Full-field optical and laser non destructive testing for aerospace applications

Dr. Marc GEORGES

Head of Laser and Nondestructive Testing Laboratory

Centre Spatial de Liège – Liège Université, Belgium

Sponsored by

SPIE.

The international society
For optics and photonics

By invitation of

SPIE. STUDENT CHAPTER

SIOM

Belgium


EUROPE
RUSSIA
FRANCE
SPAIN
ALGERIA


North Sea
NETHERLANDS
GERMANY
Zeebrugge
Oostende
Brugge
Antwerp
Gent
Hasselt
Kortrijk
BRUSSELS
Liège
Mons
Charleroi
Namur
Bastogne
LUXEMBOURG
FRANCE
0 20 40 km
0 20 40 mi

Liège, the university

- 24.000 students
- Different campuses
- In suburbs of Liege
- Other cities (agronomy)

- FACULTY OF PHILOSOPHY AND LETTERS
- FACULTY OF LAW, POLITICAL SCIENCE AND CRIMINOLOGY
- FACULTY OF SCIENCES
- FACULTY OF MEDICINE
- FACULTY OF APPLIED SCIENCES
- FACULTY OF VETERINARY MEDICINE
- FACULTY OF PSYCHOLOGY, SPEECH AND LANGUAGE THERAPY, AND EDUCATION
- HEC MANAGEMENT SCHOOL-ULIÈGE
- FACULTY OF SOCIAL SCIENCES
- FACULTY OF GEMBLOUX AGRO-BIO TECH
- FACULTY OF ARCHITECTURE

Centre Spatial de Liège

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

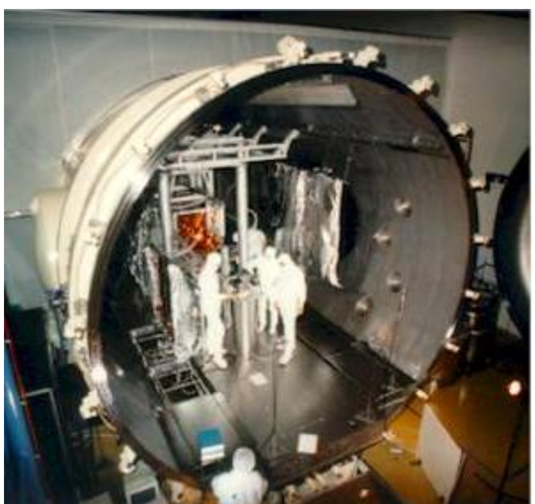
- 100 % self-funded by projects (institutions, industries)
- A few academic tasks
- Internship for students
- Master, PhD students

Centre Spatial de Liège

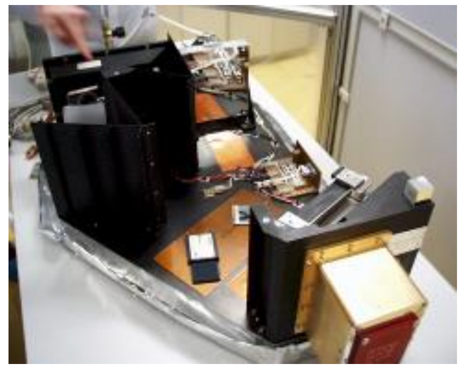
CENTRE SPATIAL DE LIÈGE

Optics for Space

Simulated space environment testing
Large chambers with optical benches



Development of optical space instrumentation



esa

NASA

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

CNSA

ISRO
Indian Space Research Organisation

Development of Advanced Technologies

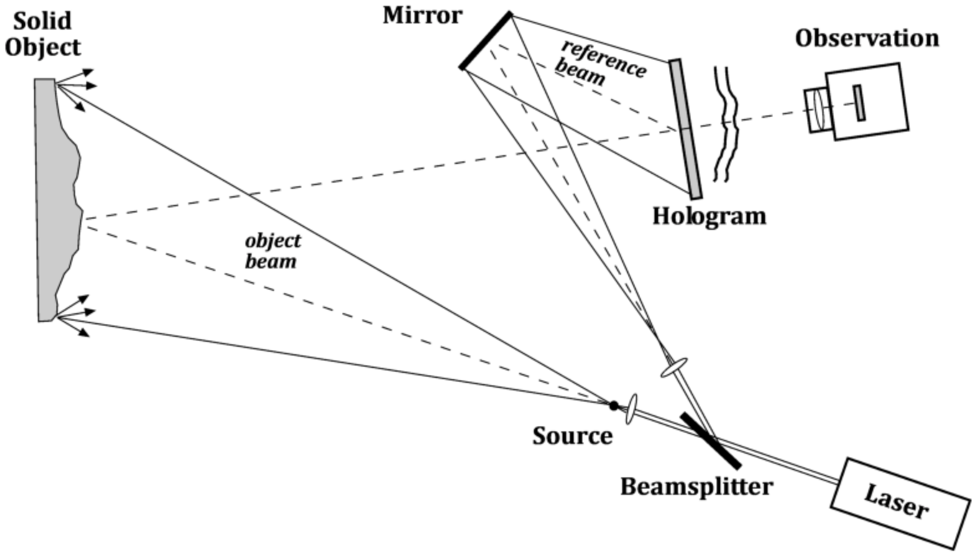
- Vacuum-Cryogeny
- Quality insurance
- Thermal Design
- Signal Processing
- Spaceborne Electronics
- Smart sensors
- Surface processing
- Optical Design
- $\boxed{\text{Optical Metrology}}$
- $\boxed{\text{Non Destructive Testing}}$

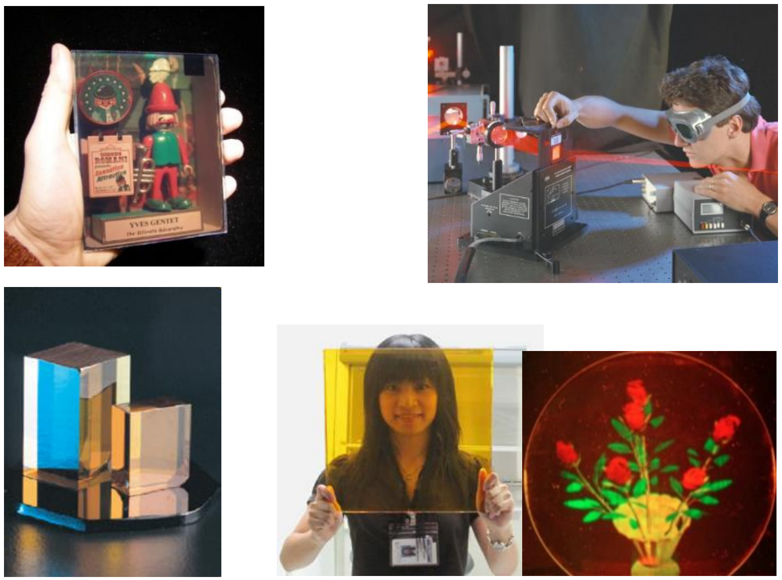
Summary

- Analog Holographic interferometry
- Digital Holographic interferometry
- Speckle interferometry
- Shearography
- Thermography
- Combination thermography-holography
- Terahertz imaging-holography

Holographic interferometry

- Holography:





Analog holographic materials

- Holographic Interferometry : different methods

$$I(x,y) = \left(U_O(x,y) + U'_O(x,y)\right).\left(U_O{}^*(x,y) + U'_O{}^*(x,y)\right)$$

$$I(x,y) = I_{av}(x,y)[1 + m(x,y)\cos\phi(x,y)]$$

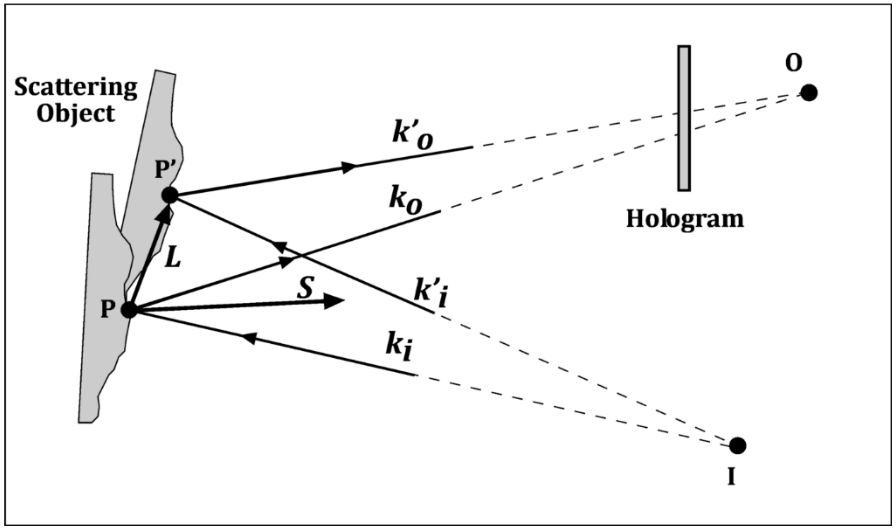
$$I_{av} = I_O + I'_O$$

$$m = 2\sqrt{I_O.I'_O}/(I_O + I'_O)$$

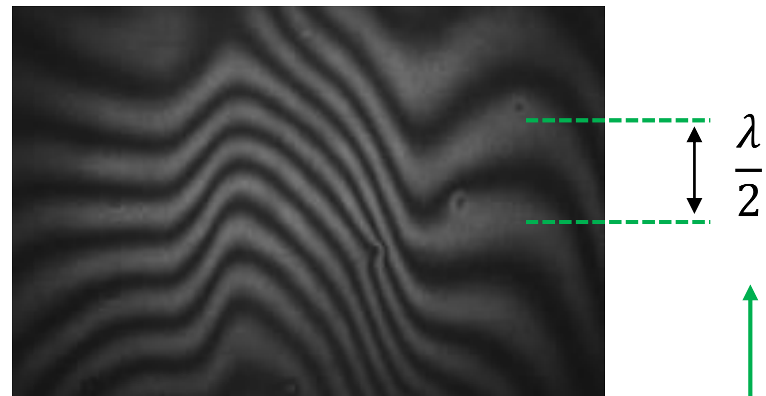
$$\phi = \varphi'_o - \varphi_o$$

Holographic interferometry

Displacements of scattering objects



$$I = I_{av}[1 + m\cos\phi]$$

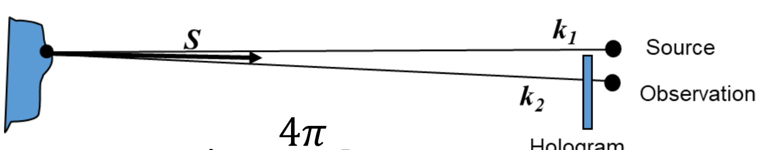


$$\phi = \boldsymbol{S}.\boldsymbol{L} = (\boldsymbol{k_o} - \boldsymbol{k_i}).\boldsymbol{L} = \frac{2\pi}{\lambda}(\hat{\boldsymbol{e}}_{\boldsymbol{o}} - \hat{\boldsymbol{e}}_{\boldsymbol{i}}).\boldsymbol{L}$$

I maximised for $\phi = \mathrm{N}\, 2\pi$

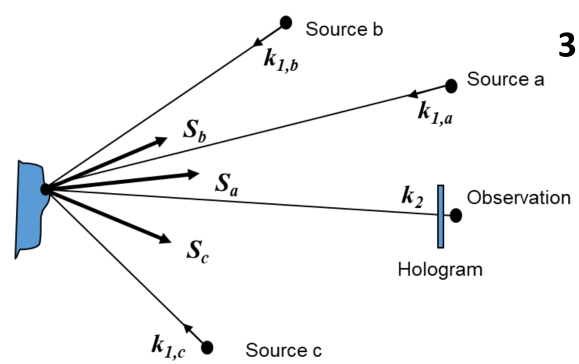
Special cases

Out-of-plane



$$\phi = \frac{4\pi}{\lambda} L_{\perp}$$

3D displacement



$$\phi_a = \boldsymbol{S}_a.\boldsymbol{L}$$
$$\phi_b = \boldsymbol{S}_b.\boldsymbol{L}$$
$$\phi_c = \boldsymbol{S}_c.\boldsymbol{L}$$

Holographic interferometry

- Determination of phase difference

$$I = I_{av}[1 + m\cos \boldsymbol{\phi}]$$

Phase-shifting technique

$$I_k = I_{av}[1 + m\cos(\phi + \beta_k)]$$

I_1

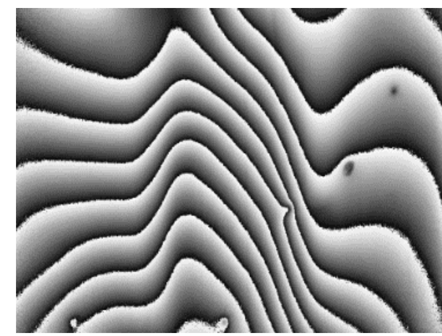
I_2

I_3

I_4

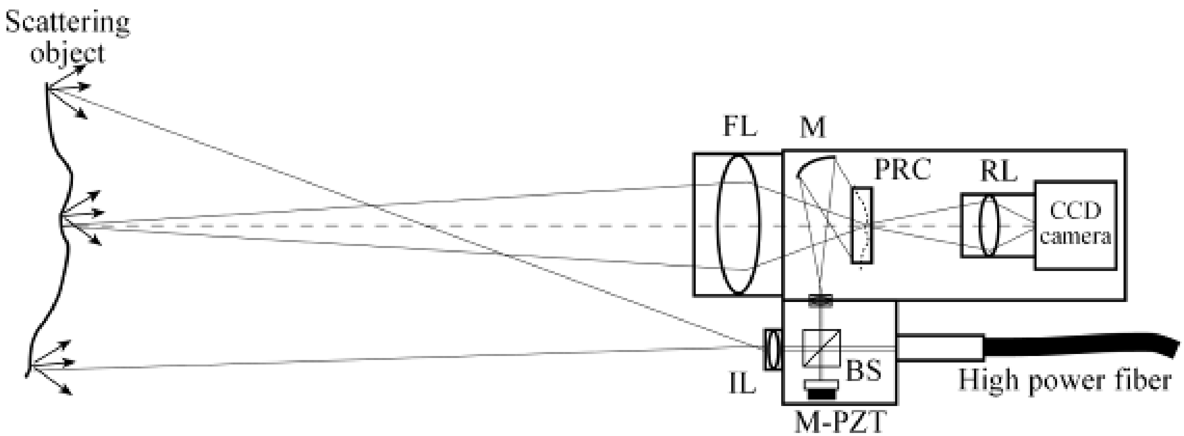
$$\phi = arctan\left(\frac{I_4 - I_2}{I_1 - I_3}\right)$$

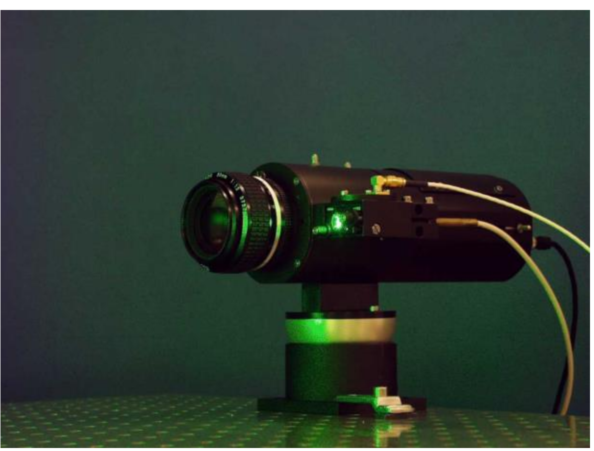
$\phi \bmod 2\pi$

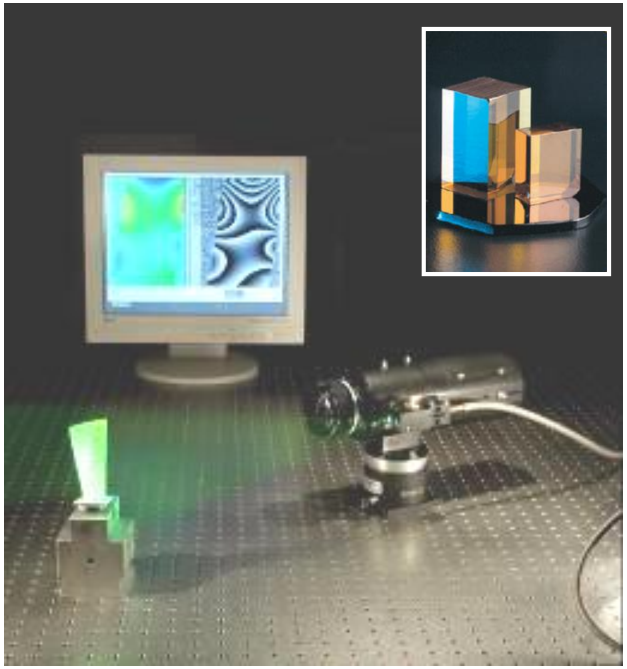


Holographic camera

- Holographic interferometer based on photorefractive crystal
  - Studied and developed between 1993-2000 (PhD thesis M. Georges)
  - Commercialised by spin-off company OPTRION since 2000



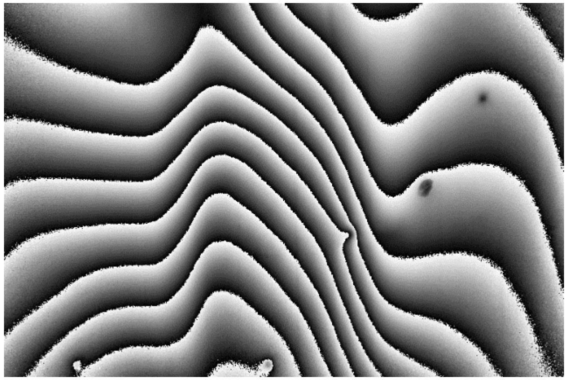
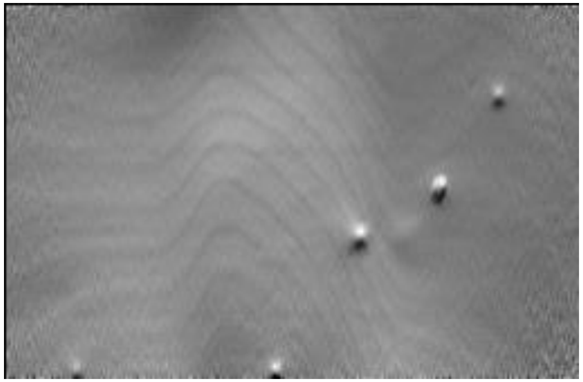




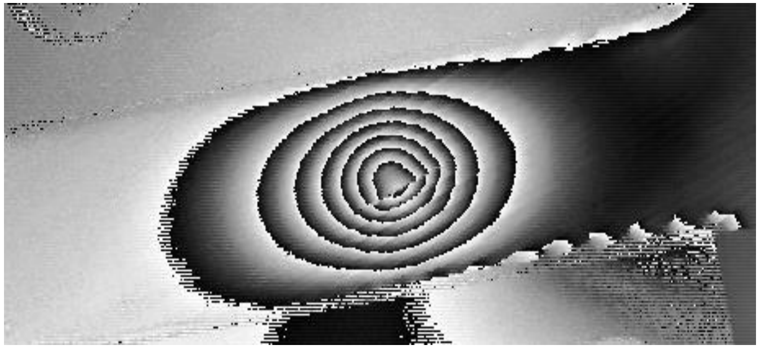
OPTRION

Holographic camera

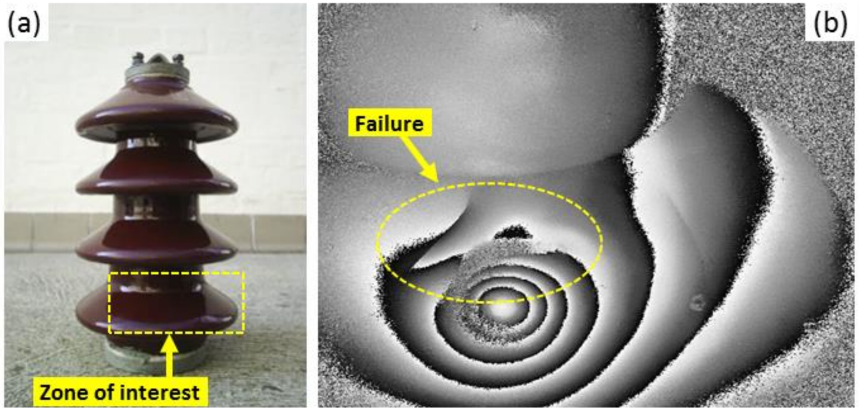
- **Application: defect detection**
  - Aeronautical composite structures


  - Flat cables

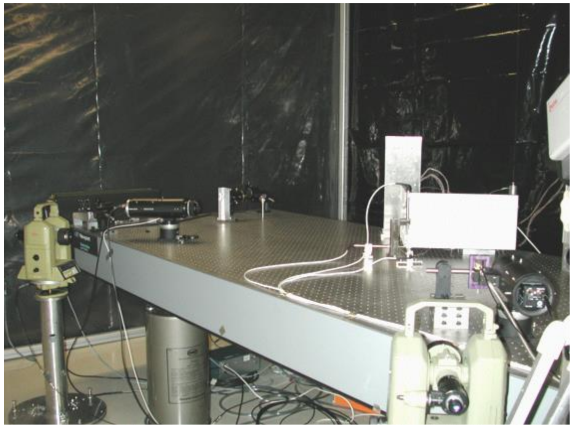


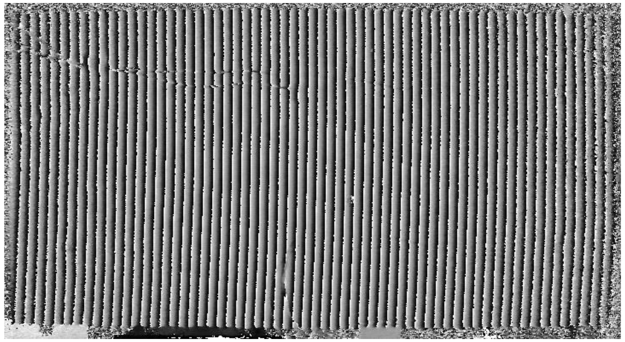
  - Industrial electric isolator

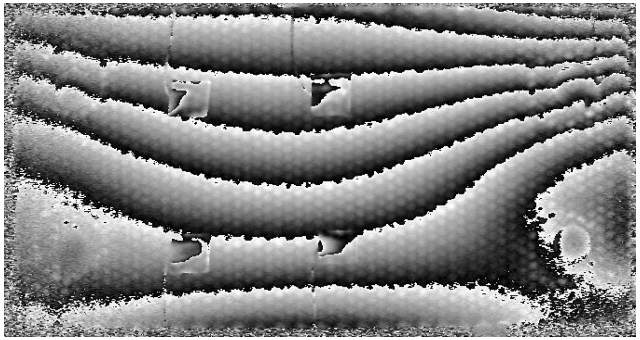


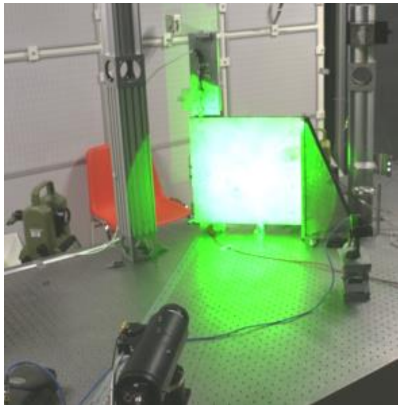
Holographic camera

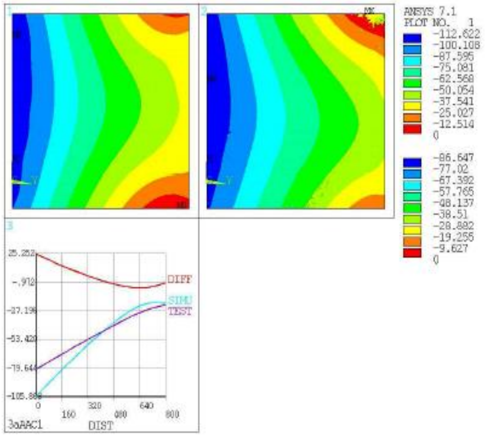
- Application: non-contact metrology of space structures
  - Thermo-mechanical assessment of composite structures for satellites
  - Comparison with Finite-Element Modeling (FEM)

