Infrared Holography : A Combination of Thermography and Holography

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Outline

- The Space Center of Liege
- The lab - Background
- Infrared Holography : Combination with thermography
  - Basic Principles
  - Motivations
  - The FANTOM project
  - Development – Results and Applications
- Infrared Holography : Other projects
- Other activities
- Future projects

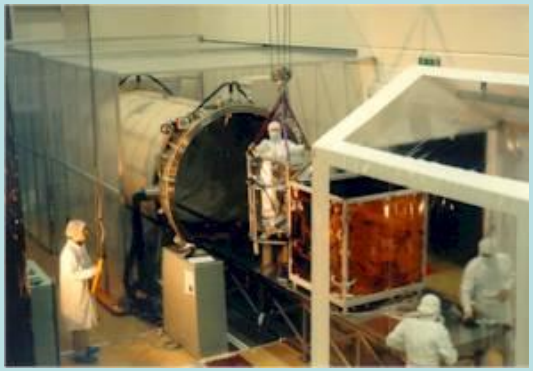
The Space Center of Liege

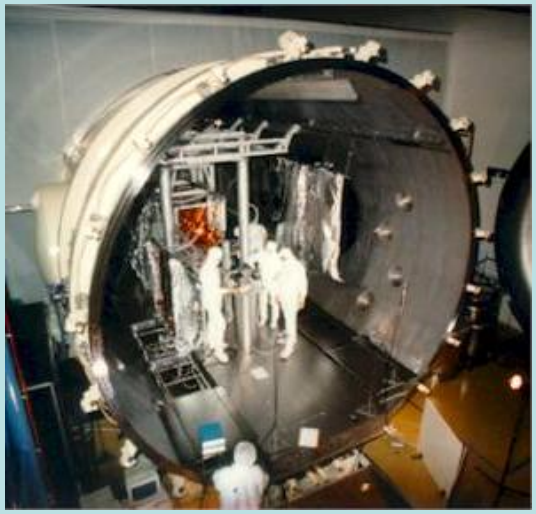
- Research Center of Liege University
- 100 people
  - Engineers/Scientists (2/3)
  - Technicians
  - Administratives
- ***Excellence Center of Optics*** of the European Space Agency (ESA)

The Space Center of Liege

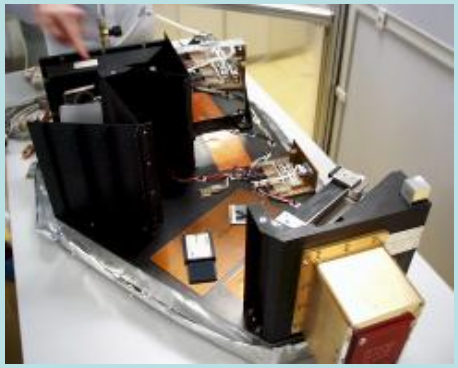
Optics for Space

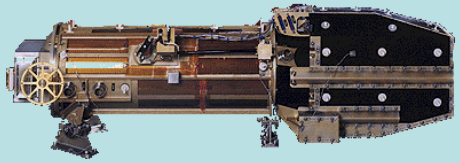
Simulated space environment testing
Large chambers with optical benches





Development of optical
Space instrumentation





Development of
Advanced Technologies

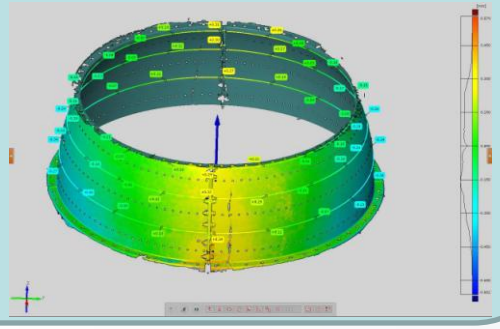
- Vacuum-Cryogeny
- Quality insurance
- Thermal Design
- Signal Processing
- Spaceborne Electronics
- Smart sensors
- Surface processing
- Optical Design
- Optical Metrology
- Non Destructive Testing

The Laser and NDT Lab

The Laser & NDT Lab

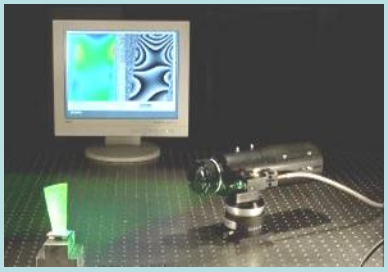
Research in laser and optical metrology and NDT for aerospace

Dimensional measurement
- Fringe projection
- Digital Image Correlation

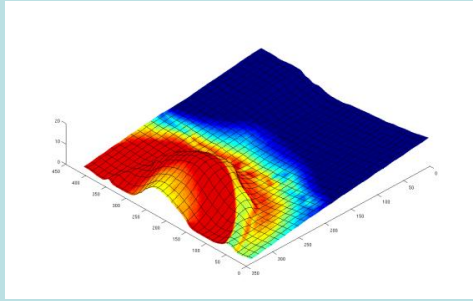


Thermography
- Pulsed + Lock-in

Deformation measurement
- Holography
- Speckle interferometry
- Shearography



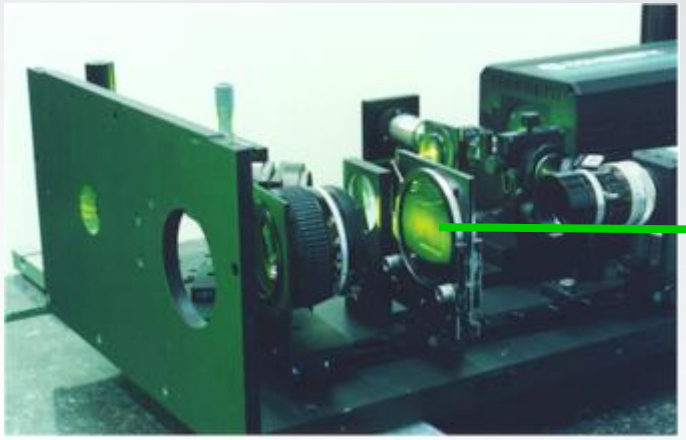
Combined Speckle-Thermography



Laser Ultrasonics

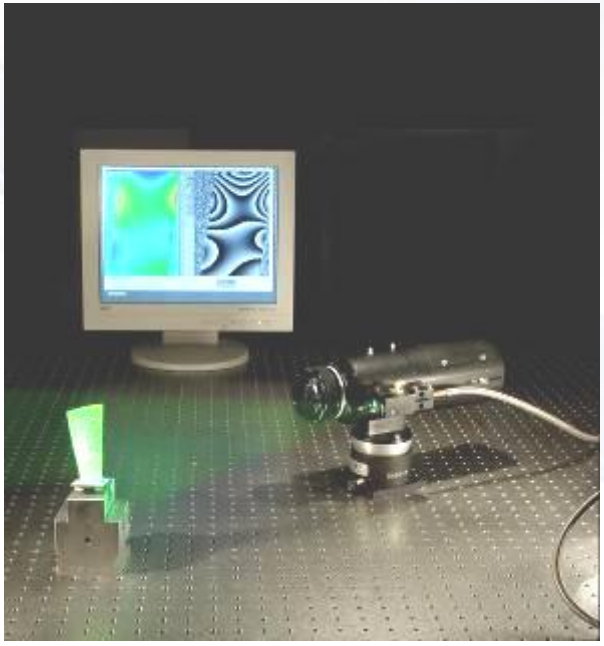
The Laser & NDT Lab

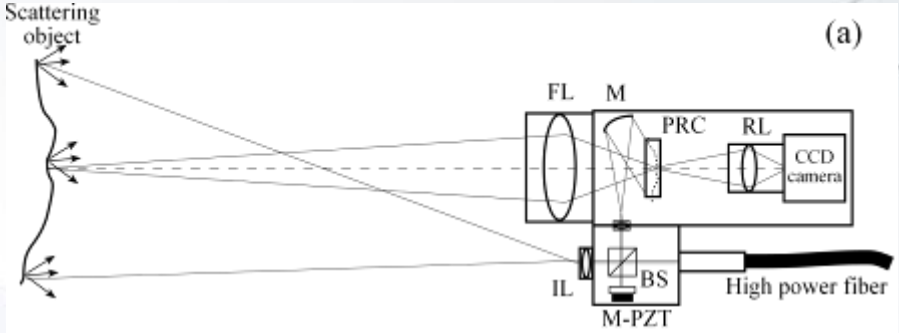
- Early developments in holography with photorefractive crystals



- Self-recording in situ
- Erasable
- Reusable indefinitely

⇒ ***Userfriendly***



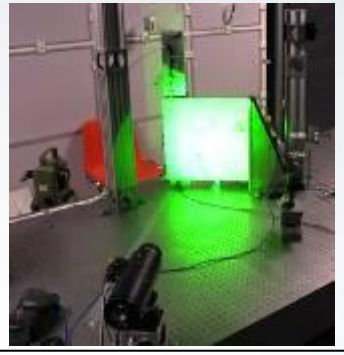


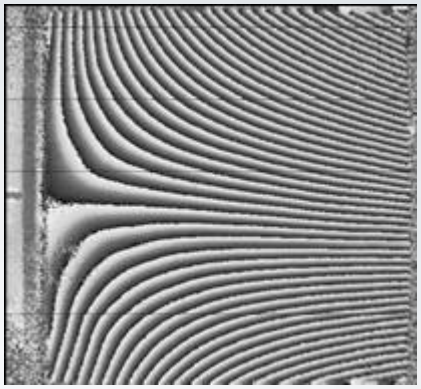
M : Mirror
M-PZT : Mirror on piezotranslator
BS : Beamsplitter
FL : Frontal lens
RL : Relay lens
IL : Illumination lens
PRC : Photorefractive crystal

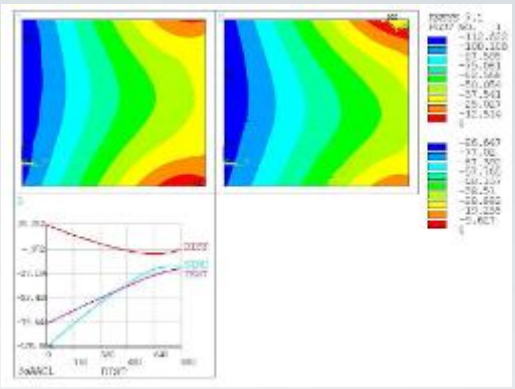
The Laser & NDT Lab

- Applications

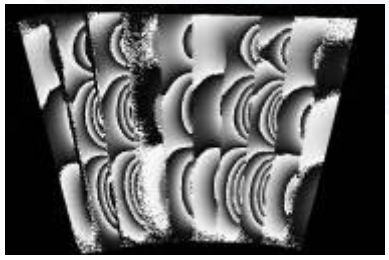
Deformation metrology



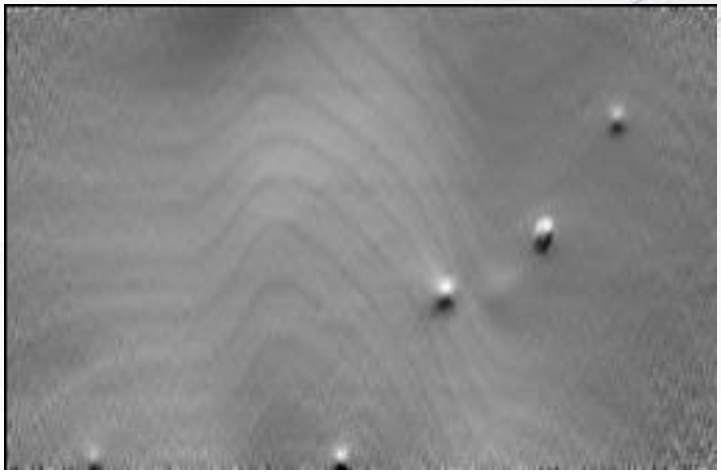




Vibration mode shapes



Defect detection



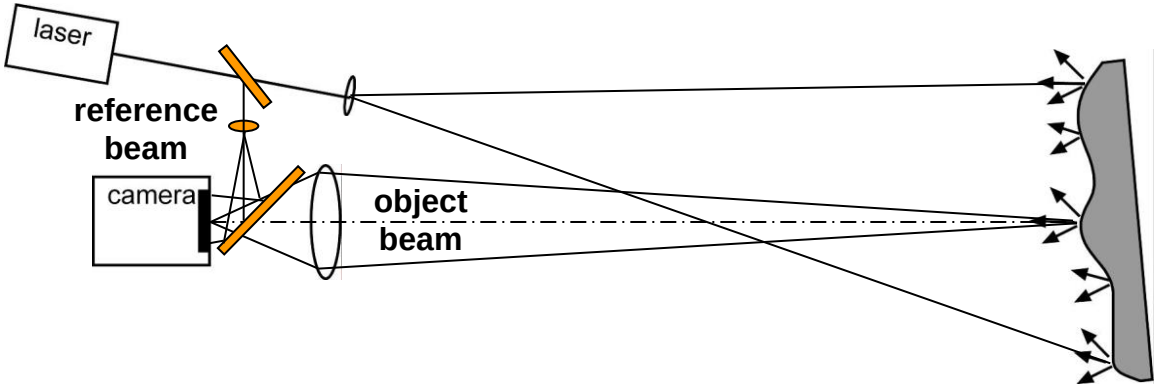
Infrared Holography:

Combination Holography-Thermography

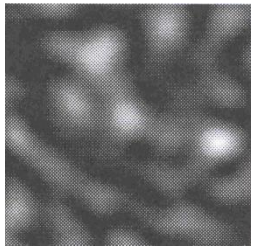
Basic Principles

- Electronic Speckle Pattern Interferometry (ESPI)

  aka : Electronic Holography – TV Holography

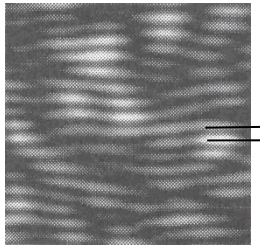


Zoom of recorded intensity pattern (speckles)



Zoom of local interference pattern (specklegram)

$I(x,y)$

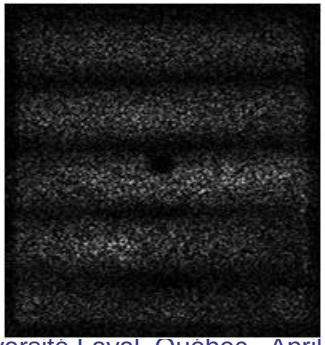


Time t_1 : $I(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos[\varphi(x,y)]$

Time t_2 : $I'(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos[\varphi(x,y) + \Delta\varphi(x,y)]$

λ ***laser wavelength***

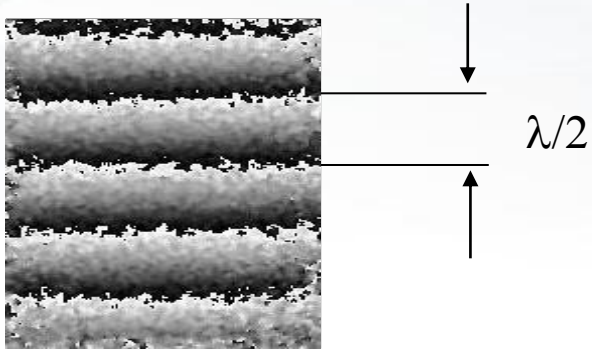
$$|I - I'|(x,y) \div \sin\left[\frac{\Delta\varphi(x,y)}{2}\right]$$



$$\Delta\varphi(x,y) = \frac{2\pi}{\lambda} d(x,y)$$

d(x,y): displacement field

Phase Map $\Delta\varphi(x,y)$



Basic Principles

Phase-shifting principle

$$I_1(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos[\varphi(x,y)]$$

$$I_2(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos\left[\varphi(x,y) + \frac{\pi}{2}\right]$$

$$I_3(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos\left[\varphi(x,y) + \frac{2\pi}{2}\right]$$

$$I_4(x,y) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos\left[\varphi(x,y) + \frac{3\pi}{2}\right]$$

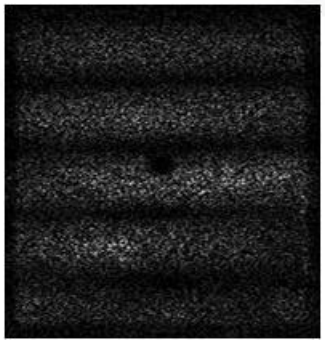
$$\varphi(x,y) = \tan^{-1}\left[\frac{I_4 - I_2}{I_1 - I_3}\right]$$

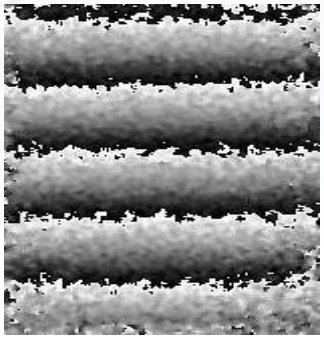
$$\{I_k(x,y)\}_{k=1,2,3,4} \Rightarrow \varphi(x,y)$$

$$\{I'_k(x,y)\}_{k=1,2,3,4} \Rightarrow \varphi'(x,y)$$

$$\Rightarrow \Delta\varphi(x,y) = \varphi(x,y) - \varphi'(x,y)$$

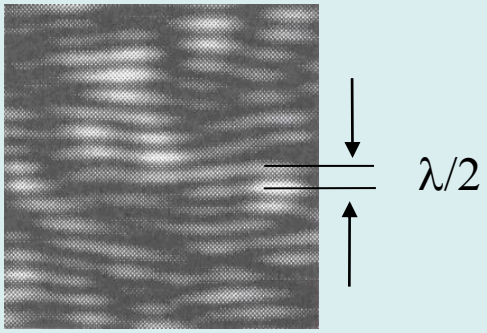
Phase Map $\Delta\varphi(x,y)$





Motivation of using LWIR

Zoom of local interference pattern (specklegram)



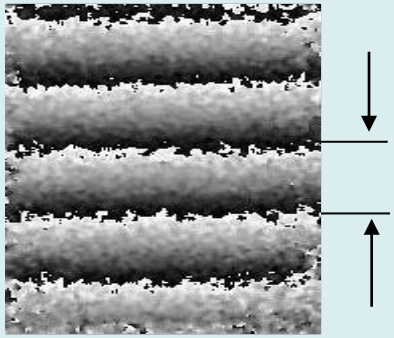
Pattern must be stable during recording (depends on frame rate)

Set-up stability criterion : < λ/10

Visible lasers : stability better than **50 nm**

Phase map / displacement field

$\Delta\varphi(x,y)$



Measurement range ⟺ Number of fringes

Visible lasers : range = **50 nm – 10 µm**

CO2 laser

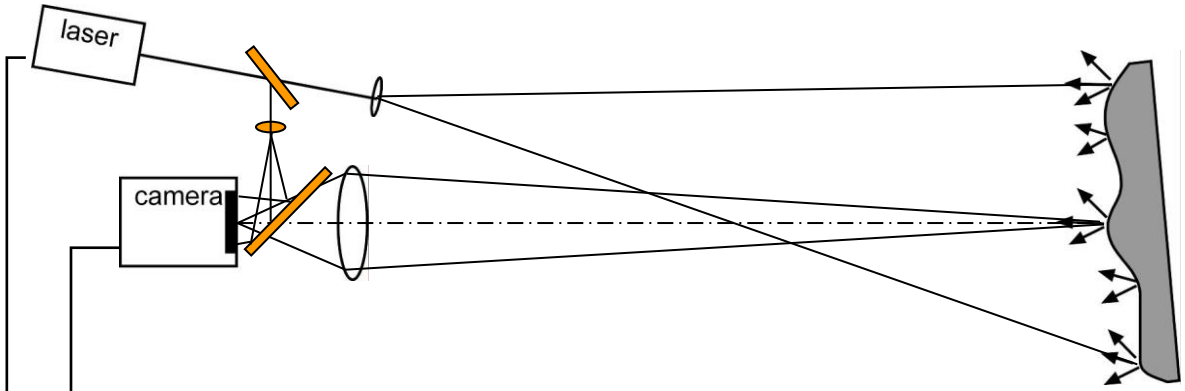
λ=10 µm

(LWIR range)

stability can be only **1 µm**

range = **1 µm – 200 µm**

LWIR Speckle Interferometry



Usually applied in the visible range

λ = 400-700 nm

In the LWIR range

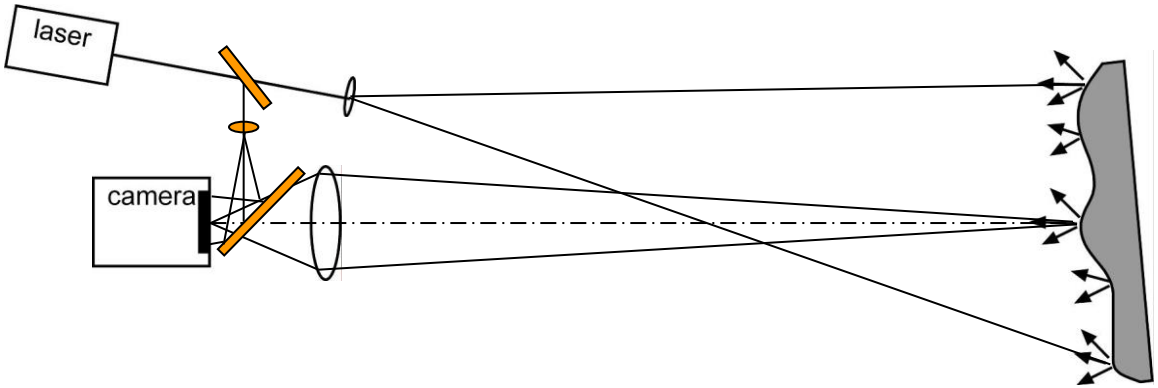
LWIR Thermographic camera (Microbolometer array)

λ = 8-14 µm

CO2 laser

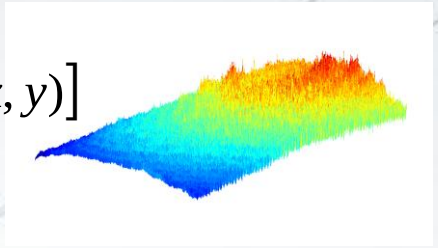
λ = 10 µm

LWIR Speckle Interferometry



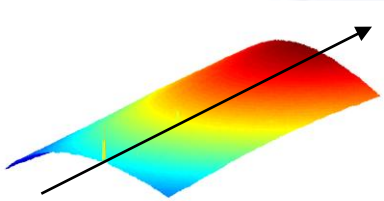
Single sensor
Simultaneous measurement of
- **Temperature variation**
- **Deformation**

$$I_1(x,y) = I_{Thermal}(x,y) + I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\cos[\varphi(x,y)]$$

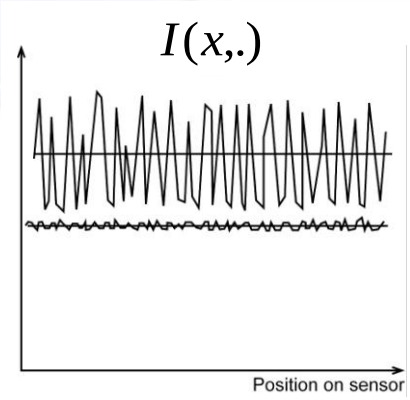


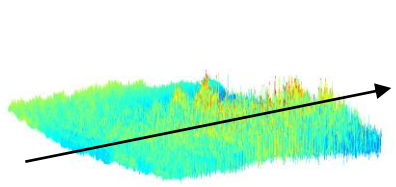
Laser **ON**

Laser **OFF**



Thermal background





Hologram/Specklegram

New concept = FANTOM project

Single sensor
Simultaneous measurement of
- **Temperature variation**
- **Deformation**

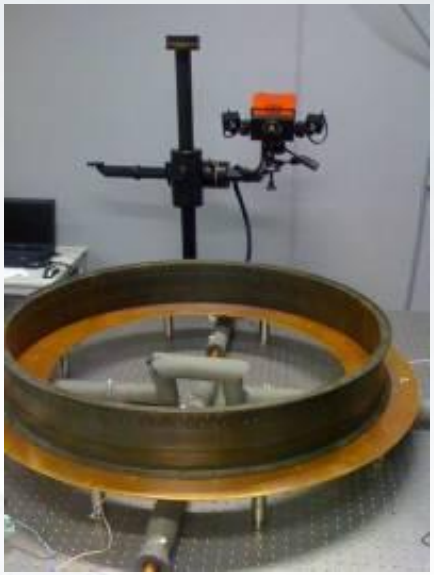
Grant : ACP7-GA-2008-213457
Start 2009 – End 2012

FANTOM : Full-Field Advanced Non-Destructive Technique for Online Thermo-Mechanical Measurement on Aeronautical Structures

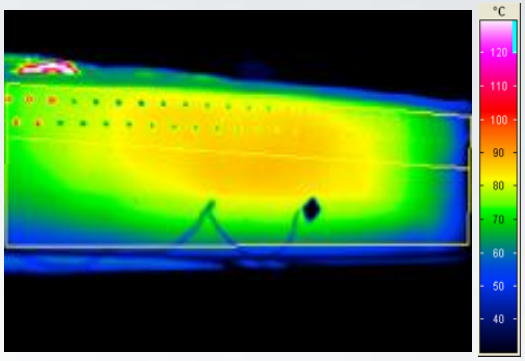
Partner	Country	Profile
Centre Spatial de Liège Université de Liège		Coordinator – University Research Centre Development/application of non destructive testing techniques
Institut für Technische Optik Universität Stuttgart		University Research Centre Specialist of Holography
InfraTec GmbH		SME – Development of Thermography system and applications
Centro de Tecnologias Aeronauticas		Research Centre Specialist of Non Destructive Testing – Structural Tests
Optrion S.A.		SME – Development of Holography system and applications
Innov Support		SME – Servicing partner

