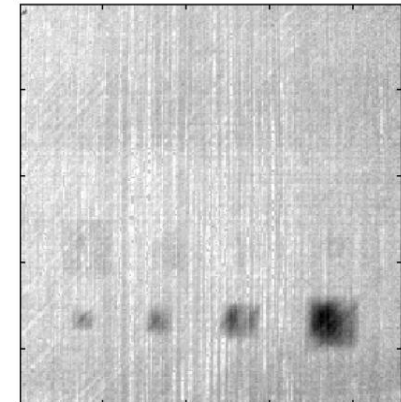


Figure 18: Phase image of the PPT analysis

z profond \longleftrightarrow t élevé
 \longleftrightarrow f basse

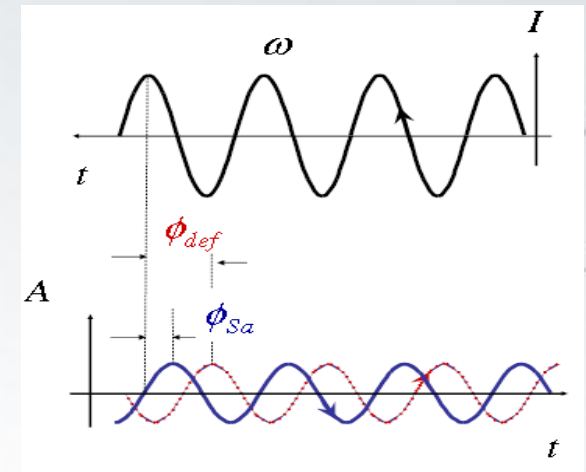
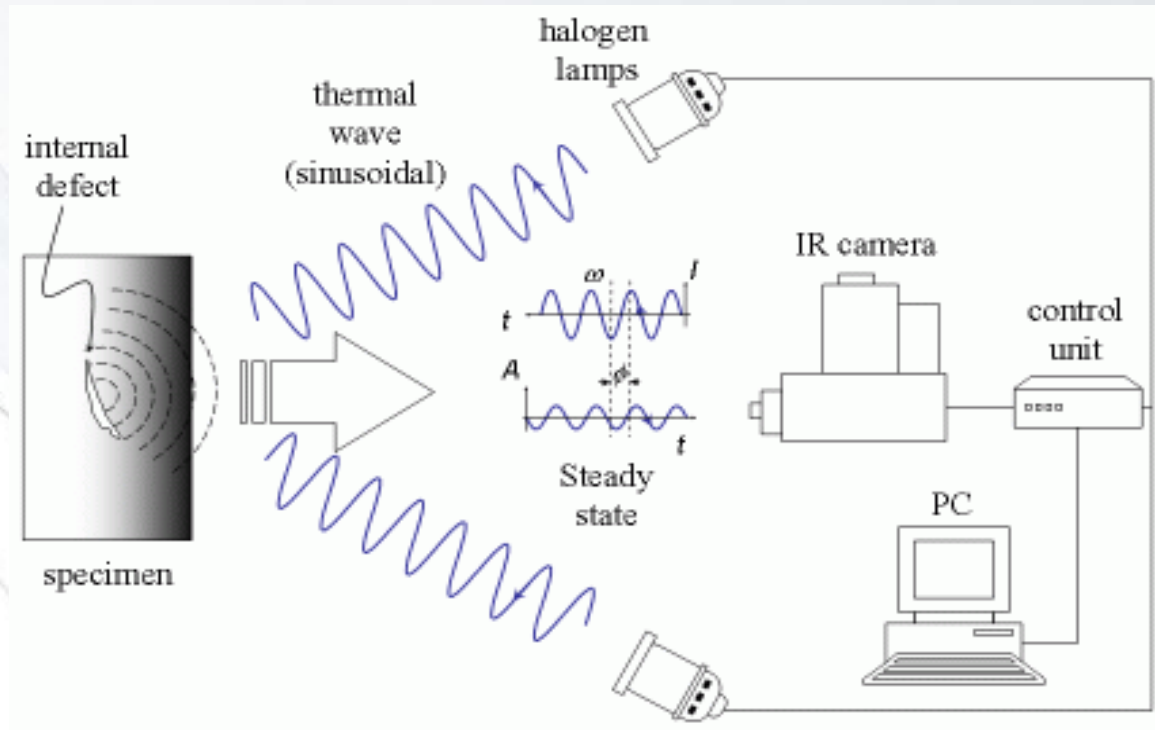


$f_1=0,06$ Hz

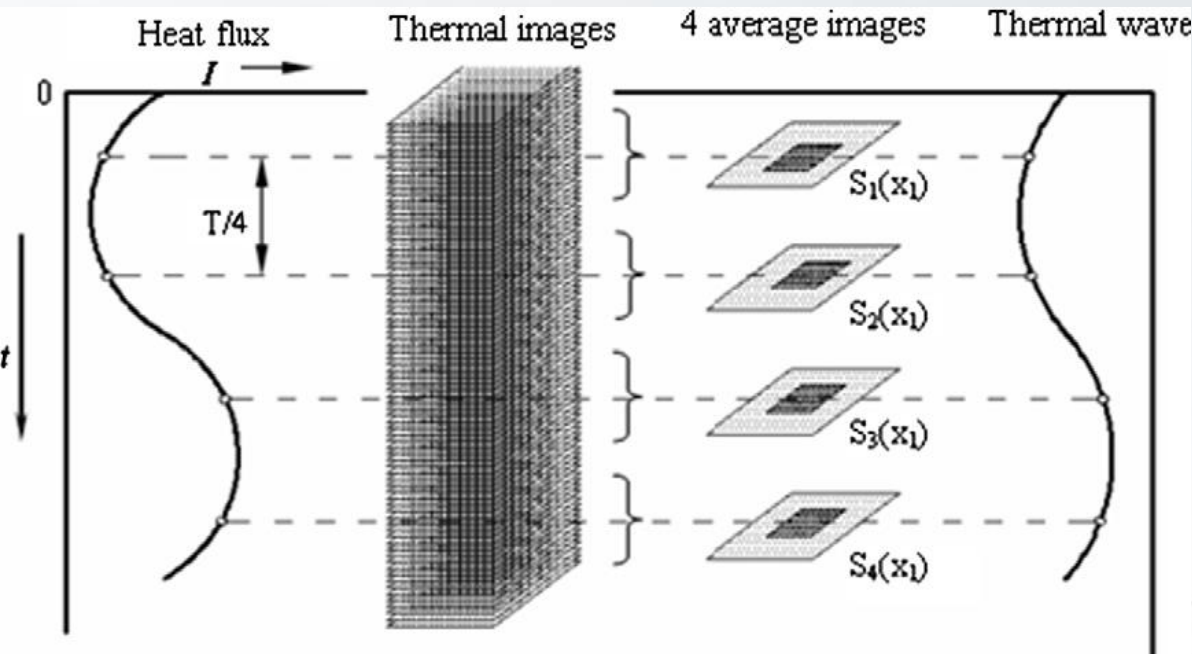


$f_7=0,44$ Hz

- Thermographie : halogène modulée + lock-in
 - Optical Lock-in Thermography (OLT)



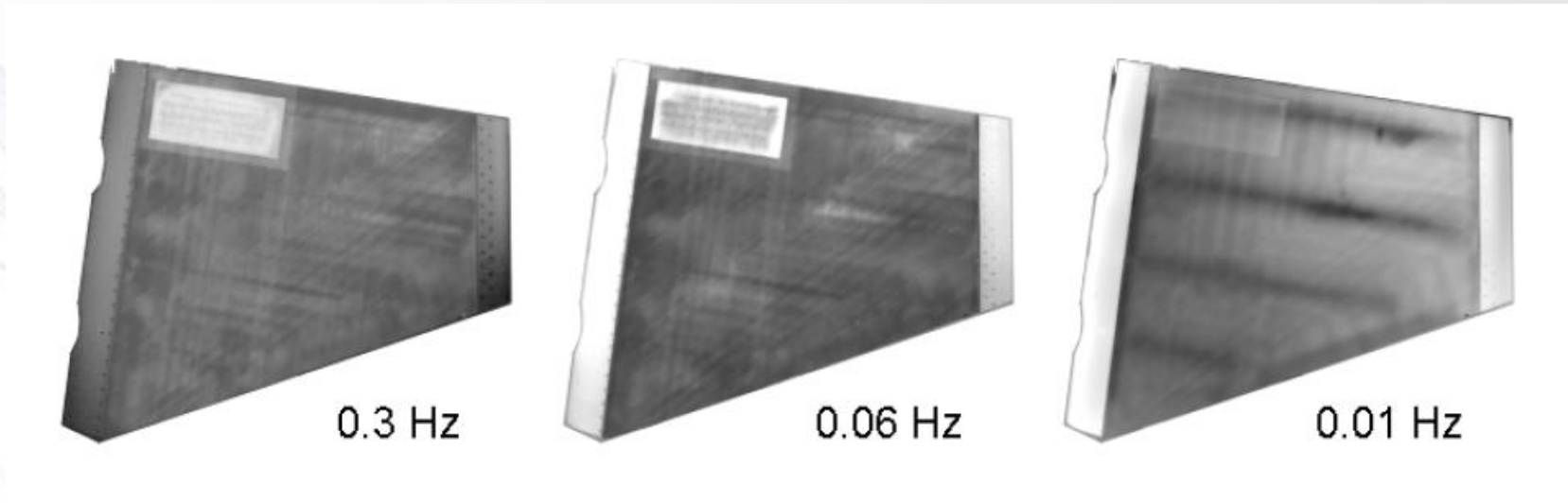
- Thermographie : halogène modulée + lock-in
 - Optical Lock-in Thermography (OLT)



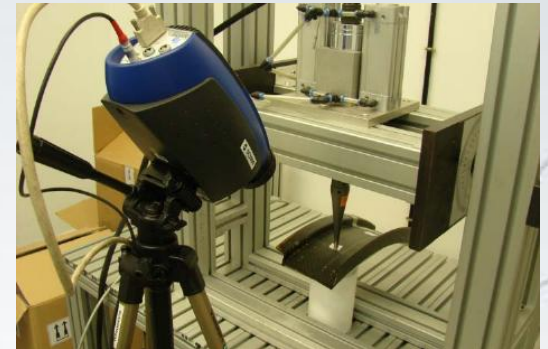
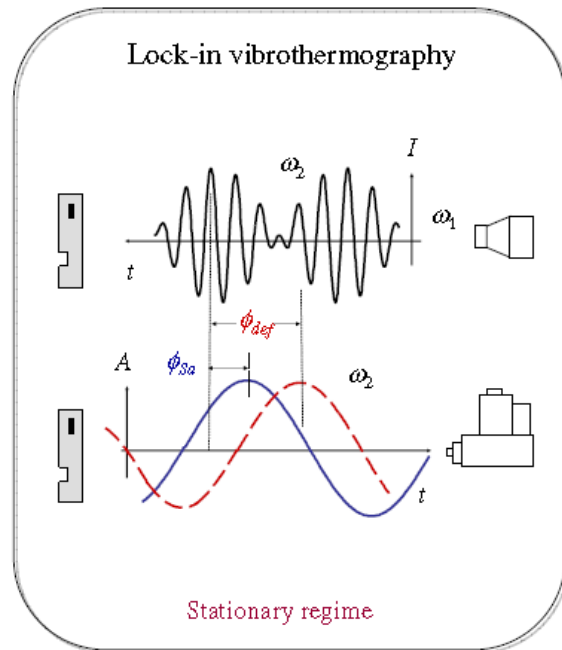
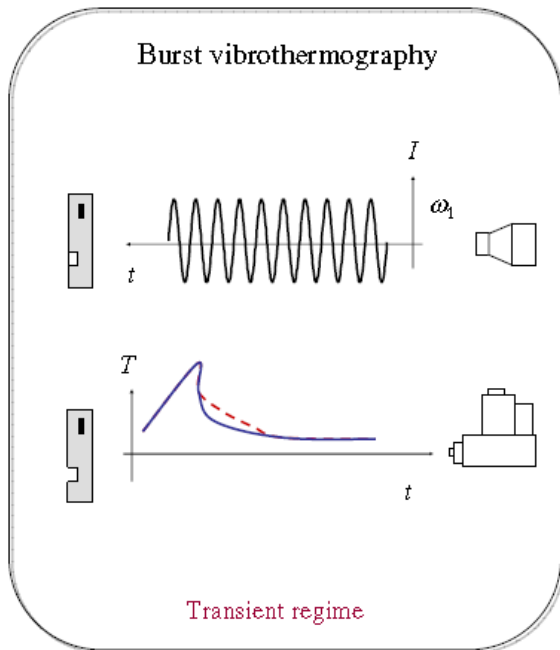
$$\varphi(x_1) = \tan^{-1} \left[\frac{S_1(x_1) - S_3(x_1)}{S_2(x_1) - S_4(x_1)} \right]$$

$$A(x_1) = \sqrt{[S_1(x_1) - S_3(x_1)]^2 + [S_2(x_1) - S_4(x_1)]^2}$$

- Thermographie : halogène modulée + lock-in
 - Optical Lock-in Thermography (OLT)
 - Plus la fréquence de modulation est petite, plus profond on observe



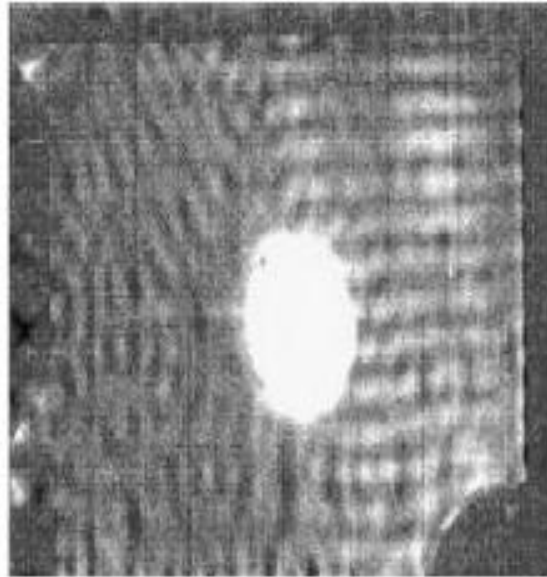
- Thermographie : Vibrothermographie + Ultrasons
 - Ultrasound lock-in Thermography (ULT)
 - Ultrasound Burst Thermography (UBT)



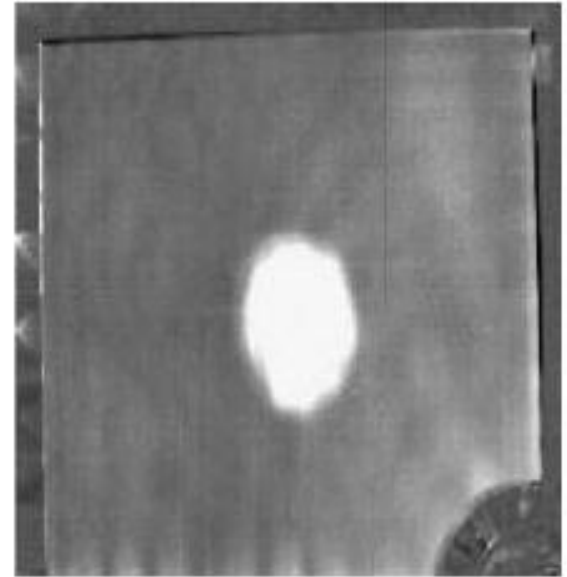
- Thermographie : Vibrothermographie + Ultrasons
 - Ultrasound lock-in Thermography (ULT)
 - Ultrasound Burst Thermography (UBT)