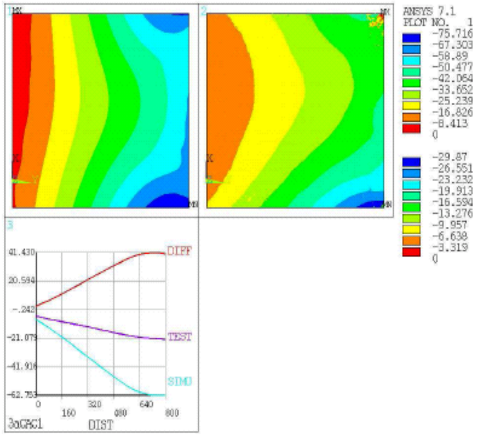


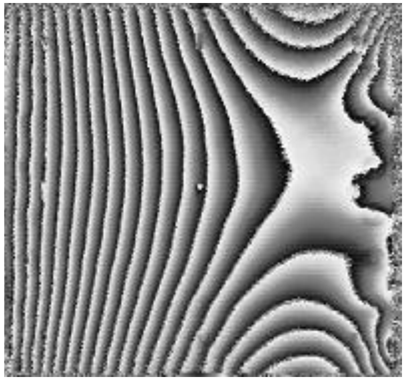






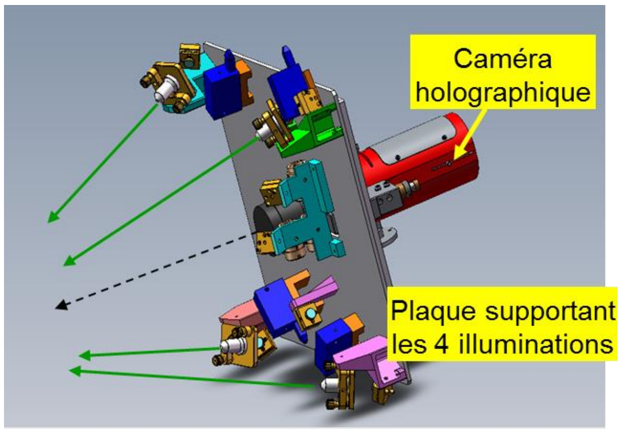


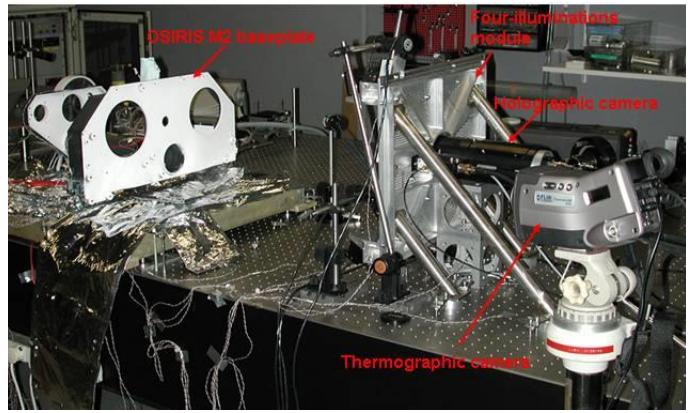


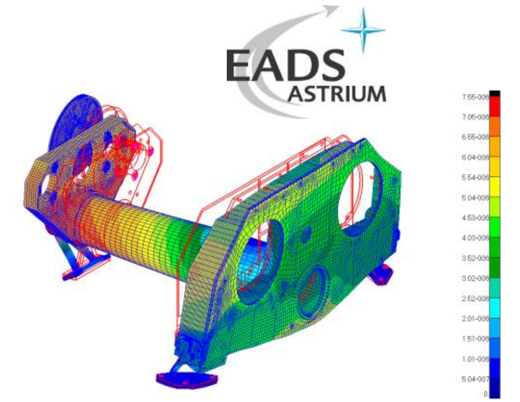


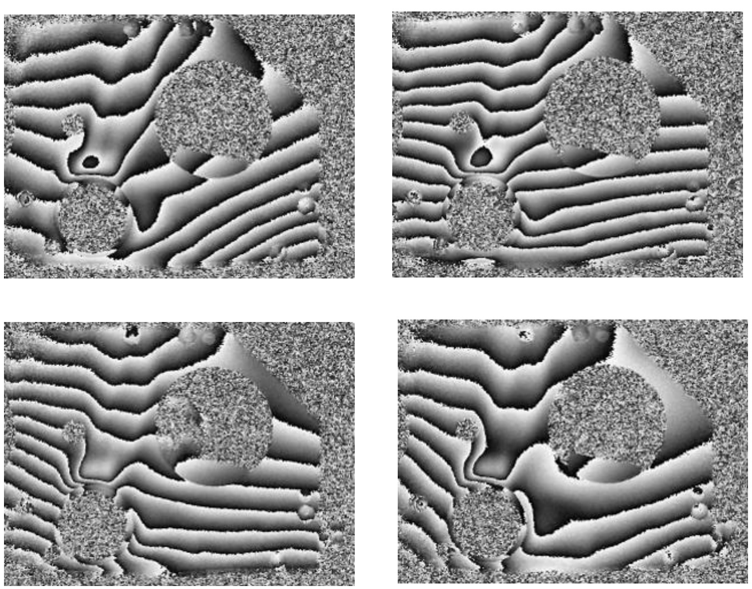
Holographic camera

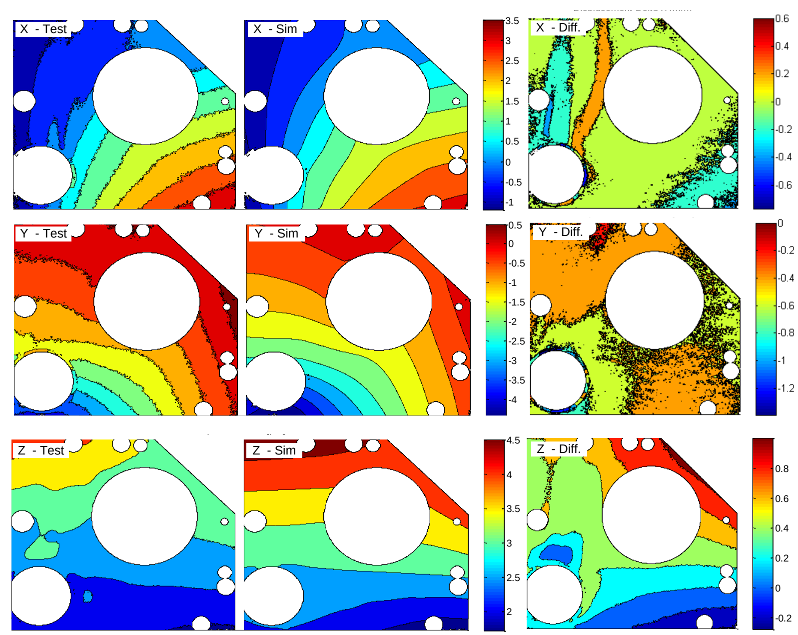
- Extension to 3D measurements
  - Complete 3D deformation of space laser bench structure – FEM comparison





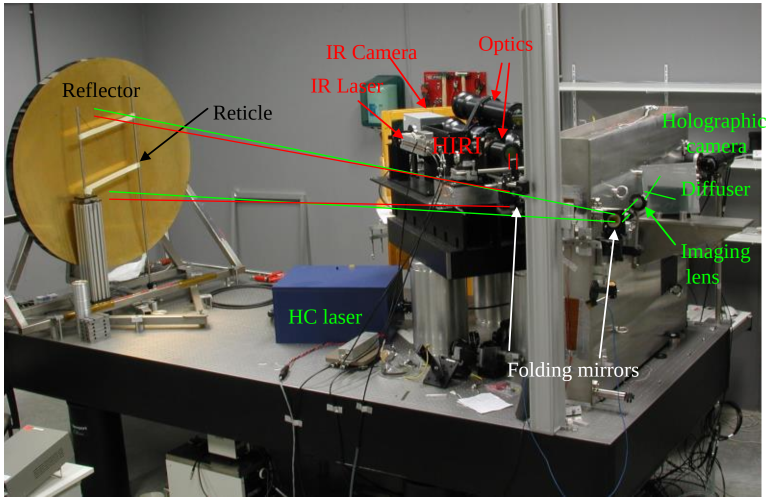


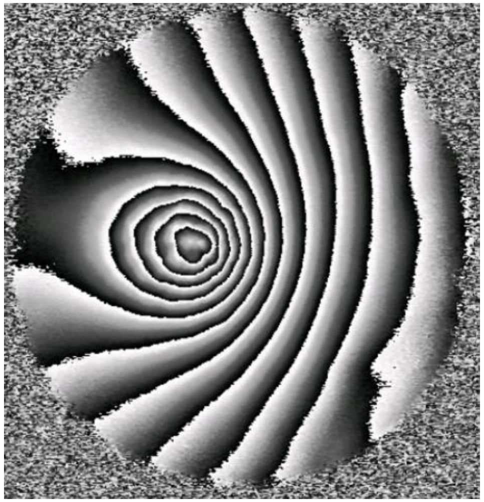




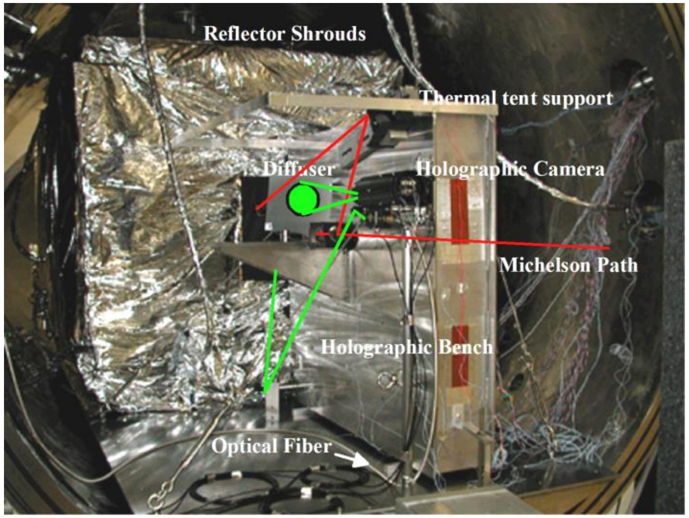
Holographic camera

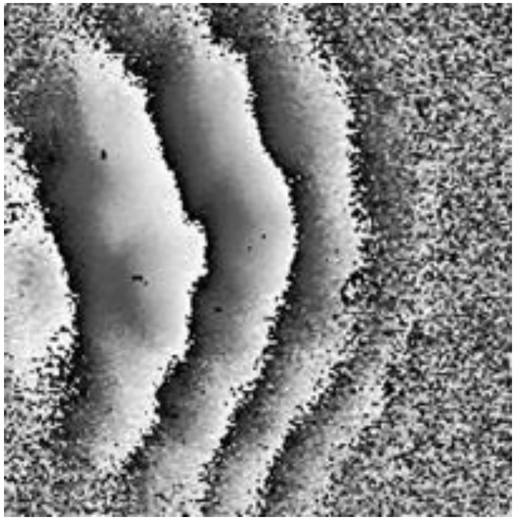
- Application: deformation of space structure
  - Under vacuum





No good results !
Vibration problems





Analog holography

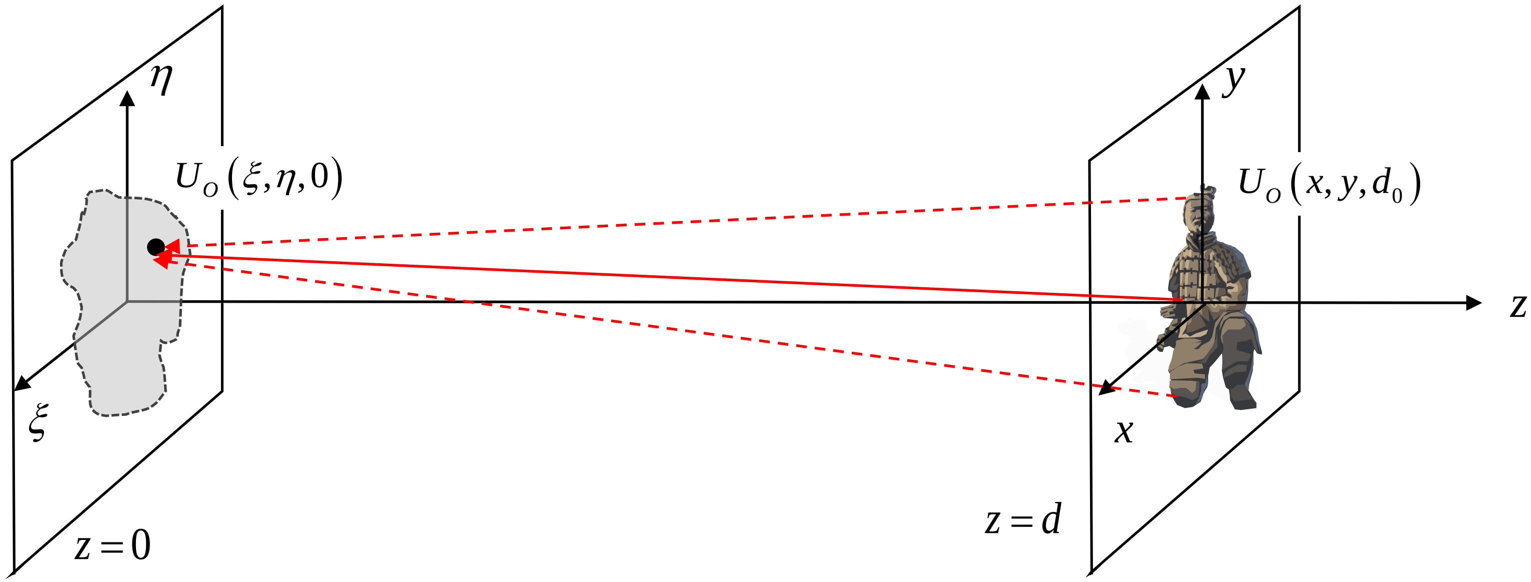
Discussion

- Analog recording of hologram
- Characteristics
  - ➢ High interferogram quality
  - ➢ High spatial resolution of recording medium
    (allows to record holograms of extented objects)
  - ➢ Usually physico-chemical processing (not immediately reusable)
  - ➢ Some materials allow in situ recording
    - Photorefractive crystals
    - Relatively slow (a few seconds)
    - Need of stability (laboratory conditions)
    - Despite this, a lot of applications demonstrated
- Alternative : numerical recording of holograms
  - ➢ Digital holography
  - ➢ Speckle pattern interferometry
  - ➢ Speckle shearing interferometry (shearography)

Digital holography

▪ Basic principle

- Propagation of light from object to sensor



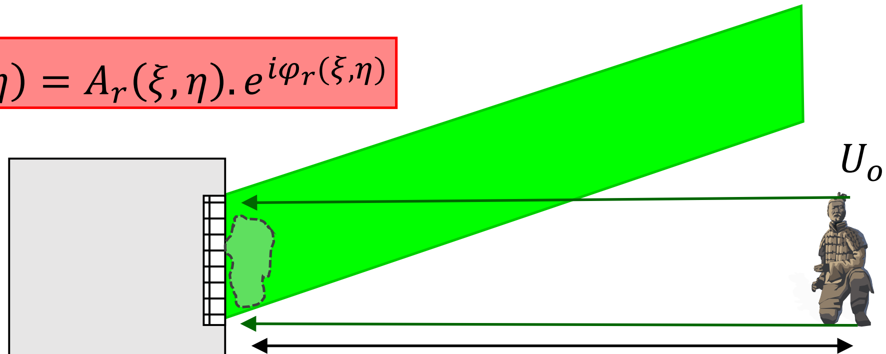
Fresnel propagation integral (paraxial approximation)

$$U_O(x,y,d_0)=\frac{\exp(ikd_0)}{i\lambda d_0}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}U_O(\xi,\eta,0)\exp\left\{\frac{i\pi}{\lambda d_0}\left[(x-\xi)^2+(y-\eta)^2\right]\right\}d\xi d\eta$$

Digital holography

- Recording

$$U_r(\xi,\eta) = A_r(\xi,\eta).e^{i\varphi_r(\xi,\eta)}$$



$$U_o(x,y) = A(x,y).e^{i\varphi_o(x,y)}$$

$$U_o(\xi,\eta) = A(\xi,\eta).e^{i\varphi_o(\xi,\eta)}$$

Intensity of recorded hologram

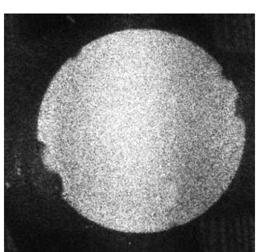
$$H(\xi,\eta\ ) = H_{av}[1 + m\cos(\varphi_r - \varphi_o)]$$

- Reconstruction by Fresnel

$$U_o(x,y,z=d) = \frac{i}{\lambda d}e^{-i2\pi d/\lambda}\exp\left[-i\frac{\pi}{\lambda d}(x^2+y^2)\right]\underbrace{\iint \boxed{H(\xi,\eta)}\boxed{U_r(\xi,\eta)}\exp\left[-i\frac{\pi}{\lambda d}(\xi^2+\eta^2)\right]\exp\left[i\frac{2\pi}{\lambda d}(x\xi+y\eta)\right]d\xi d\eta}_{}$$

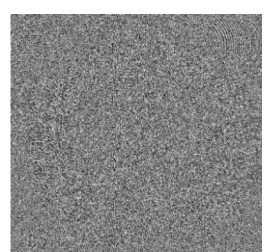
"S-FFT" algorithm

$$\text{FT}\left[H(\xi,\eta)U_r(\xi,\eta)\exp\left[-i\frac{\pi}{\lambda d}(\xi^2+\eta^2)\right]\right]$$



Amplitude

$$A_o(x,y,d) = \sqrt{\begin{matrix} Re^2(U_o(x,y,d)) \\ +Im^2(U_o(x,y,d)) \end{matrix}}$$



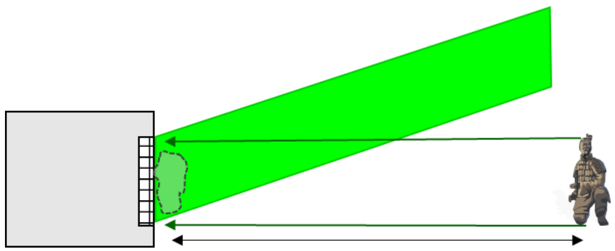
Phase

$$\varphi_o(x,y,d) = \tan^{-1}\left[\frac{Im(U_o(x,y,d))}{Re(U_o(x,y,d))}\right]$$

Digital holography

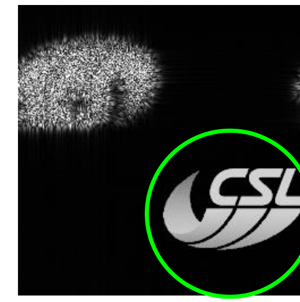
Useful configurations

Off-Axis



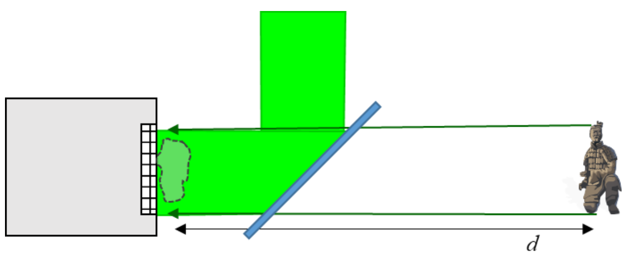
Preliminary capture of separated beams

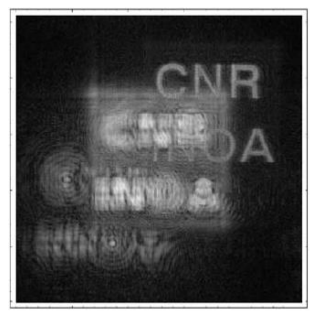
Suppress unwanted orders



Resolution: 1/4

In-line



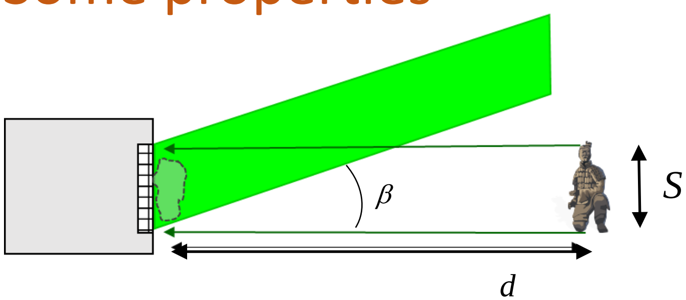


Phase-shifting (4 acquisitions)

Extract object image

Resolution: full

Some properties



$$\beta \leq 2\arcsin\left(\frac{\lambda}{4\Delta}\right)$$

λ: wavelength

Δ: dimension pixel

Angle between objet and reference – Dimension of objects

- In order to resolve hologram, angle β must be well chosen
- Angle too large = fringes too close to be resolved
- Resolving fringes : satisfy Shannon sampling theorem