Potential applications

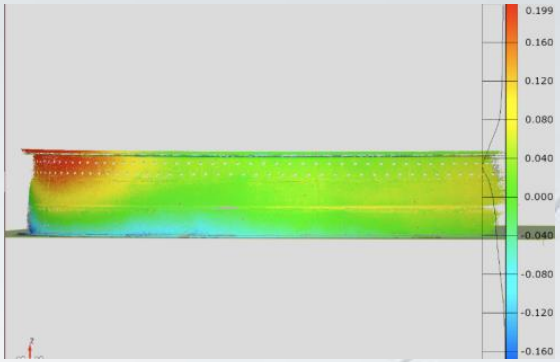
Thermo-mechanical deformation of aeronautics composite structures



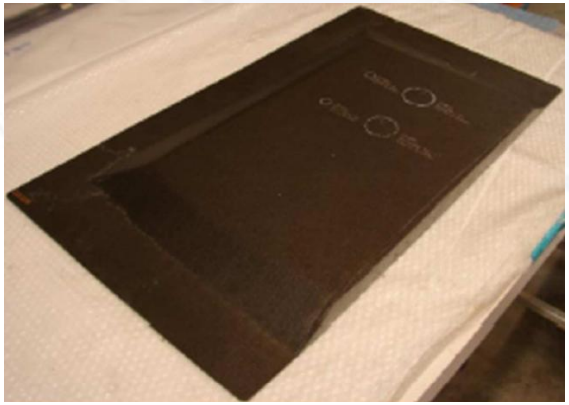
Thermography :
Temperature Measurement



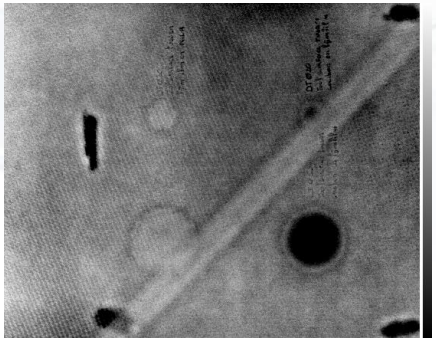
Fringe Projection method :
Global deformation



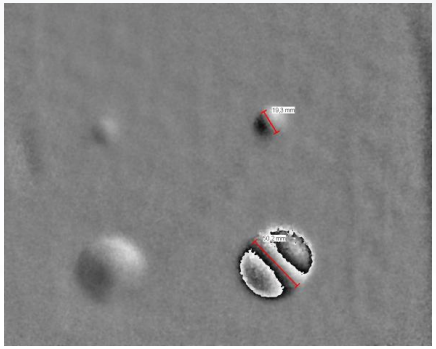
Defect detection in aeronautics composite structures