Burst



Lock-in ω

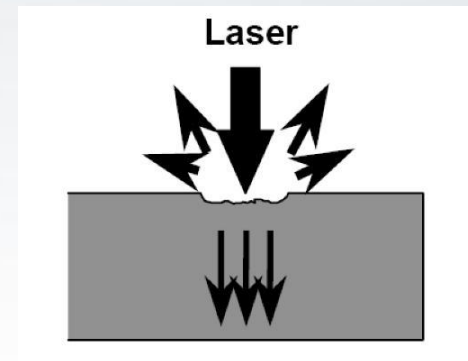
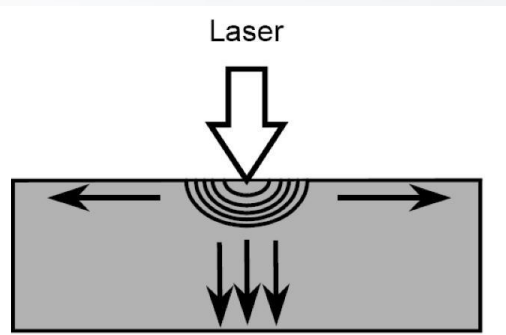


Lock-in $\omega_1 \rightarrow \omega_2$

Description des techniques : Les Ultrasons Laser

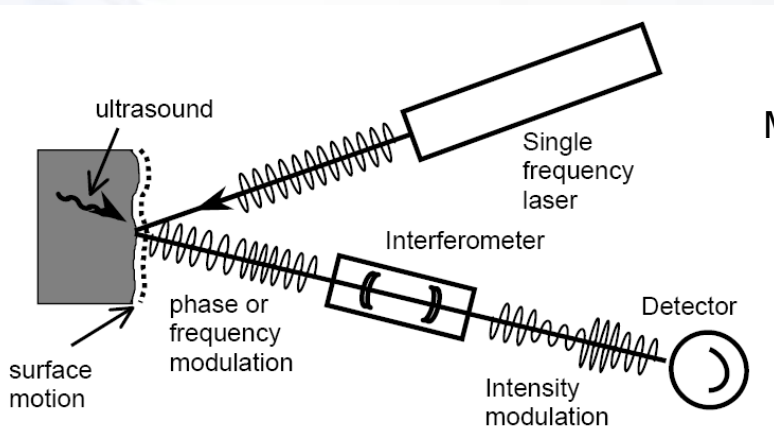
- Ultrasons Laser = Combinaison de 2 principes
- Génération d'ultrasons par Laser
- Détection d'ultrasons par Laser
- Lasers distincts
- Caractéristiques:
 - Sans contact (qqc cm à qqc mètres)
 - Sans couplant (air)
 - Spots laser : qqc millimètres, peut atteindre des endroits anguleux, difficiles d'accès

- Génération par laser impulsionnel
- Deux processus possibles
 - Régime thermo-élastique : non destructif
 - Régime ablatif : destructif



- Efficacité de génération dépend de
 - Du matériau
 - La longueur d'onde du laser
 - La densité d'énergie de l'impulsion (en restant $<$ seuil d'ablation)

- Détection par interféromètre laser
- Divers principes commercialisés
 - Fabry-Perot confocal (F-P)
 - Mixage d'ondes dans cristal photoréfractif (TWM)
- Fabry-Perot

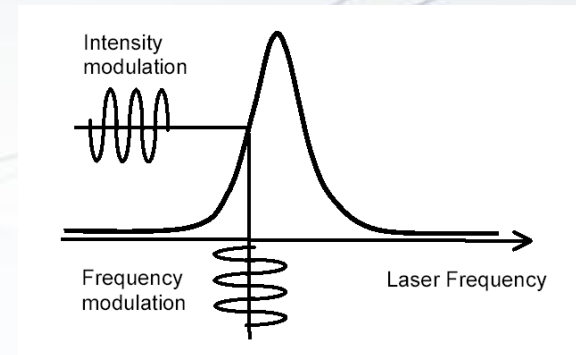


Mouvement ultrasonique de la surface



Shift Doppler de la fréquence laser

Modulation de fréquence transformée en modulation d'intensité



- Systèmes existants

LUIS (Tecnocampus Nantes)



LUIS (Sacramento, 1996)



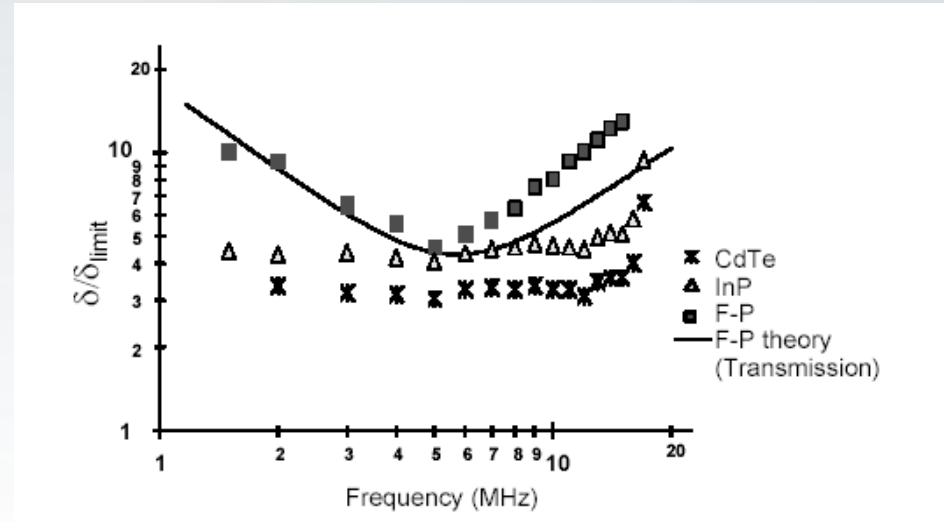
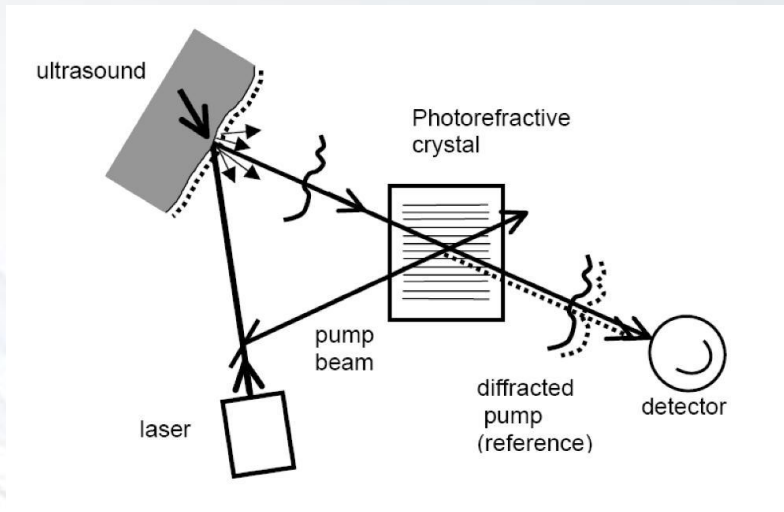
Lockheed Martin (2000)



LUCIE (Tecnocampus, 2011)



- Détection par TWM

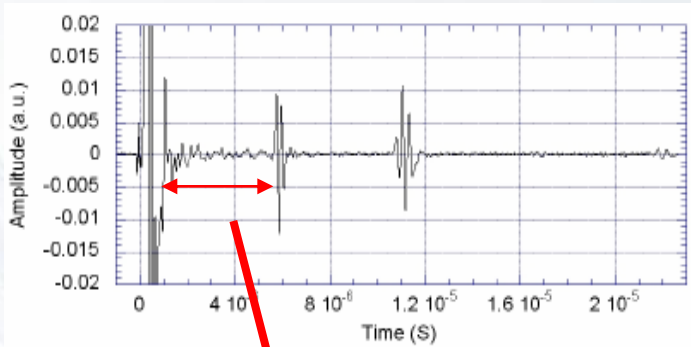


- Réponse plate en fréquence
- Meilleure réponse aux basses fréquences que FP
- Beaucoup plus compact
- Mieux adapté aux composites
- Modes très basse fréquence : « LASER TAPPING »



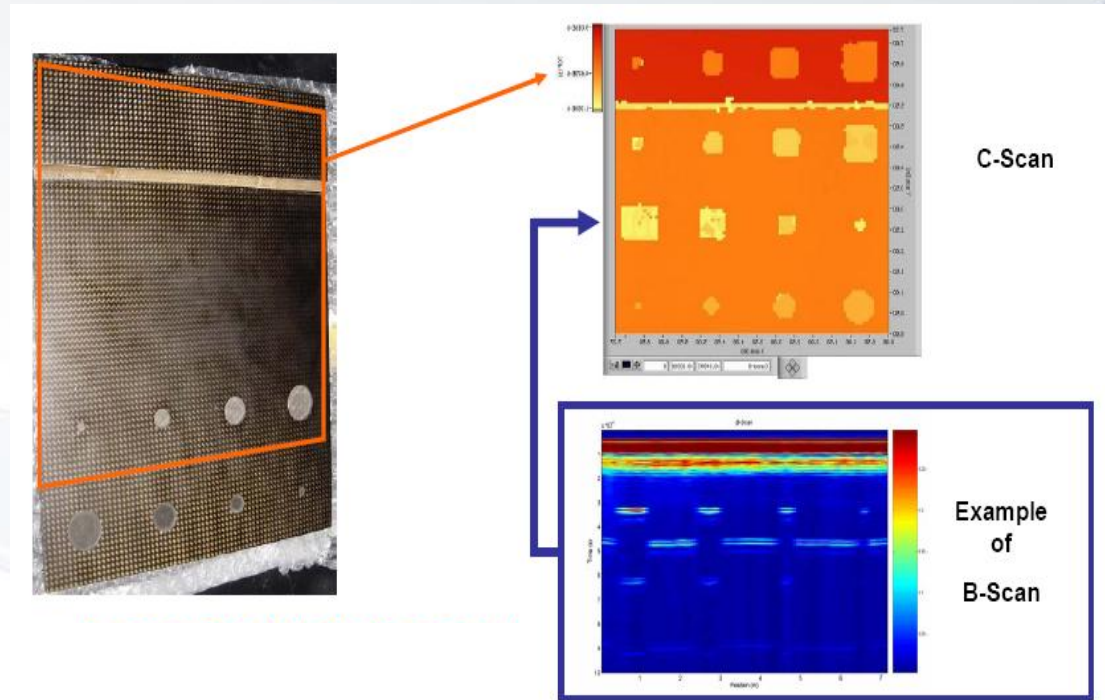
- Les UT Laser s'appliquent comme des UT
- Nécessitent un balayage

A-scan



Profondeur du défaut

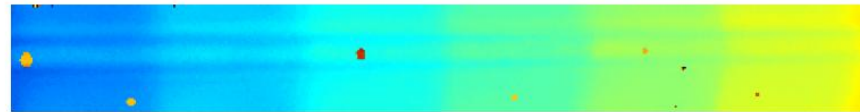
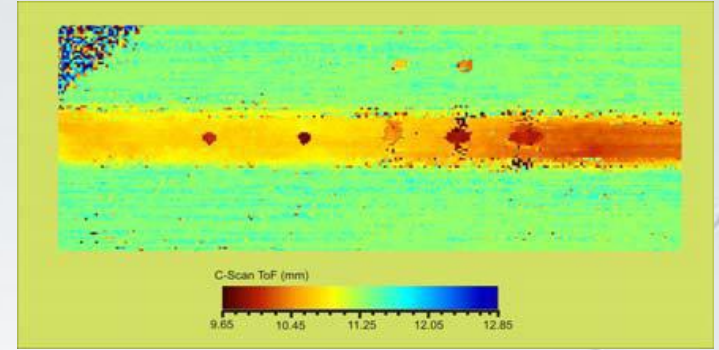
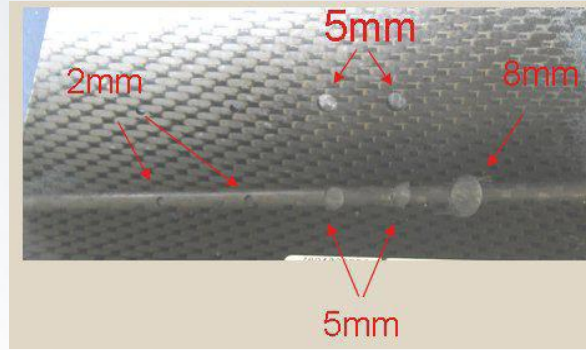
Epaisseur de la pièce



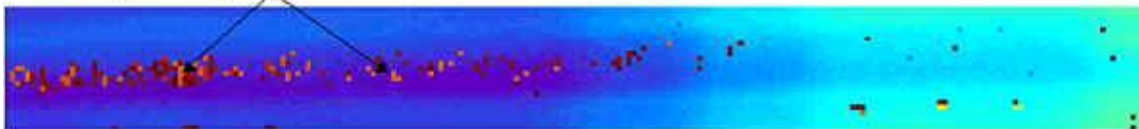
C-Scan

Example of B-Scan

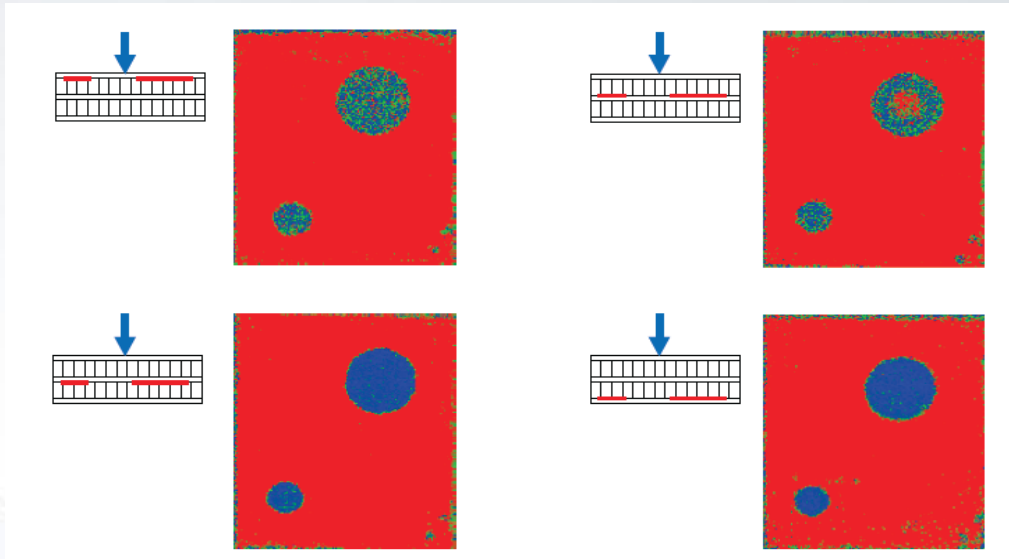
- Application : détection de défauts dans structures composites de formes complexes



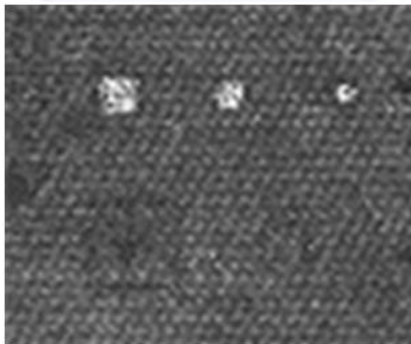
porosity in the radius



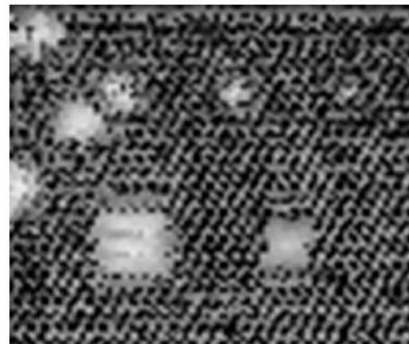
- Laser Tapping (basses fréquences)