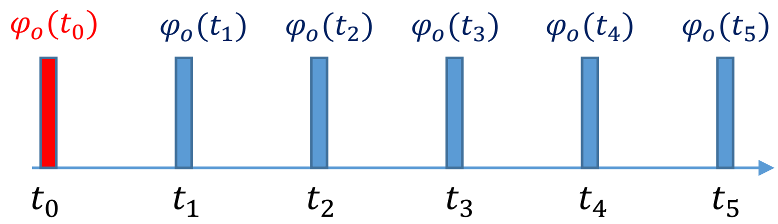
- Maximum size of objects

$$S_{\max} = \frac{d\lambda}{2\Delta}$$

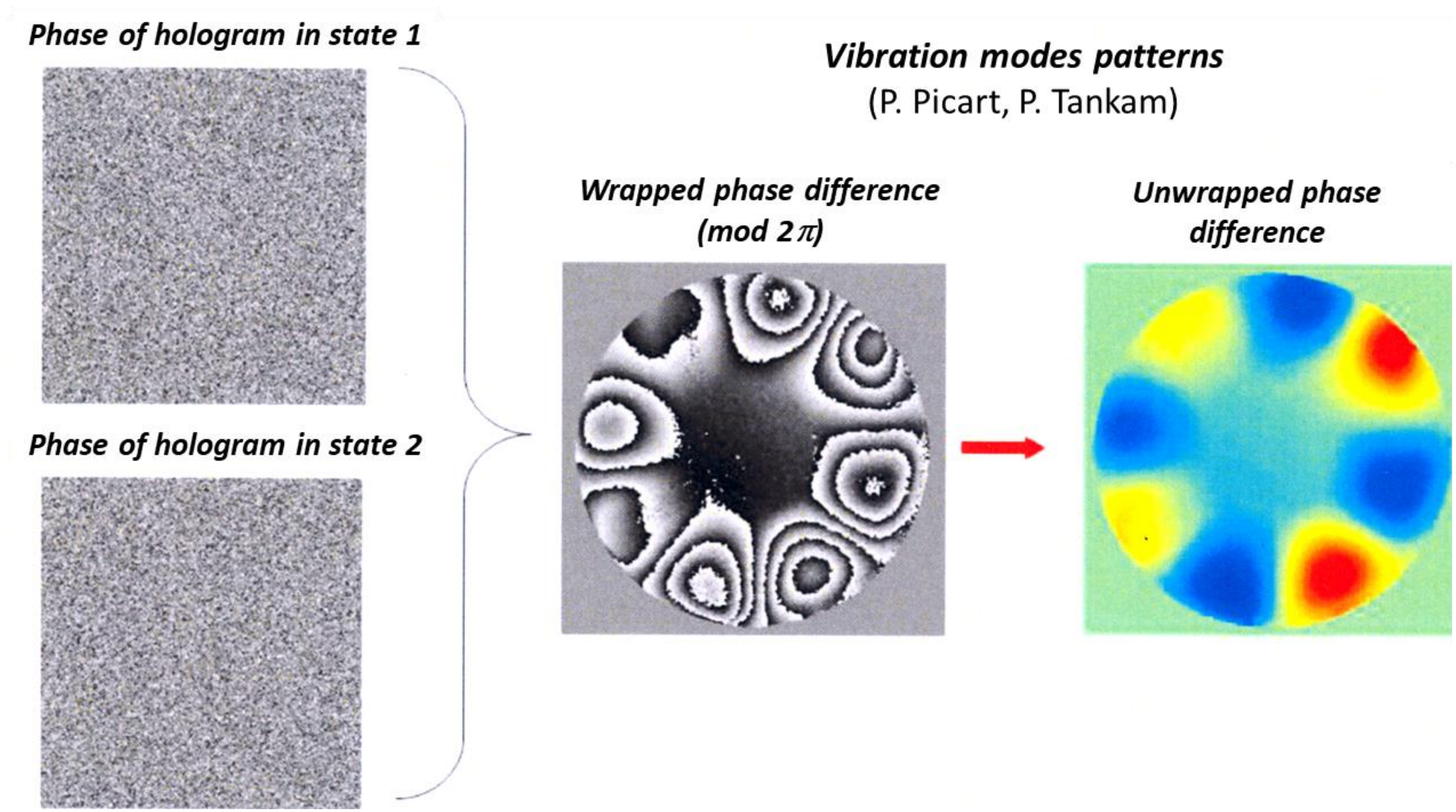
d: reconstruction distance

Digital holography

- Digital holographic interferometry



$$\phi(t_k) = \varphi_o(t_k) - \varphi_o\,(t_0)$$

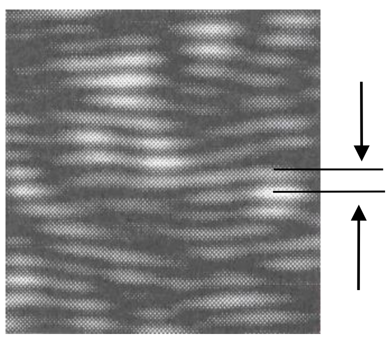


Digital holographic interferometry

▪ Digital holographic interferometry in the Long-Wave InfraRed

- Motivation

Zoom of local interference pattern (digital hologram)



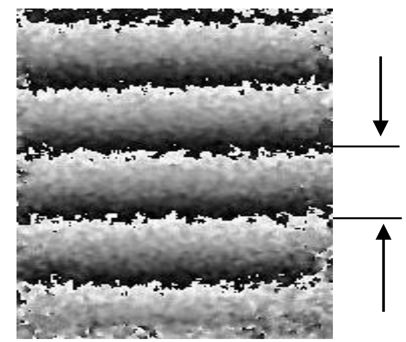
Pattern must be stable during recording (depends on frame rate)

Set-up stability criterion : < $\lambda/10$

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

Phase difference / displacement field

$\Delta\phi(x,y)$



Measurement range ⟺ Number of fringes

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

stability can be only **1 µm**

CO_2 laser
λ=10 µm
(LWIR range)

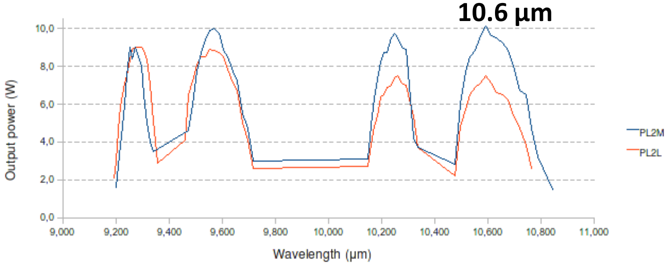
range = **1 µm – 200 µm**

LWIR DH Interferometry

LWIR Equipment - Components

LWIR Laser

10.6 µm



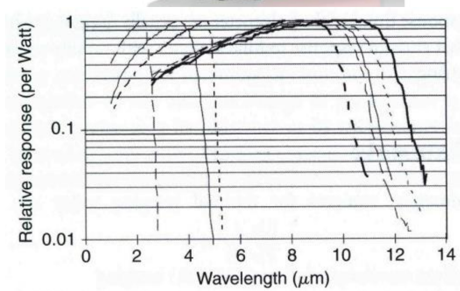
Edinburgh Instruments

LWIR Camera

Uncooled microbolometer camera *Jenoptik LOS*

Spectral range 8-14 µm

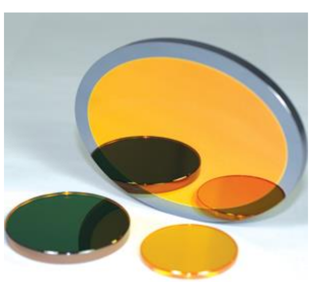
Cooled MCT camera *Infratec GmbH*



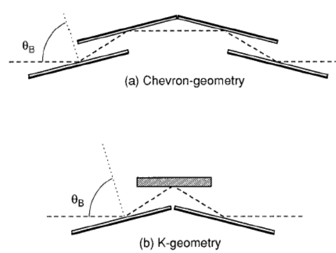
LWIR Optics

ZnSe Lenses

Beamsplitters

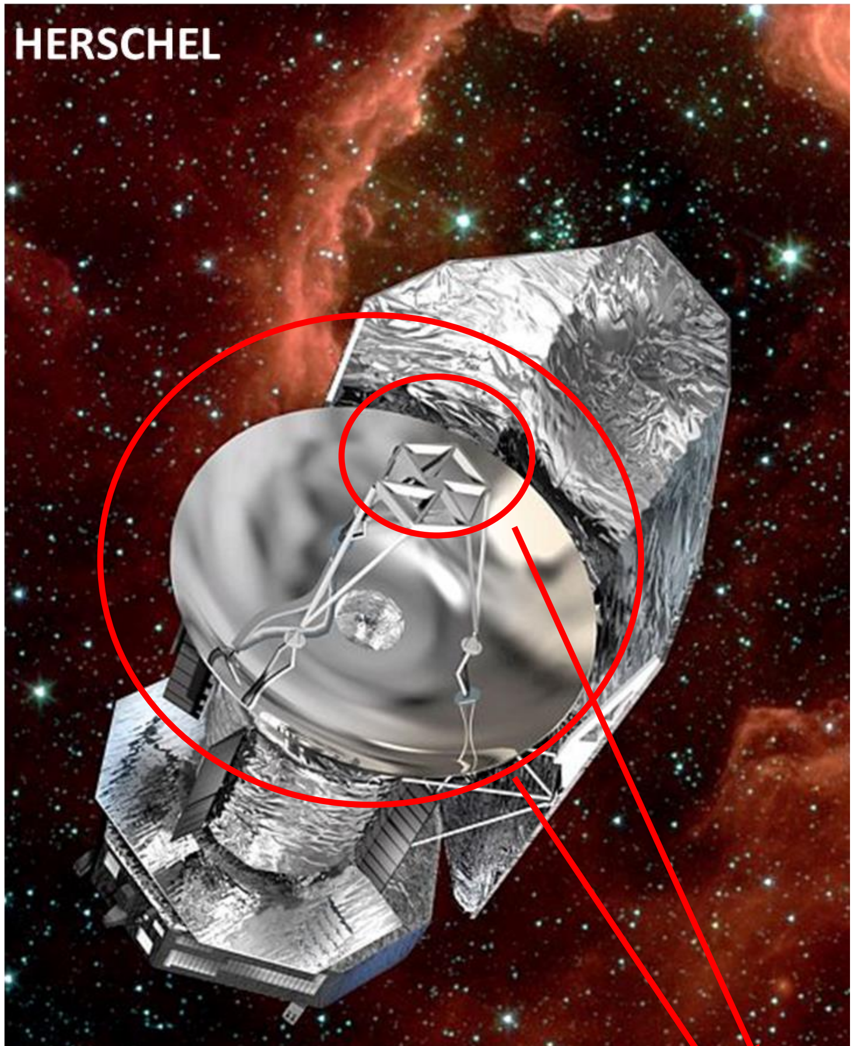


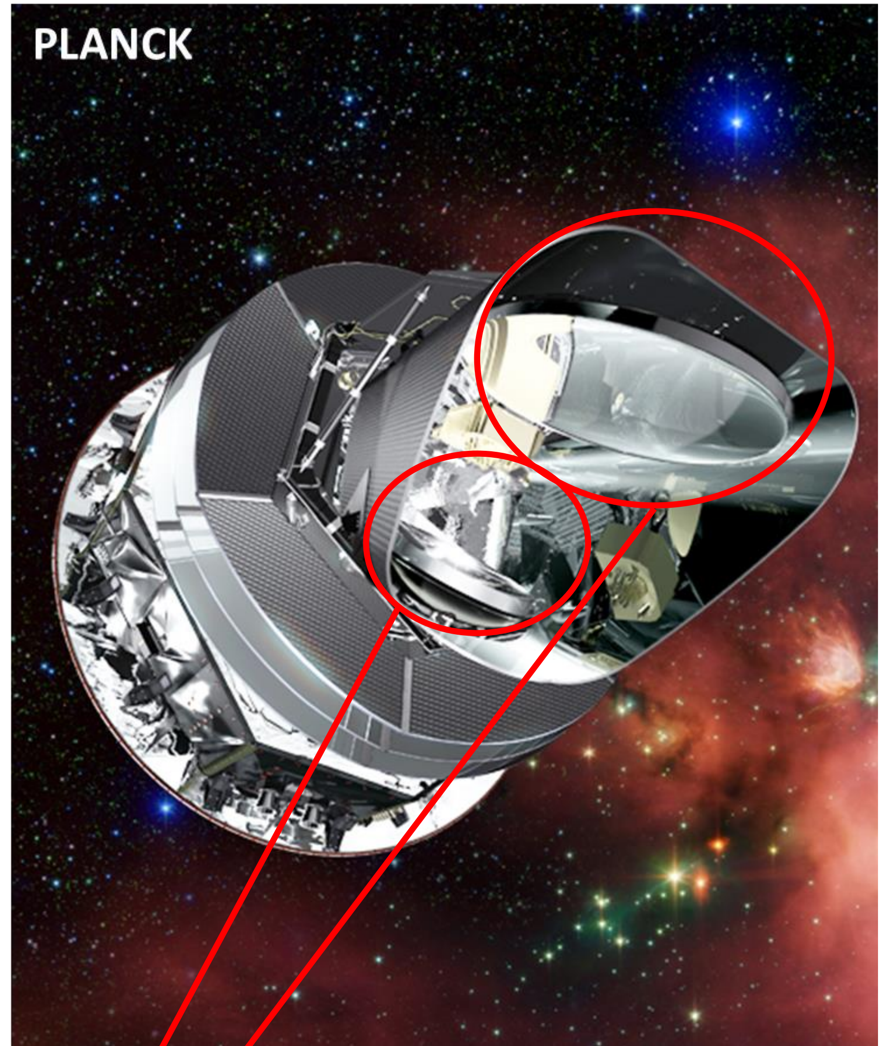
Polarizers



LWIR DH Interferometry

- Application in space metrology for European Space Agency (ESA)

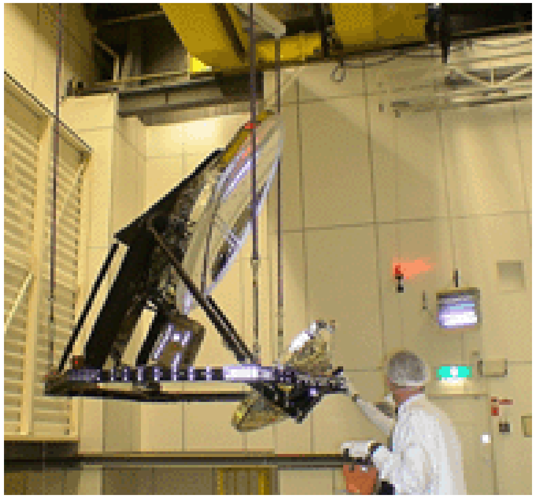




Aspheric reflectors

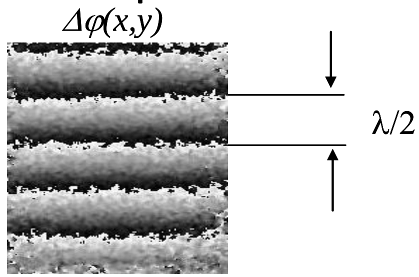
LWIR DH Interferometry

- Application in space metrology for European Space Agency (ESA)
- ESA needs:
  - Full-field **<u>deformations</u>** of reflectors in vacuum-thermal testing
  - Large reflectors: up to 4 m diameter
  - Range of deformations: 1 µm – 250 µm
  - **Reflectors cannot be equipped with cooperative targets nor sprayed with scattering powder !**



LWIR DH Interferometry

- Specific features of LWIR DHI for space metrology
  - Reduce sensitivity to displacement to measure ?   **YES**



  - Reduce sensitivity to external perturbations ?   **YES**

  - Large objects ? **YES**

$$S_{\max} = \frac{d\lambda}{2\Delta} \qquad \left(\frac{\lambda}{\Delta}\right)_{10\mu m} \approx 7\left(\frac{\lambda}{\Delta}\right)_{532nm} \longrightarrow \boxed{\text{Observable objects 7 x larger at 10 µm}}$$

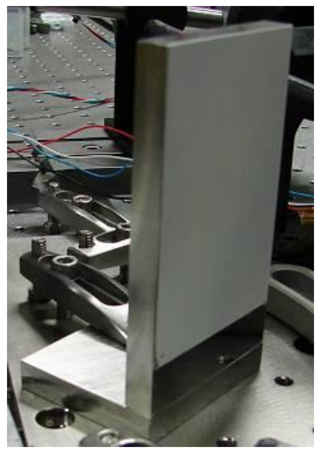
  - **BUT:** Objects reflects more specularly than in visible

LWIR DH Interferometry

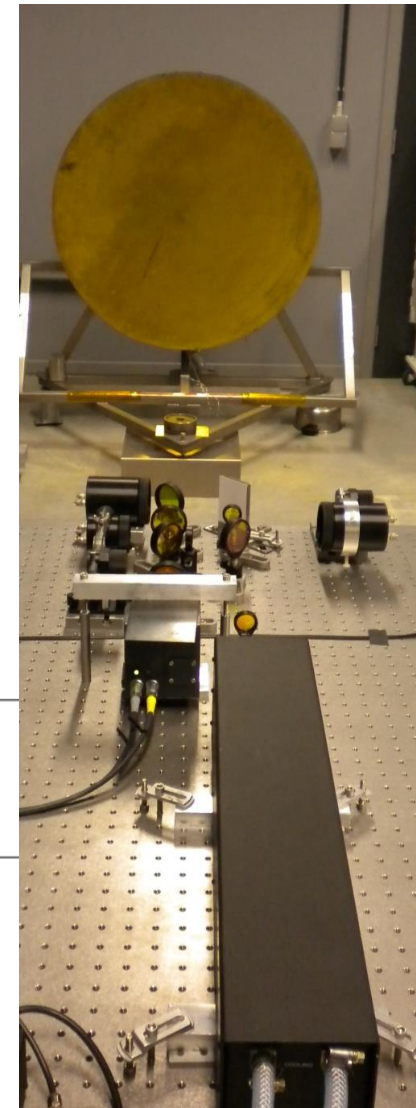
- Development of DH interferometer for space aspheric testing

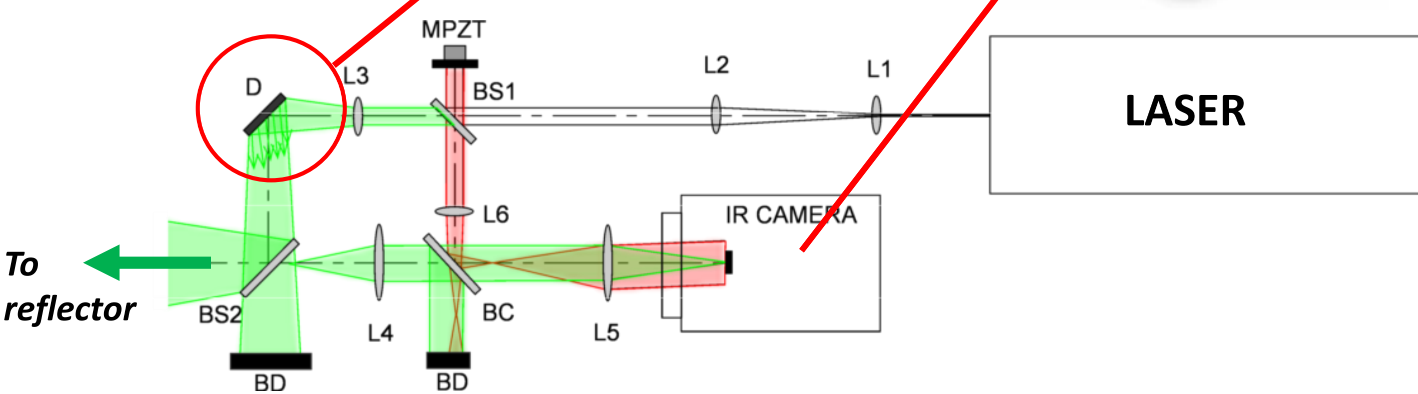
M. Georges et al., OSA Topical Meeting, DH2013, Miami, Paper DW4C.1 (2012)
M. Georges et al., Applied Optics ***52****(1), A102-A116 (2013)*

