



Centre Spatial de Liège

Holography from thermal infrared to terahertz in view of applications in metrology and nondestructive testing

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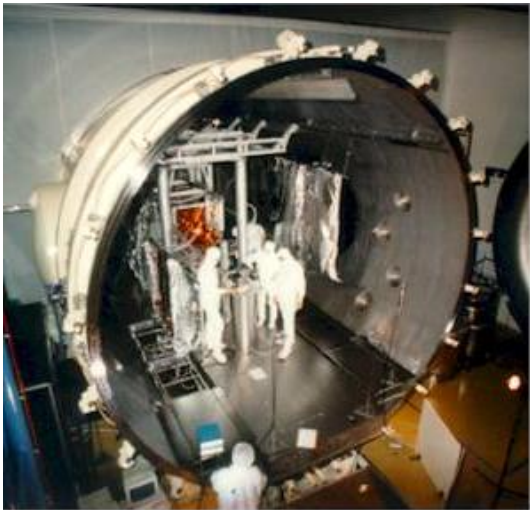
Centre Spatial de Liège – Liège Université, Belgium

Co-workers: Jean-François VANDENRIJT, Cédric THIZY, Fabian LANGUY, Yuchen ZHAO



Changchun Institute of Optics, Fine Mechanics and Physics,
Chinese Academy of Sciences

Testing of space payloads in vacuum-thermal chambers



Development of optical space instrumentation

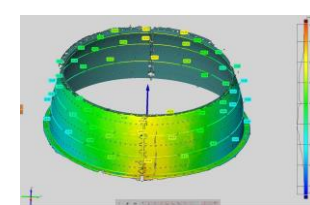
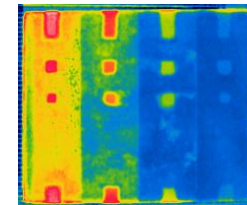
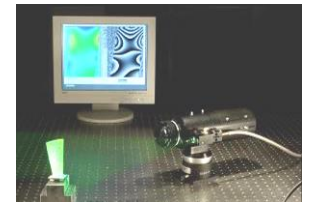
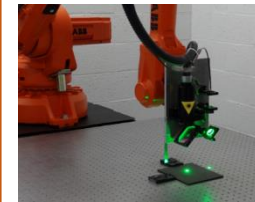


CENTRE NATIONAL D'ÉTUDES SPATIALES



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



Summary

- Some basics of holography
 - Recording-reconstruction
 - Applications
 - Where long wavelengths matter
- Long-wave IR digital holography
 - Applications in aerospace
- THz digital holography
 - FIR
 - Sub-THz

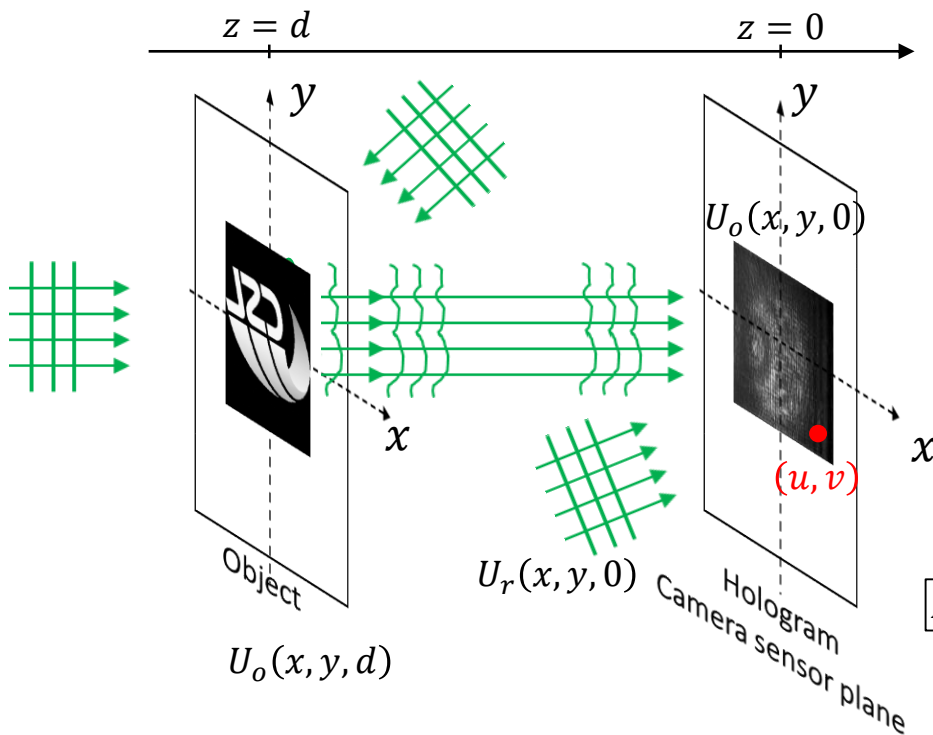
Holography

■ Holography at long wavelength (IR to THz waves)