Hautes fréquences



Basses fréquences



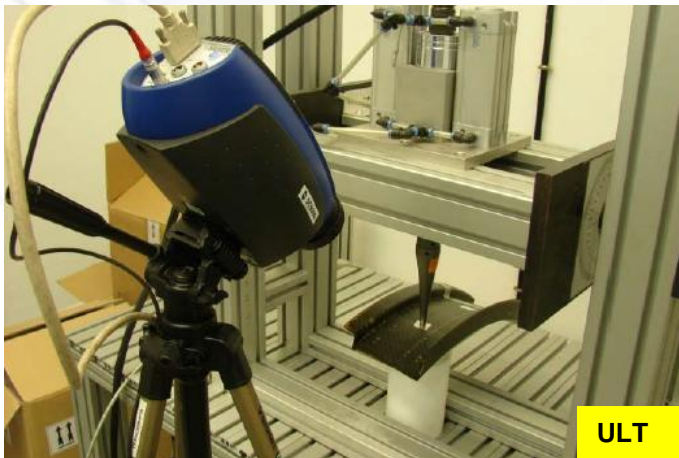
Investigations des techniques

- Investigations par thermographie

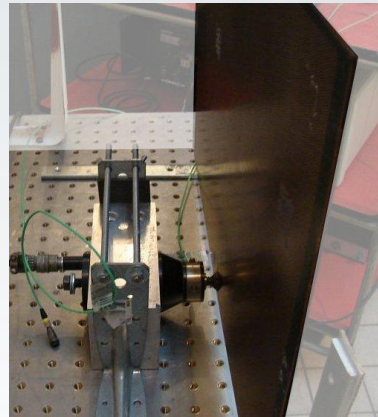


CTA Espagne

- Caméra refroidie
 - FLIR MWIR
 - 320x250
- OPT+OLT+ULT : Edevis



- Investigations par thermographie

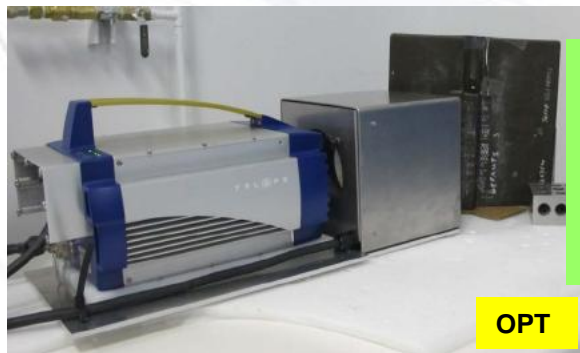


HEPL (ISIL) – Ph.Demy

-Caméra non refroidie
-Xenics LWIR
-386x288

Vibrothermo

CTA Montréal



-Caméra refroidie
-Telops MWIR
-640x512

OPT : VisioImage

OPT

GEL-MIVIM / VisioImage (Québec)

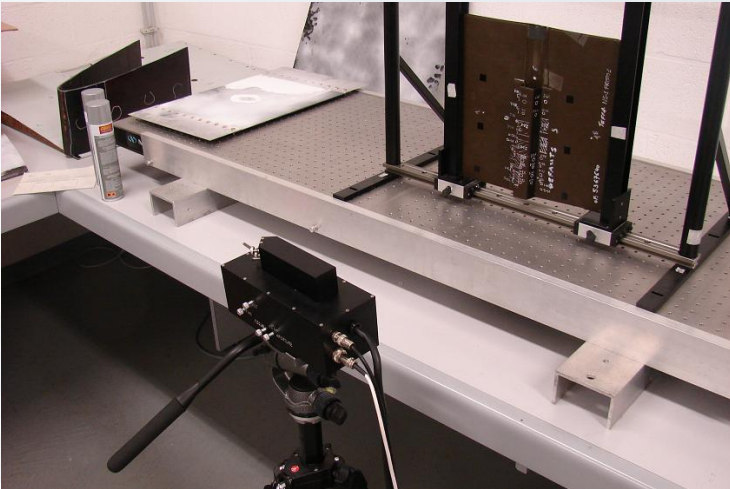


-Caméra non refroidie
-Jenoptik LWIR
-640x480

OPT

OPT

- Investigations par shearographie



CSL - Optrion - Airbus

- Caméra Megapixel
- Univ. Cape Town
- Diode laser 70 mW

Chaufferette
Halogène



CTA Montréal

- Caméra Megapixel
- Dantec Q810
- Diode laser 8x120 mW

Lampes Quartz



- Investigations par Ultrasons Laser

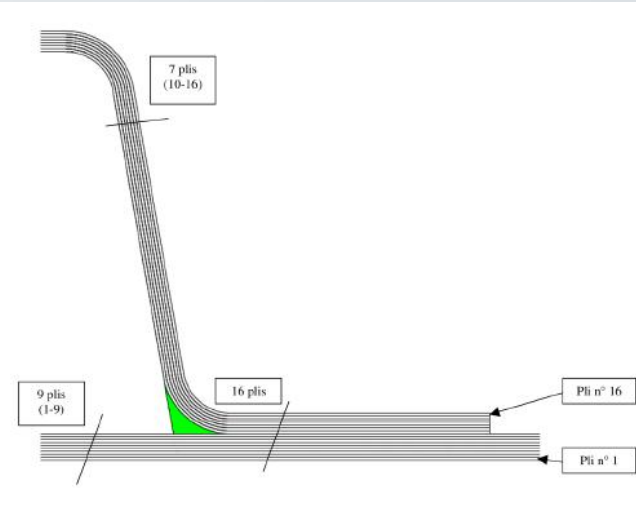
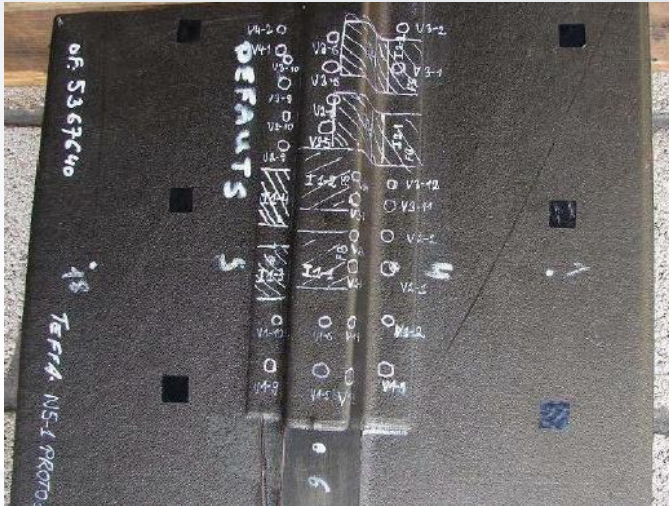


CTA Montréal

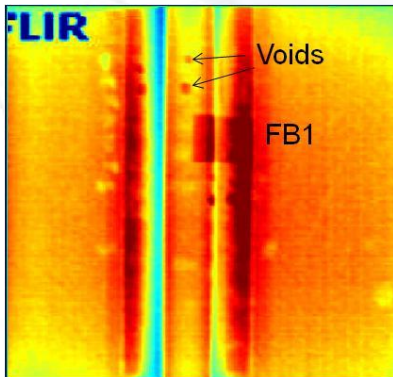
- Génération : laser pulsé CO₂
- Détection : laser pulsé YAG (1064 nm)
- Sonde TWM
- Taux répétition : 100 Hz
- Spot : 2 mm
- Balayage : 0,5 mm
- TECNAR



- Echantillon 1

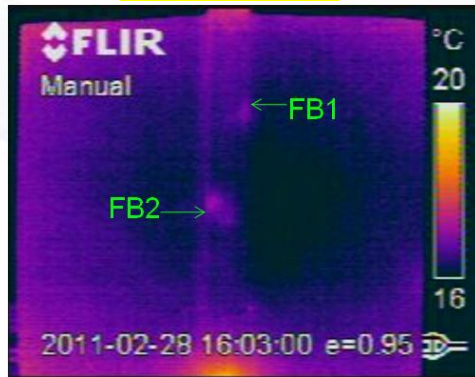


OPT+ PCT



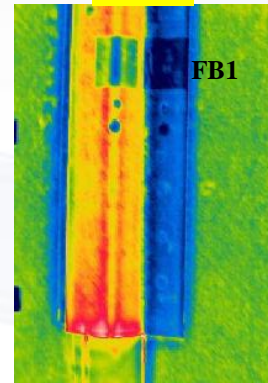
HEPL

Vibrothermo



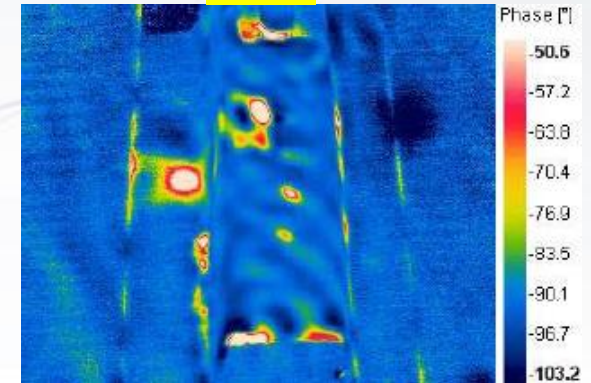
HEPL

OLT



CTA Espagne

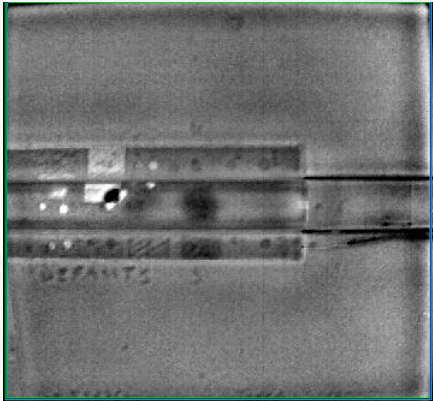
ULT



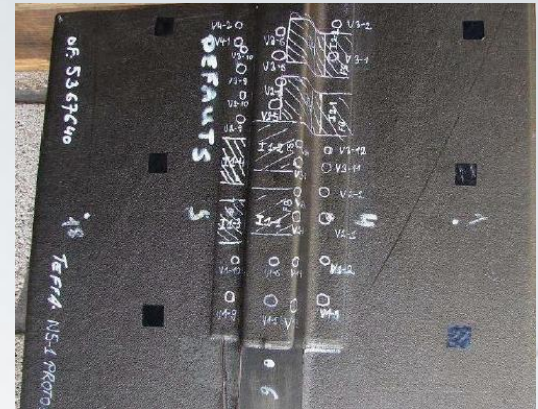
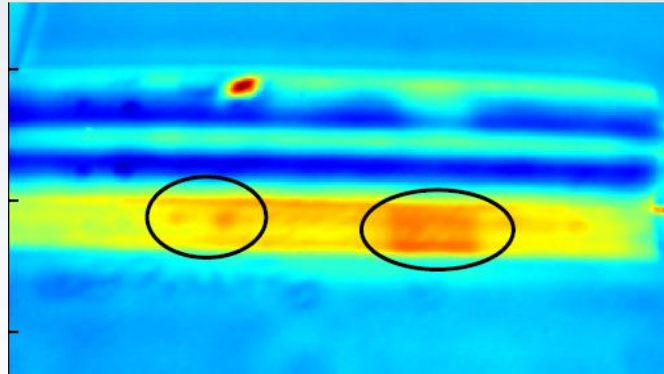
CTA Espagne

- Echantillon 1

OPT+ PCT

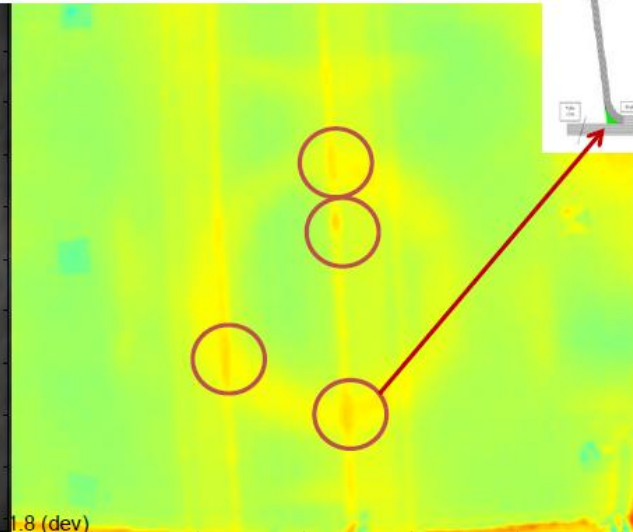
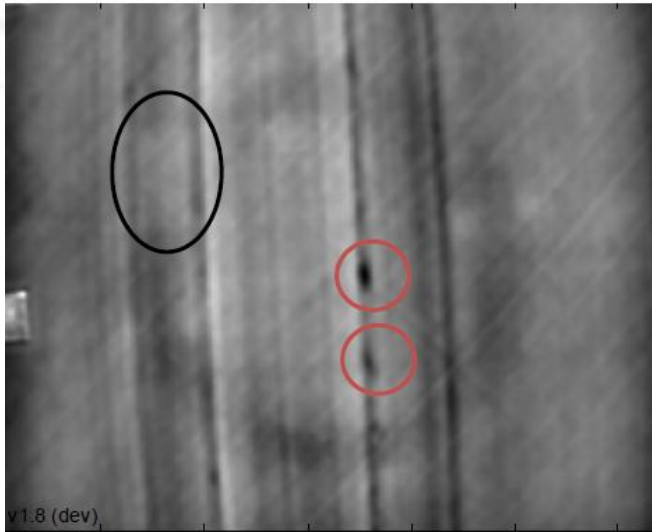


OPT+PCT



VisioImage/FLIR refroidie

CTA Montréal

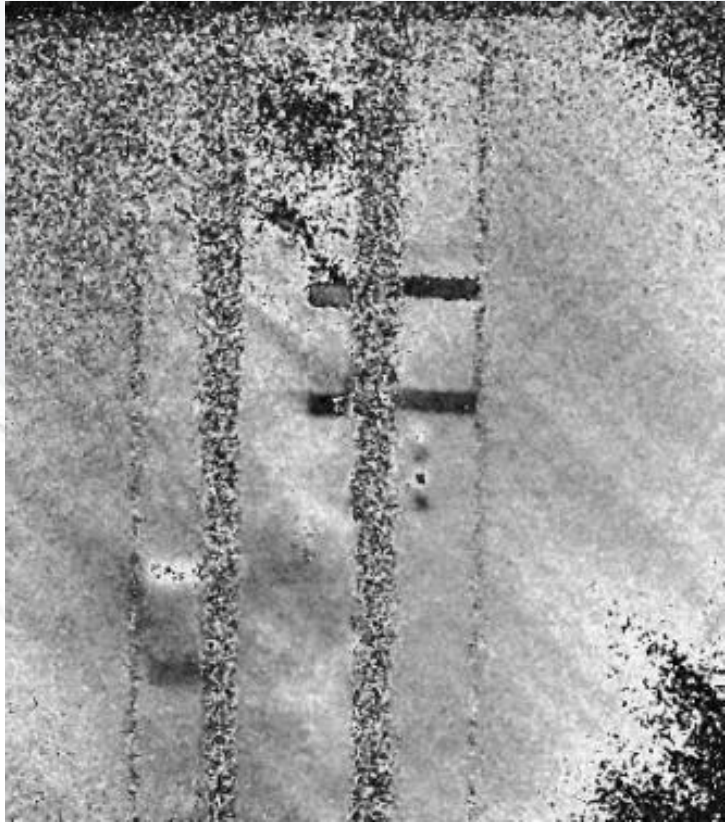


v1.8 (dev)

1.8 (dev)