Thermography :
Local Temperature change

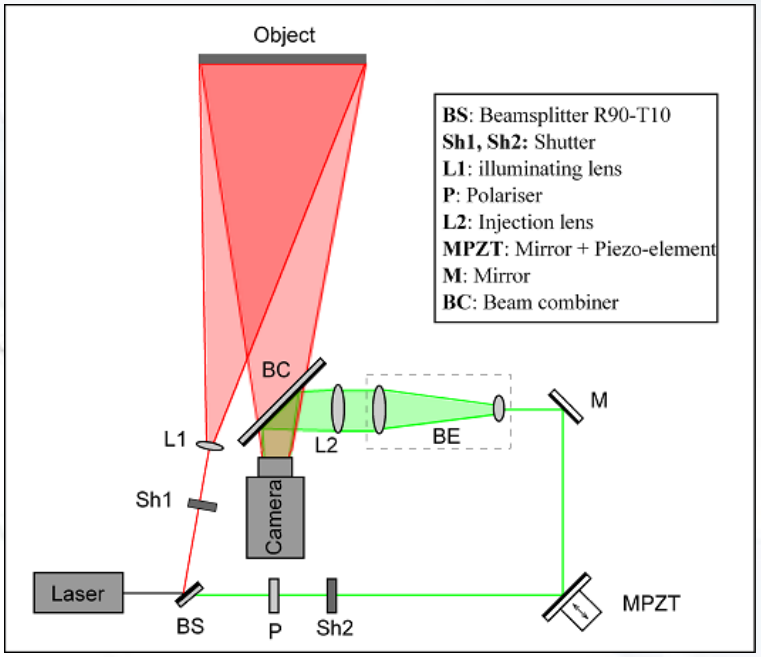


Speckle interferometry -
Shearography :
Local deformation

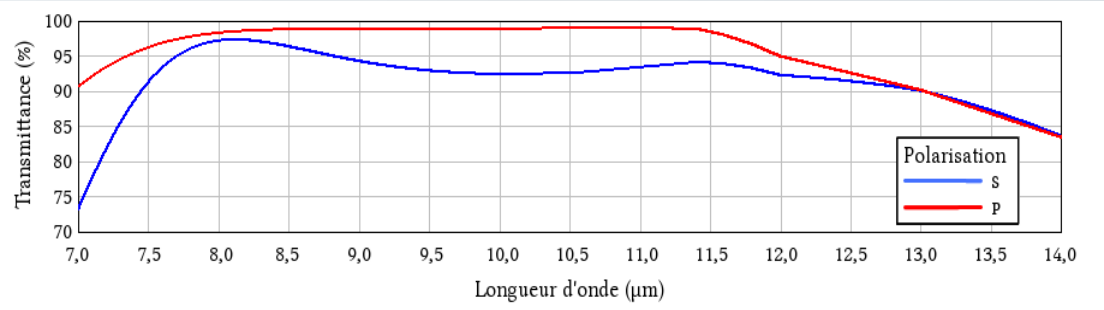


FANTOM sensor development

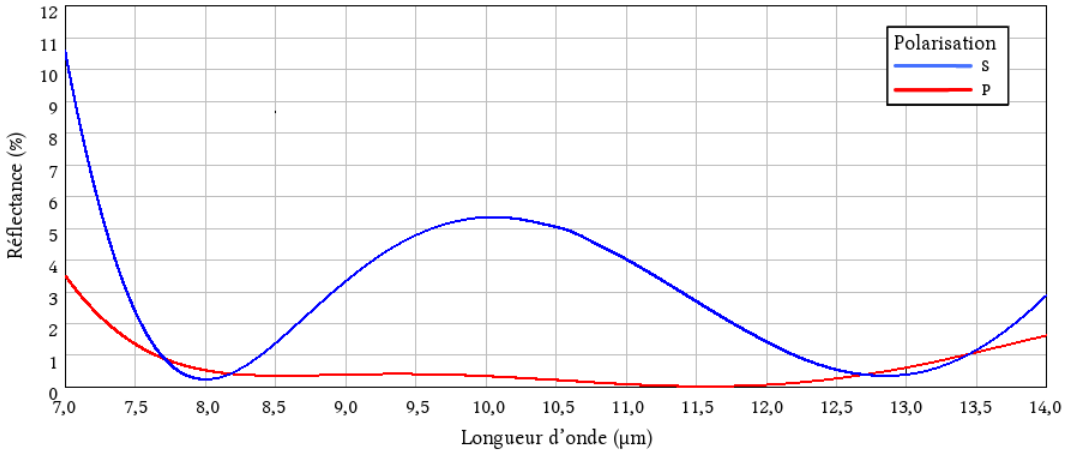
Beam combiner characteristics



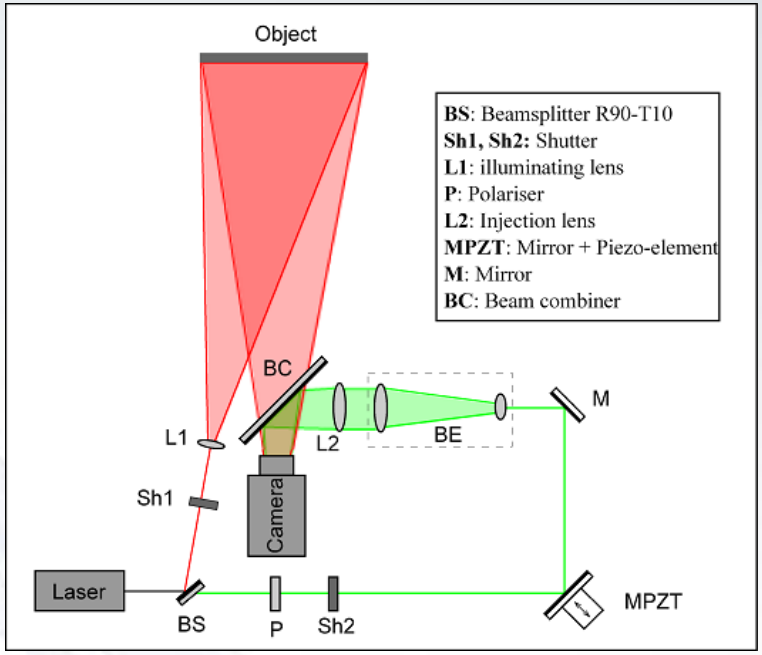
Transmittance



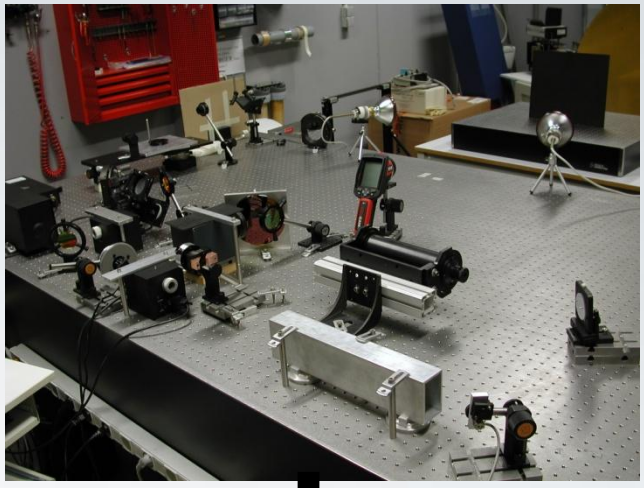
Reflectance



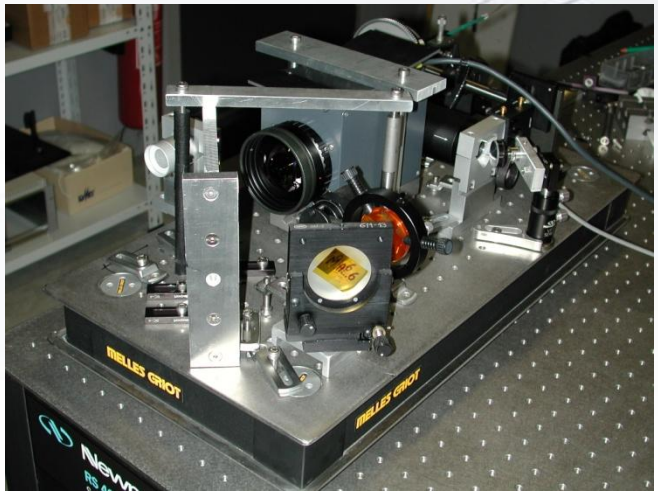
FANTOM sensor development



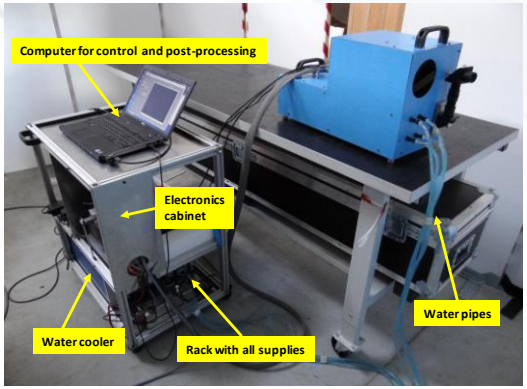
Laboratory set-up



Laboratory compact prototype

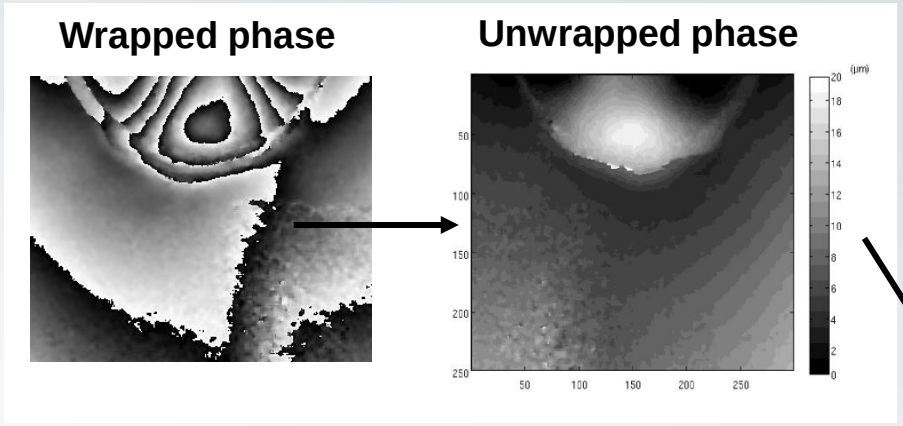


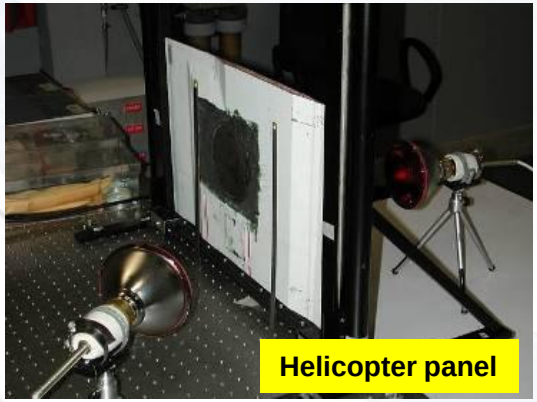
Transportable field prototype

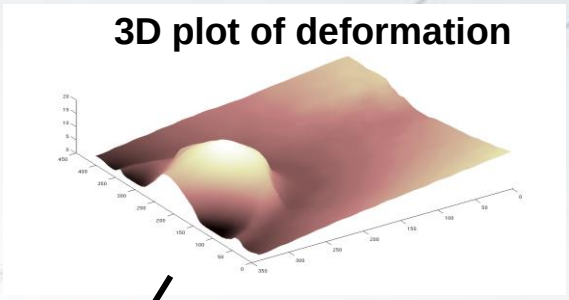


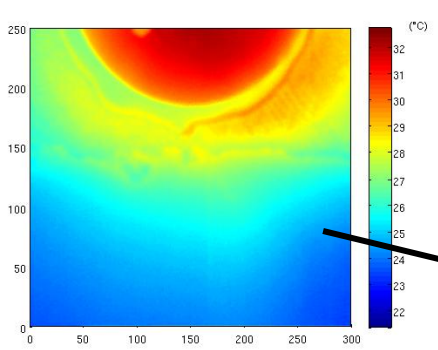
Proof of Concept

- Decoupling temperature and deformation

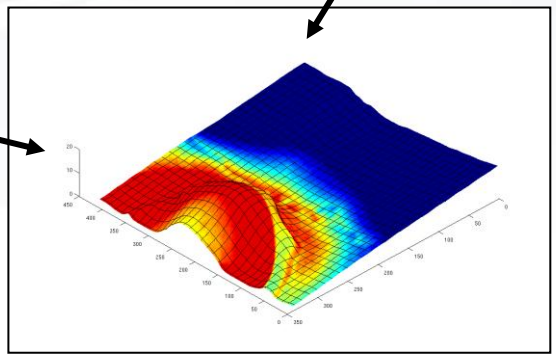








Temperature variation



Processing

Phase-shifting principle

$$\begin{cases} I_1 = I_{Therm} + I_R + I_O + 2\sqrt{I_R I_O}\cos[\varphi] \\ I_2 = I_{Therm} + I_R + I_O + 2\sqrt{I_R I_O}\cos\left[\varphi + \frac{\pi}{2}\right] \\ I_3 = I_{Therm} + I_R + I_O + 2\sqrt{I_R I_O}\cos\left[\varphi + 2\frac{\pi}{2}\right] \\ I_4 = I_{Therm} + I_R + I_O + 2\sqrt{I_R I_O}\cos\left[\varphi + 3\frac{\pi}{2}\right] \end{cases}$$

Deformation (phase map)

$\{I_k\}_{k=1,2,3,4}$

$\{I'_k\}_{k=1,2,3,4}$

$$\varphi = \tan^{-1}\left[\frac{I_4 - I_2}{I_1 - I_3}\right] \rightarrow \begin{cases} \varphi \\ \varphi' \end{cases}$$

$$\Delta\varphi = \varphi - \varphi'$$

Temperature variation

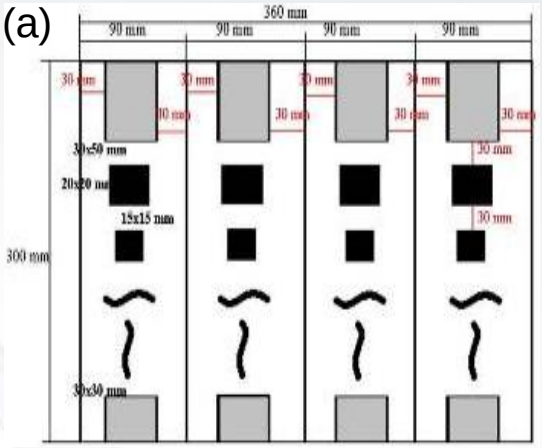
$$I_{Therm} = \frac{I_1 + I_2 + I_3 + I_4}{4} - I_R - I_O \rightarrow \begin{cases} I_{Therm} \\ I'_{Therm} \end{cases}$$

$$\Delta I = I_{Therm} - I'_{Therm}$$

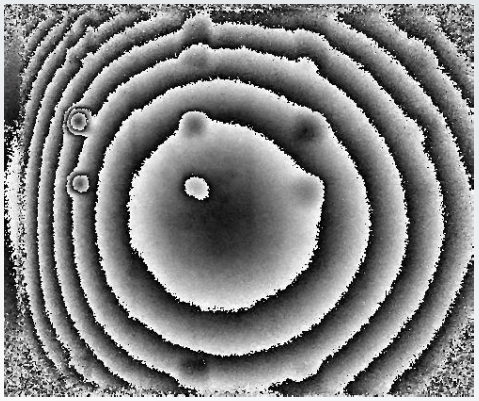
Applications

- Defect detection

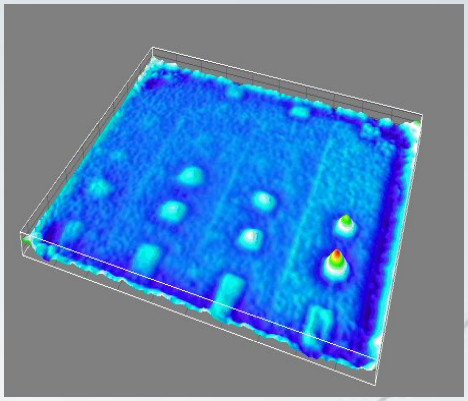
(a)

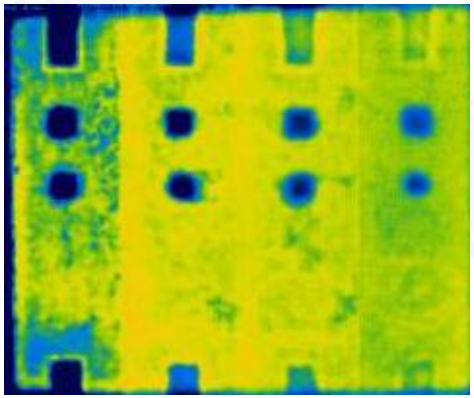


(b) FANTOM interferogram

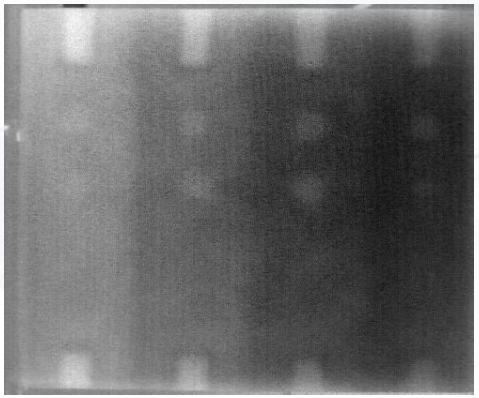


(c) FANTOM deformation

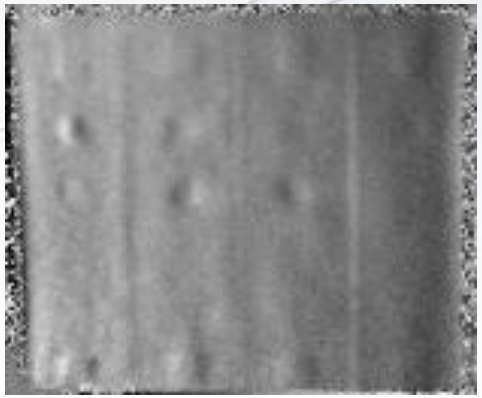




(d) OLT phase thermogram



(e) FANTOM thermogram

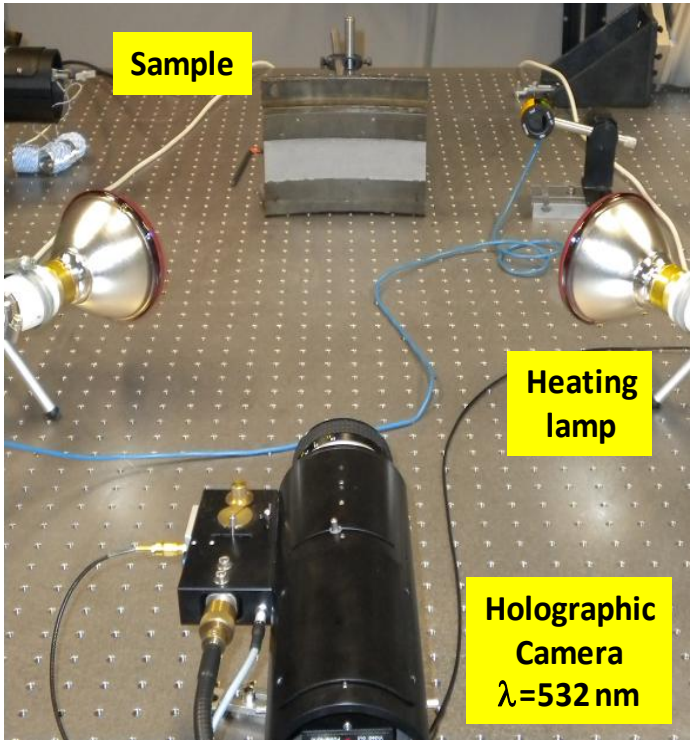


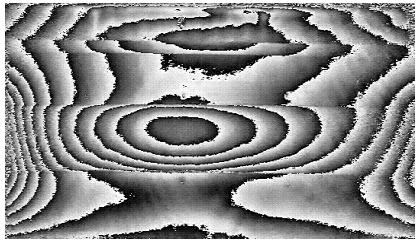
(f) SHEARO deformation

Applications

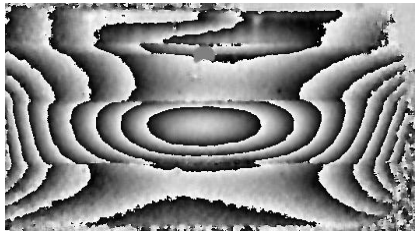
- Thermo-mechanical analysis

(a)