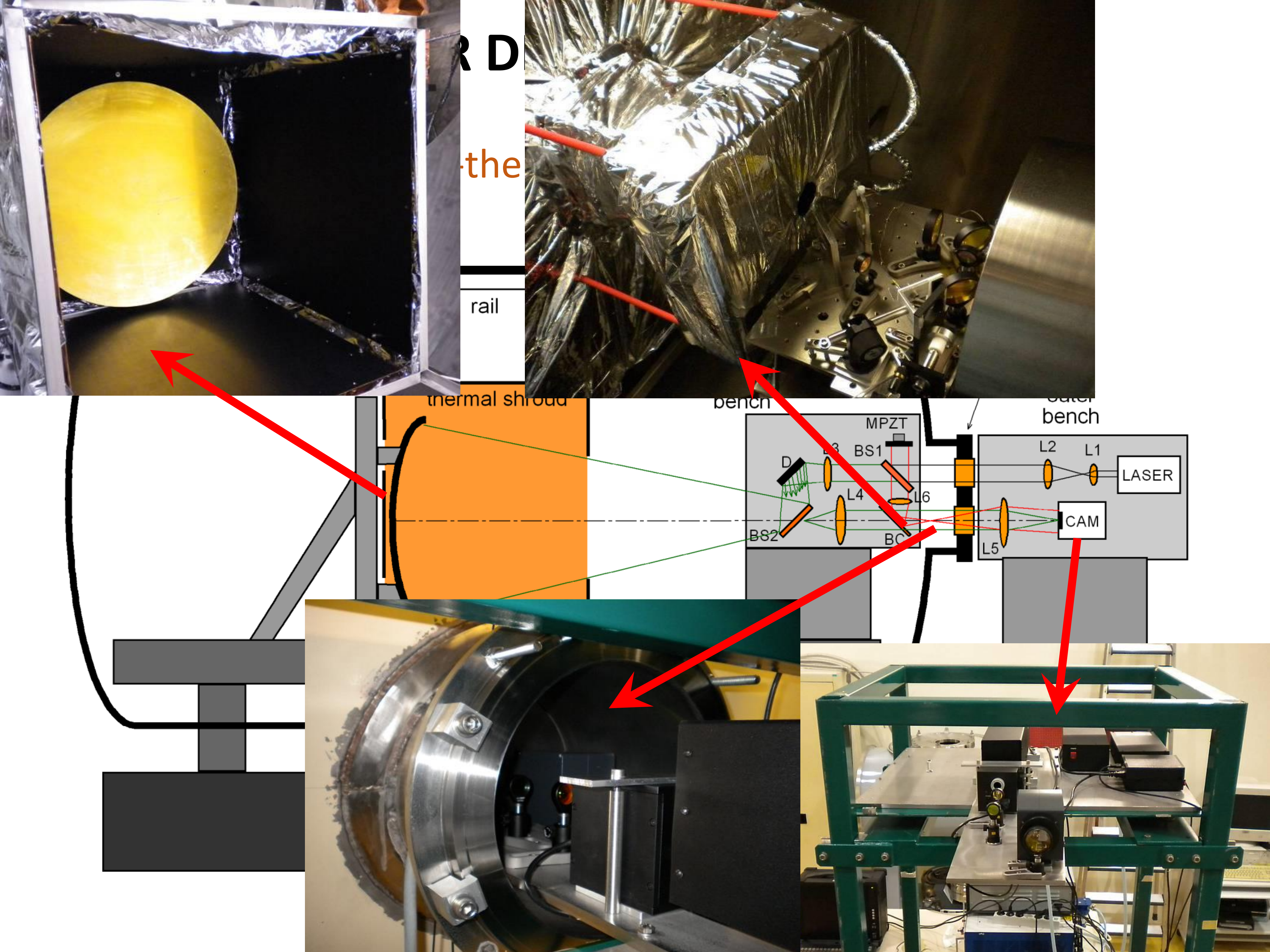
Diffuser



Uncooled µ-bolometer
640x480 pixels
Pixel Pitch : 25 µm
Frame rate 60 Hz
16 bits

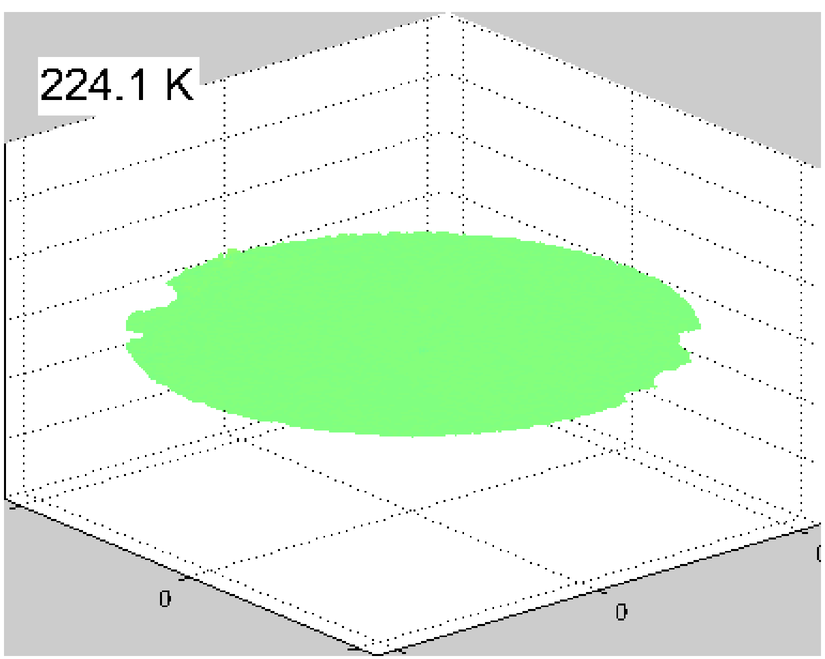


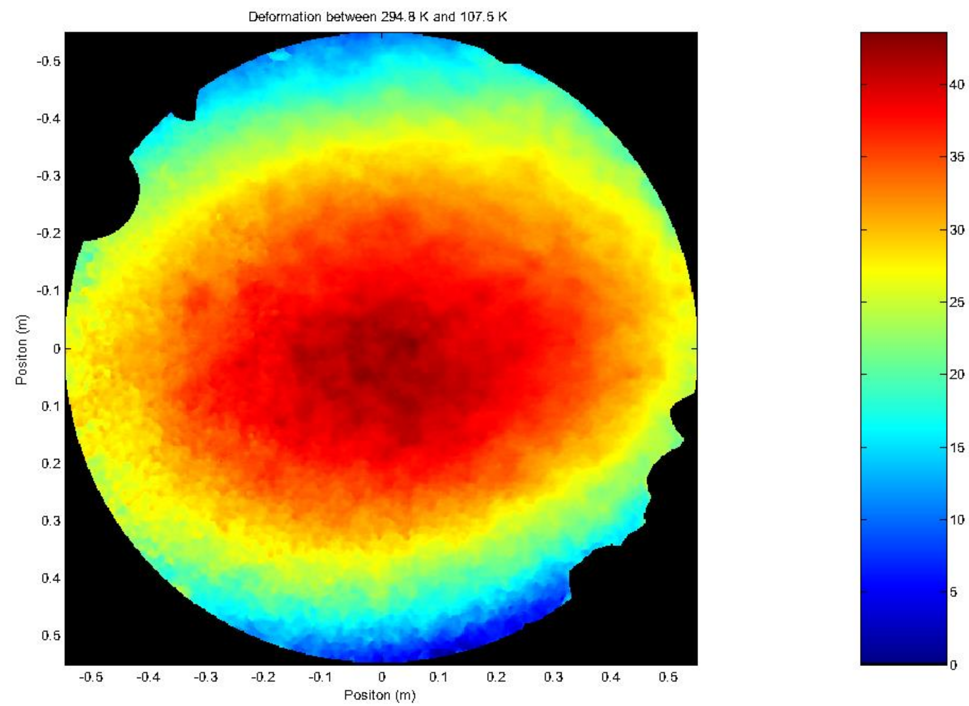



rail
thermal shroud
bench
bench
MPZT
BS1
L2
L1
LASER
D
L4
L6
CAM
BS2
L5

LWIR DH Interferometry

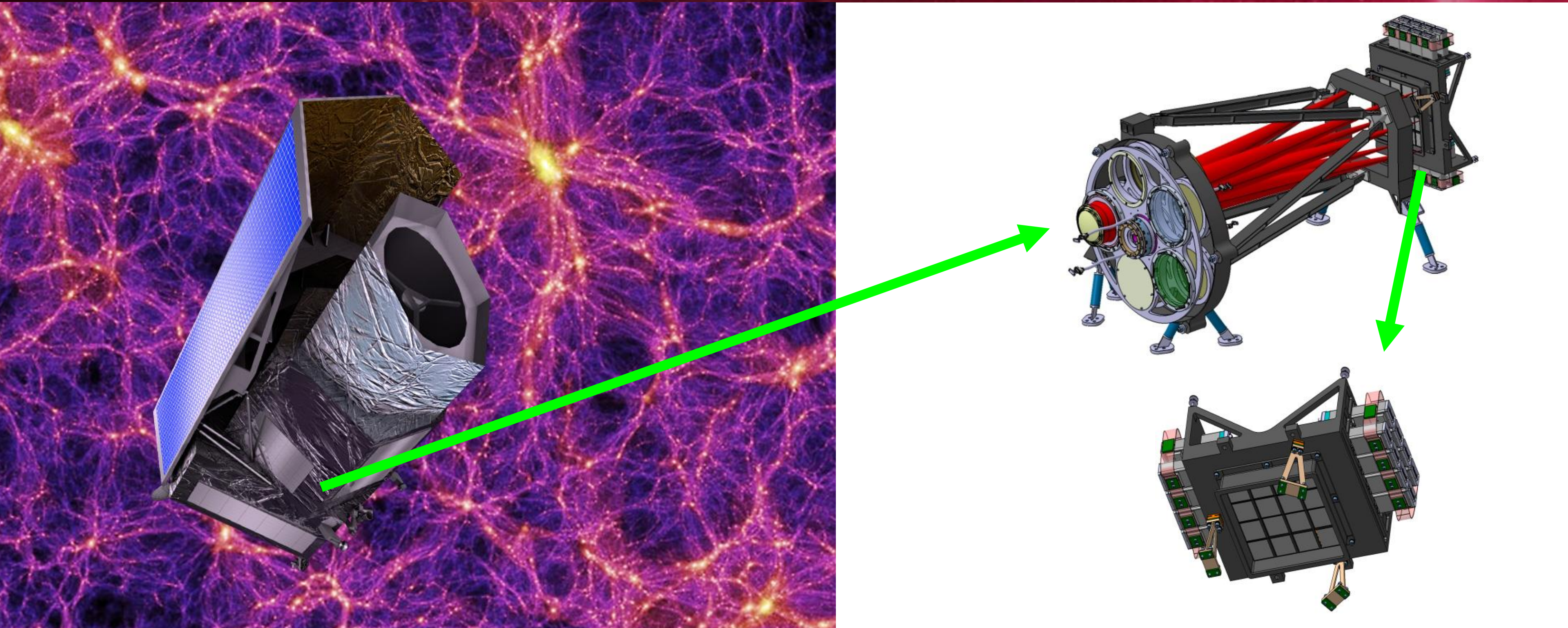
- Results of vacuum-thermal testing
- Deformation between 295 K and 107 K (ΔT = 188 K)
  - Error on 1 ! Measurement : 0.5 – 1 µm
  - Combination of 3 consecutive measurements
  - Total error estimated : 1.5 – 3 µm
  - After tilt and defocus removal





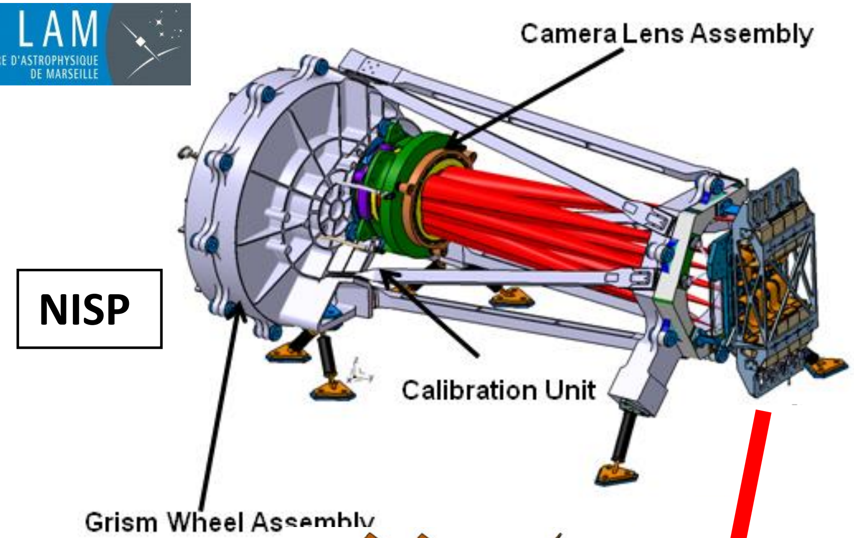
LWIR DH Interferometry

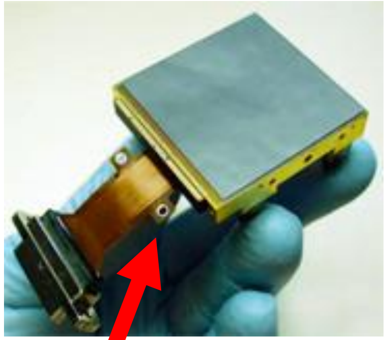
- Application in space metrology : EUCLID focal plane array



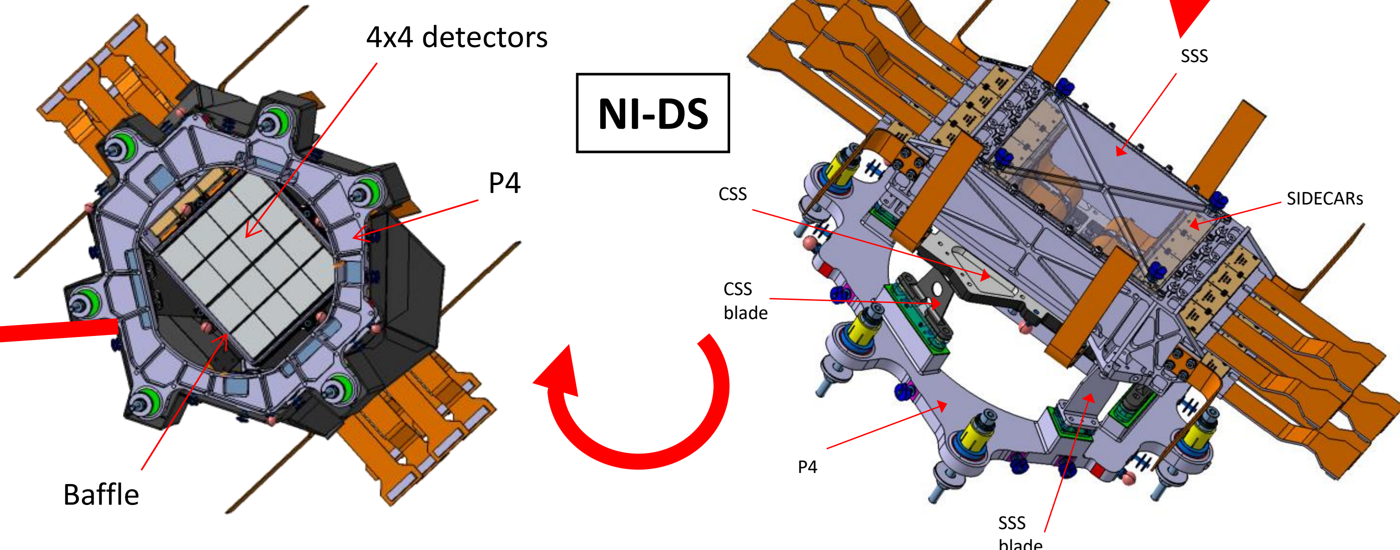
LWIR DH Interferometry

- Application in space metrology : EUCLID focal plane array
  - NISP Detection System (NI-DS)
    - Matrix of 4×4 detectors
    - Teledyne TIS H2RG detectors
    - FPA dimensions: 170 × 170 mm^2
    - Range: 1000 nm – 2000 nm

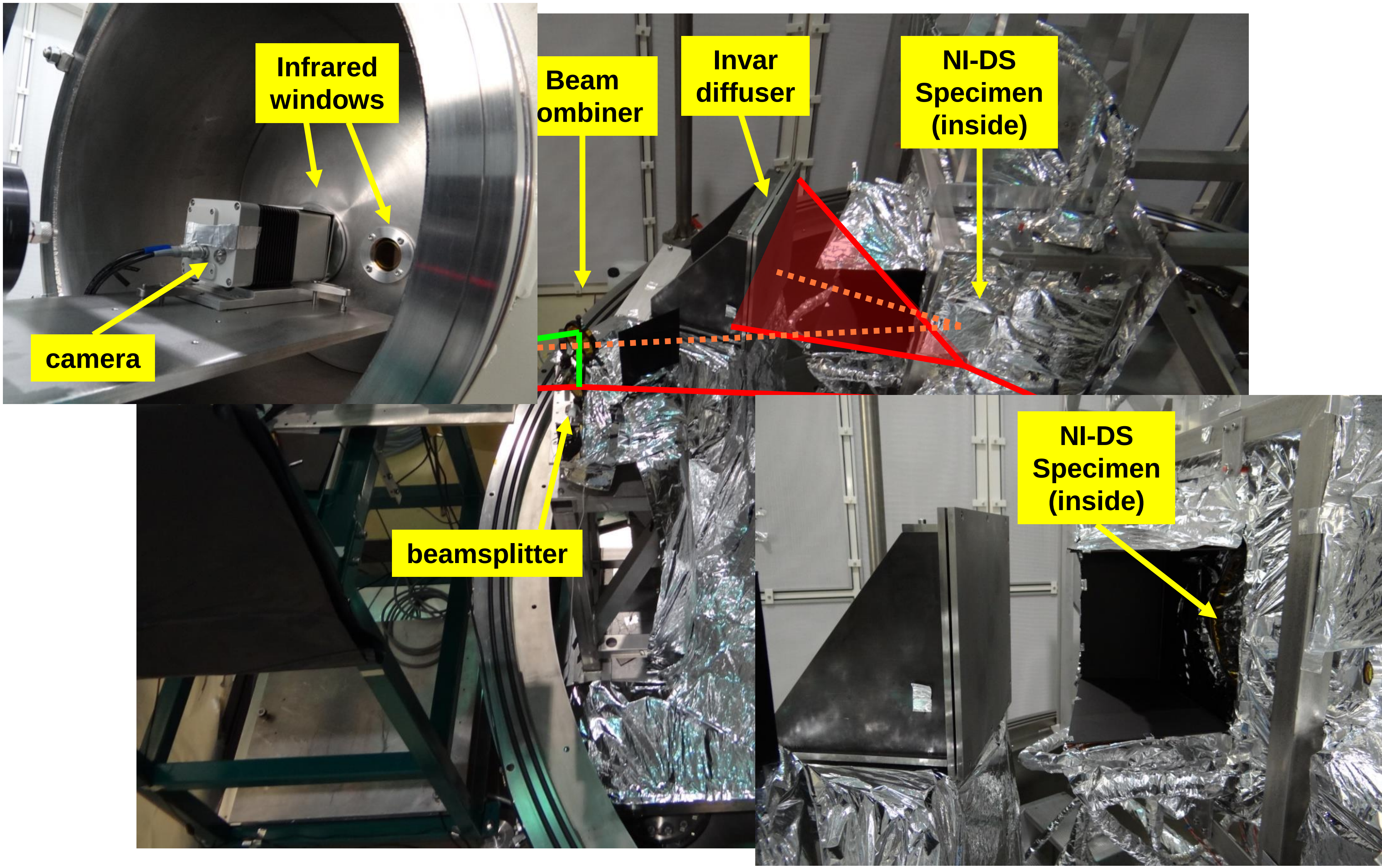




STM	STM	STM	STM
STM	STM	STM	STM
STM	STM	MUX	FM
STM	STM	FM	MUX

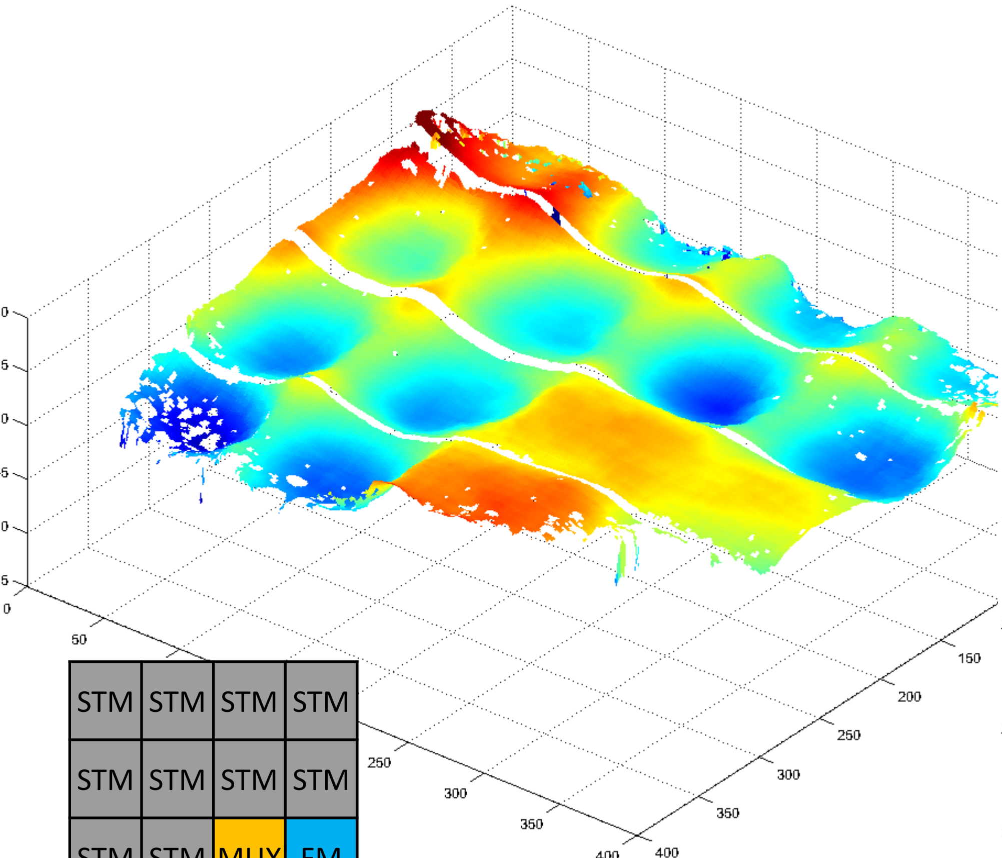


LWIR DH Interferometry

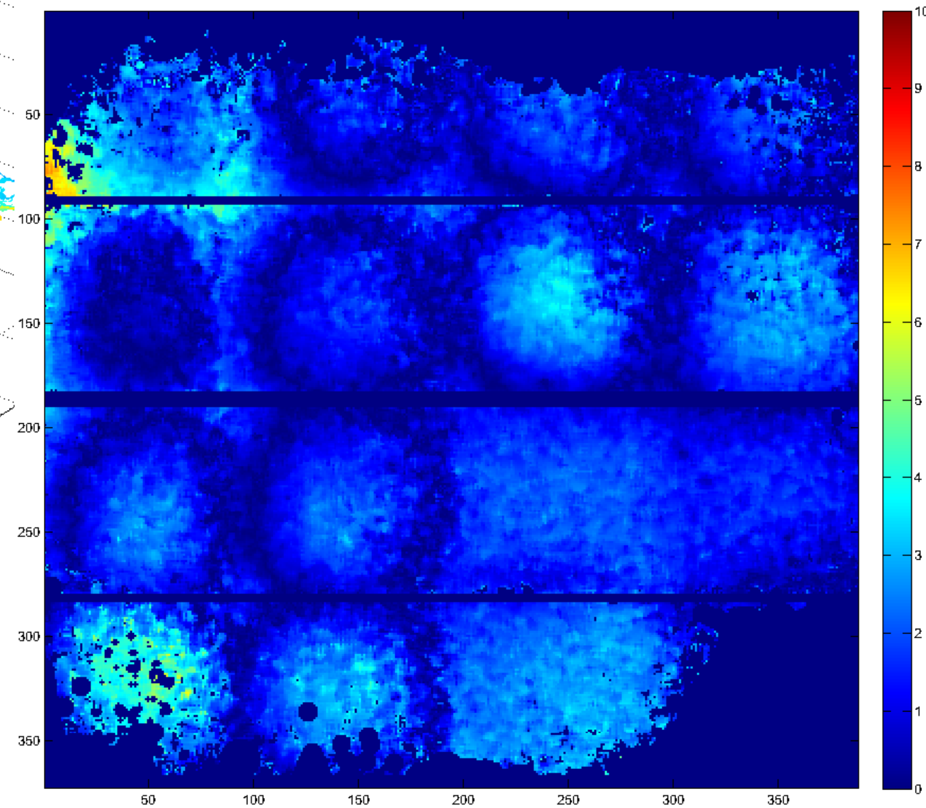


LWIR DH Interferometry

- Results: deformation map

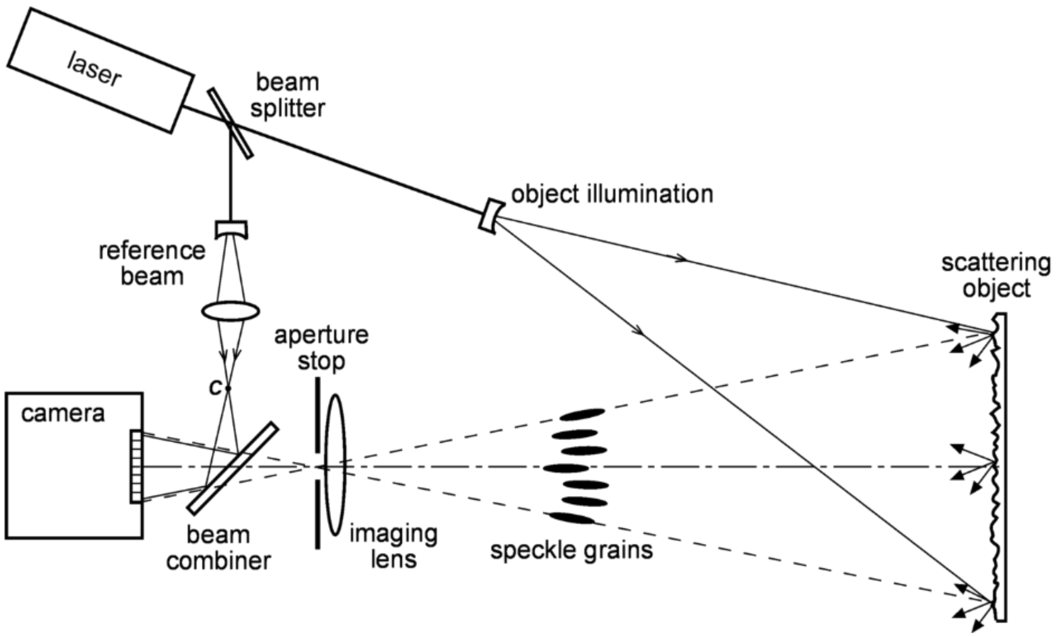


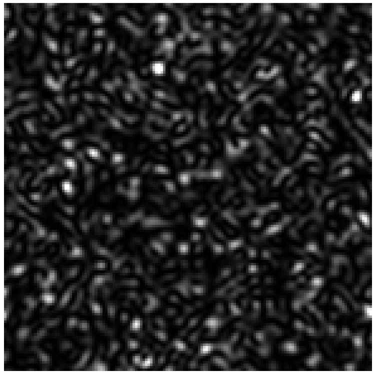
STM	STM	STM	STM
STM	STM	STM	STM
STM	STM	MUX	FM
STM	STM	FM	MUX



Speckle interferometry

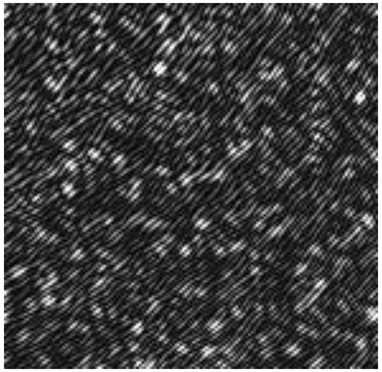
- Principle





$$\sigma_u = \sigma_v = 2.44\frac{\lambda d}{D}$$

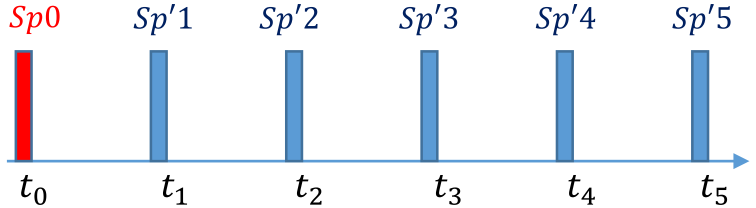
Specklegram
(interference object-reference beams)



$$Sp(x,y) = I_O(x,y) + I_R(x,y) + 2\sqrt{I_O I_R}\cos(\psi(x,y))$$

$$\psi(x,y) = \phi_R(x,y) - \phi_O(x,y)$$

Multiple exposures during object deformation



Speckle interferometry

▪ Principle - 2

After mathematical transformations:

$$|Sp(x,y) - Sp'(x,y)| \ = 2\sqrt{I_O I_R}[\cos(\psi(x,y)) - \cos(\psi(x,y) + \phi(x,y))]$$

$$|Sp(x,y) - Sp'(x,y)| \ = 4\sqrt{I_O I_R} \ \sin\left[\psi(x,y) + \frac{\phi(x,y)}{2}\right] \sin\frac{\phi(x,y)}{2}$$