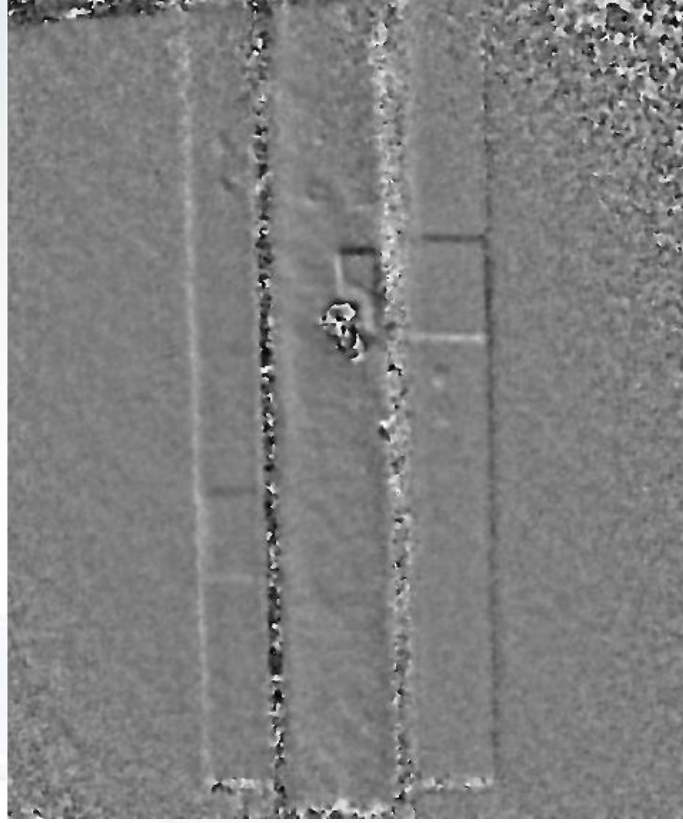
- Echantillon 1

Chaufferette

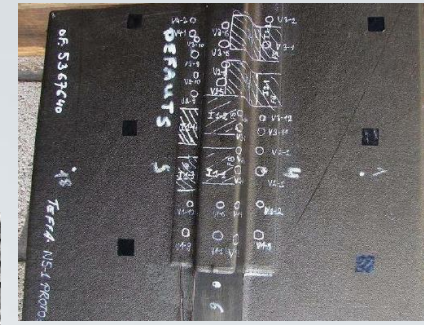


CSL

Lampe Quartz



CTA Montréal

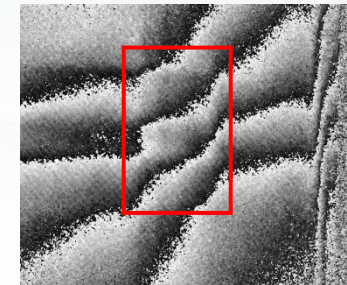
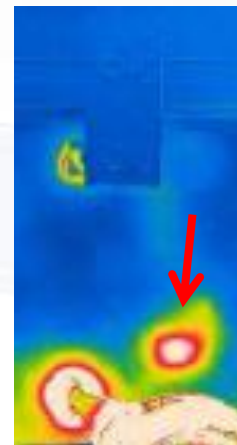
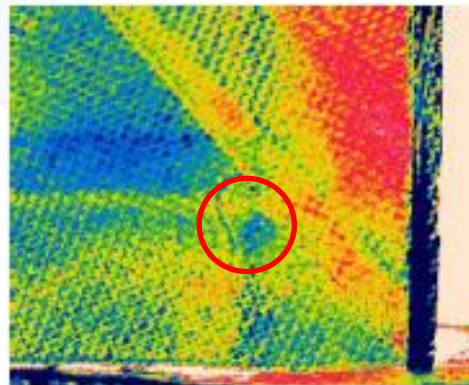
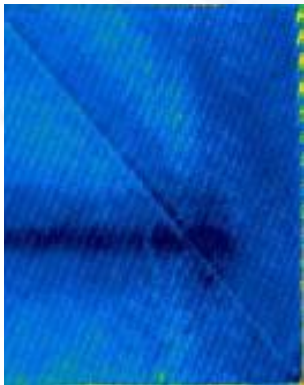
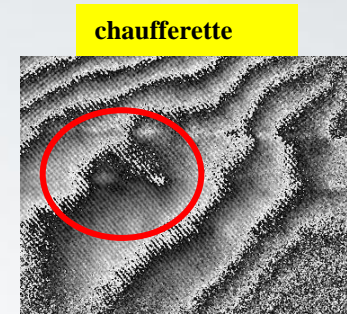
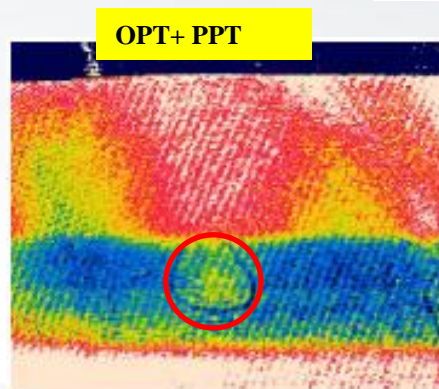
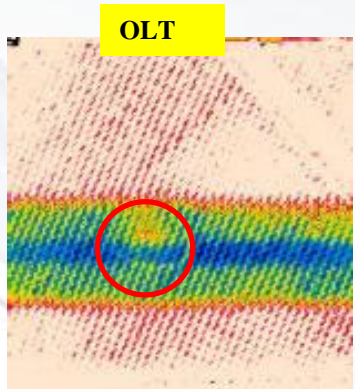
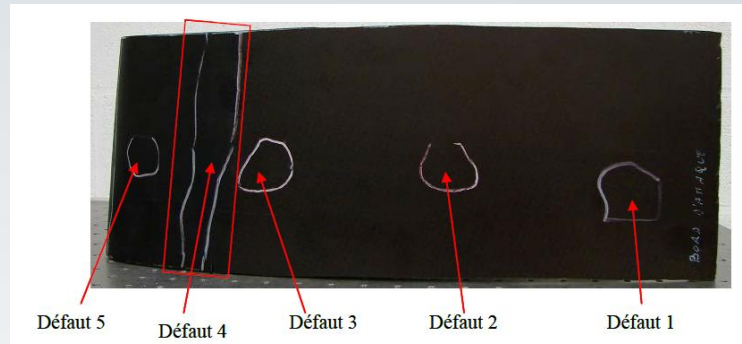


- Echantillon 1



CTA Montréal

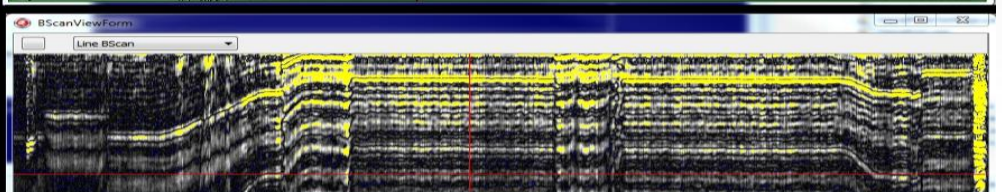
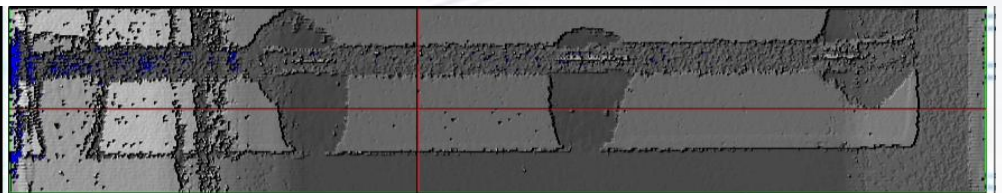
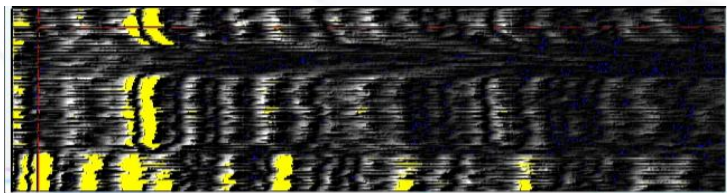
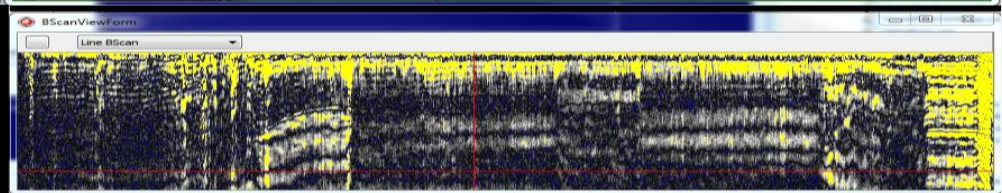
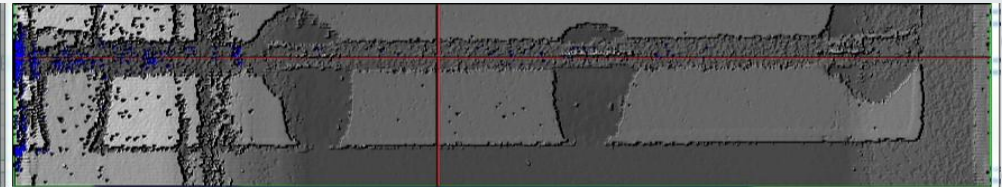
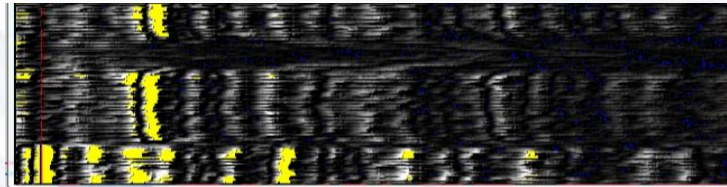
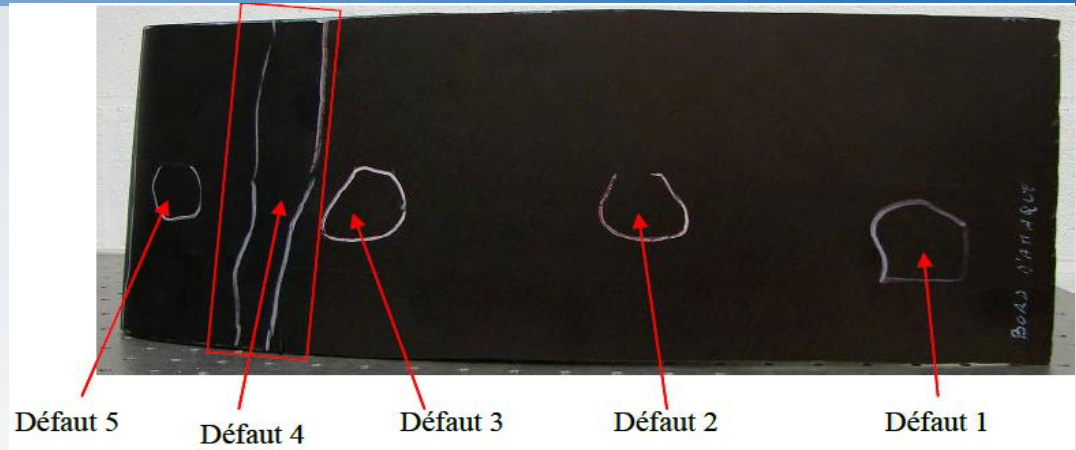
- Echantillon 2



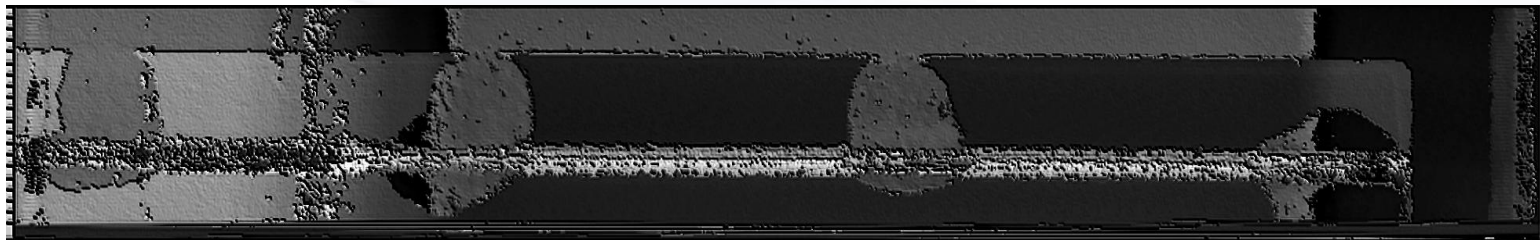
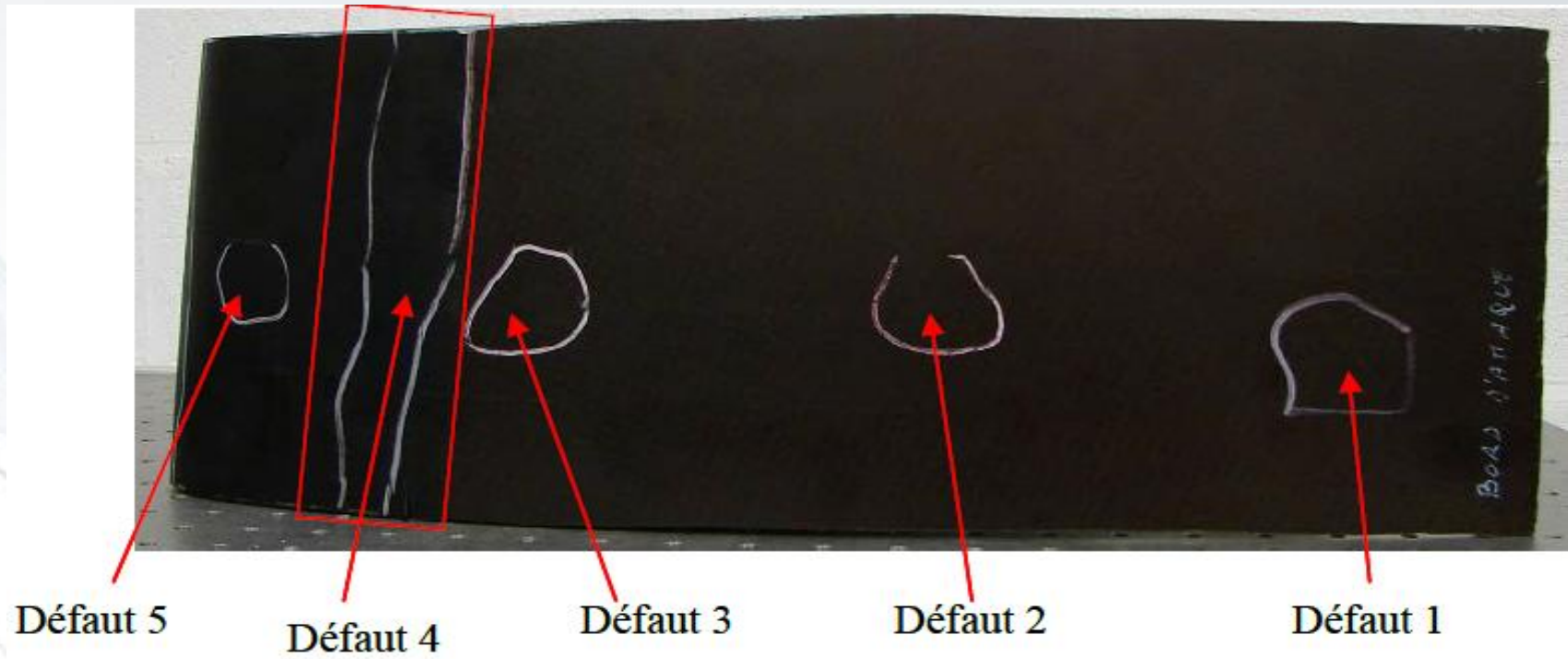
CTA Espagne