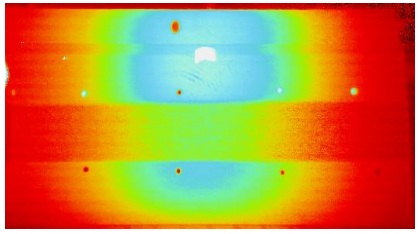




(b) Holographic Interferometry Deformation λ=532 nm



(c) FANTOM Deformation λ=10.6 µm

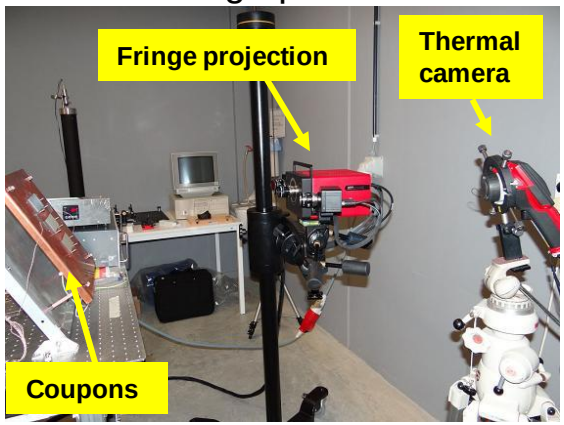


(d) FANTOM Thermogram

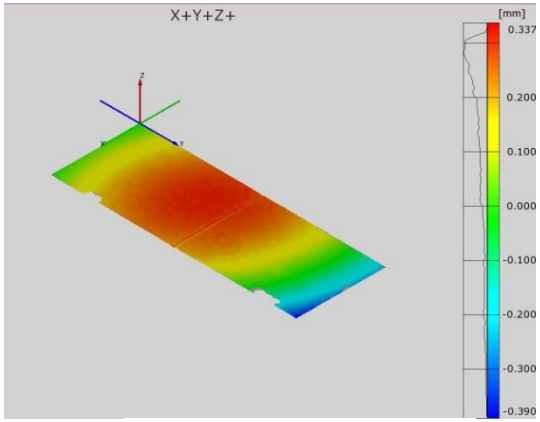
Applications

- Thermo-mechanical analysis

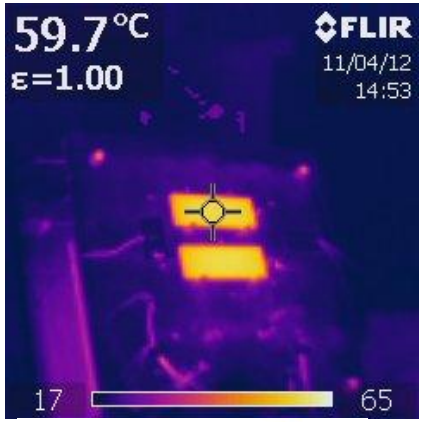
(a) Fringe projection + Thermographic camera

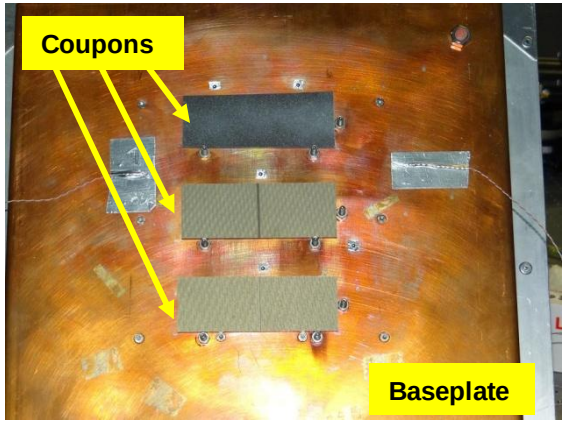


(b) Fringe projection deformation

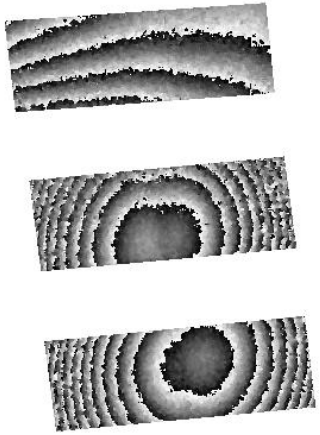


(c) Thermogram

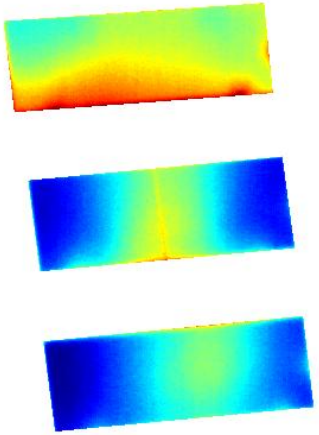




(d) Coupons on heating baseplate



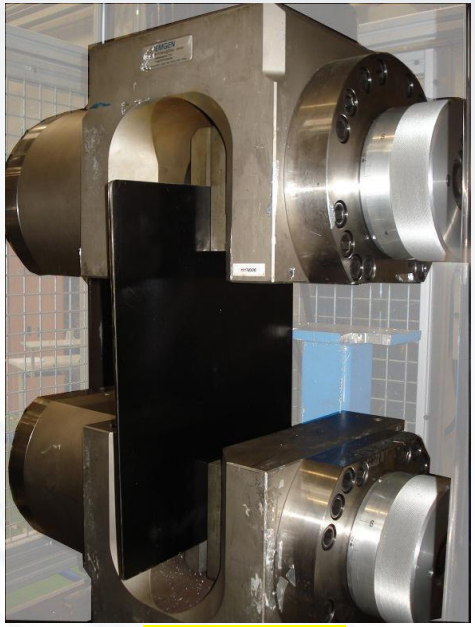
(e) FANTOM deformation



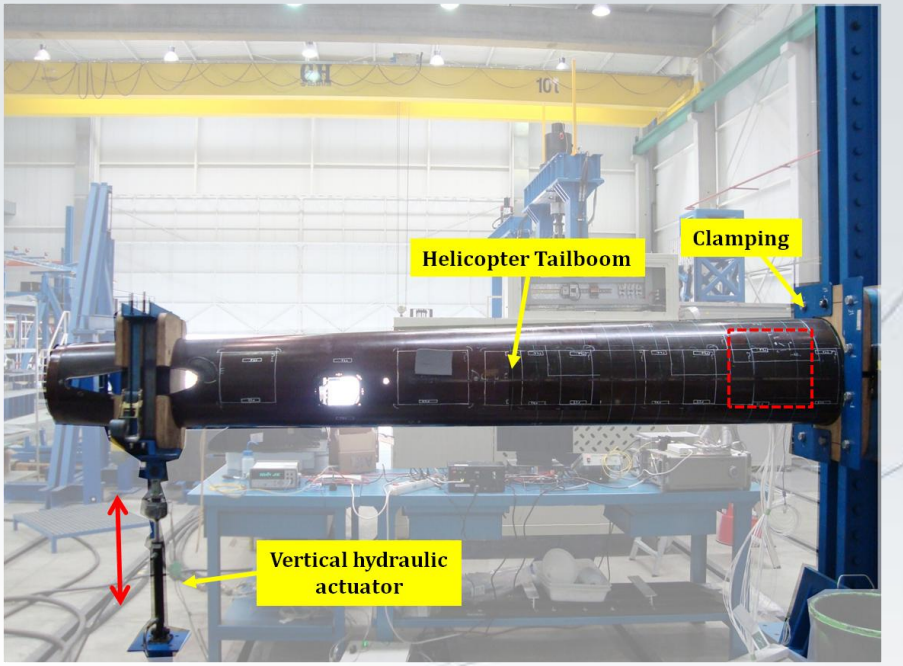
(f) FANTOM thermogram

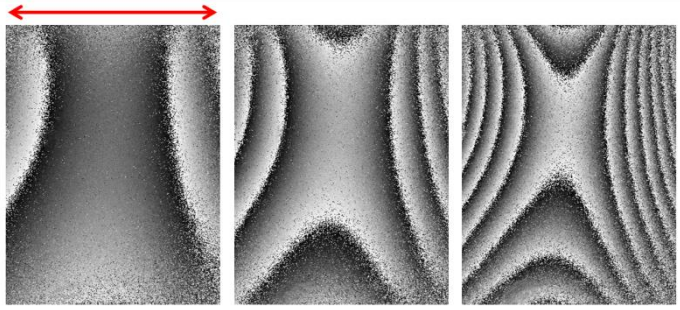
Applications

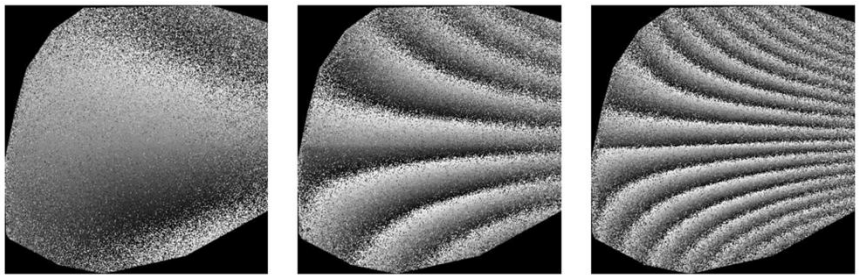
- On-site measurements : CTA plant, Vitoria (Spain)



Tensile Test







Applications

- On-site measurements : Airbus D41 plant, Toulouse

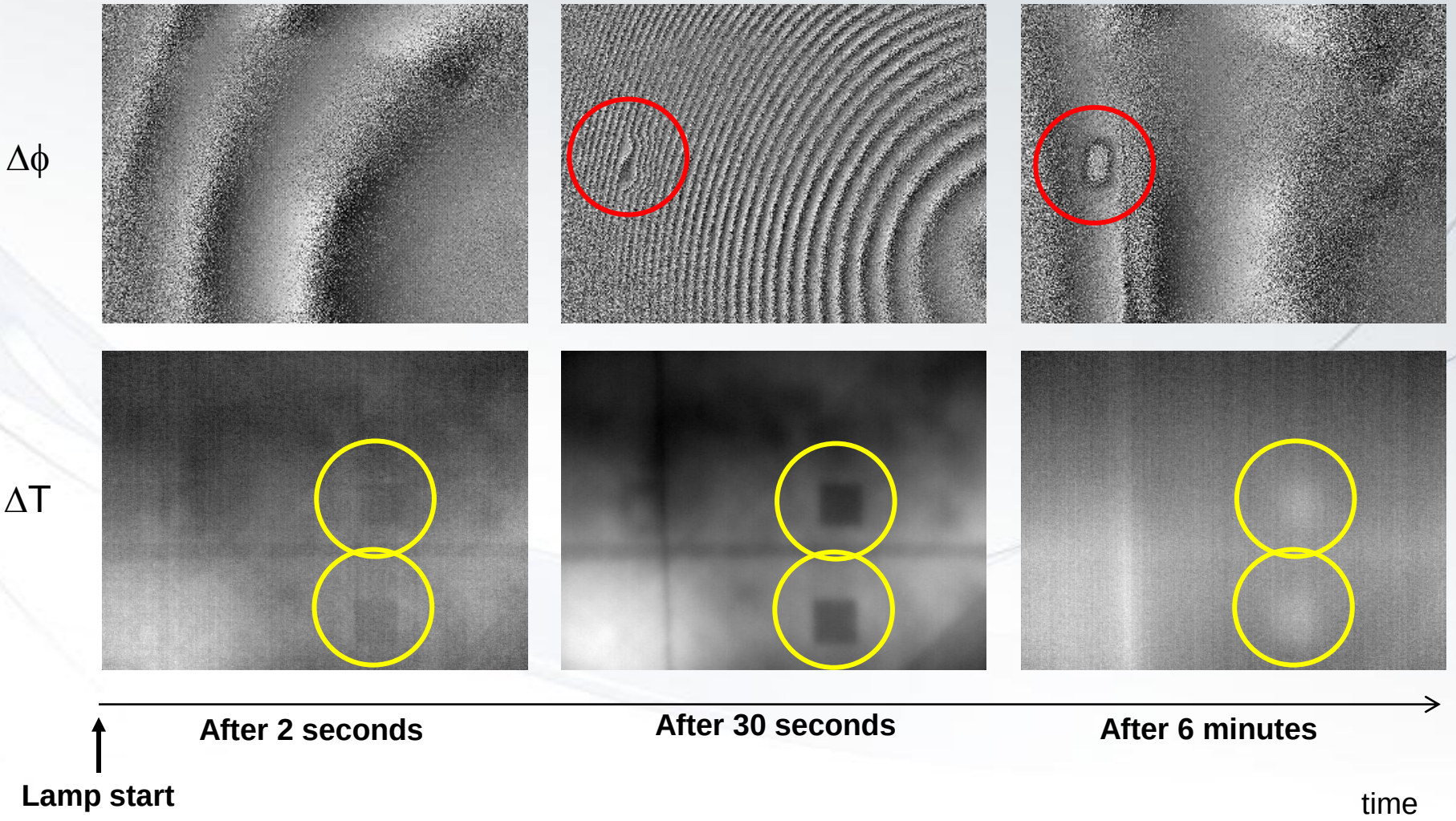

Airbus D41 « Tear Down »


« All Composite Aircraft » A350 Fuselage

FANTOM industrial prototype

Applications

- On-site measurements



Infrared Holography :

Other Projects

Current project : A.O.C.