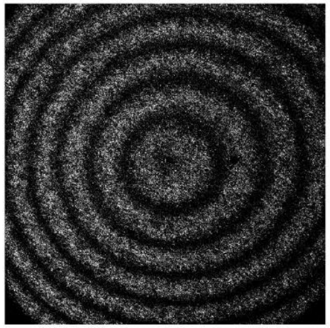
Signal at high spatial frequency

Contains the speckle

Signal at low spatial frequency

Fringes related to the deformation

"Correlation fringes"



Phase-shifting can be applied

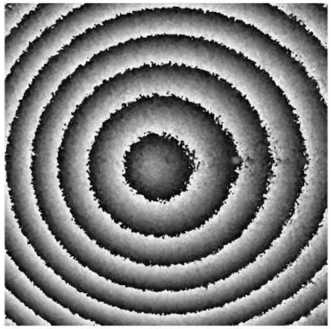
4 specklegrams with 90° phase shifts are recorded before deformation

$$\varphi(x,y) = \tan^{-1}\left[\frac{Sp_4(x,y) - Sp_2(x,y)}{Sp_1(x,y) - Sp_3(x,y)}\right]$$

4 specklegrams with 90° phase shifts are recorded after deformation

$$\varphi'(x,y) = \tan^{-1}\left[\frac{Sp'_4(x,y) - Sp'_2(x,y)}{Sp'_1(x,y) - Sp'_3(x,y)}\right]$$

$\phi(x,y)$ mod 2π

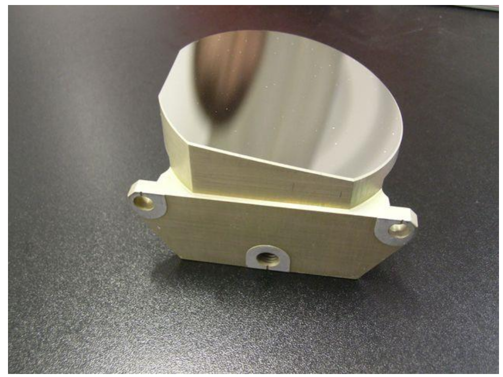


$$\phi(x,y) = \varphi'(x,y) - \varphi(x,y)$$

Speckle interferometry

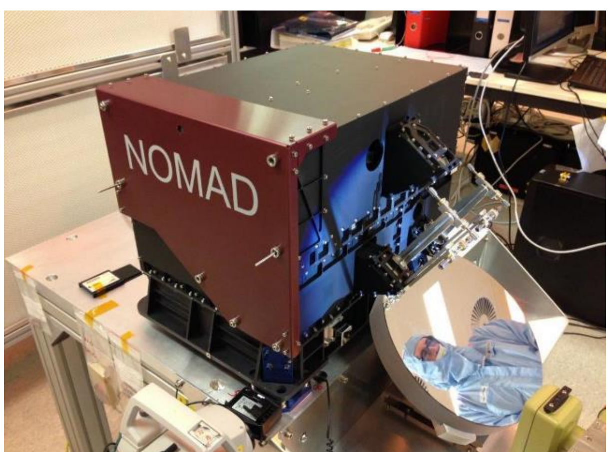
- Applications: deformation of space mirrors and comparison with multiphysics simulation

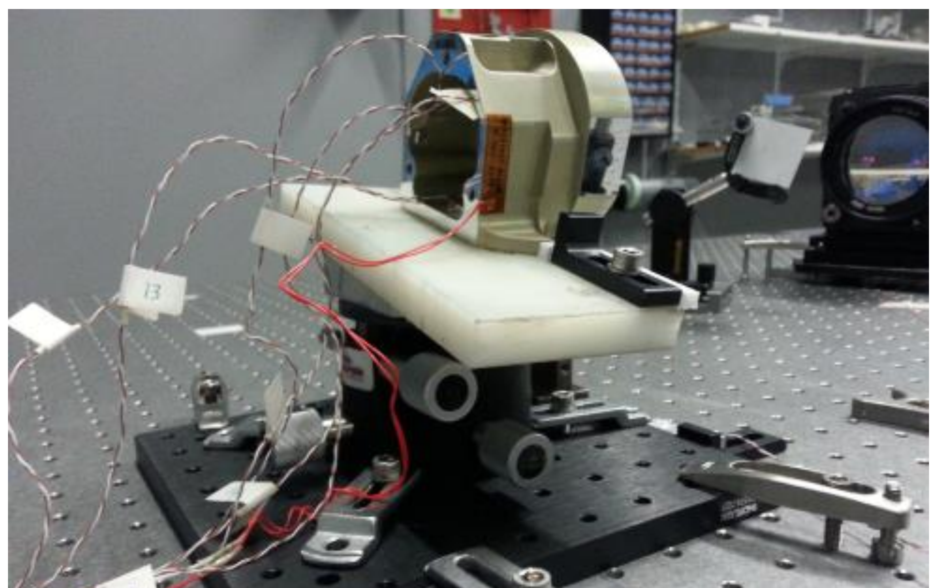
EXOMARS probe



- ***Off-axis parabola*** ∅=80 mm
- ***Full aluminum***
- ***Optical surface: diamond turning and polishing***

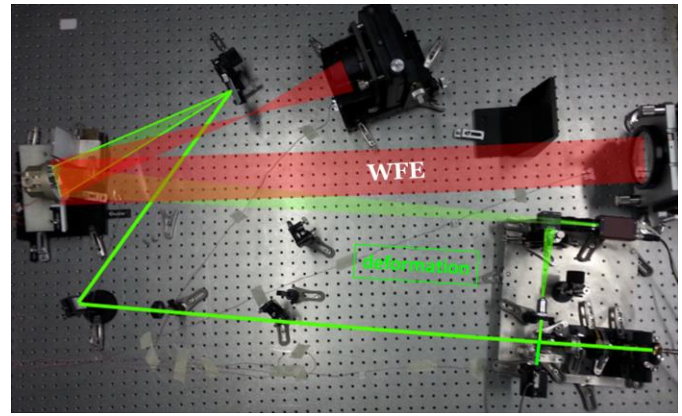
Spare mirror from NOMAD instrument

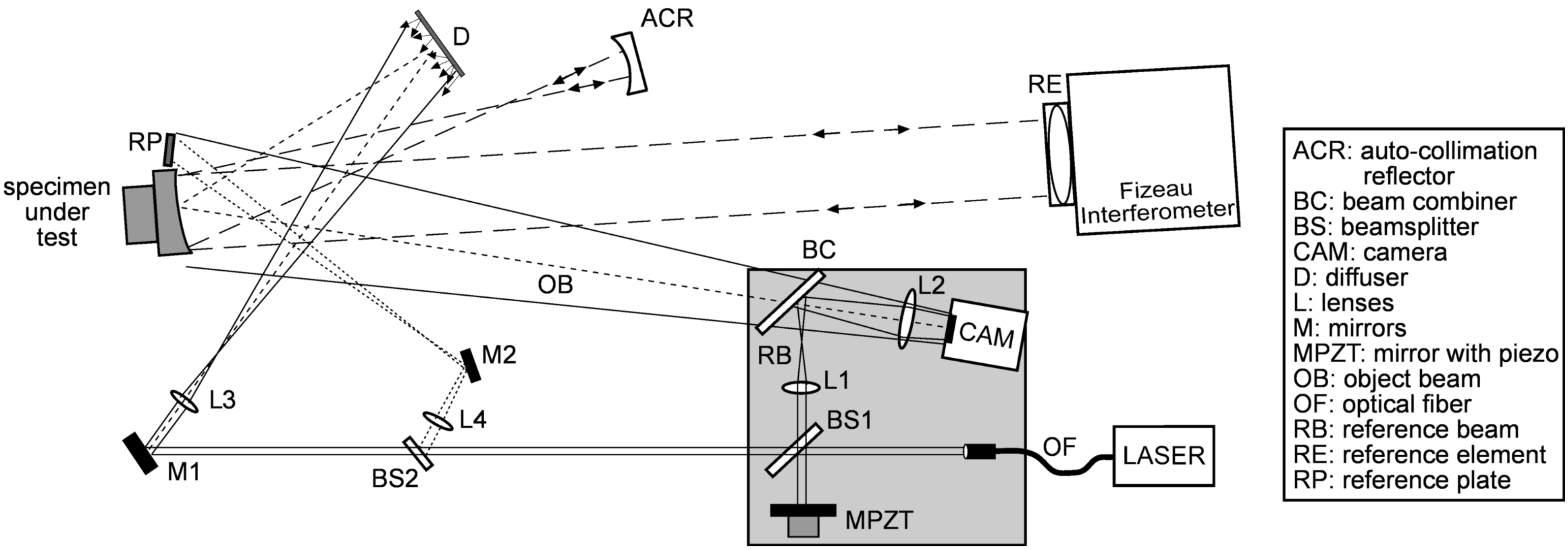




Speckle interferometry

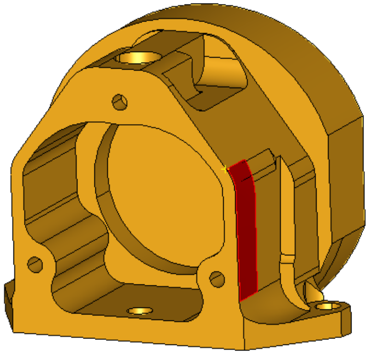
- Applications: deformation of space mirrors and comparison with multiphysics simulation
  - Measurement set-up

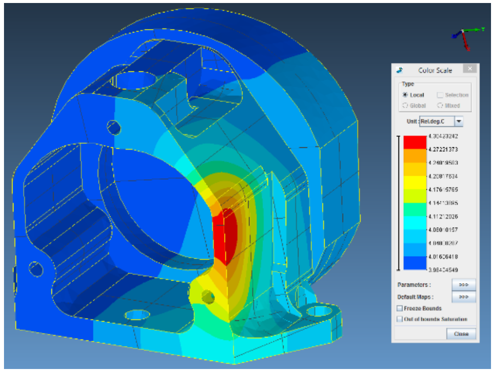




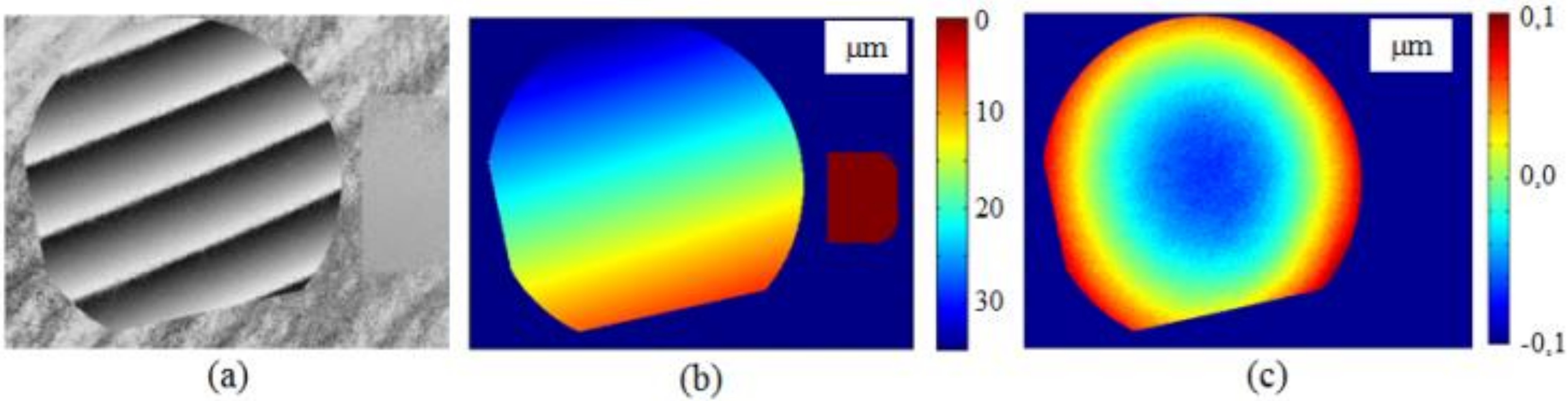
Speckle interferometry

- Applications: deformation of space mirrors and comparison with multiphysics simulation
  - Heater: temperature change well controlled and regulated for different power of heating





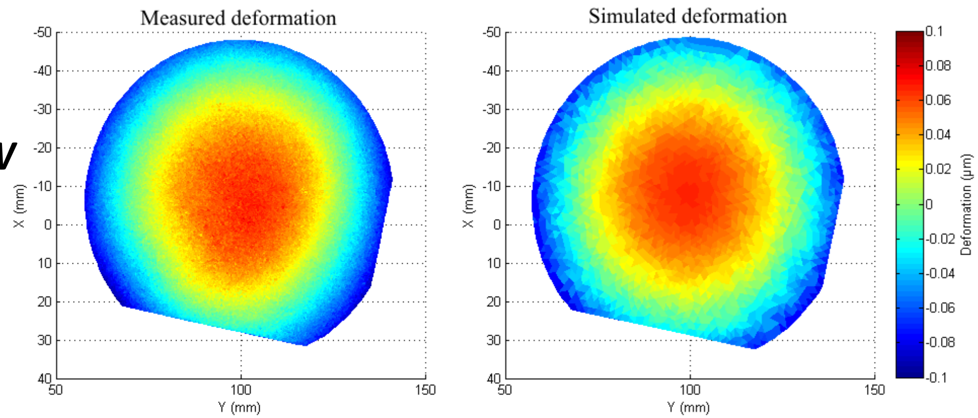
  - Measurement of deformation over time (temporal phase unwrapping)



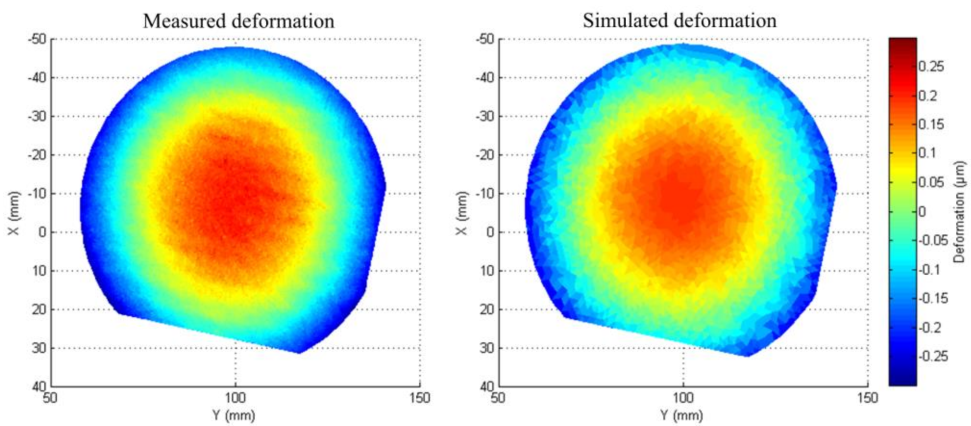
Speckle interferometry

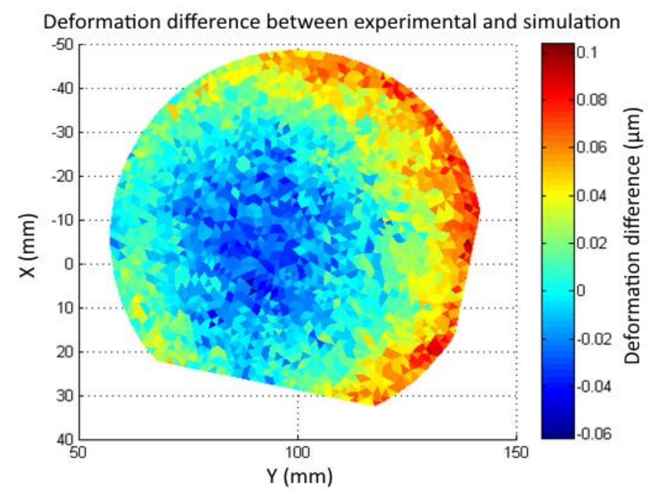
- Applications: deformation of space mirrors and comparison with multiphysics simulation
  - Residual deformation for different powers of heating

Power: 0.5 W



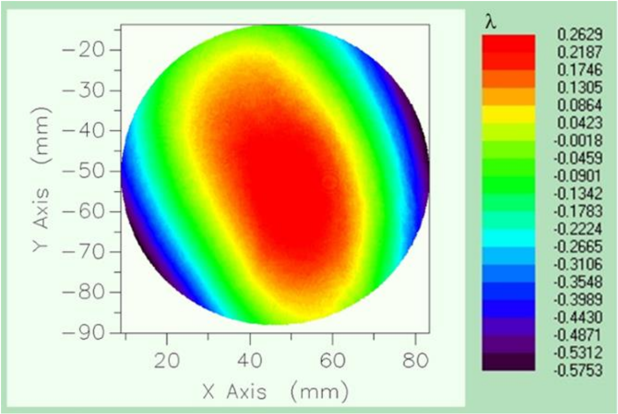
Power: 2 W



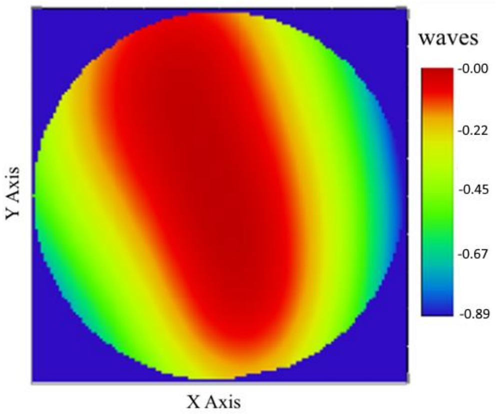


Speckle interferometry

- Applications: deformation of space mirrors and comparison with multiphysics simulation
  - Optical aberrations:
    - ➢ Measured by Fizeau interferometer and processed by Intelliwave software
    - ➢ Simulated deformed surface is prepared for Zemax optics software and aberration computed by Zemax



Experimental



Simulated

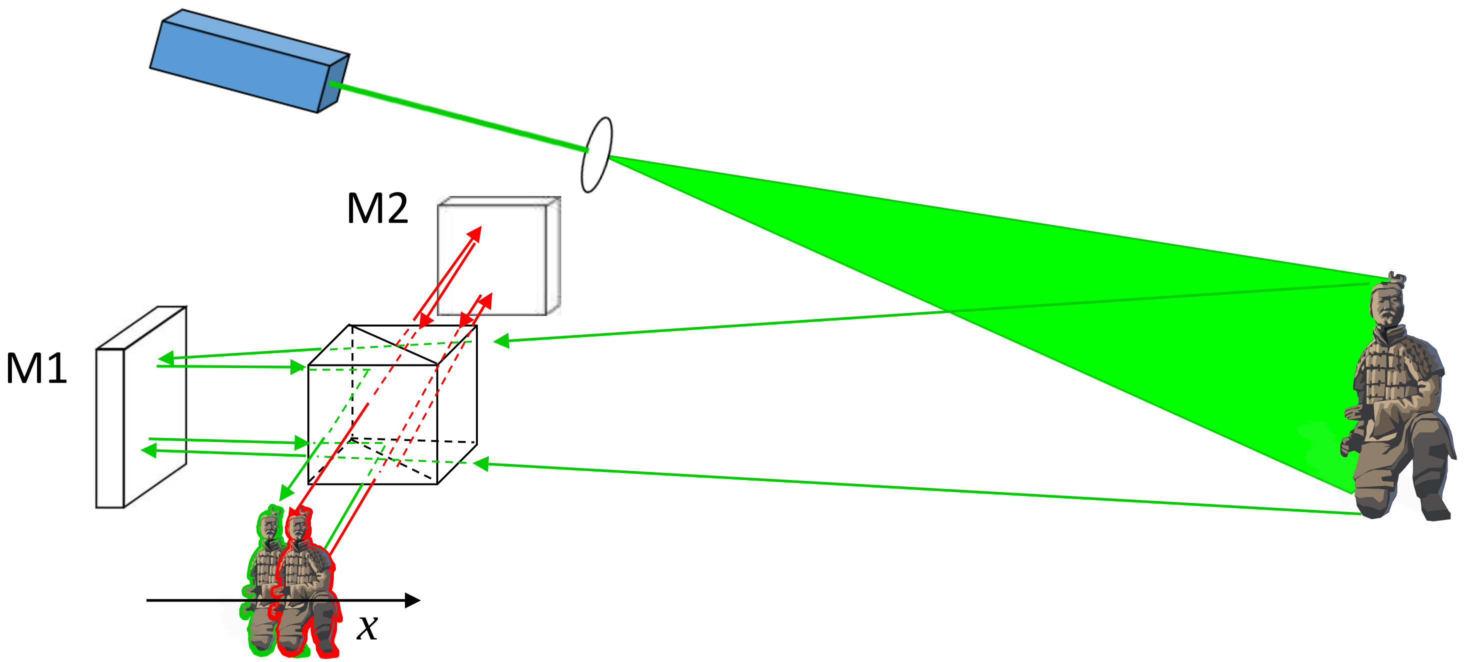
Table 2. Comparison Between Experimental (exp) and Simulated WFE Indicators