CSL

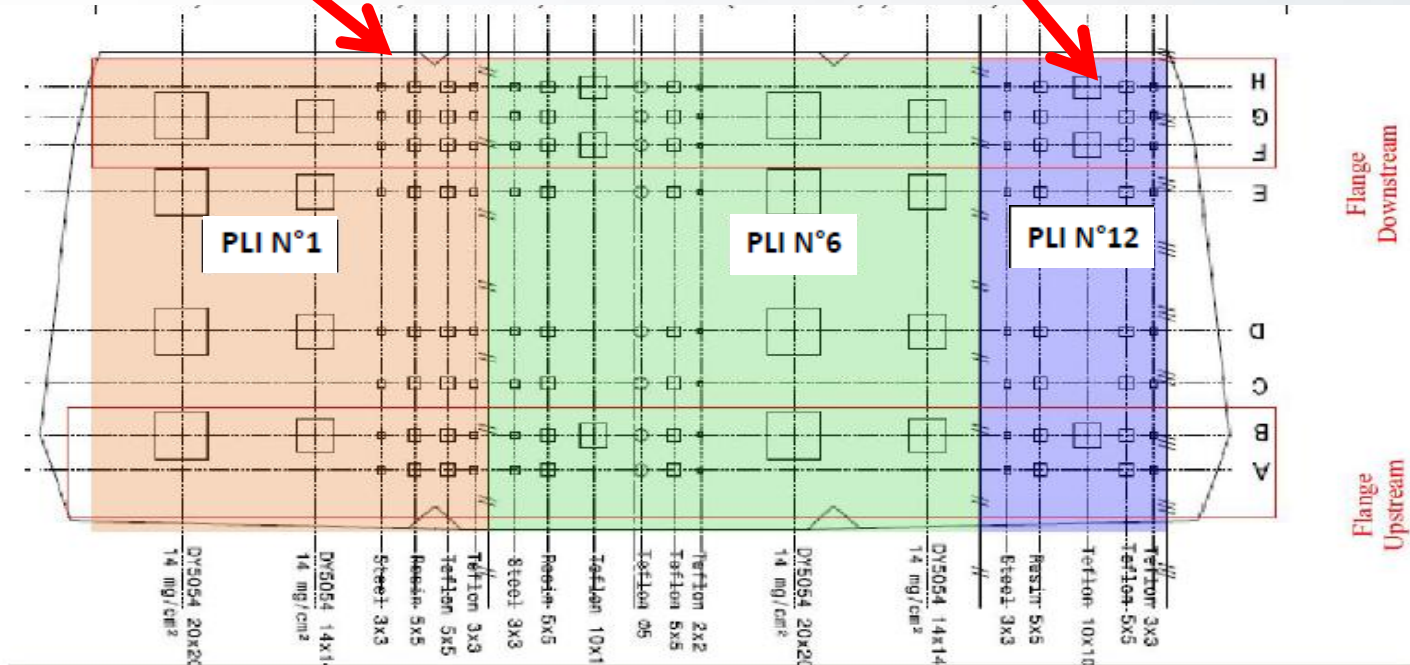
- Echantillon 2



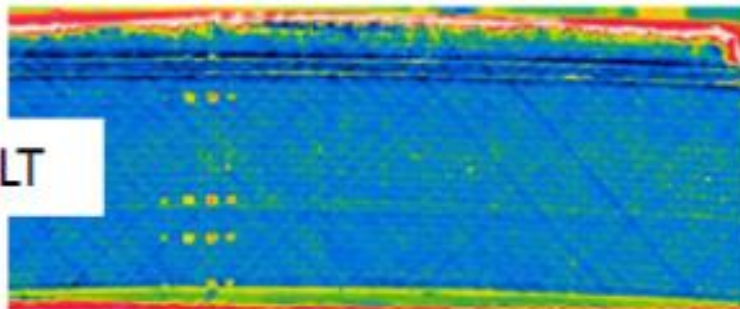
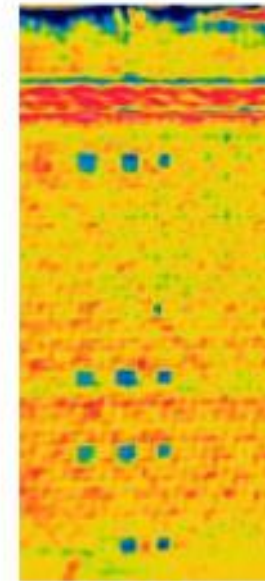
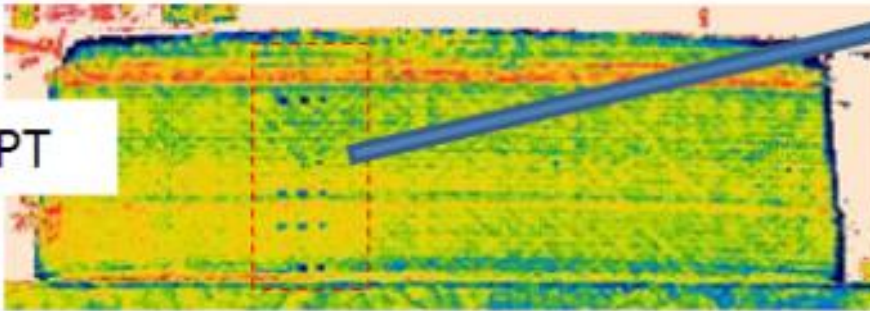
- Echantillon 2



- Echantillon 3



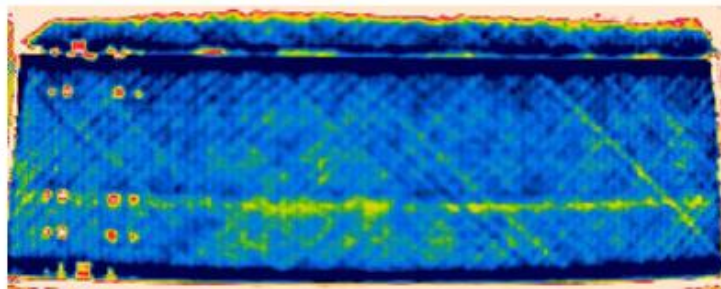
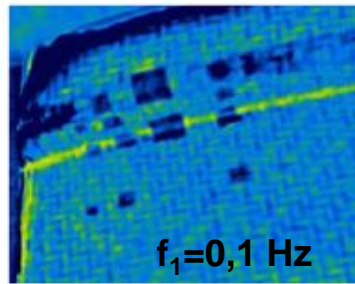
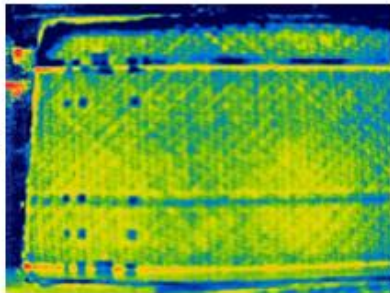
- Echantillon 3



CTA Espagne

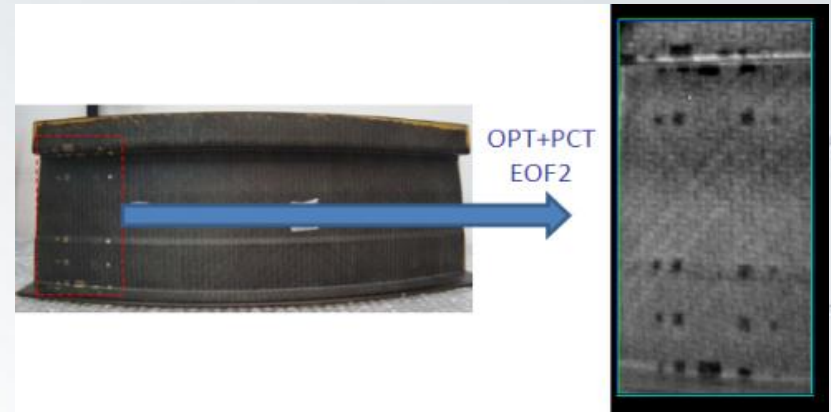
- Echantillon 3

CTA Espagne



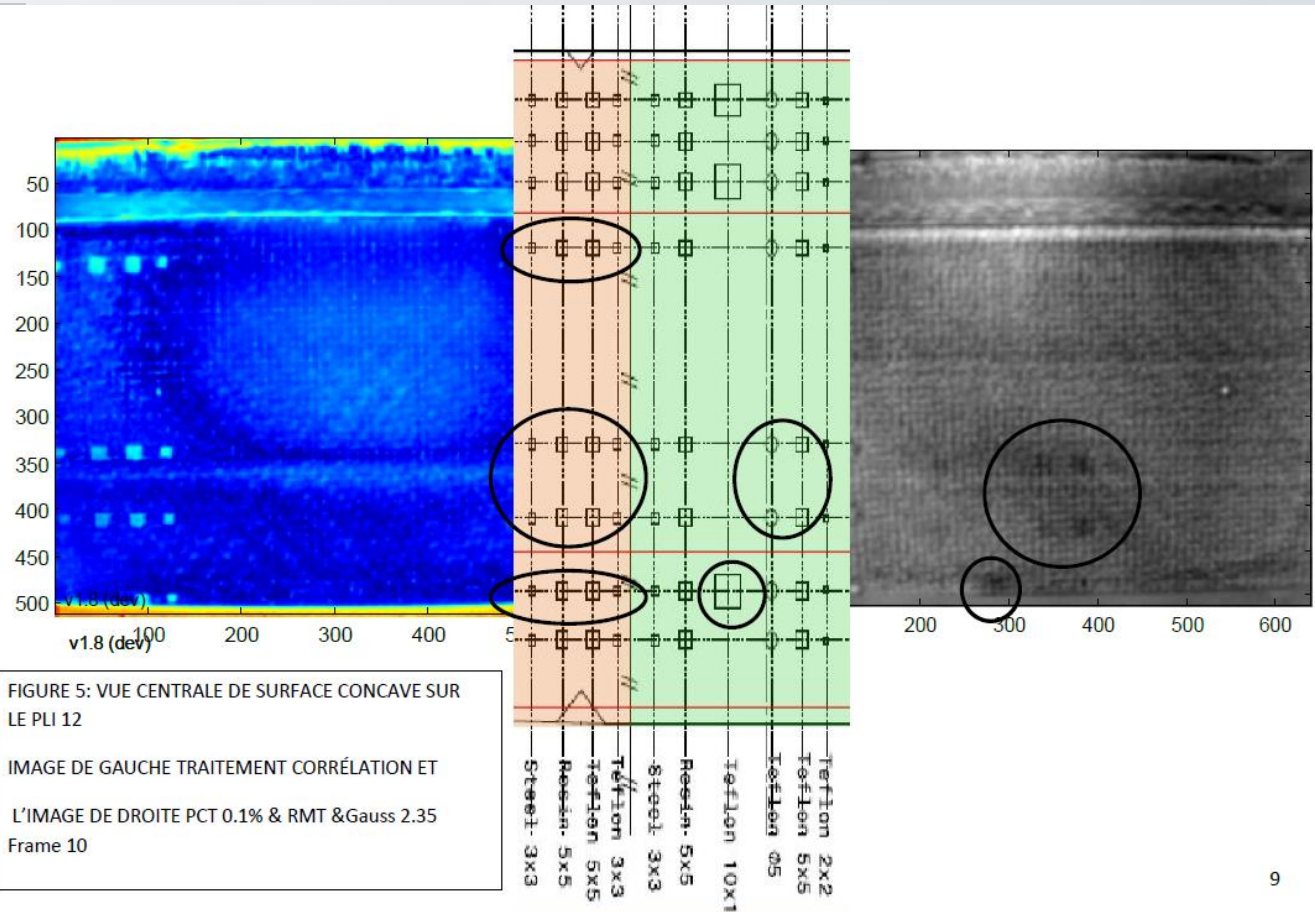
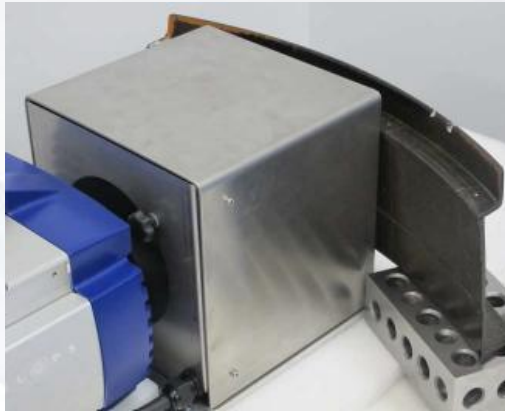
$f_1=0,05 \text{ Hz}$
(2 périodes)

VisioImage



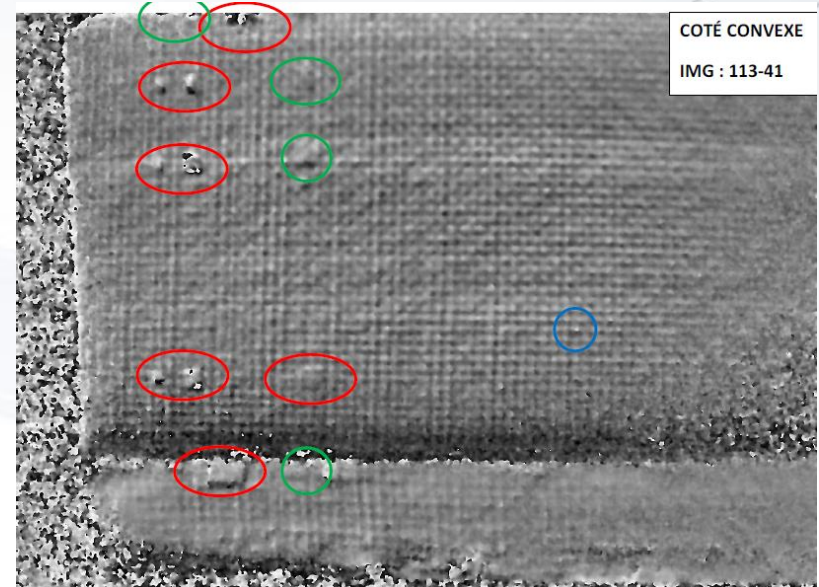
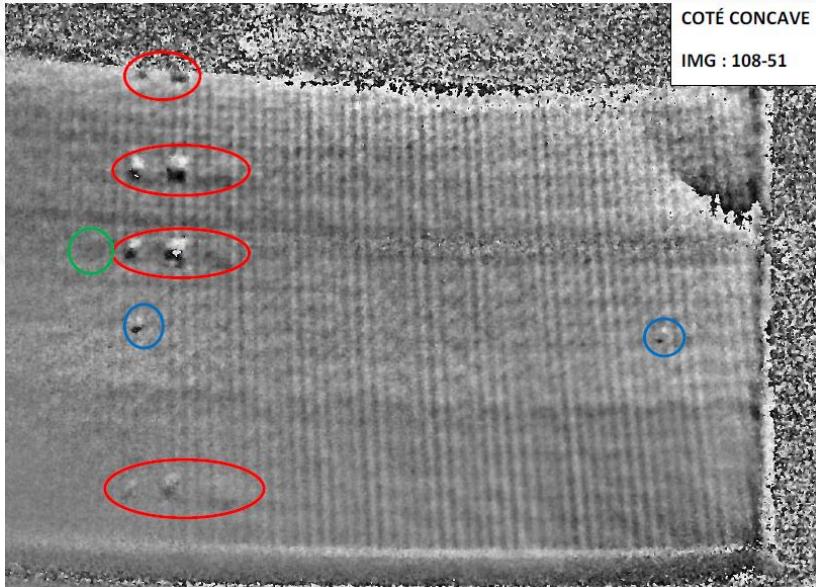
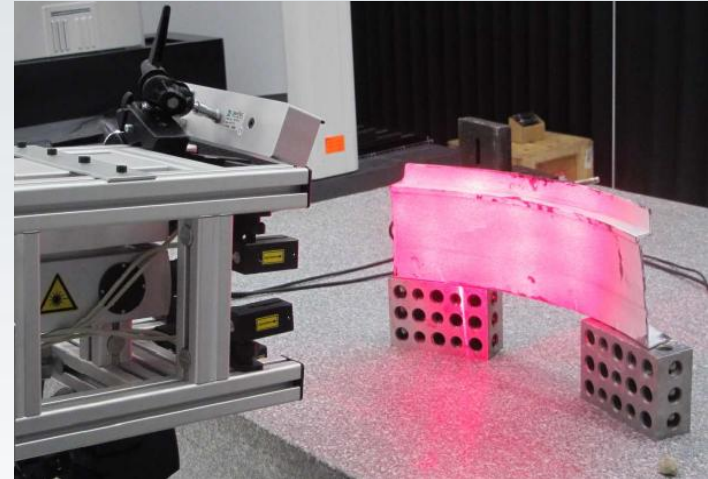
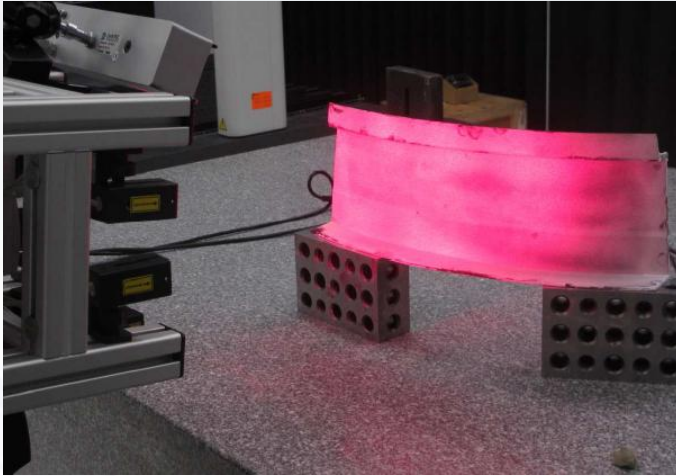
- Echantillon 3