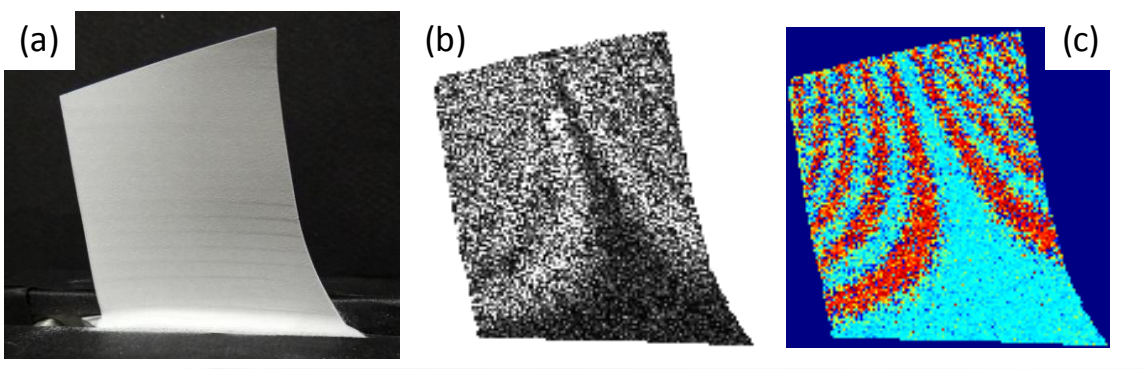
- Vibration measurements with FANTOM

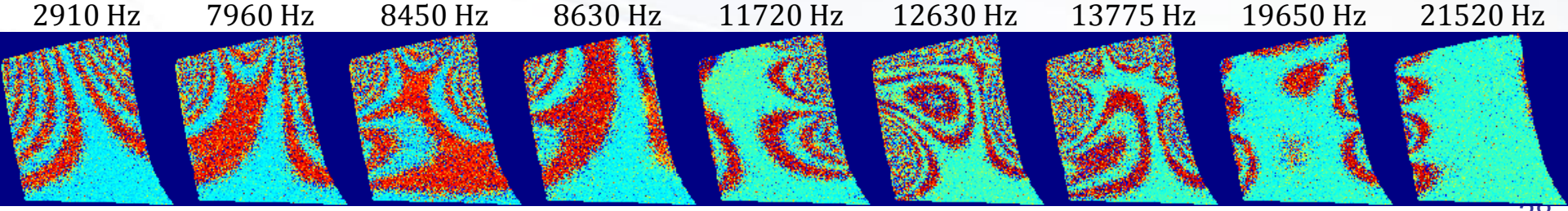
$$I(x,y,t) = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\,\cos\left[\varphi(x,y) + \Delta\varphi(x,y,t)\right]$$

$$\boxed{\Delta\varphi(x,y,t) = \frac{2\pi}{\lambda}\,d(x,y,t) = \frac{2\pi}{\lambda}\,\varphi_A(x,y)\sin(\omega t)}$$

Averaged intensity: $$\left\langle I(x,y,t)\right\rangle = I_R(x,y) + I_O(x,y) + 2\sqrt{I_R(x,y)I_O(x,y)}\,\cos\left[\varphi(x,y)\right] J_0\left(\varphi_A\right)$$

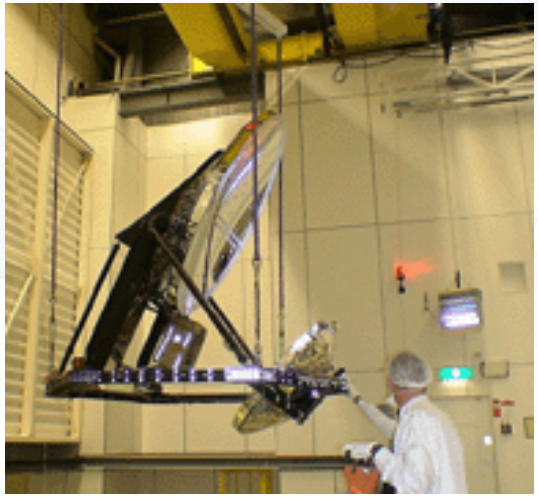
Real-time Speckle Interferometry $$I = I_{rest}(t_0) - \left\langle I(x,y,t)\right\rangle = 2\sqrt{I_R(x,y)I_O(x,y)}\,\cos\left[\varphi(x,y)\right]\left[1 - J_0\left(\varphi_A\right)\right]$$





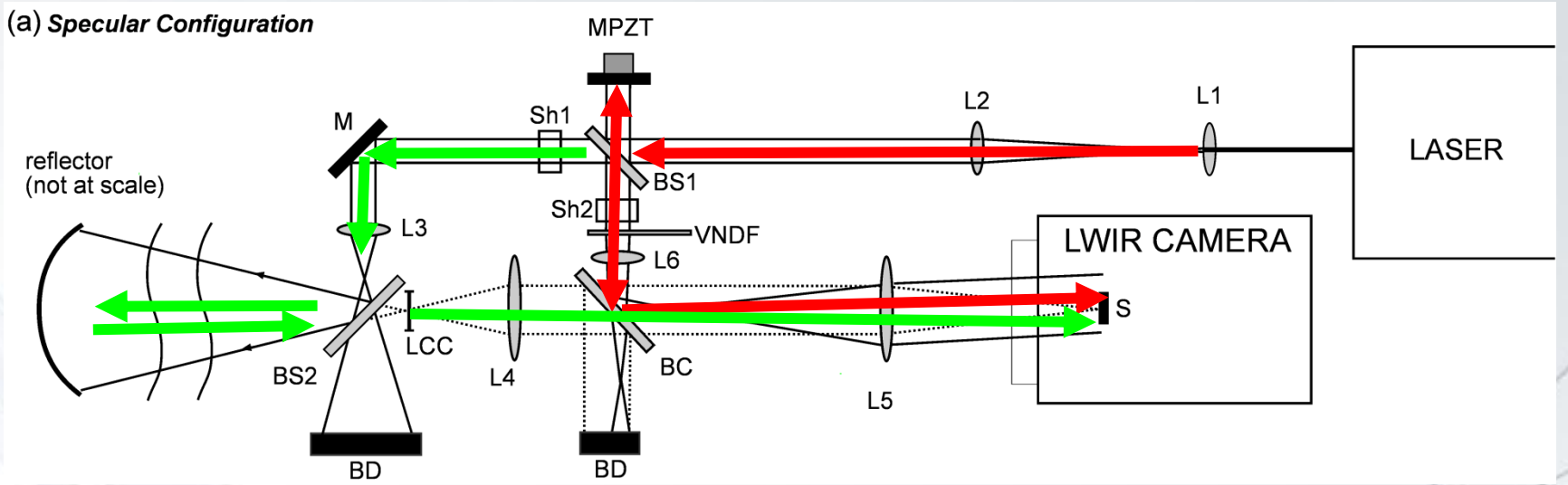
Past project : HOLODIR

- Infrared digital holography for space structures
- ESA and other space agencies need:
  - Full-field **deformations** of reflectors in vacuum-thermal testing
  - Large reflectors: up to 4 m diameter
  - Range of deformations: 1 µm – 250 µm



Past project : HOLODIR

- Infrared digital holography for space structures



Herschel demo reflector

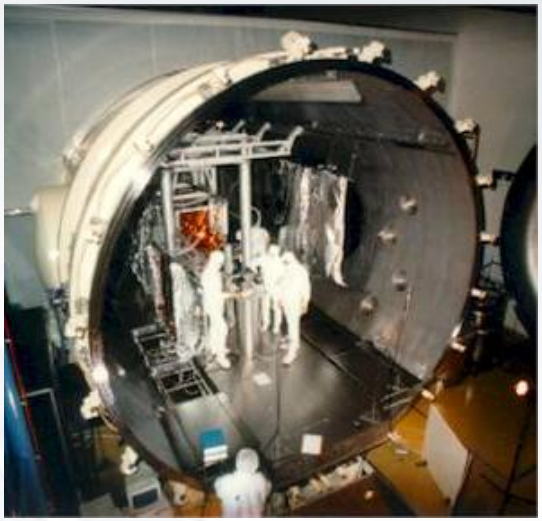
Diameter: 1.1 m
Focal Length: 1.58 m

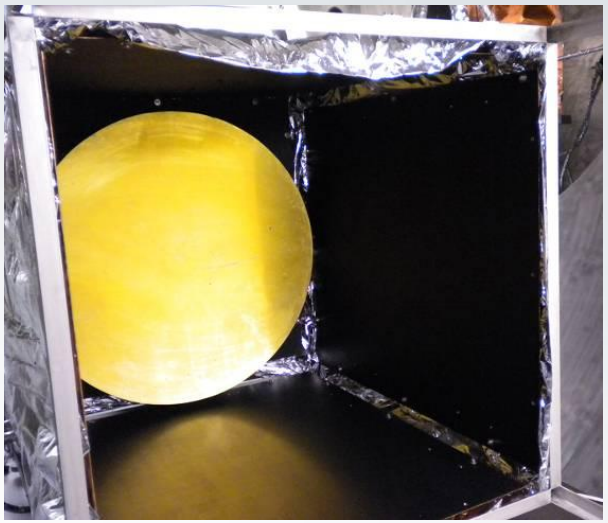
In-line Digital Holographic Interferometry

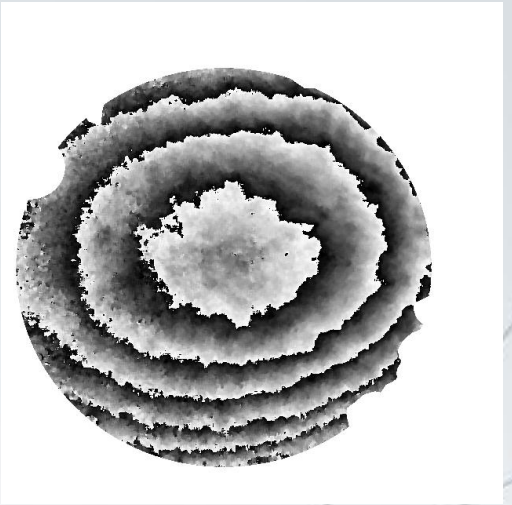
- Higher lateral resolution than Off-Axis DH
- Phase-shifting for removing overlapping orders
- Slow deformation phenomena

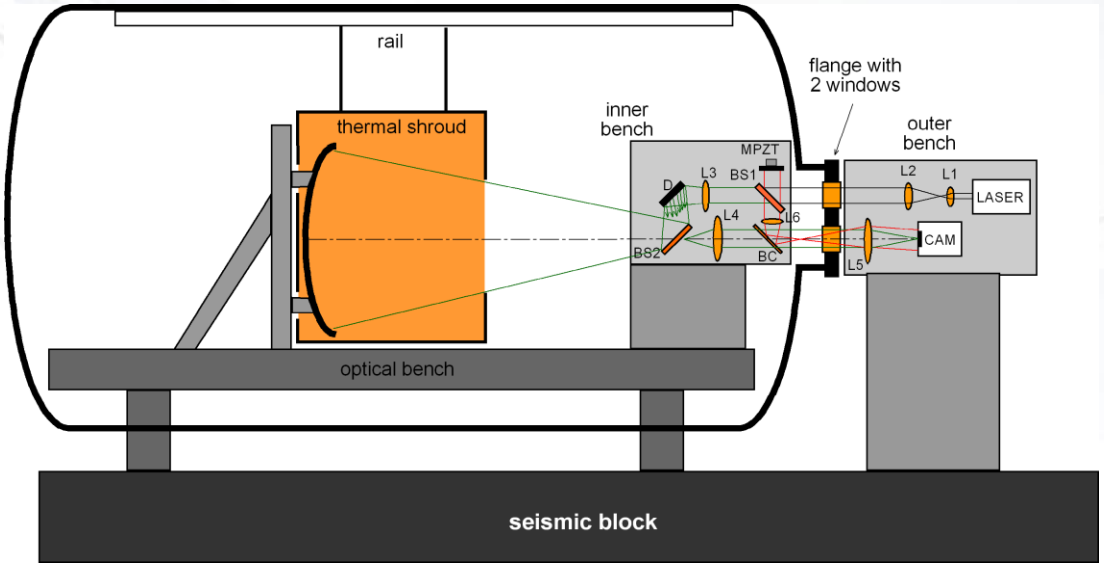
Past project : HOLODIR

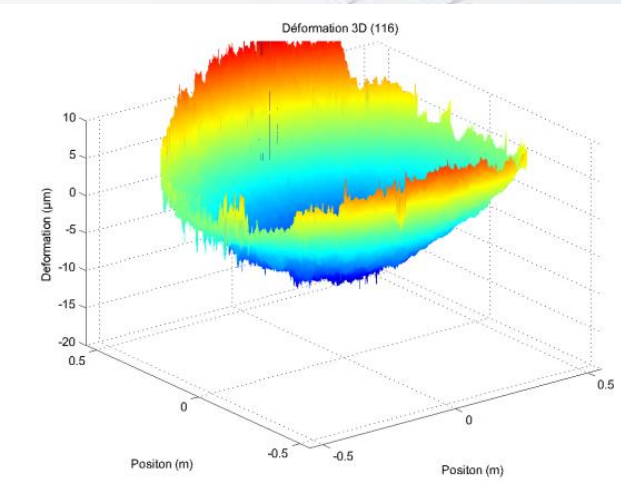
- Application in vacuum-thermal test at CSL