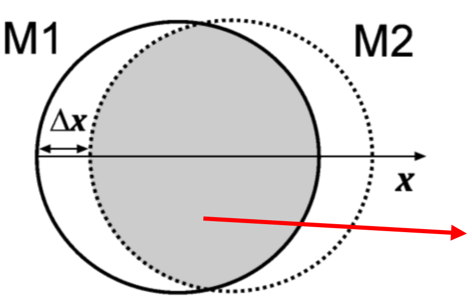
	Exp Value (waves)	Simulated Value (waves)	Relative Error (%)
PtV	0.86	0.89	3.5
RMS	0.20	0.20	0
Focus	−0.27	−0.25	7.4
X-ast	−0.22	−0.28	27.3
Y-ast	−0.20	−0.18	10.0

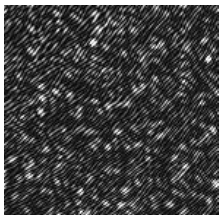
F. Languy et al, "Space mirror deformation: from thermomechanical measurements by speckle interferometry to optical comparison with multiphysics simulation", Appl. Opt. 57 (2018)

Shearography

- Principle: speckle shearing interferometry







$$Sh(x,y) = I_{O,M1}(x,y) + I_{O,M2}(x,y) + 2\sqrt{I_{O,M1} I_{O,M2}} \cos(\psi(x,y))$$

$$\psi = \varphi_{O,M1} - \varphi_{O,M2} = \frac{\partial \varphi_O}{\partial x} \Delta x$$

x : direction optical shear

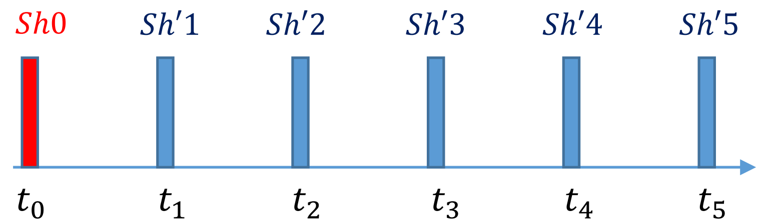
Δx : amplitude of shear

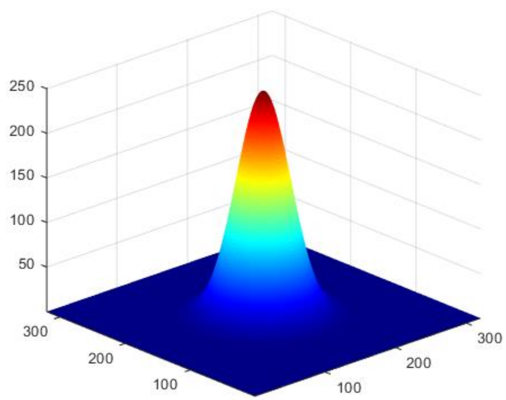
Shearography

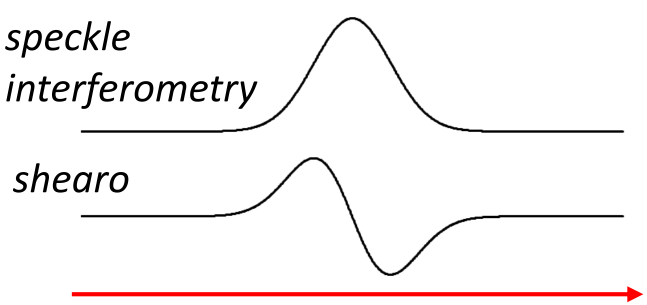
- Principle: speckle shearing interferometry - 2

Multiple exposures during object deformation

Application of phase-shifting for each state





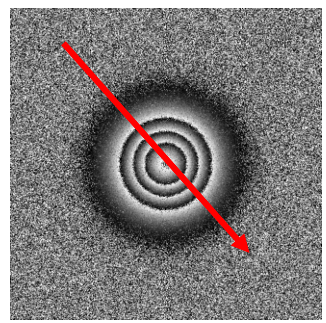


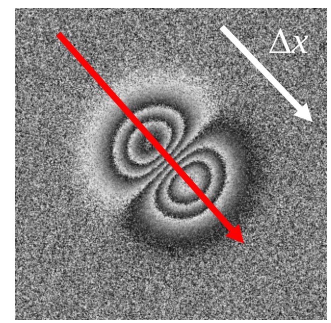
speckle interferometry

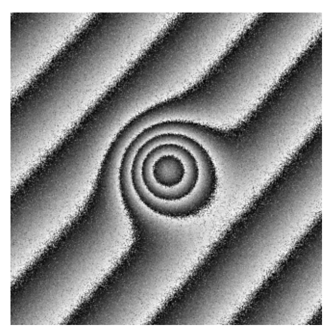
$$\phi = \frac{4\pi}{\lambda} L_{\perp}$$

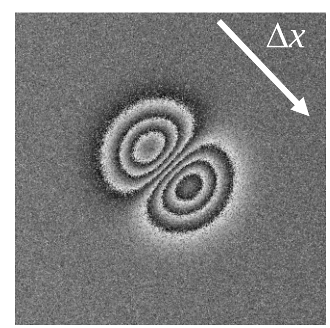
shearography

$$\phi = \frac{4\pi}{\lambda} \frac{\partial L_{\perp}}{\partial x} \Delta x$$



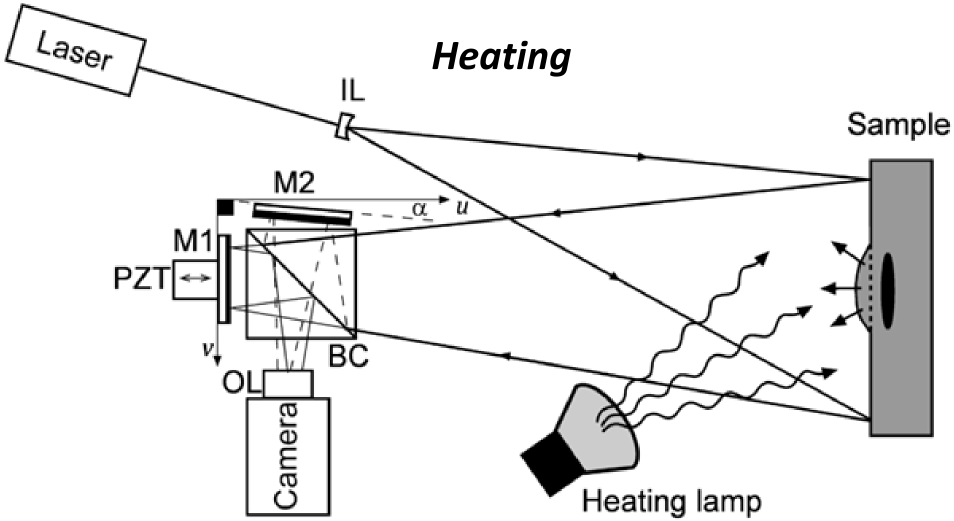




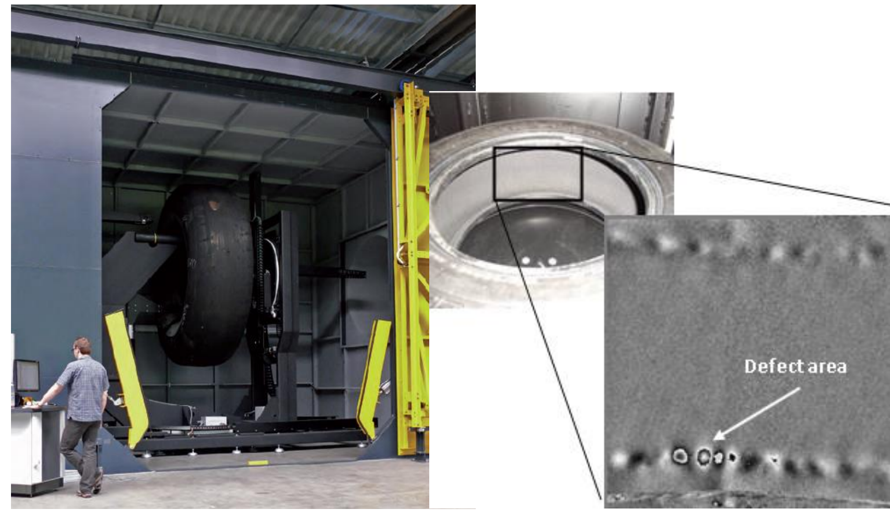


Shearography

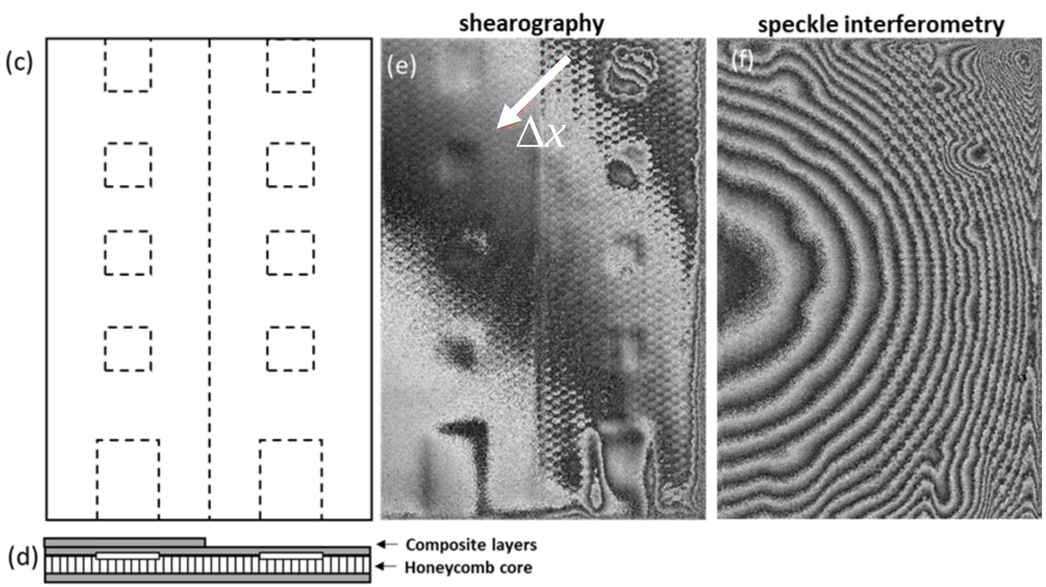
- Application in defect detection

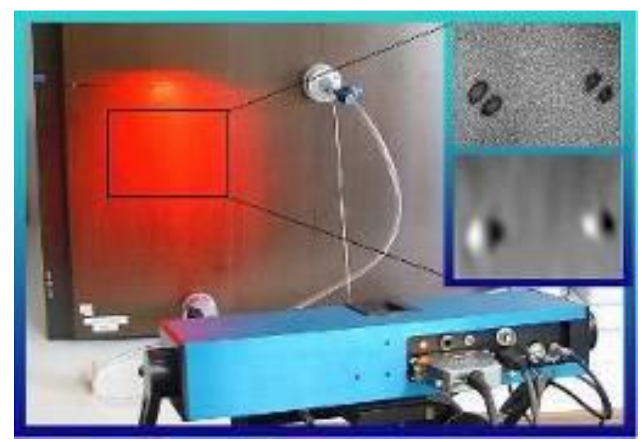


Heating



Pressure variations



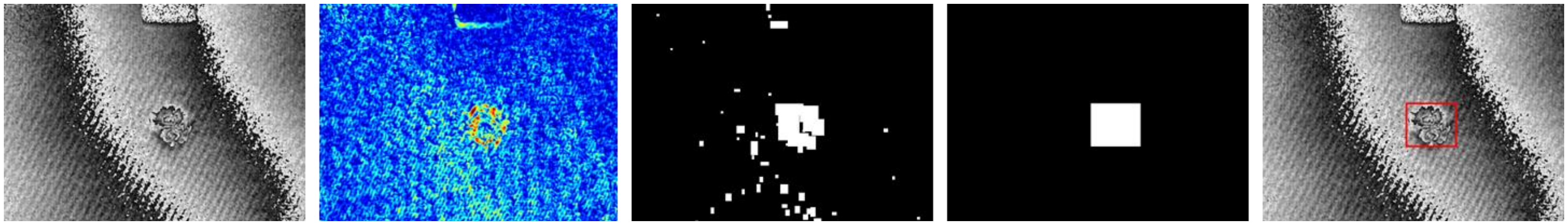


Vibration

Shearography

▪ New post-processing methods

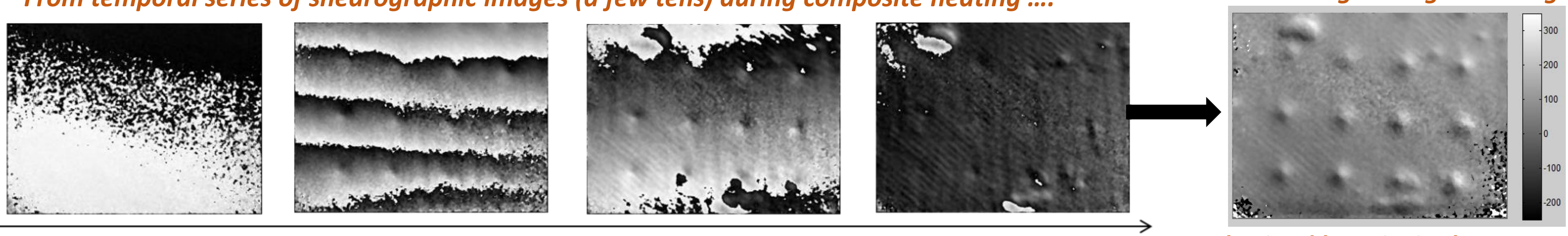
Automated recognition of defect signature in shearography



Analysis of temporal series

From temporal series of shearographic images (a few tens) during composite heating ….

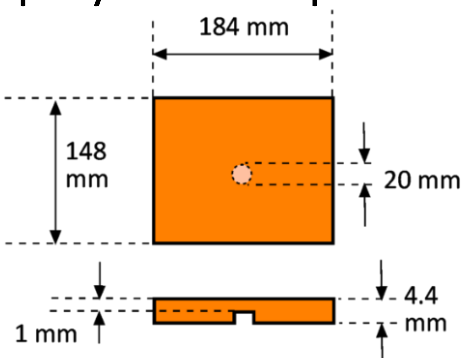
… To a single image showing all



obtained by Principal Components

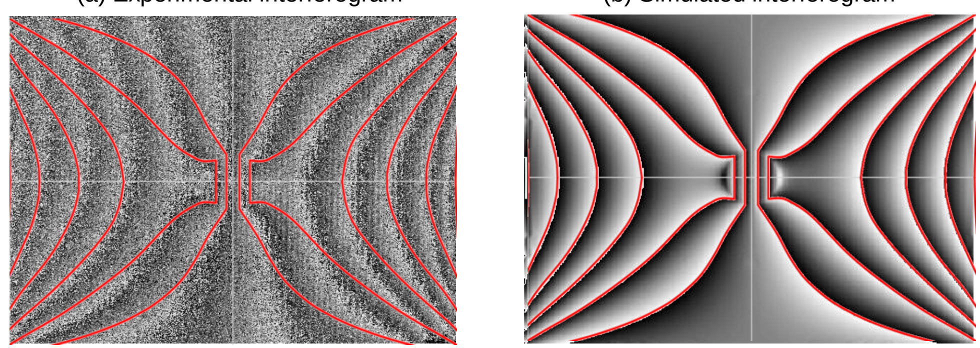
▪ Comparison with finite element modeling

Simple symmetric sample



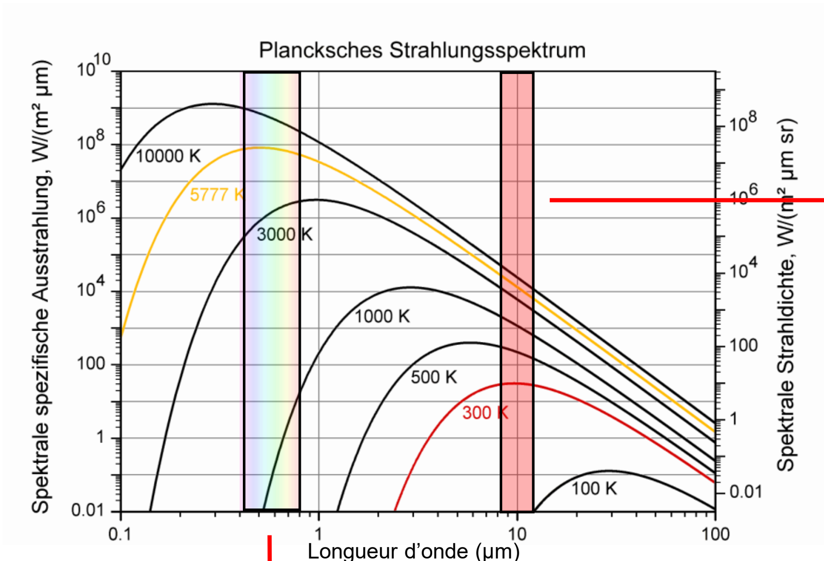
(a) Experimental interferogram

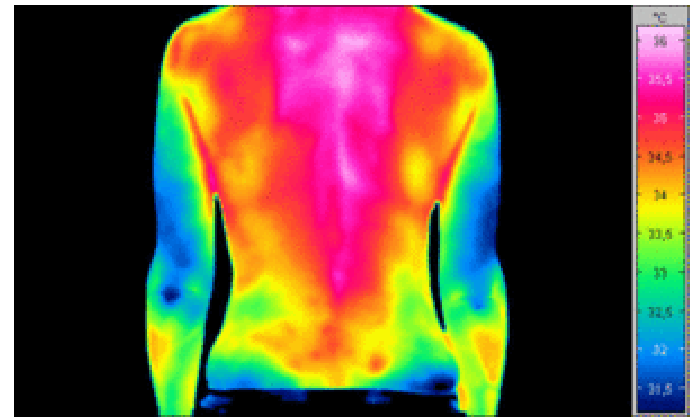
(b) Simulated interferogram

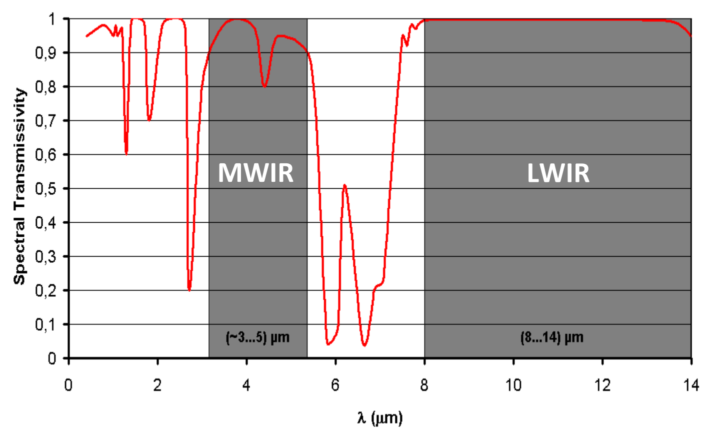


Thermography

- Measure infrared radiation emitted by objects

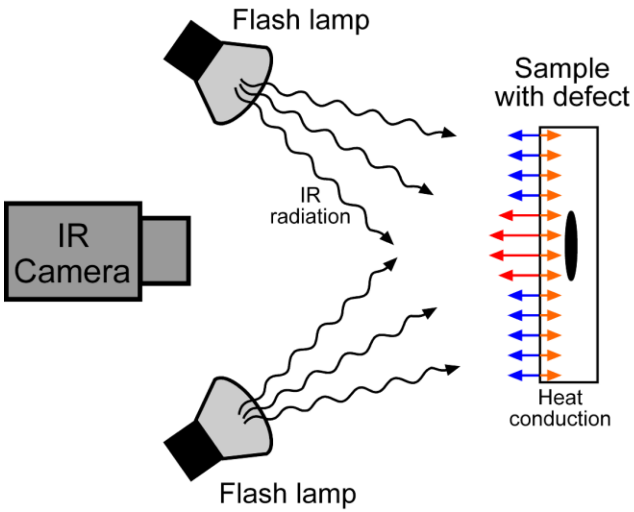


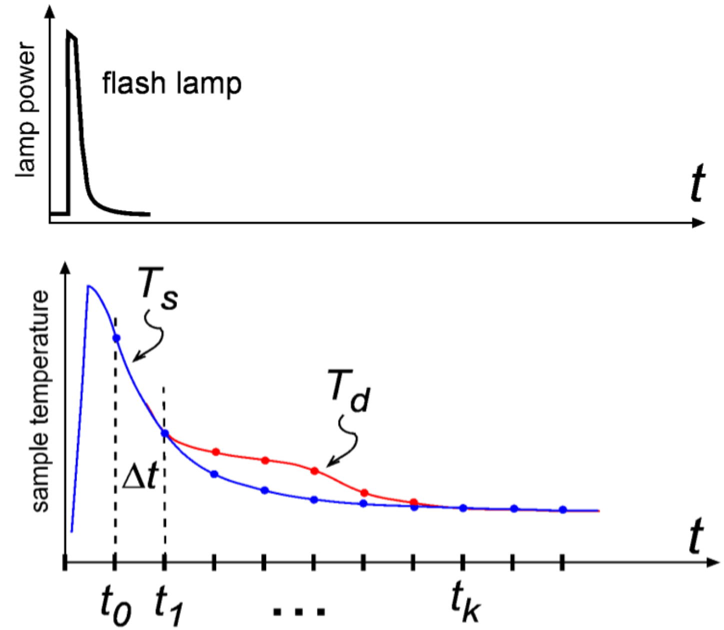


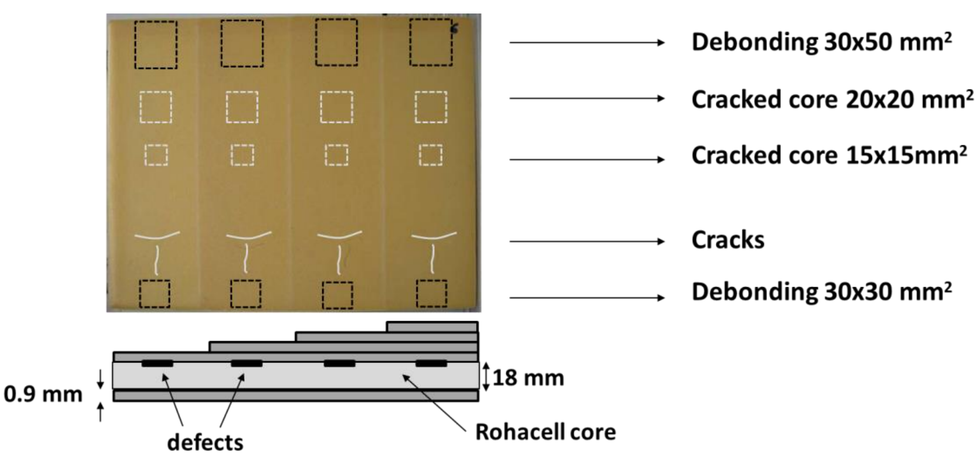


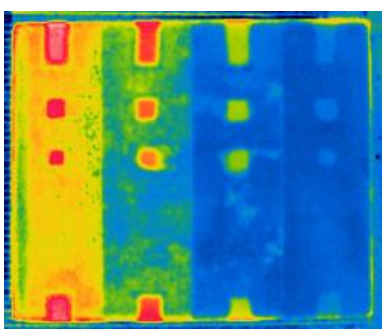
Active Thermography

- Method for detecting defects





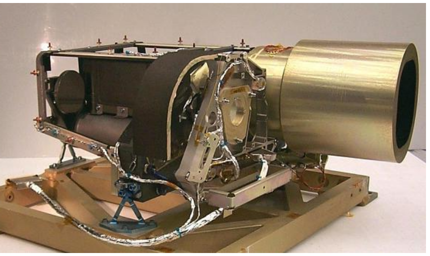


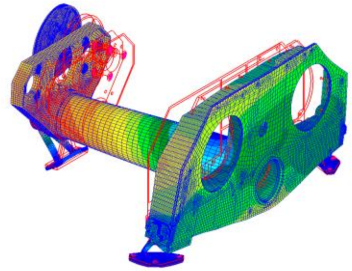


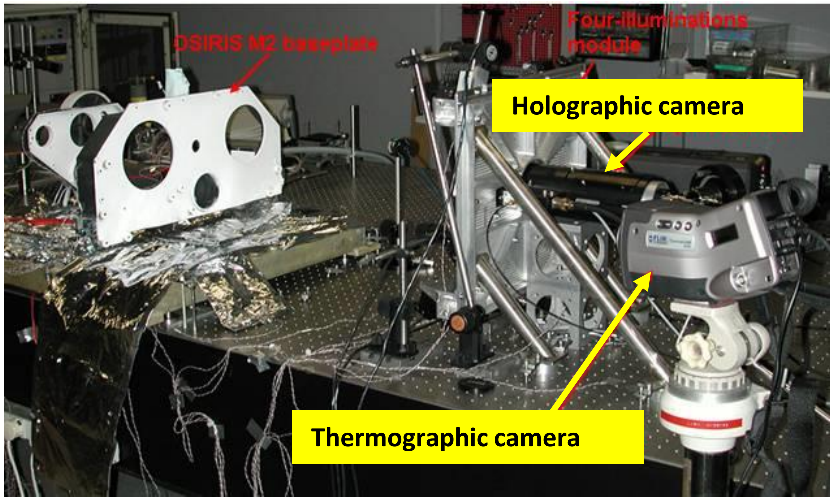
Combination holography-thermography

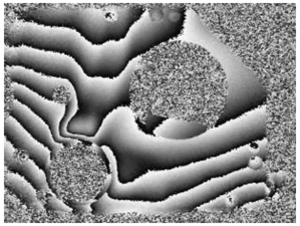
- Useful examples

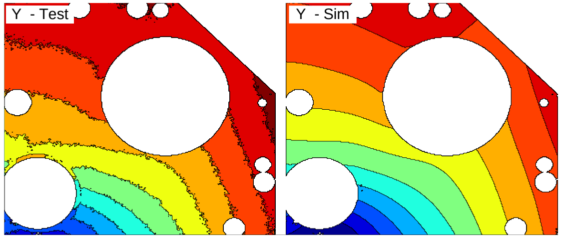
Thermo-mechanical deformation of space composite structures