CTA Montréal



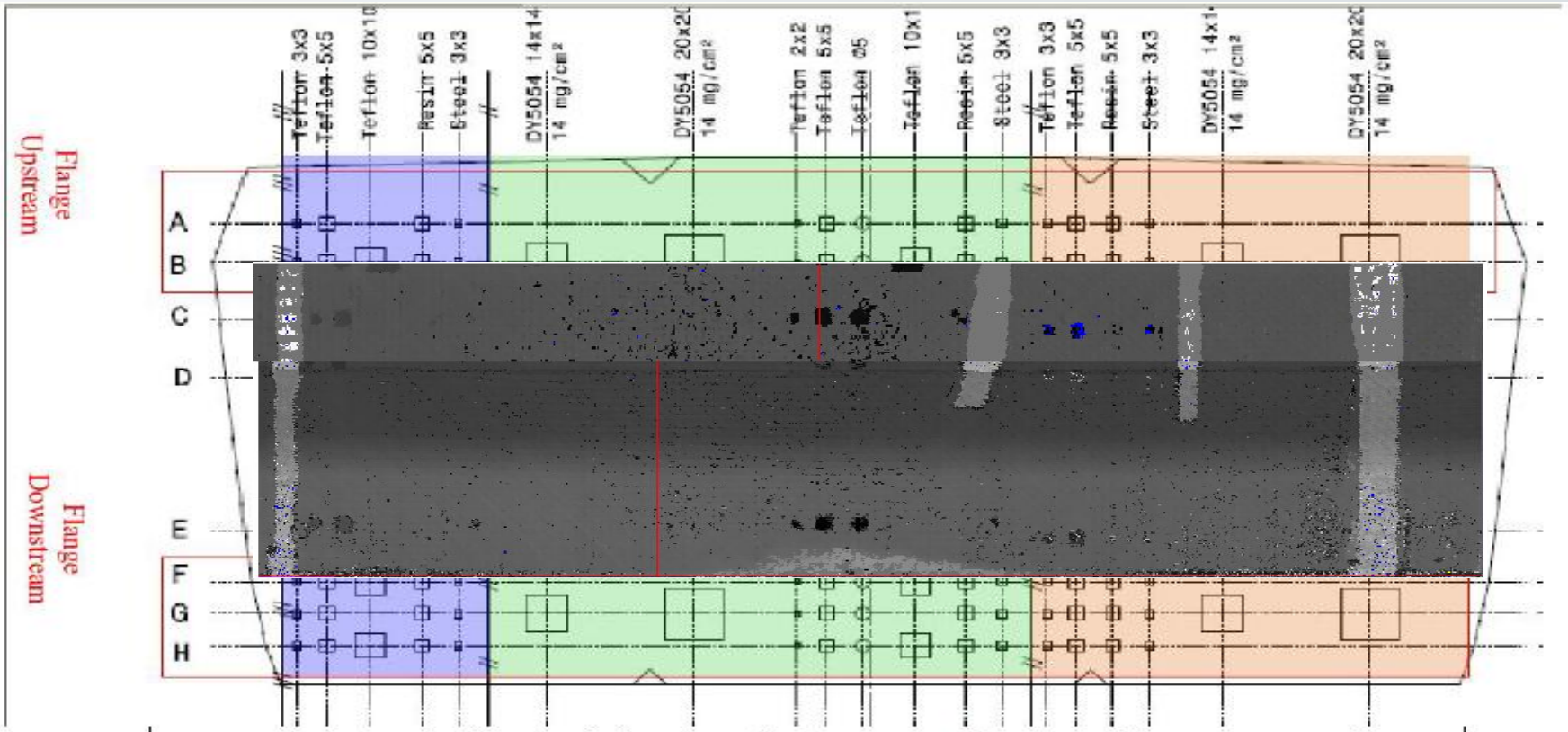
- Echantillon 3

CTA Montréal

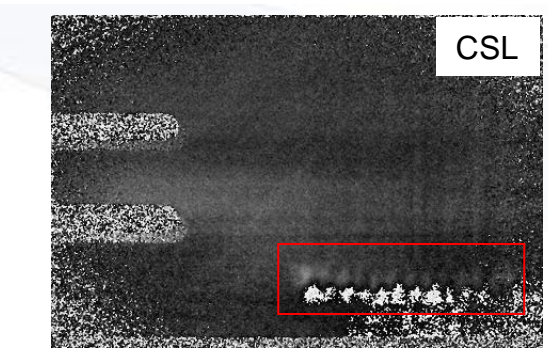
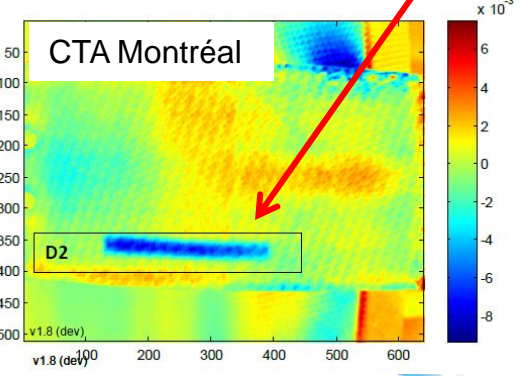
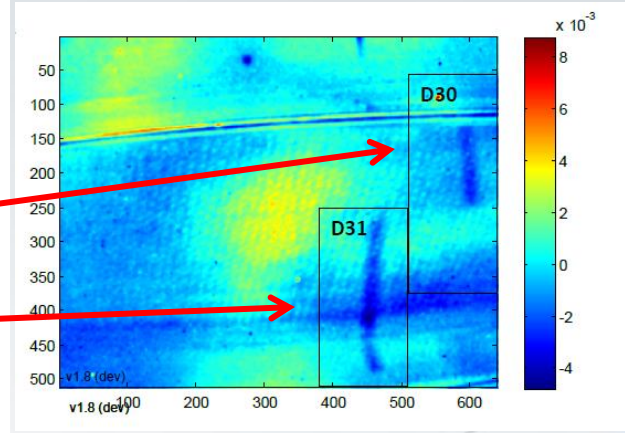
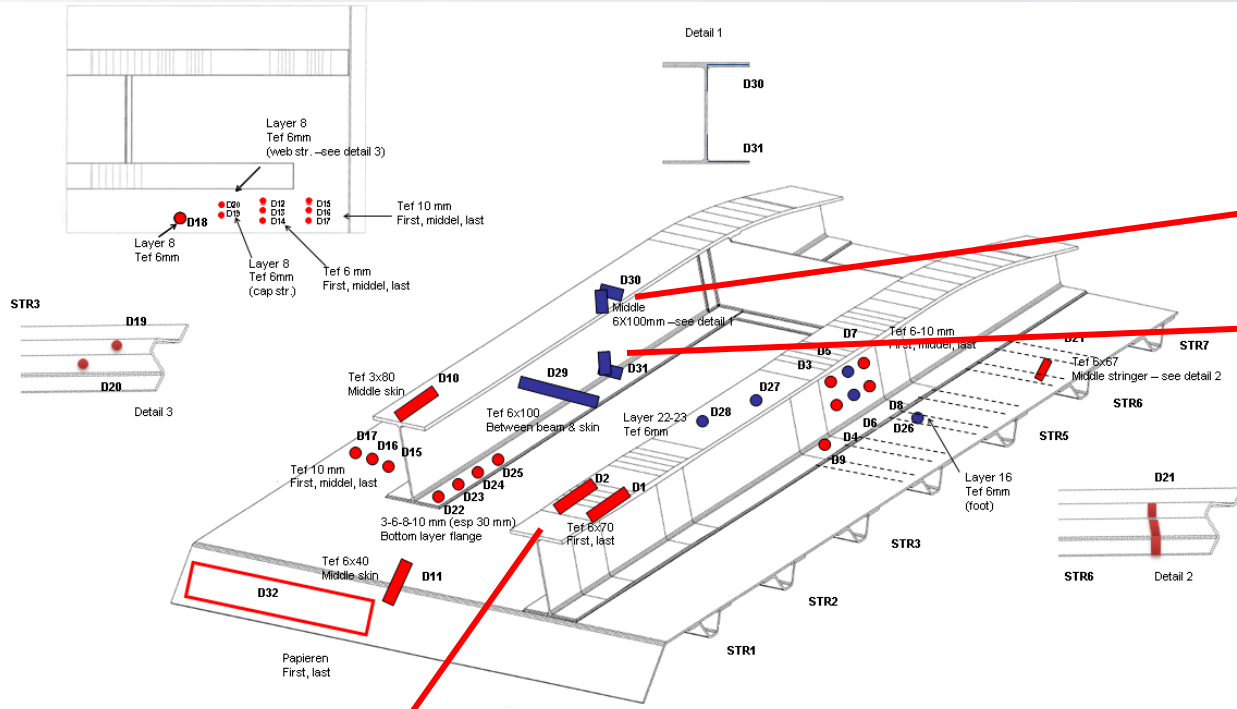


- Echantillon 3

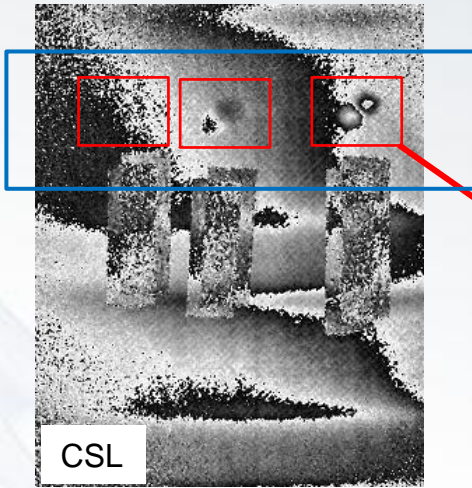
CTA Montréal



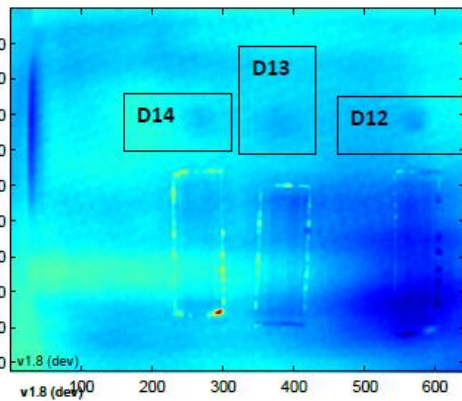
- Echantillon 4



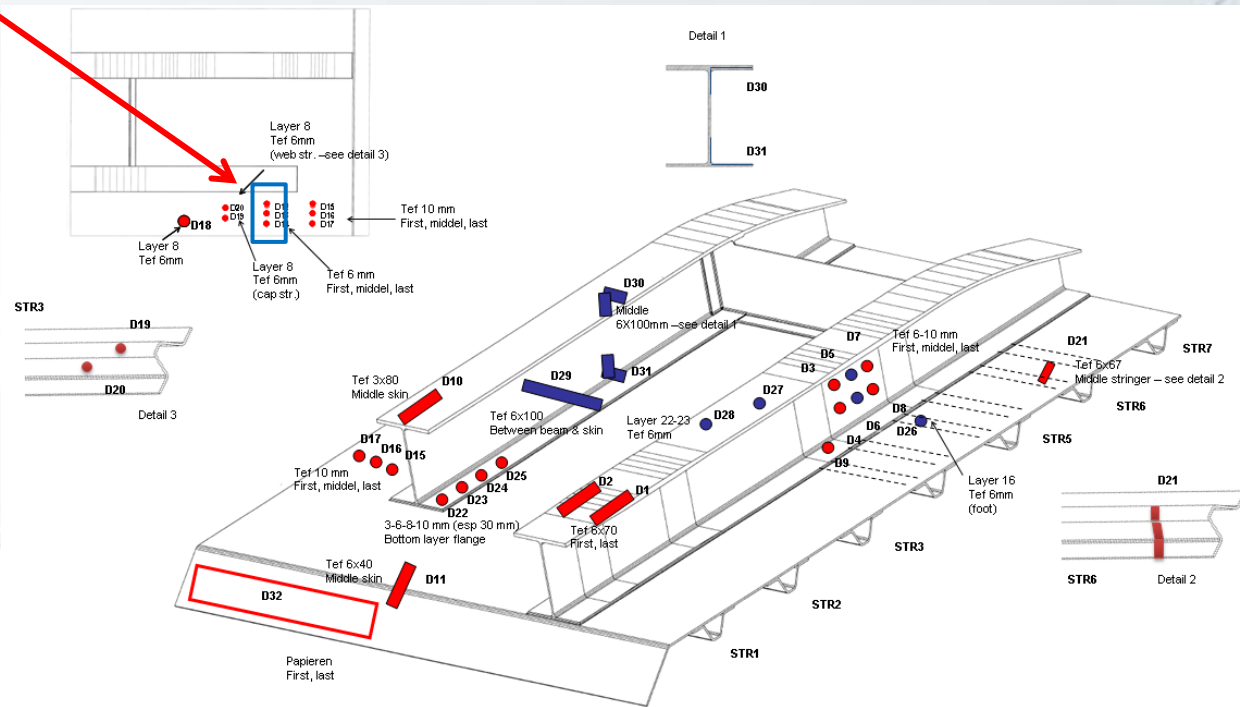
- Echantillon 4



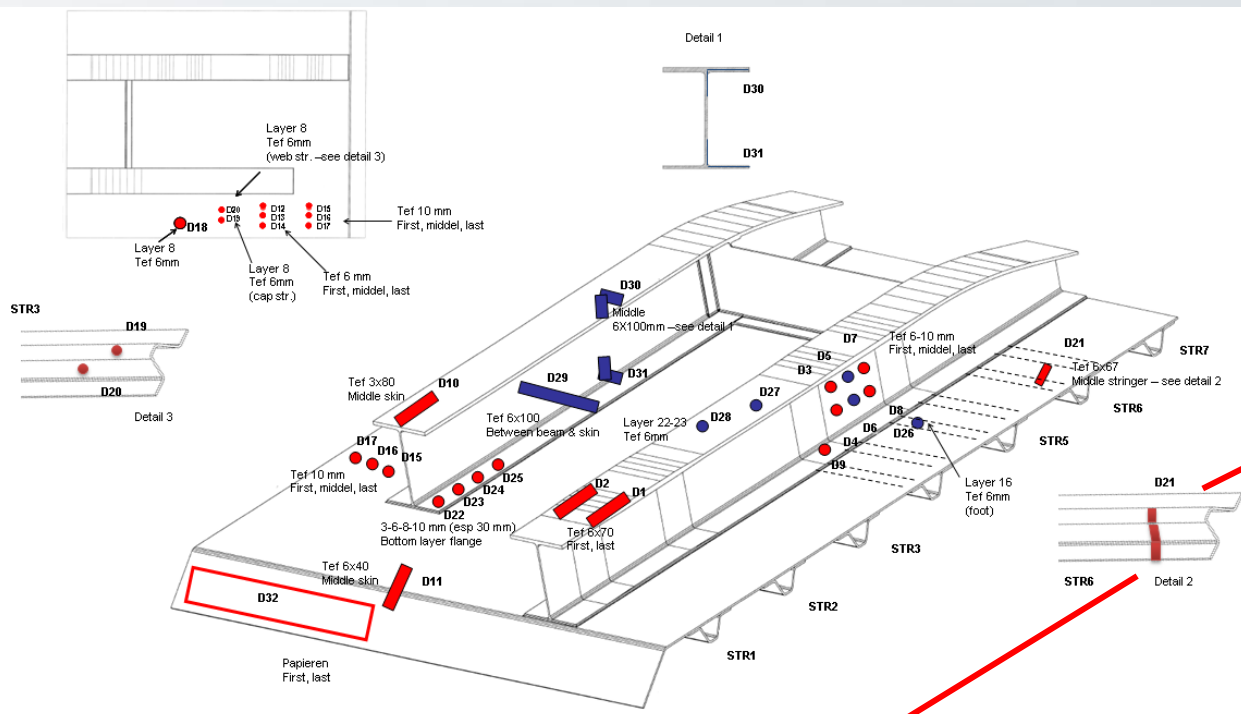
2,4 mm 1,5 mm 0,7 mm



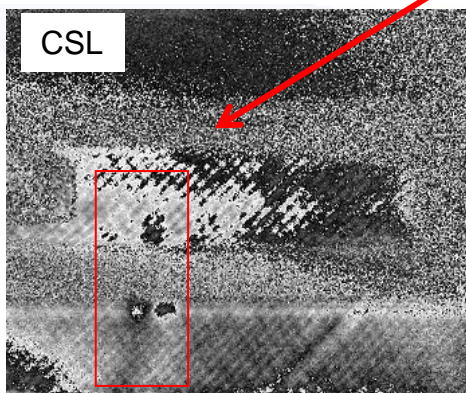
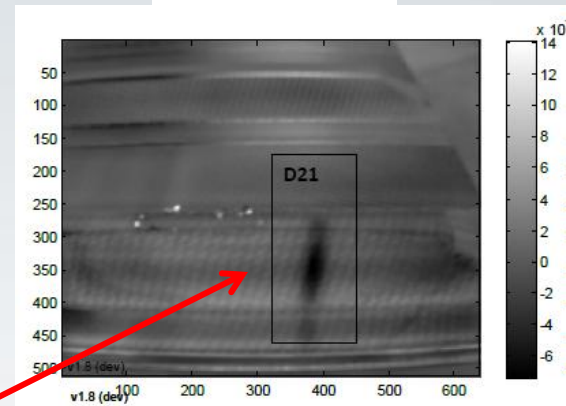
CTA Montréal