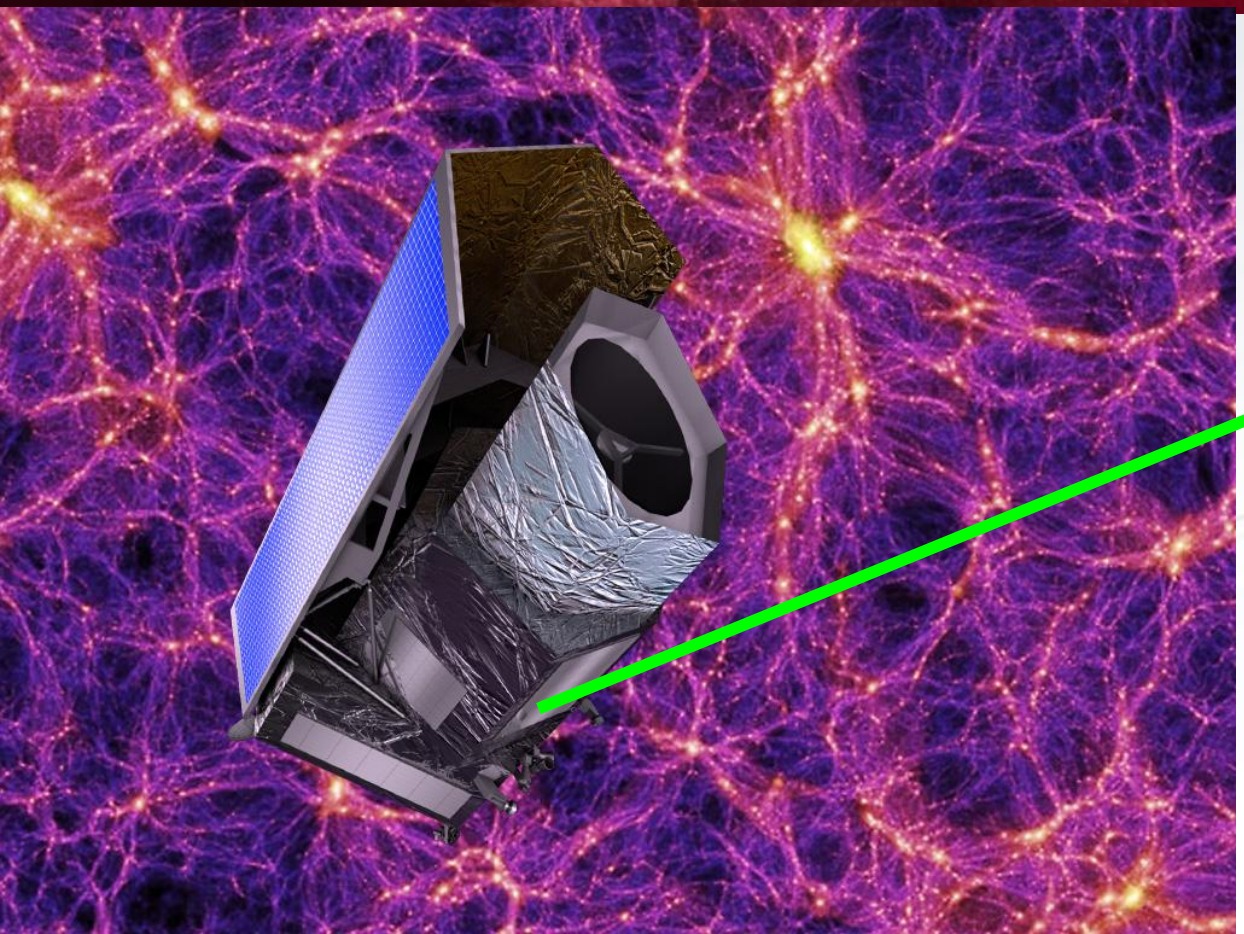


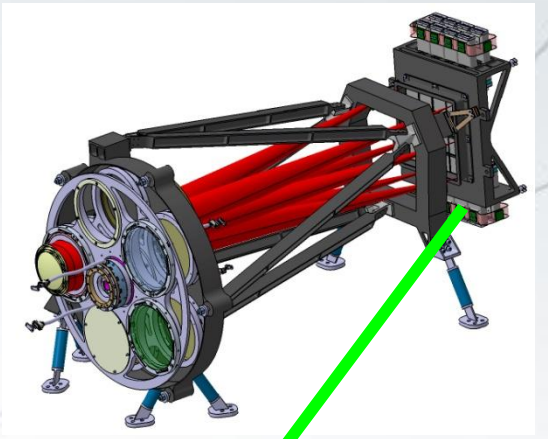


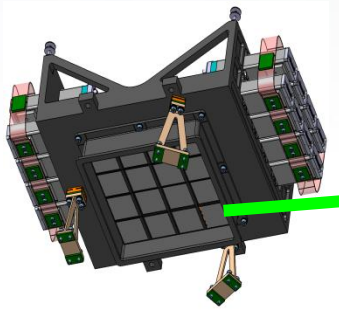
Current project : EUCLID

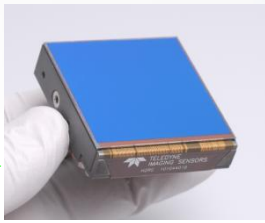
euclid

esa





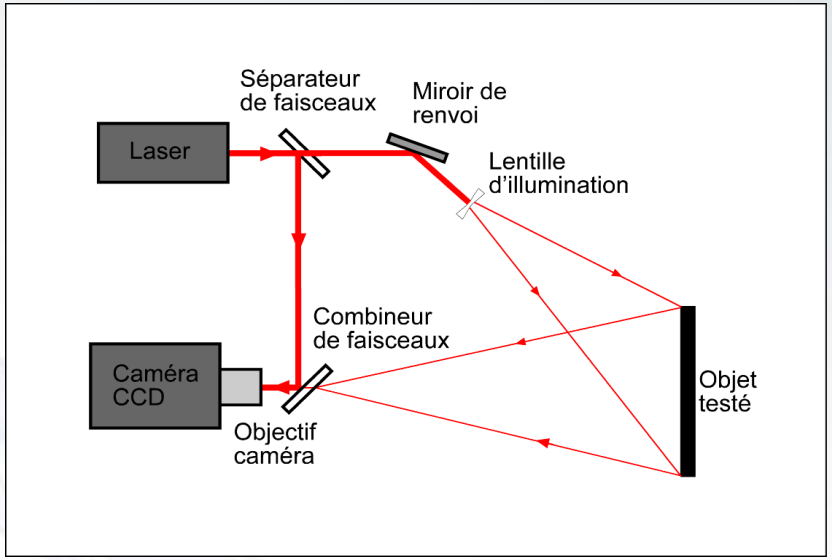


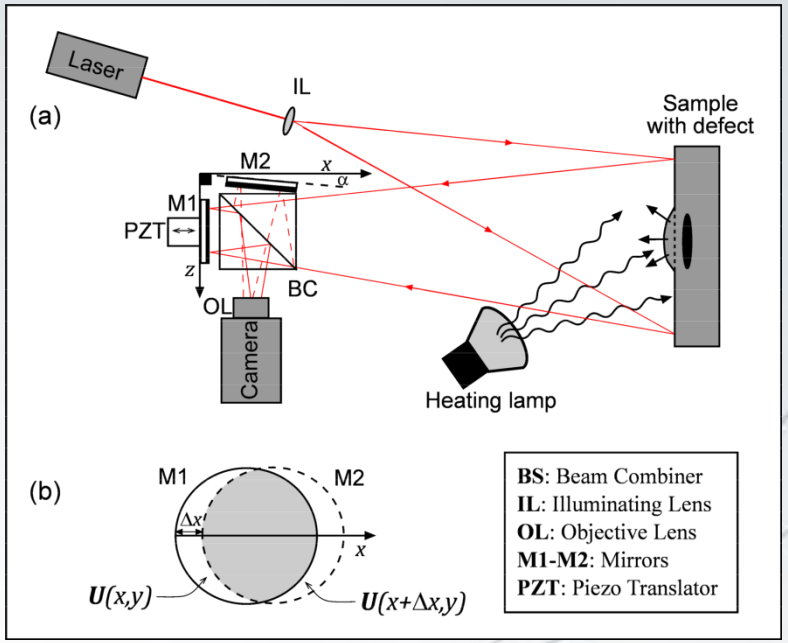


Other activities

Current projects

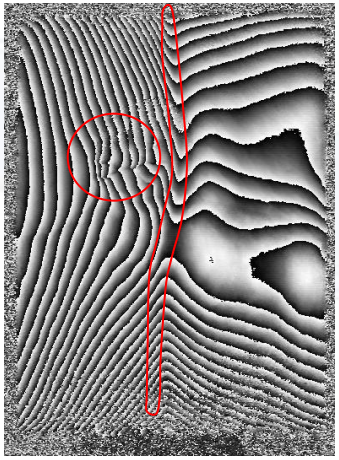
- Holography/Speckle vs. Shearography





$$\Delta\varphi(x,y) = \frac{2\pi}{\lambda} d(x,y)$$

d(x,y): displacement field

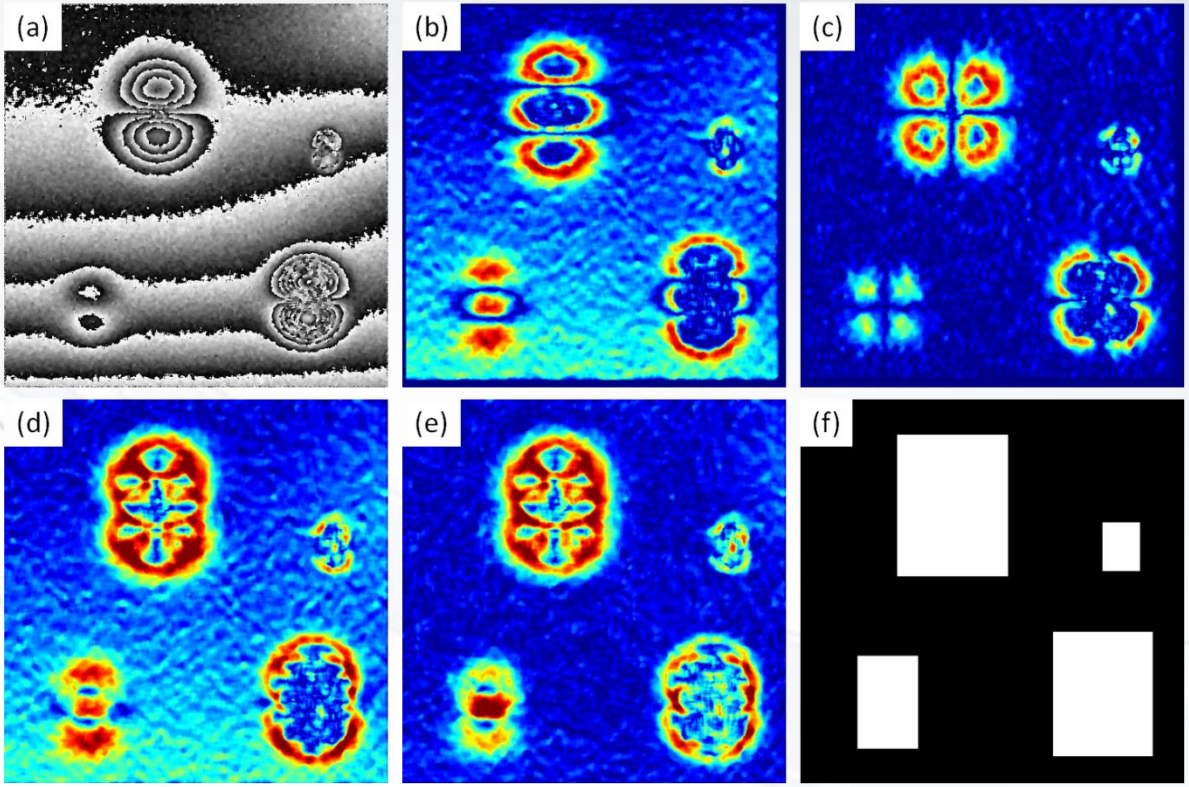


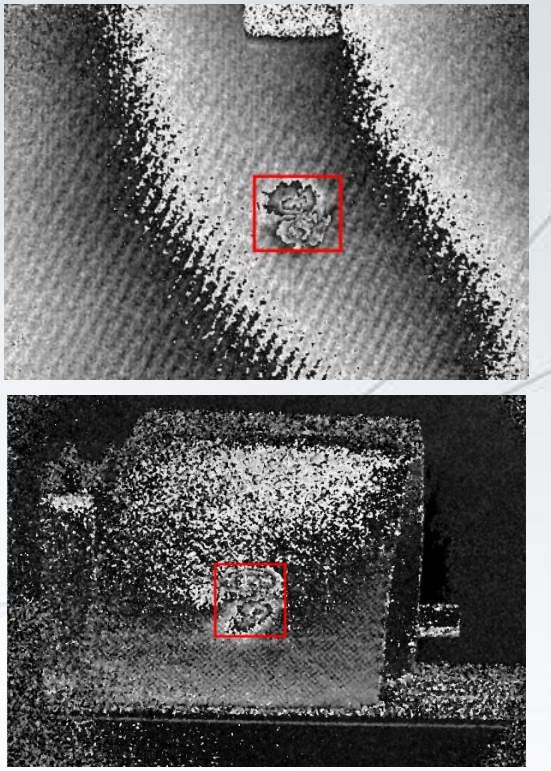
$$\Delta\varphi(x,y) = \frac{2\pi}{\lambda} \frac{\partial d(x,y)}{\partial x} \Delta x$$