- Holography: recording of whole wavefield information: amplitude and phase
- No analog hologram recording material
- Numerical recording of hologram with camera sensors: « Digital Holography »

■ Digital Holography principle

Step 1: Recording hologram



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

$$U_o(x, y, 0) = A(x, y, 0). e^{i\varphi_o(x, y, 0)}$$

$$U_r(x, y, 0) = A_r(x, y, 0). e^{i\varphi_r(x, y, 0)}$$

$$I(u, v) = [U_o(u, v) + U_r(u, v)]. cc$$

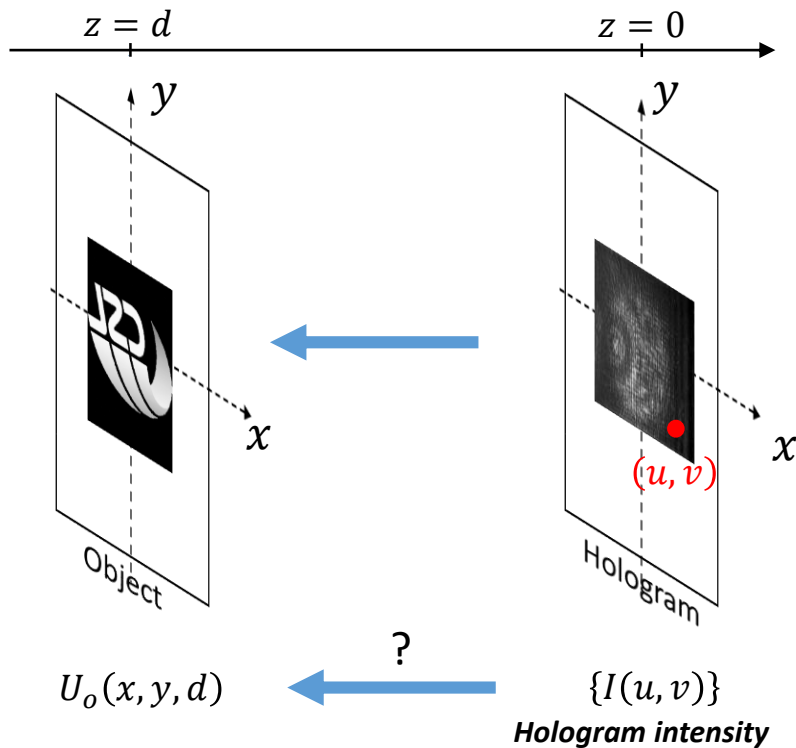
$$I(u, v) = I_{av}(u, v) [1 + m(u, v) \cos(\varphi_r(u, v) - \varphi_o(u, v))]$$

Hologram intensity at point (u, v)

Holography

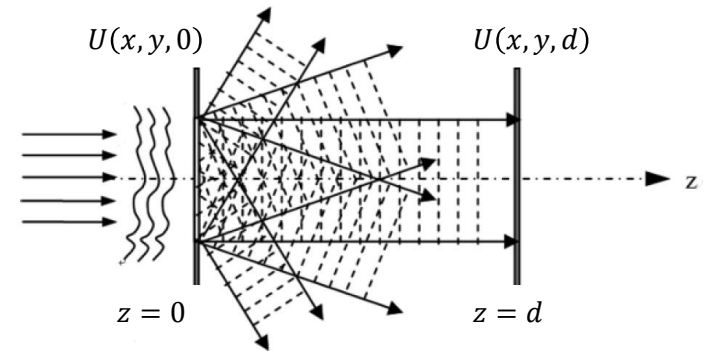
■ Digital Holography principle - 2

Step 2: Reconstruction by scalar diffraction theory



$$U(x, y, d) = \mathcal{F}^{-1}\{\mathcal{F}\{U(x, y, 0)\} \cdot H(f_x, f_y)\}$$

Rigorous : *Angular Spectrum Method (ASM)*



$$H_{ASM}(f_x, f_y) = \exp\left[i\frac{2\pi}{\lambda}d\sqrt{1 - \lambda^2(f_x^2 + f_y^2)}\right]$$

$$f_x = x/\lambda d \quad ; \quad f_y = y/\lambda d$$

Paraxial approximation: distance $d \gg$ object size

$$H_{Fresnel}(f_x, f_y) \approx \exp\left[i\frac{2\pi}{\lambda}d\left(1 - \frac{\lambda^2}{2}(f_x^2 + f_y^2)\right)\right]$$

Fresnel lens-less DH reconstruction principle

$$U(x, y, d) = \frac{i}{\lambda d} e^{-i2\pi d/\lambda} \exp\left[-i\frac{\pi}{\lambda d}(x^2 + y^2)\right] \iint I(u, v) U_r(u, v) \exp\left[-i\frac{\pi}{\lambda d}(u^2 + v^2)\right] \exp\left[i\frac{2\pi}{\lambda d}(xu + yv)\right] dudv$$