- Echantillon 4



CTA Montréal

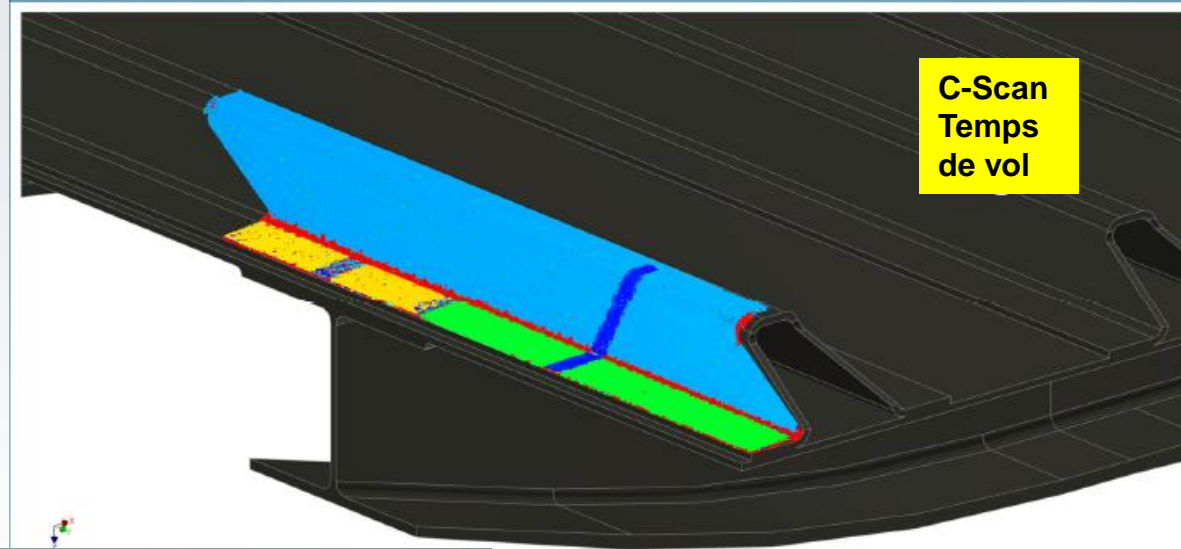


- Echantillon 4

CTA Montréal



- Echantillon 4

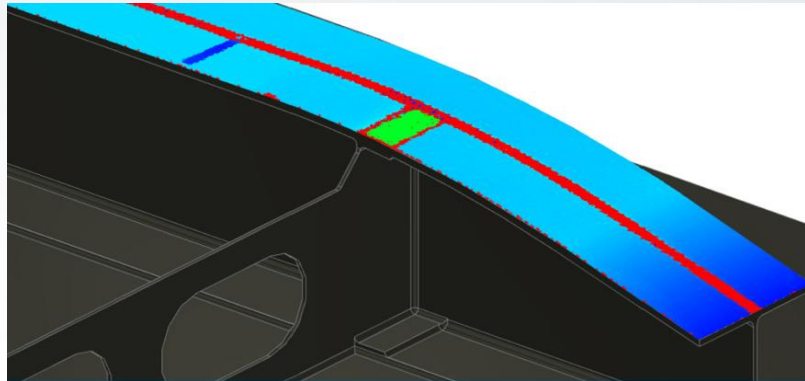
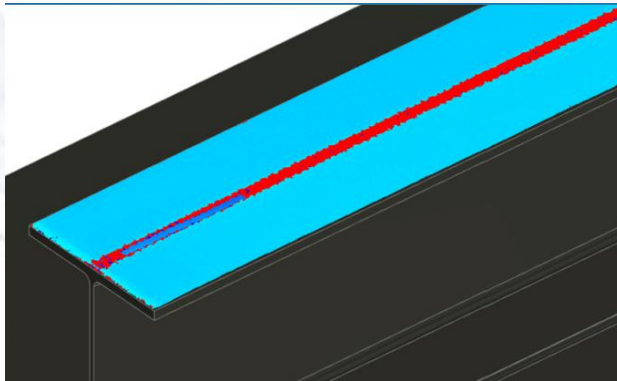


CTA Montréal

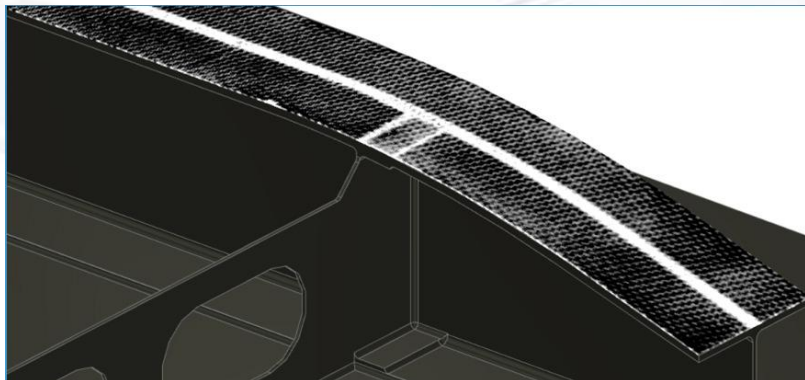
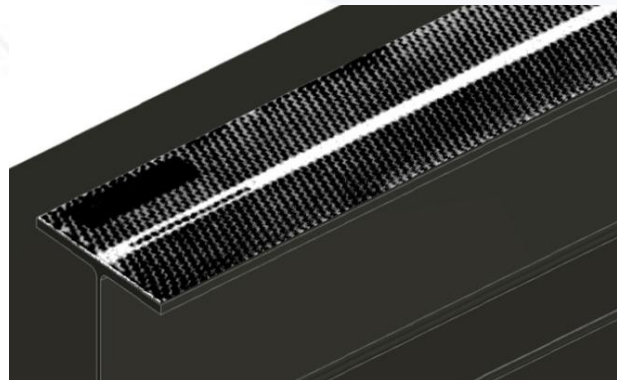
- Echantillon 4



CTA Montréal



C-Scan
Temps de vol

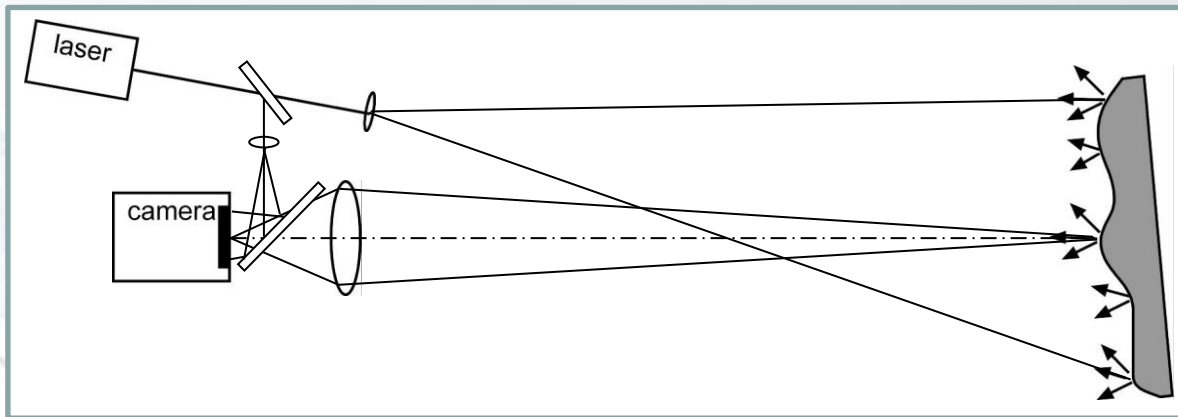


C-Scan
Amplitude

| | Thermographie | Shearographie | UT Laser |
|-----------------------------|---------------|---------------|-----------------|
| Profondeur | 1,5 mm | > 1,5 mm | >>> 1,5 mm |
| Dimensions | 3-4 mm | 3-4 mm | 2 mm |
| Interprétation | + | - | ++ |
| Détermination de profondeur | - | - | ++ |
| Mise en œuvre | + | + | - (balayage) |
| Coût | €€ | € | €€€€ |

Développements actuels

- FANTOM : FP7 (fini Déc 2012)
 - CSL : coordinateur
 - Combinaison Interférométrie de speckle-Thermographie
 - Système portable – NDT chez Airbus



*Interférométrie de speckle
en Infrarouge thermique*

**Caméra
Thermographique**



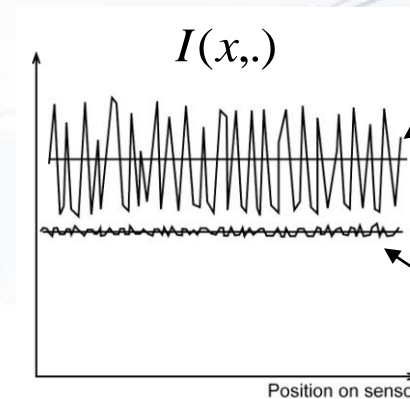
CO2 laser



$\lambda = 8-14 \mu\text{m}$



$\lambda = 10 \mu\text{m}$



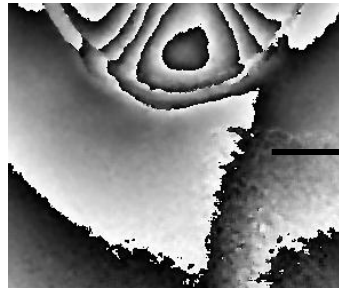
Hologramme
Specklegramme

Thermogramme

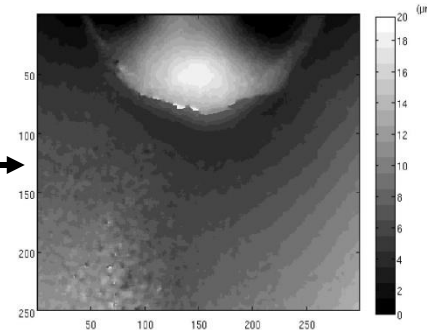
- Découplage des signaux de déformation et température



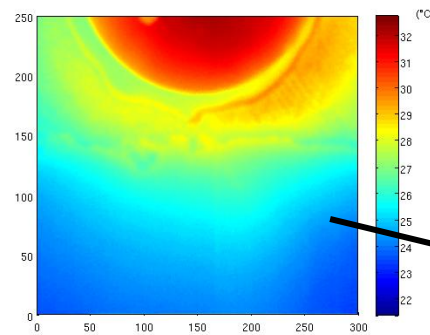
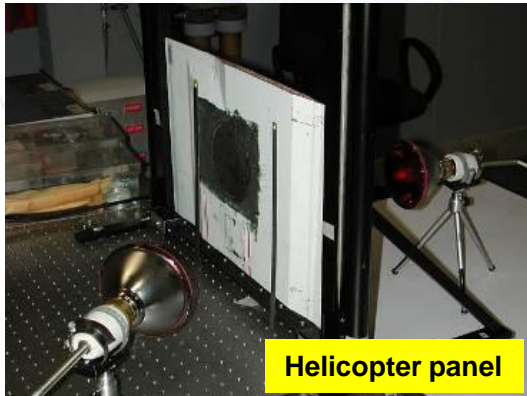
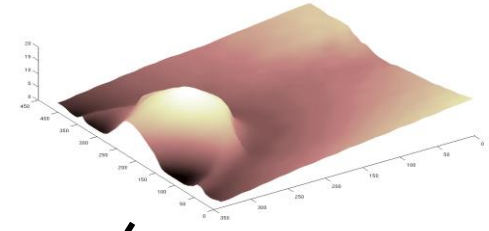
Wrapped phase



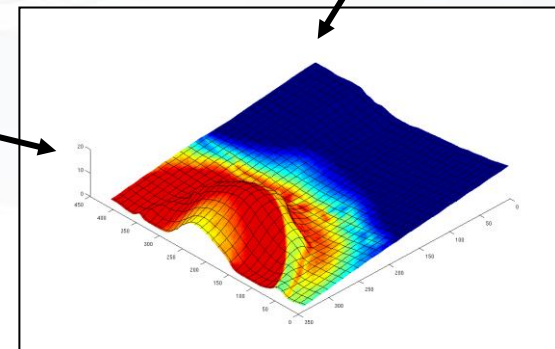
Unwrapped phase

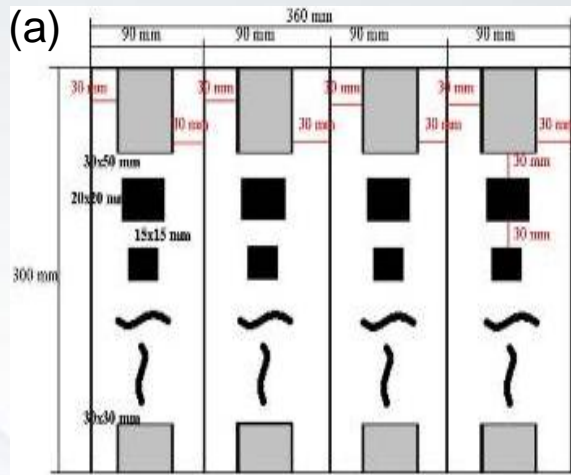


3D plot of deformation

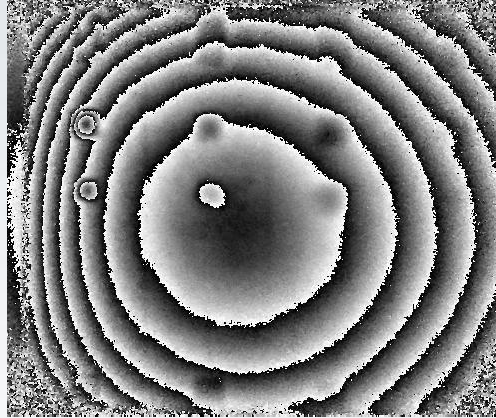


Temperature variation

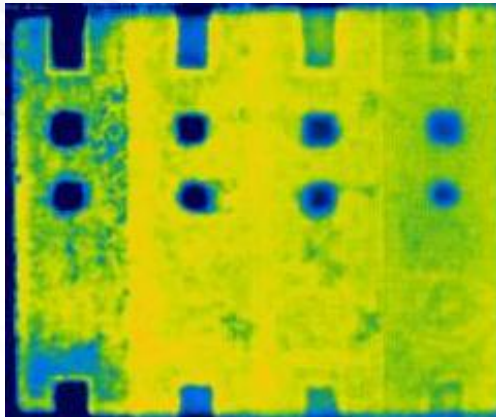
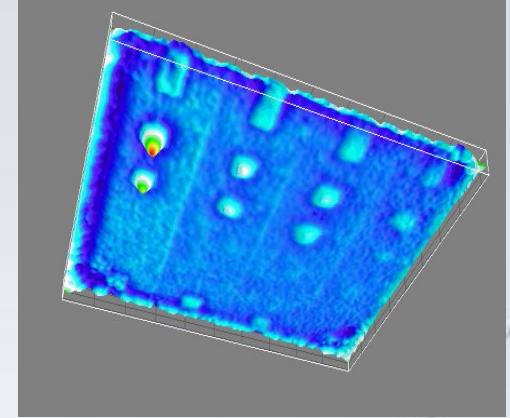