Current projects

- Post-processing of Shearography

Automated defect detections in shearographic images



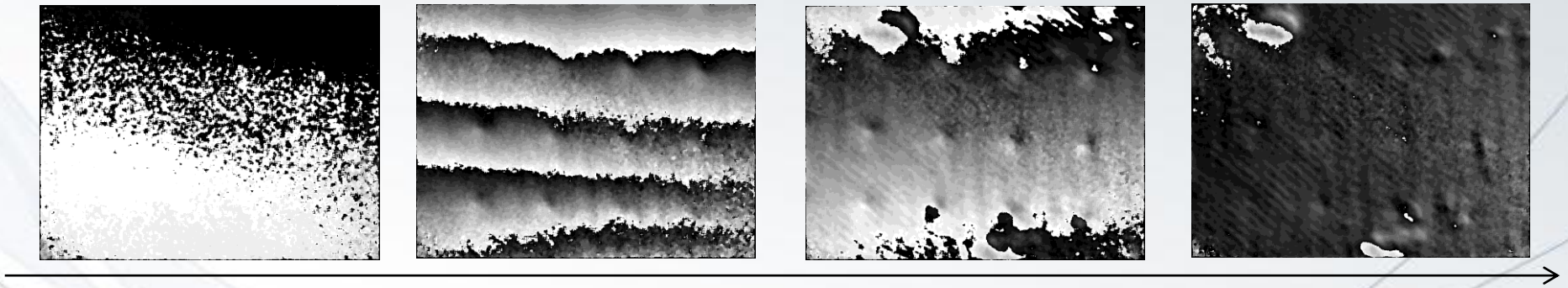


Current projects

- Post-processing of Shearography

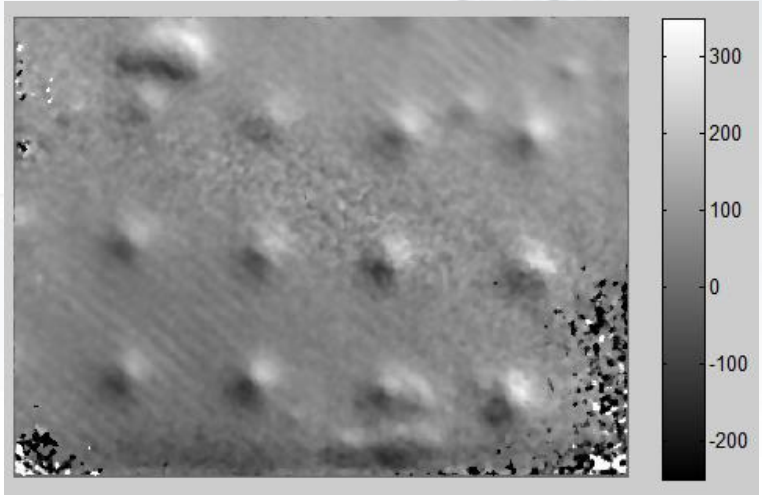
Temporal sequence shows various defects at different instants

Heat wave travelling through the sample



Principal Components Analysis provides

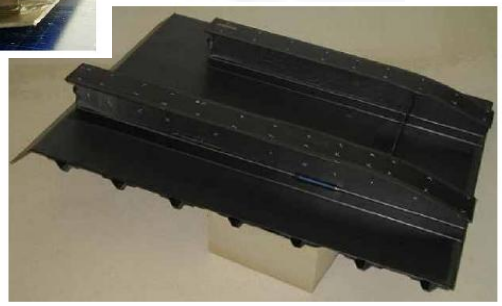
- Empirical Orthogonal Functions
- With all defects at once
- Same visibility of defects independent of depth

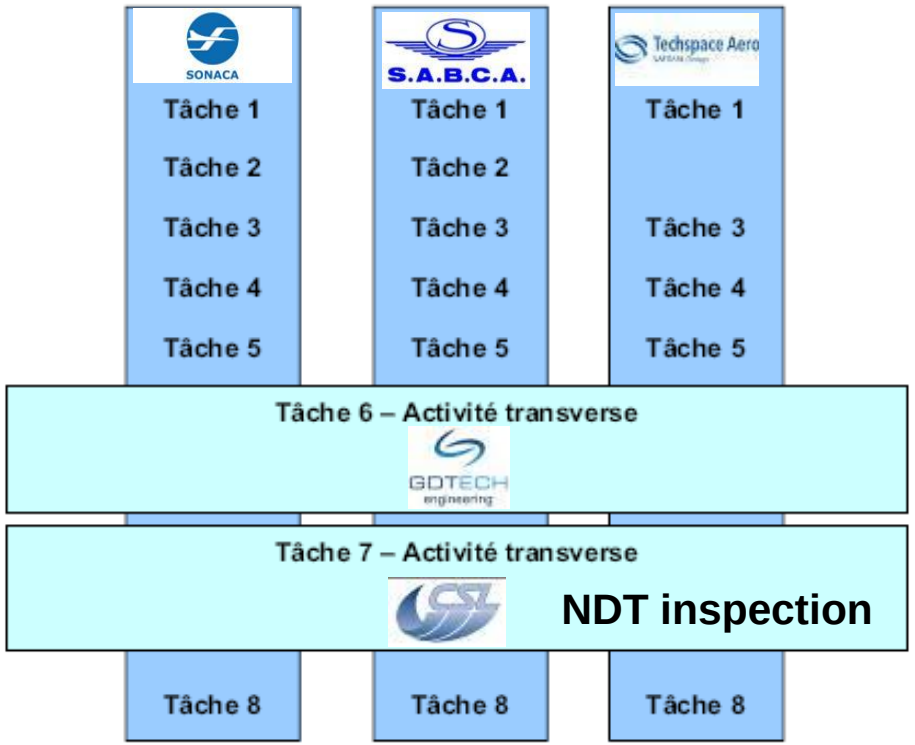


Current projects

- **Efficient Composite Technologies for Aircraft Components** (ECOTAC) – Wallonia DG06 – Marshall plan
- Phase 1: benchmarking (2011-2012)
  - Study emerging laser/optical NDT techniques
  - Complex shape aeronautical structures in CFRP

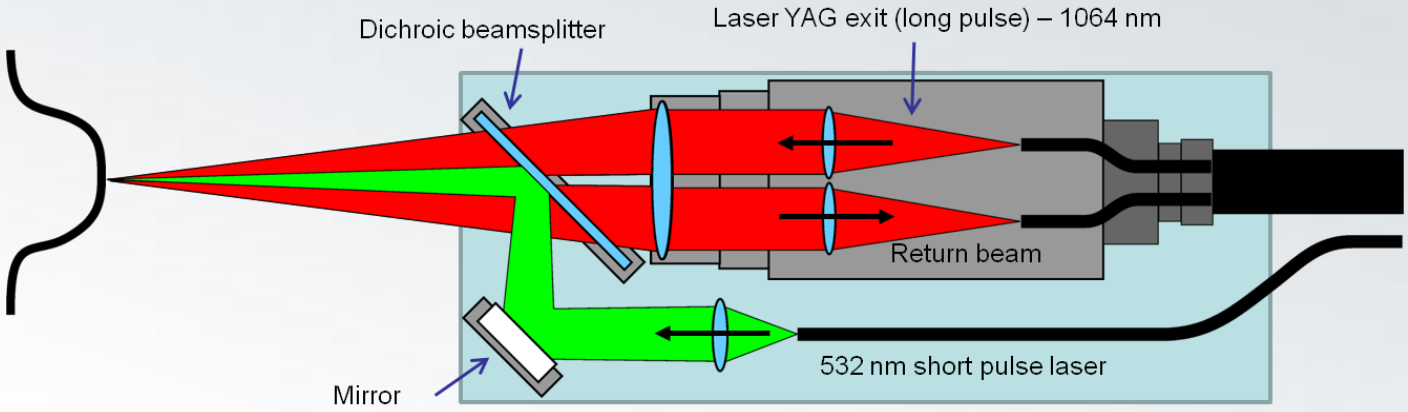
Techniques considered
- Thermography
- Shearography
- Laser Ultrasound

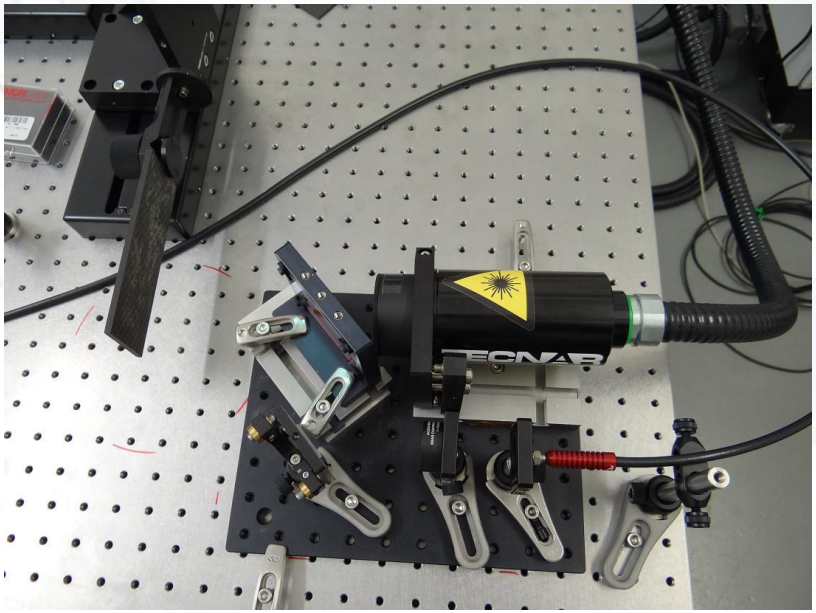


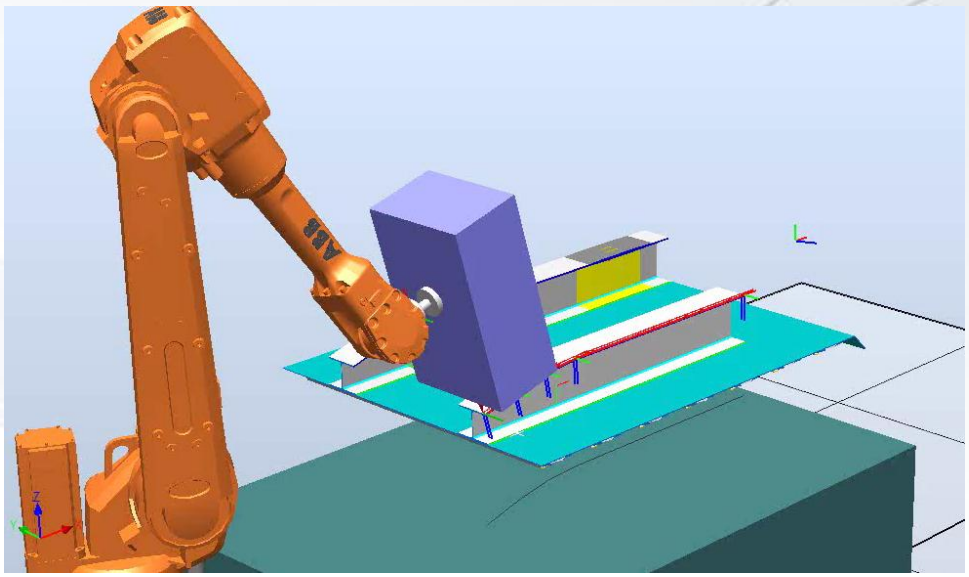


Current projects

- ECOTAC Phase2 : Laser ultrasonics







Future projects

- TECCOMA (follow up of ECOTAC)
  - Laser ultrasonics : continue ECOTAC
  - Shearography combined with Finite Element Modelling for
    - Improved NDT procedure
    - Reverse Engineering for defect parameters assessment
  - NDT data fusion
    - Laser scanner on measurement arm or robot
    - NDT heads (thermo/shearo/laser ultrasound)
    - Include defect images in CAD images

Thanks for Your Attention !

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www.csl.ulg.ac.be

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