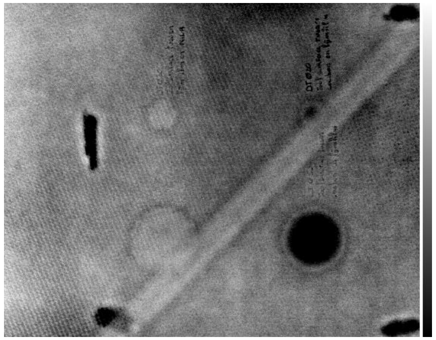




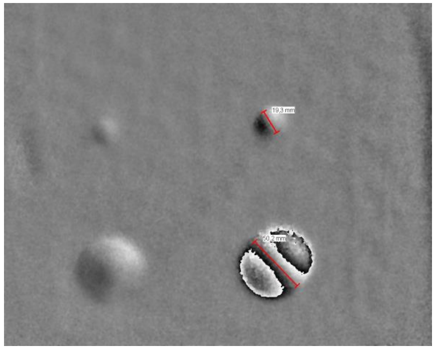


Defect detection in aeronautics composite structures

Thermography



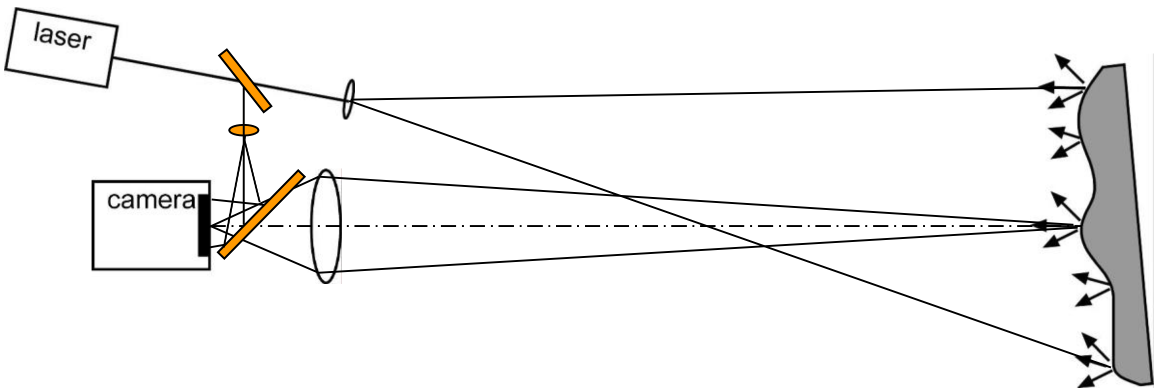
Shearography



LWIR Speckle interferometry

- Combination of thermography and holography in a single sensor

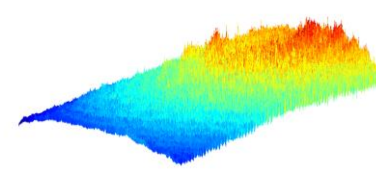
Holography: Speckle interferometry (“image holography” setup)



LWIR Thermographic camera
(Microbolometer array)

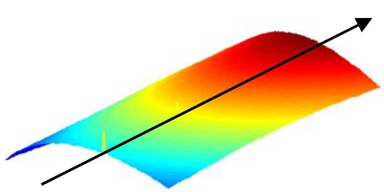
CO2 laser

$$Sp_{LWIR}(x,y) = I_{thermal}(x,y) + I_o(x,y) + I_r(x,y) + 2\sqrt{I_o I_r}\cos(\psi(x,y))$$



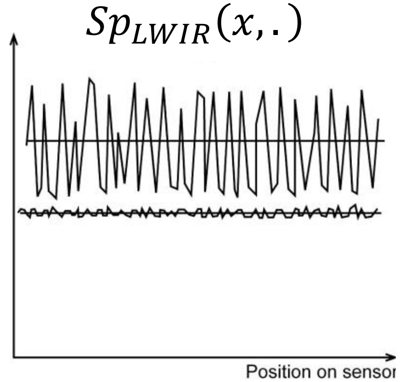
$$\psi(x,y) = \varphi_r(x,y) - \varphi_o(x,y)$$

Laser **OFF**

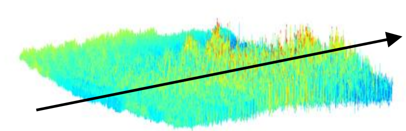


Thermal background

$Sp_{LWIR}(x,.)$



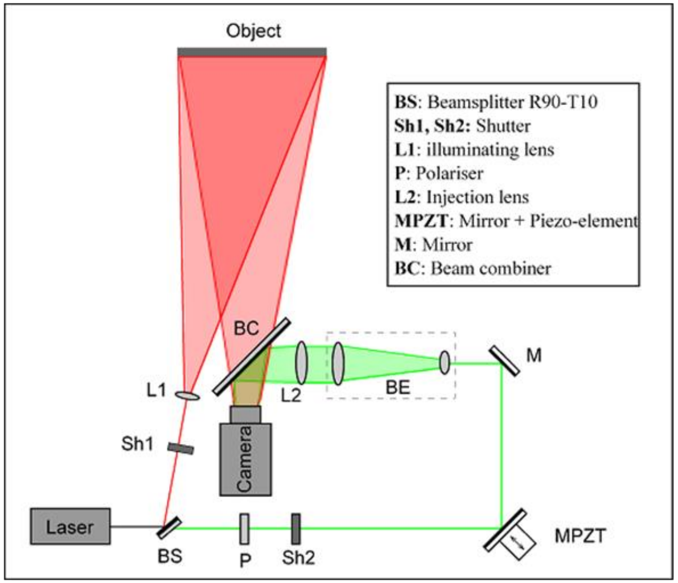
Laser **ON**



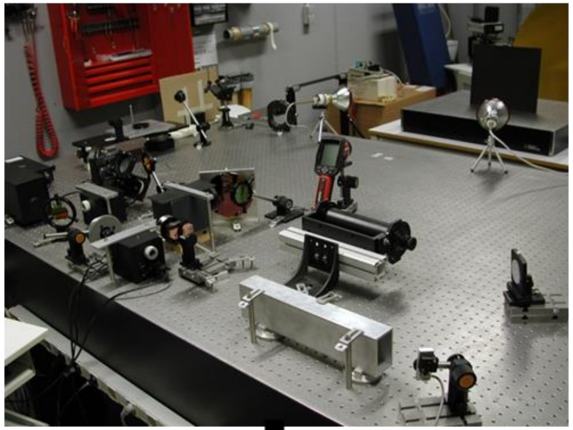
Hologram/Specklegram

LWIR Speckle interferometry

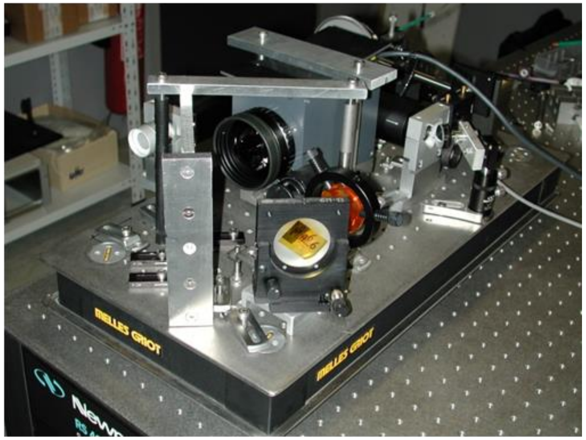
- Development of setup (collaboration with ITO, Optrion)



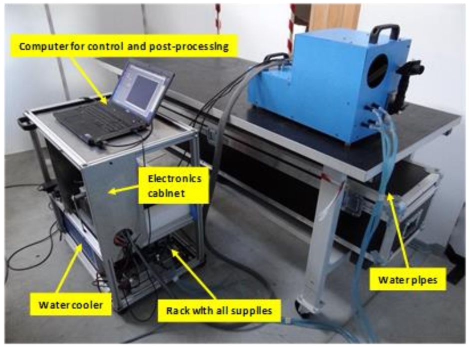
Laboratory set-up



Laboratory compact prototype

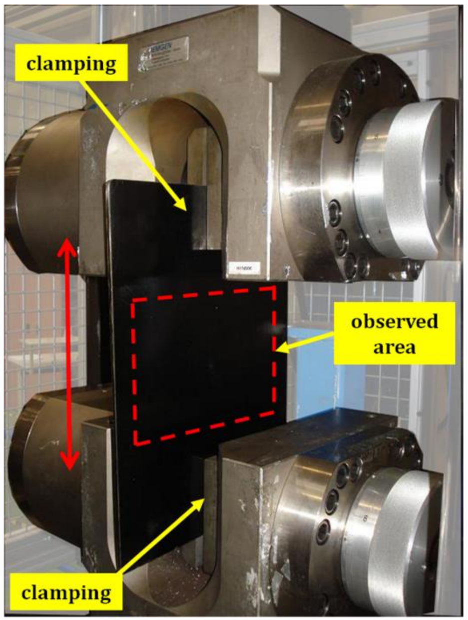


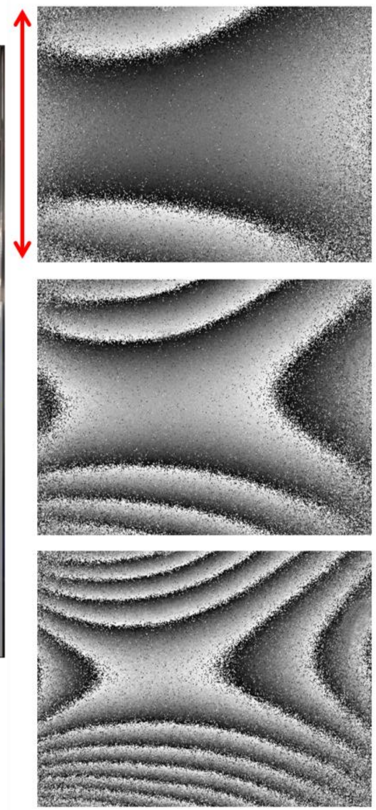
Transportable field prototype

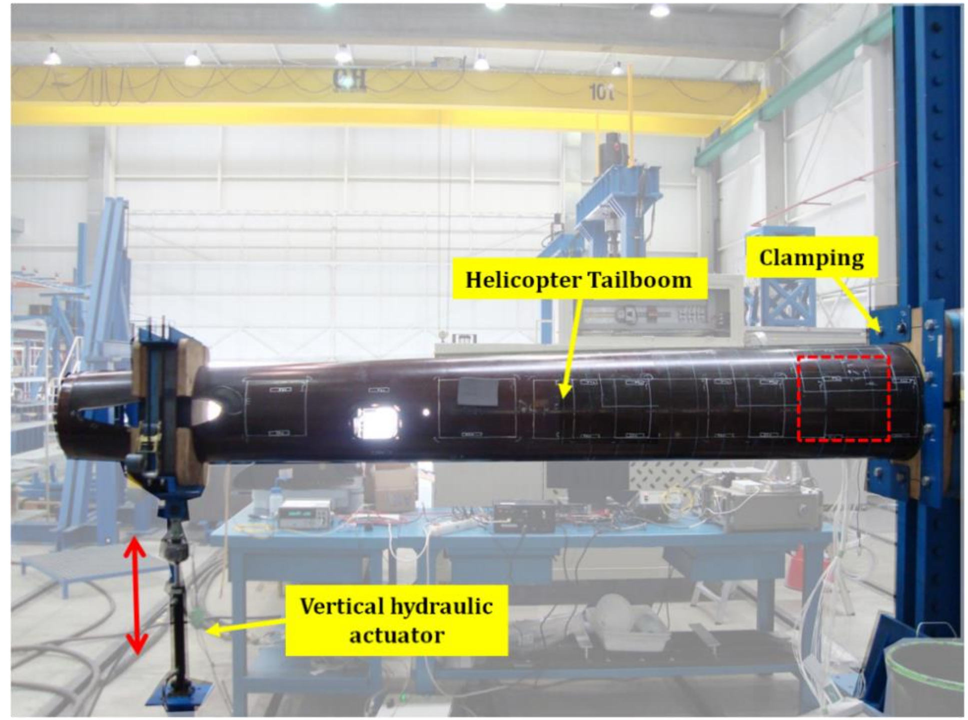


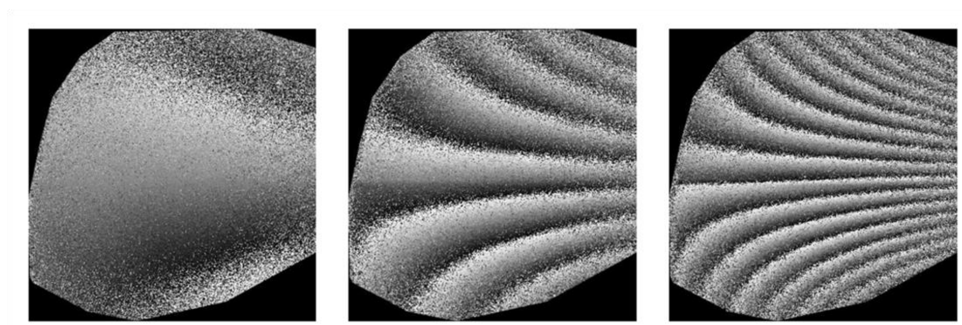
LWIR Speckle interferometry

- Measurements of large deformations in field conditions



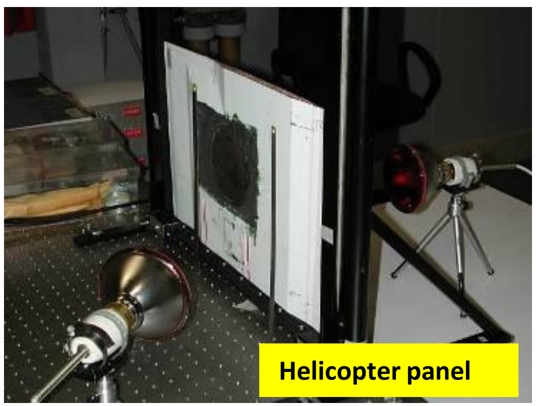




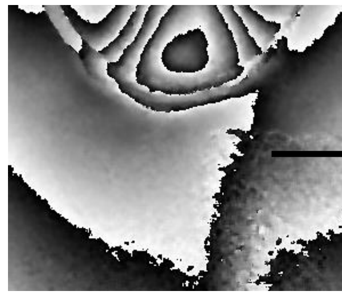


LWIR Speckle interferometry

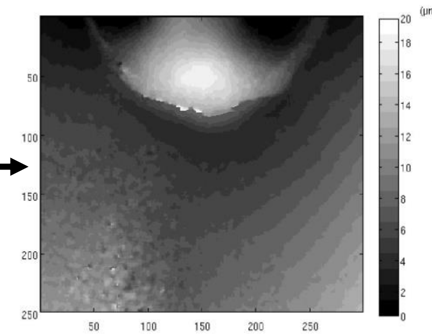
- Decoupling temperature and deformation information



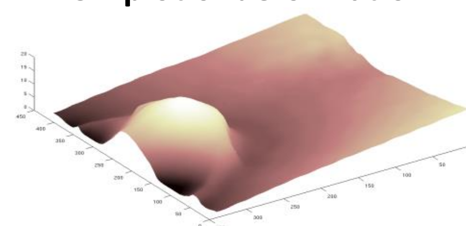
Phase mod 2π



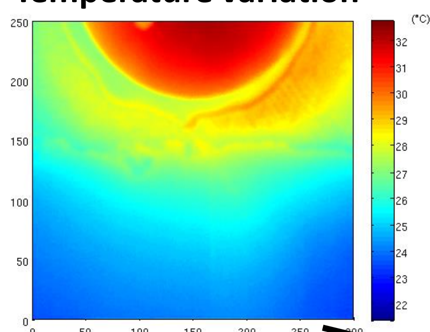
Unwrapped phase

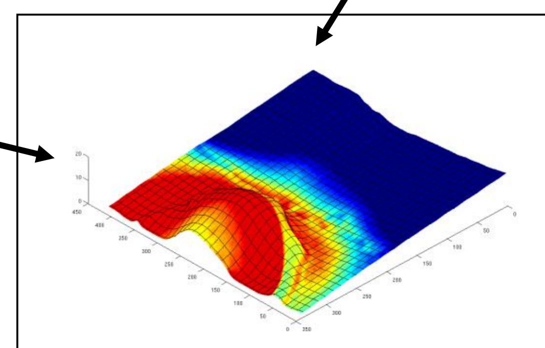


3D plot of deformation



Temperature variation





LWIR Speckle interferometry

- Measurements in industrial facilities at Airbus

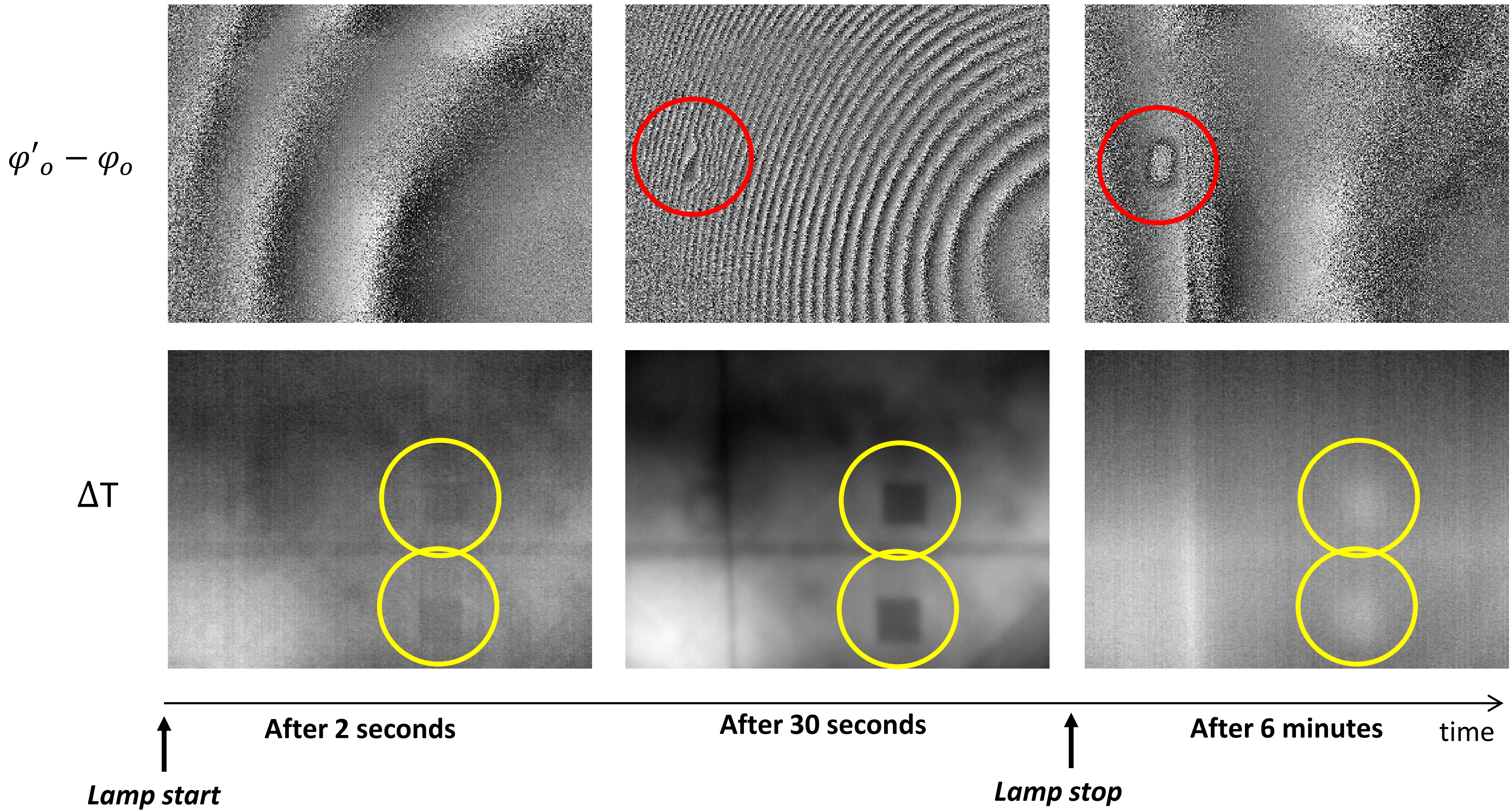
Airbus D41 « Tear Down »