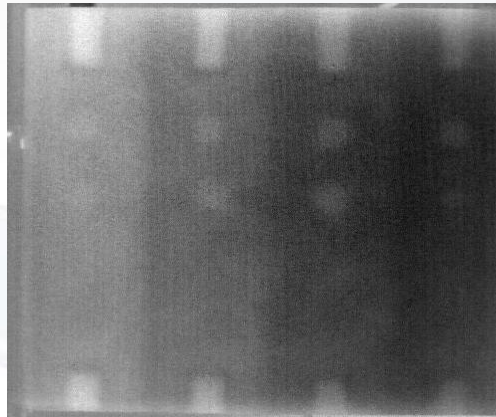
(b) FANTOM interferogram



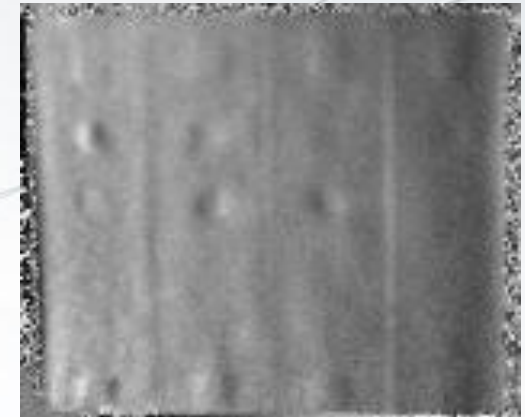
(c) FANTOM deformation



(d) OLT phase thermogram

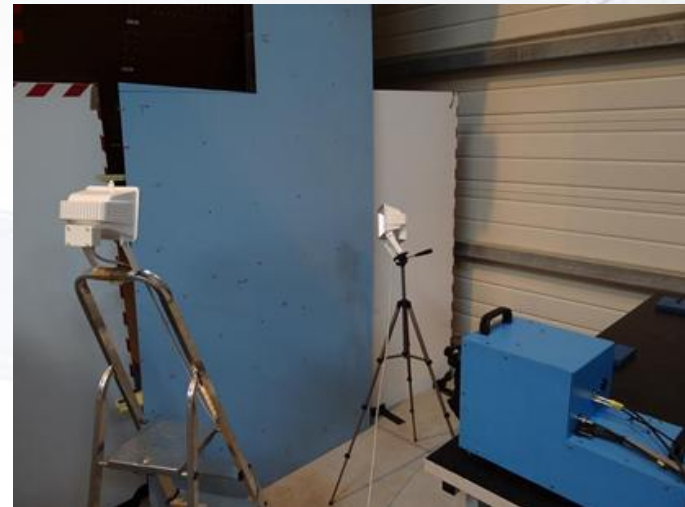
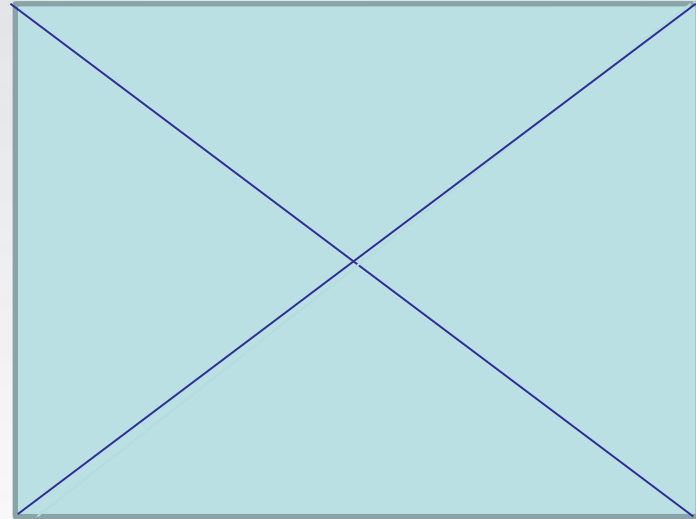
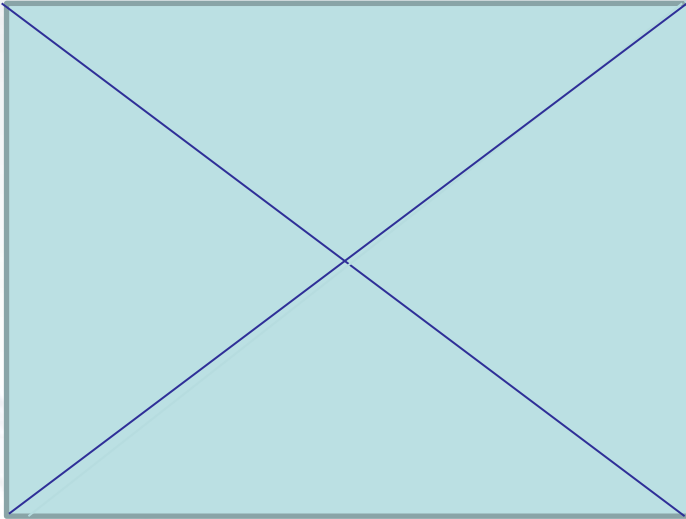


(e) FANTOM thermogram

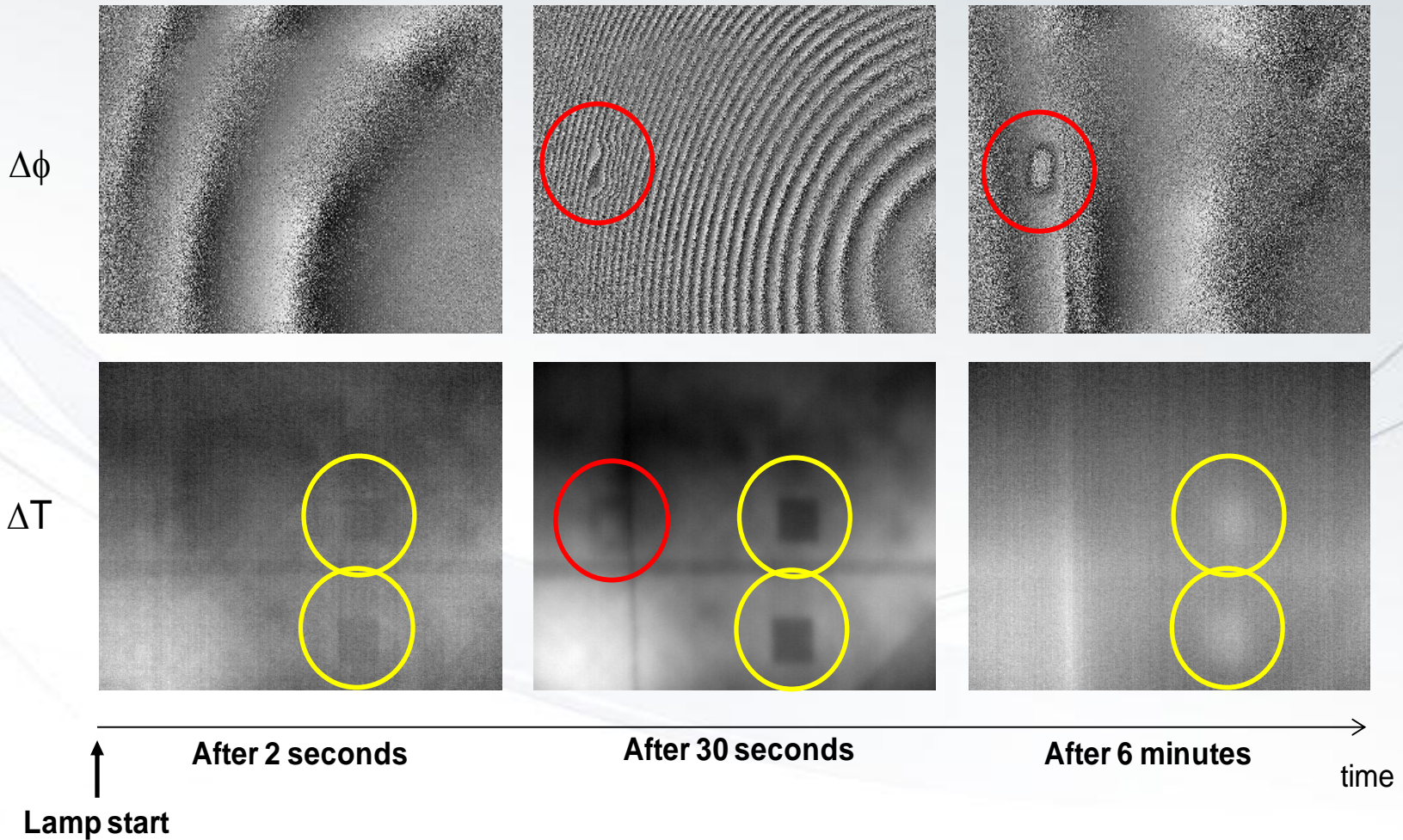


(f) SHEARO deformation

- Validation industrielle: Airbus (D41, Toulouse)



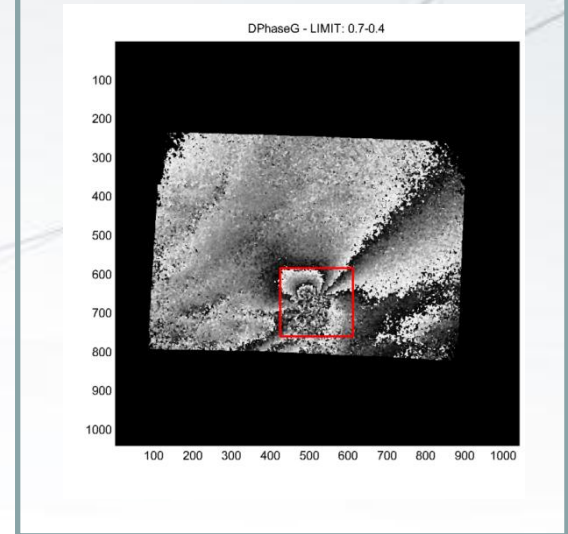
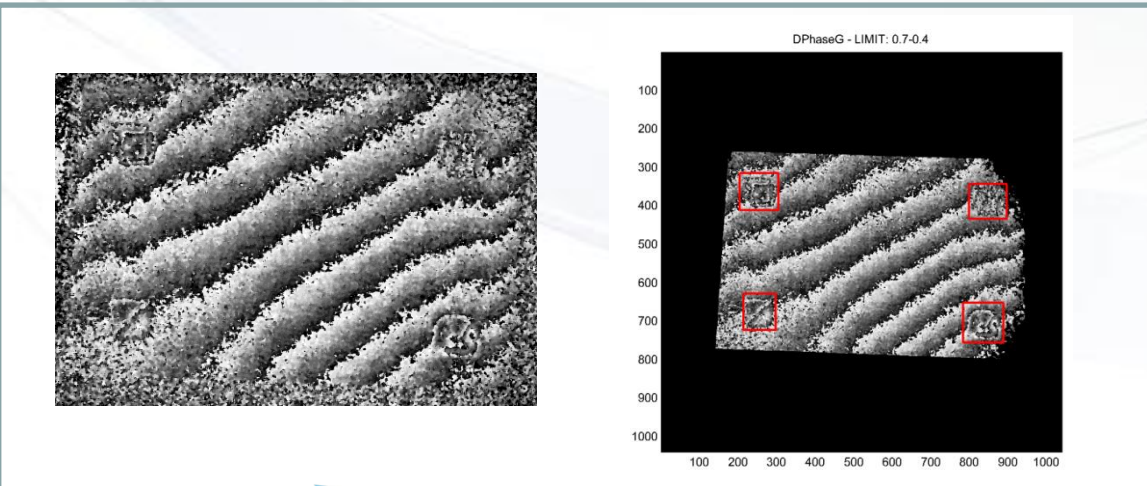
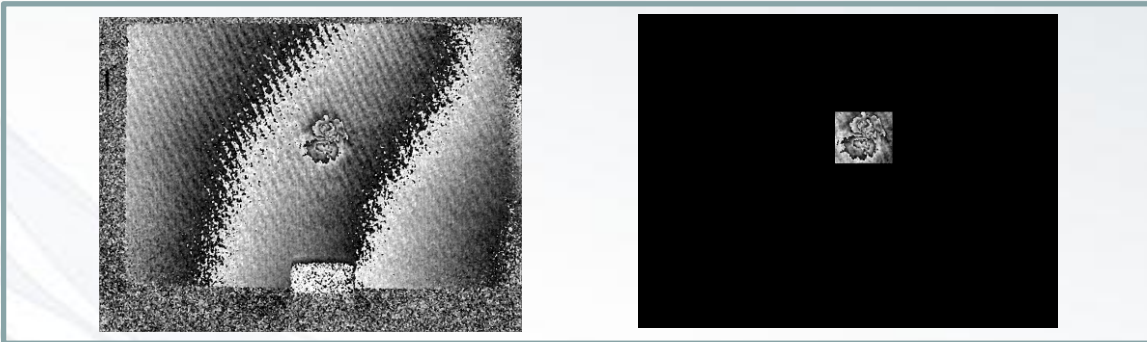
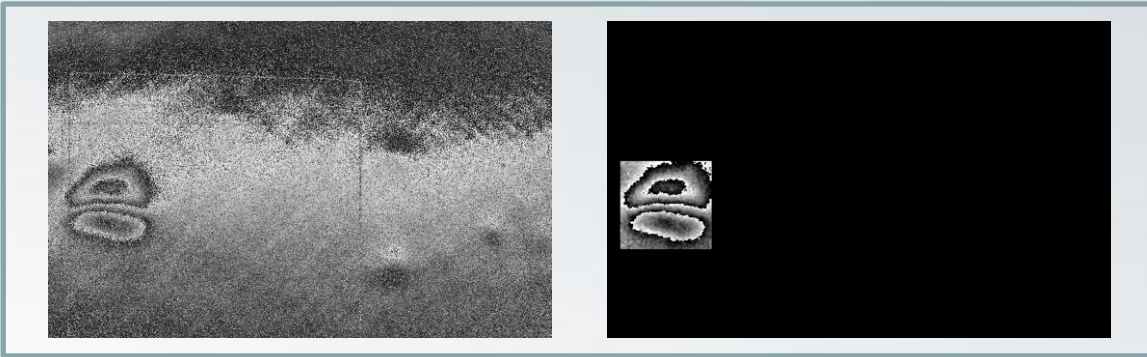
- Défauts dans structure composite



- FANTOM : FP7 (fini Déc 2012)
 - CSL : coordinateur
 - Combinaison Interférométrie de speckle-Thermographie
 - Système portable – NDT chez Airbus

- ECOTAC Phase 2 (2013-2014) : Ultrasons Laser
 - Développement des Ultrasons Laser
 - Sonde TWM, inclus Laser Tapping
 - Bras-robot
 - Poursuites investigations par thermo-shearo

- De-Composit (Région Wallonne – Cwality):
 - Optrion S.A. : développe tête shearo portable
 - CSL : Post-processing pour détection automatique des défauts
 - Délaminages – décollements
 - Inspection aéronautique en maintenance
 - Go/No Go



Le Futur

- Thème à approfondir : Détermination des paramètres de défauts assistée par simulation – Reverse Engineering
- R&D de nouvelles technologies NDT (ex. FANTOM, De-Composit, Ultrasons Laser,...)
- Prestations
- ***Peut-être avec vous ?***

Merci de votre attention !