« All Composite Aircraft » A350 Fuselage

FANTOM industrial prototype

LWIR Speckle interferometry

- Measurements in industrial facilities at Airbus

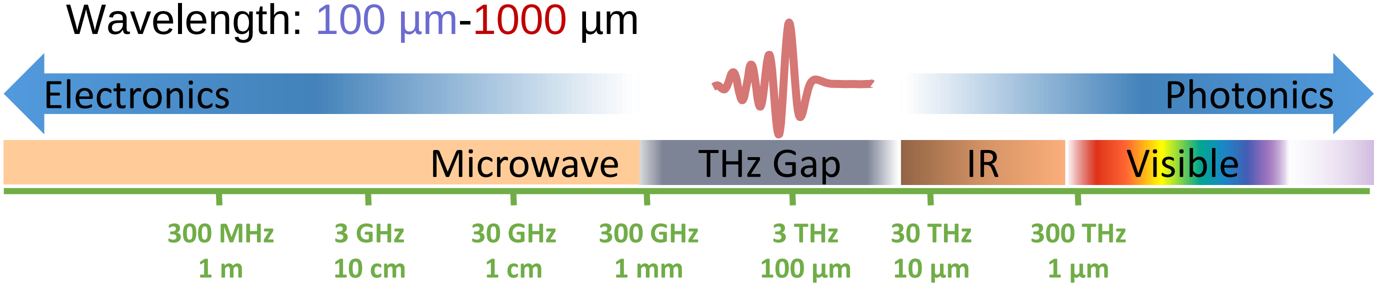


Terahertz Imaging and Holography

Generalities

- Terahertz wave range (1 THz=10^{12} Hz)
- Sandwiched between the microwave and infrared
- Frequency: 0.3-3 THz

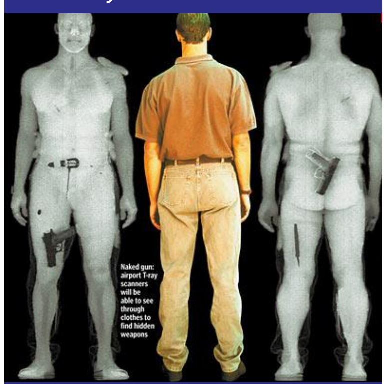
  Wavelength: 100 µm-1000 µm



The “cliché” about THz:

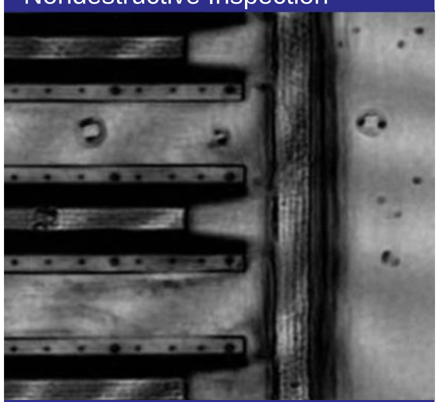
- ✓ Nonpolar material penetration without ionization
- ✓ Spectroscopic features

Security and Defense



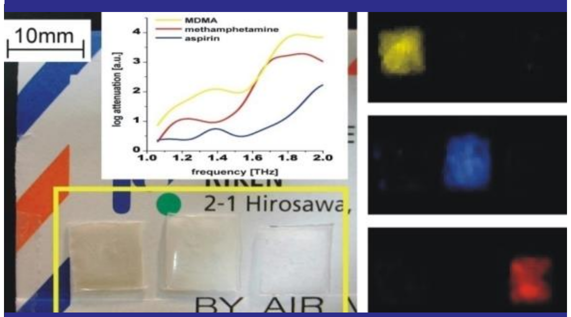
Source: “THz scanner imagery”, www.dailymail.co.uk

Nondestructive Inspection



Source: “Damage and defect inspection with terahertz waves” by Redo-Sanchez *et al.*, 2006

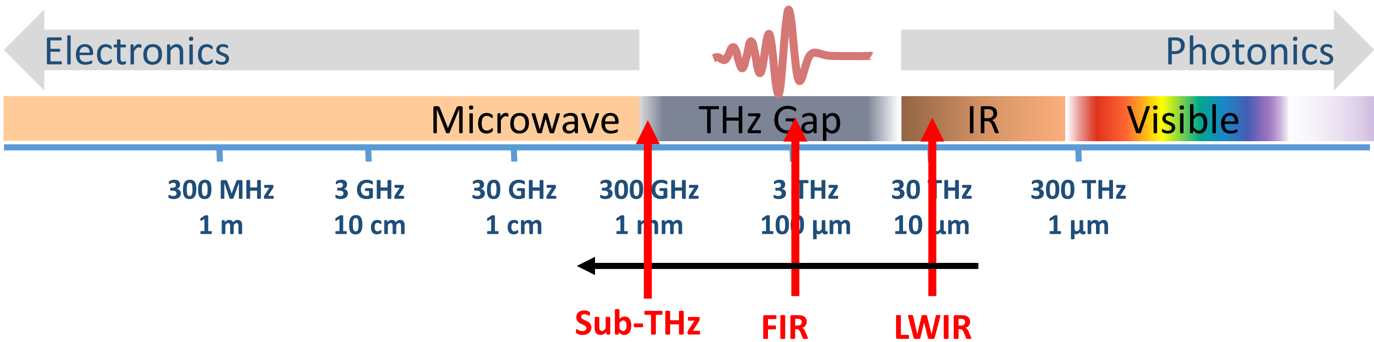
Identification of drugs and explosives



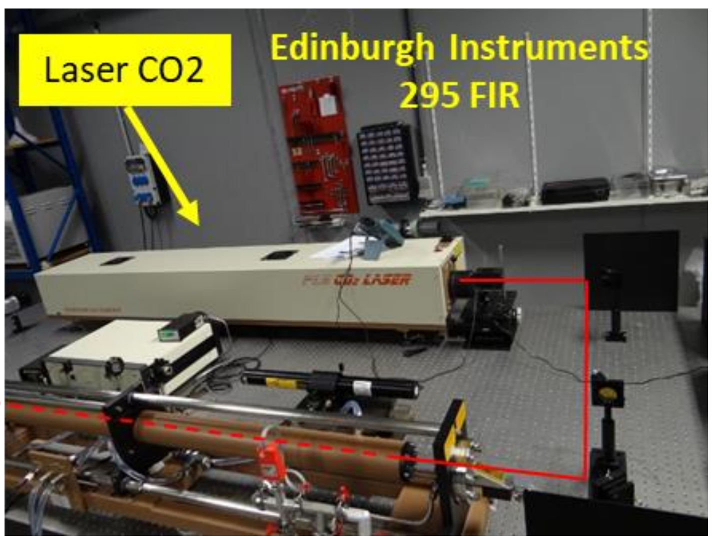
Source: “Non-destructive terahertz imaging of illicit drugs using spectral fingerprints” by Kawase *et al.* ,2003

Terahertz Imaging and Holography

- Our motivation: transfer our knowledge of LWIR to FIR and beyond



Gas laser



P=500 mW @ λ=118 μm

Uncooled microbolometer array cameras

Optimized FIR camera

384×288
35 μm pitch

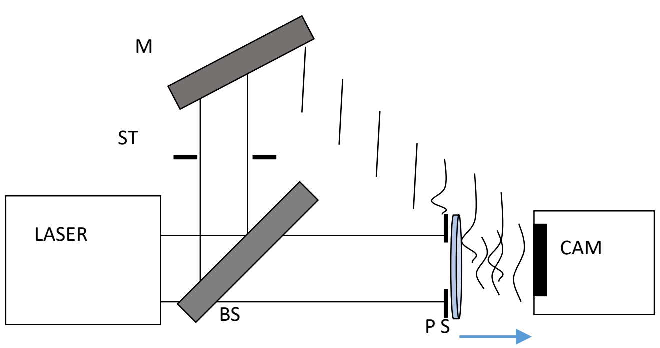
LWIR camera

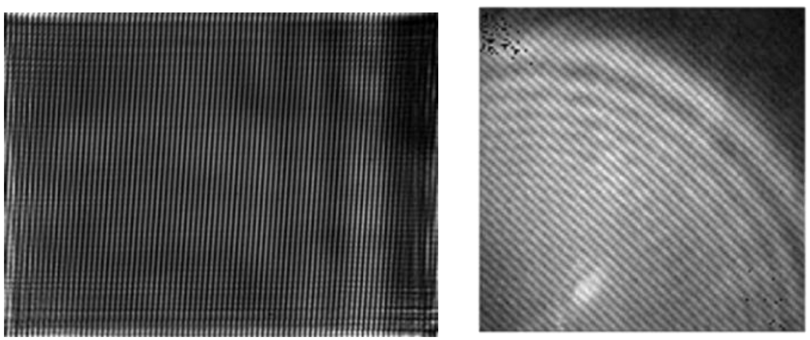
640x480
17 μm pitch

LWIR camera has good response in FIR !!
(Without lens…)

Terahertz Imaging and Holography

- Validity of paraxial approximation at FIR
  - Object must be very close to the sensor (a few cm)
  - Cannot enter the reference beam…..
  - Reconstruction by S-FFT feasible but lateral resolution very poor
- Solution: Use Angular Spectrum Method (ASM)
  - Size of reconstructed object = size of detector
  - Lateral resolution proportional to distance object-sensor z
  - Good resolution = object close
  - Reference beam occlusion ***Image degradation !***



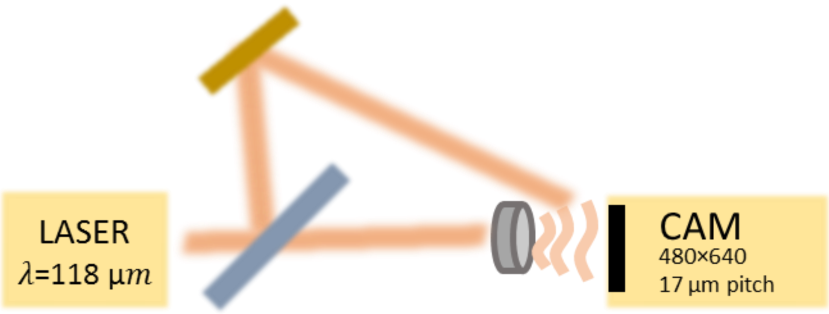


Recorded hologram with occlusion

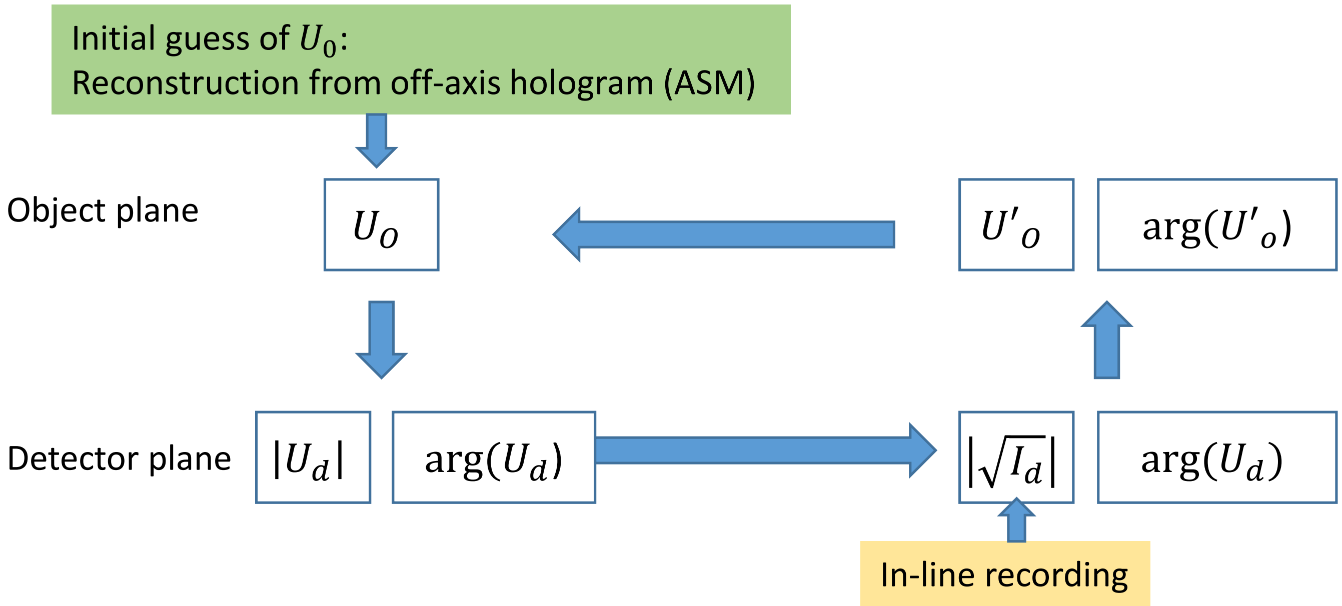
Terahertz Imaging and Holography

- Use of phase retrieval to improve resolution

Initial guess   Off-axis digital hologram

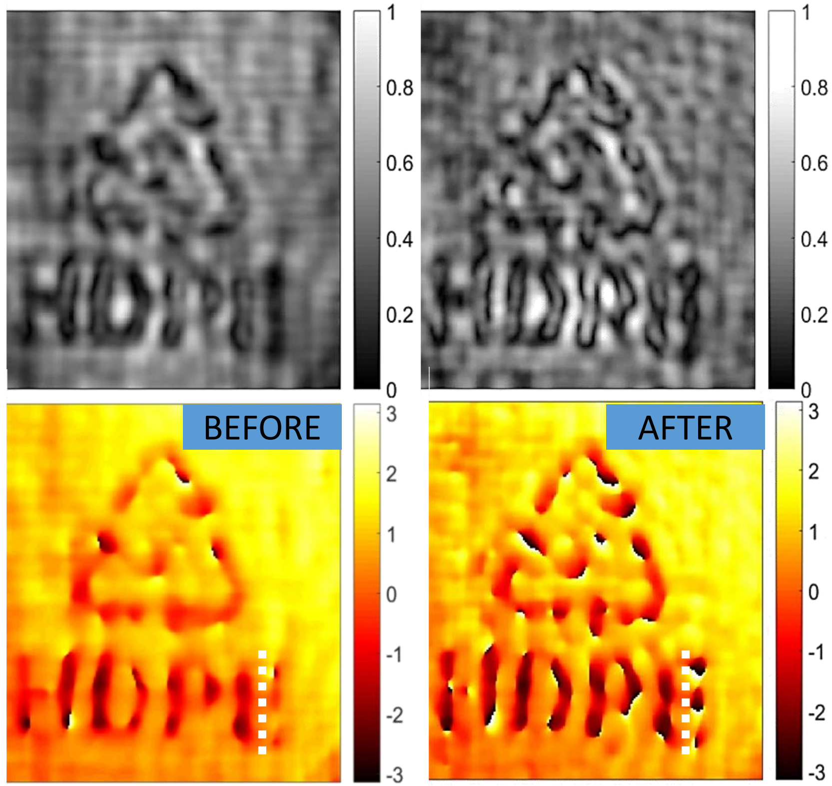


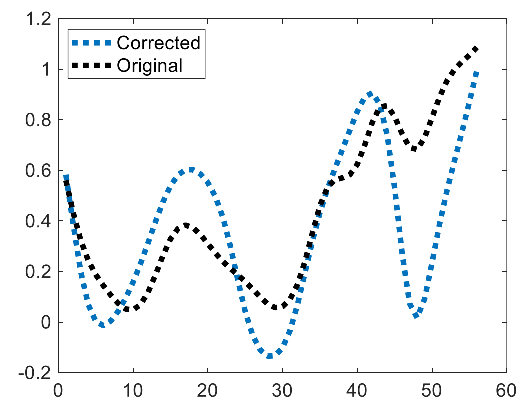
In-line recording



Terahertz Imaging and Holography

- Use of phase retrieval to improve resolution





line width	162 µm
depth	60 µm
Camera size	10,88mm ×8,16mm
distance	10,5 mm
λ	**118,8 µm**

Resolution: $d_r = \frac{\lambda z}{Detector\ size}$

$d_{r,\mathrm{H}}$ = **114,7 µm**

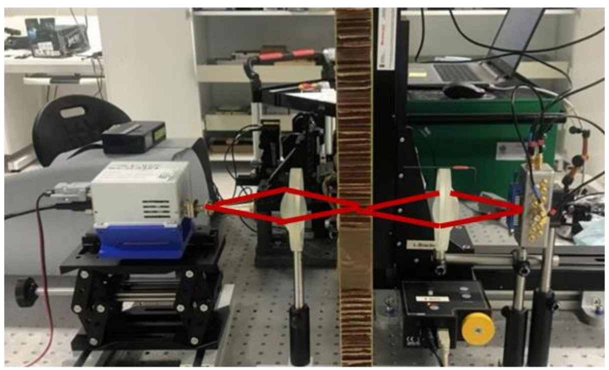
$d_{r,\mathrm{V}} = 152{,}9\ \mu\mathrm{m}$

Terahertz Imaging and Holography

- Many composite materials are not transparent enough at FIR
- Move to sub-THz (1-3 mm wavelength)

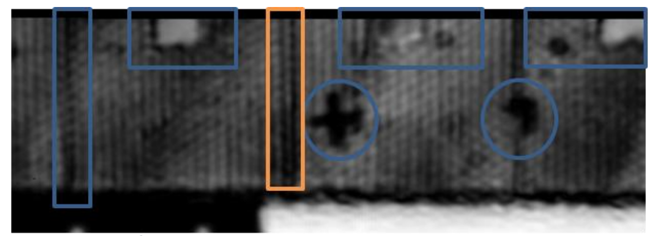
Collaboration with CENTERA Poland

  - Other detectors/sources
  - No cameras - Single point detectors or line sensors (FET)
- Transparency test with true aerospace materials



Focal plane Imaging

Pitch 0,5mm

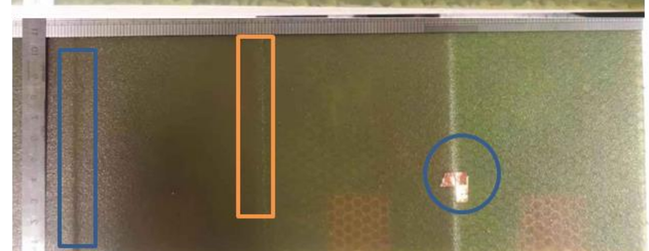


Metal holder with 2 holes

Air

Front
(source side)

Back
(detector side)

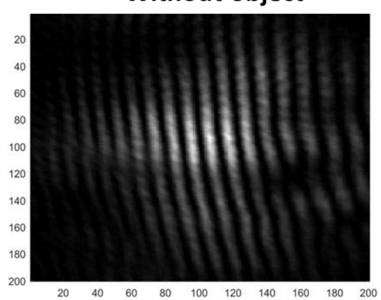


Terahertz Imaging and Holography

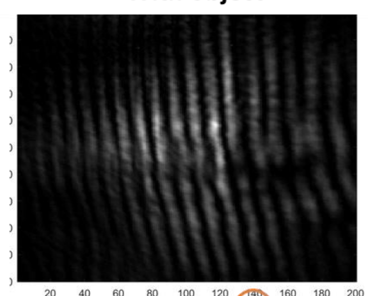
- Scanning hologram with single point detectors
- Digital holography validation

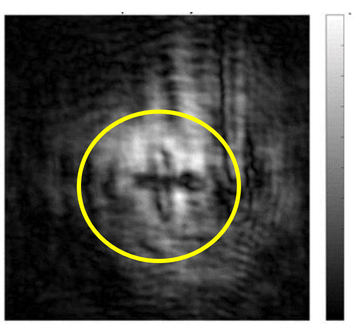
Amplitude object: metallic cross
Phase object: plastic stick

Without object

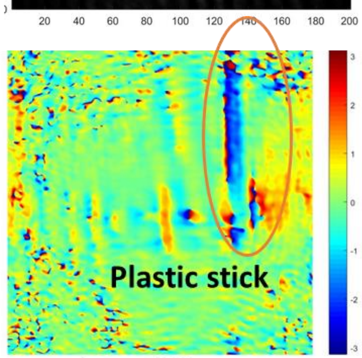


With object



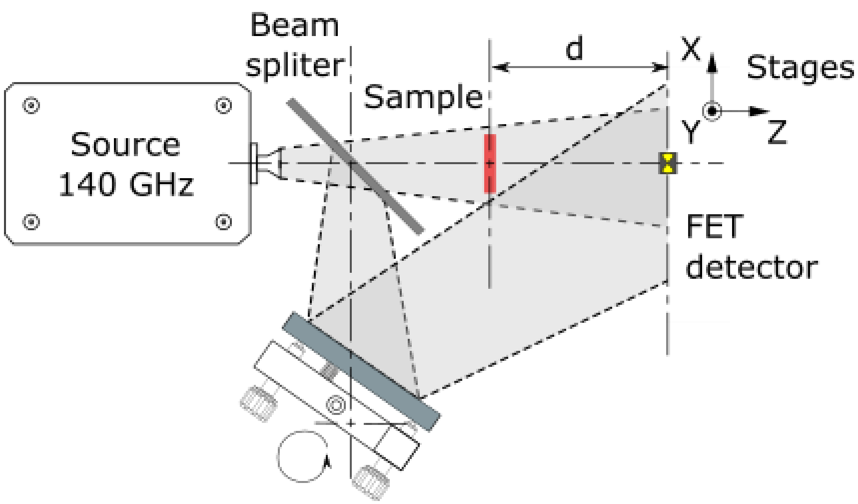


Object amplitude



Phase difference

Setup (CENTERA Poland)



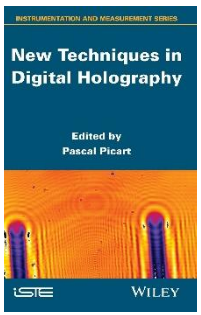
- 100 mm*100 mm hologram
- pitch: 0,5mm
- 2 hours scan

Further readings

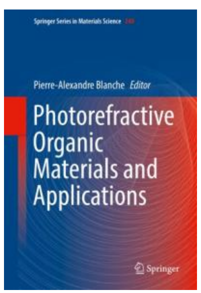
- Publications

  https://orbi.uliege.be/ph-search?uid=U027964

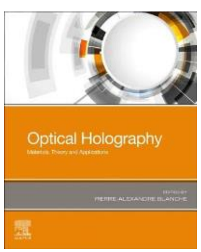
- Book chapters



"Long-wave Infrared Digital Holography"
in *New Techniques in Digital Holography*
Wiley-ISTE, 2014



"Photorefractives for holographic interferometry and nondestructive testing"
in *Photorefractive Organic Materials and Applications*
Springer, 2016



"Holographic interferometry: From History to Modern Applications"
in *Optical Holography. Materials, Theory and Applications*
Elsevier, 2019 (in press)

Announcement

謝謝

Thanks for your attention !

mgeorges@uliege.be