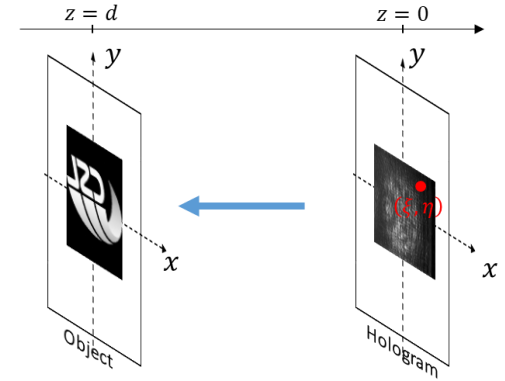
Holography

Digital Holography principle - 3

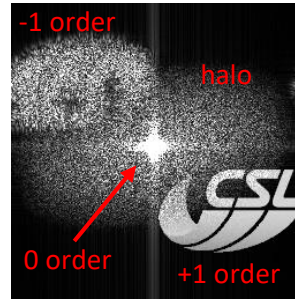
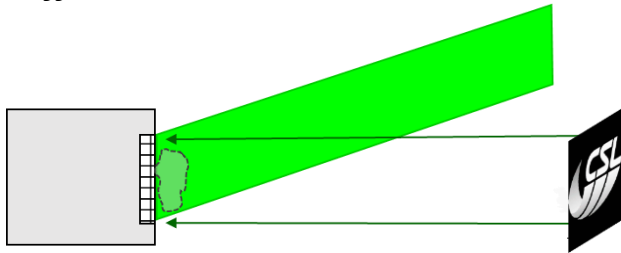
Reconstruction by Fresnel lensless DH principle

$$U(x, y, d) \div \iint I(u, v) U_r(u, v) \exp \left[-i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \exp \left[i \frac{2\pi}{\lambda d} (xu + yv) \right] dudv$$

$$\mathcal{F} \left\{ I(u, v) U_r(u, v) \exp \left[-i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \right\} \quad \text{"S-FFT"}$$



Off-Axis



$U(x, y, d)$

Preliminary capture of separated beams

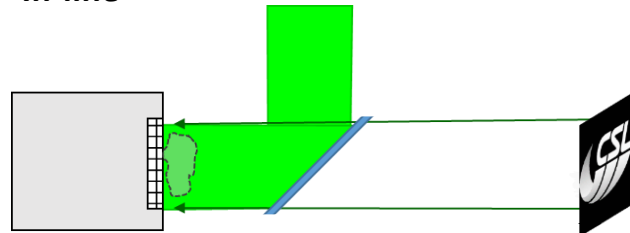


Suppress unwanted orders



Resolution: 1/4 $U_o(x, y, d)$

In-line



all orders superimposed

Phase-shifting (4 acquisitions)



Extract object image



Resolution: full

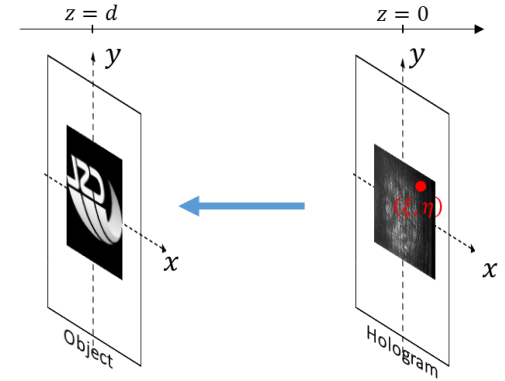
Holography

■ Digital Holography principle - 3

Reconstruction by Fresnel lensless DH principle

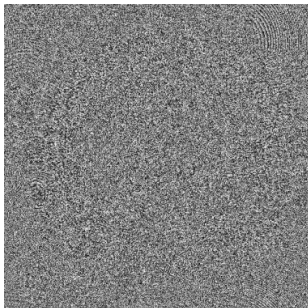
$$U(x, y, d) \div \iint I(u, v) U_r(u, v) \exp \left[-i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \exp \left[i \frac{2\pi}{\lambda d} (xu + yv) \right] dudv$$

$$\mathcal{F} \left\{ I(u, v) U_r(u, v) \exp \left[-i \frac{\pi}{\lambda d} (u^2 + v^2) \right] \right\} \quad \text{"S-FFT"}$$



Amplitude

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



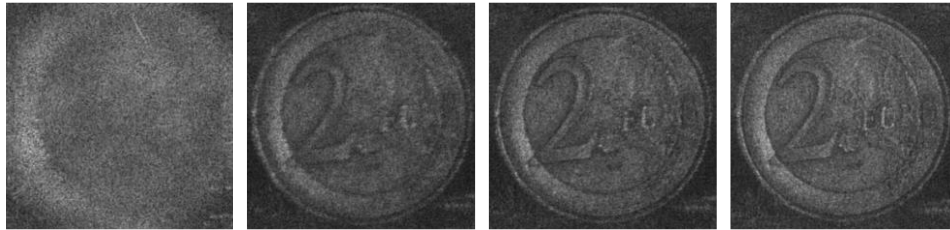
Phase

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

Applications

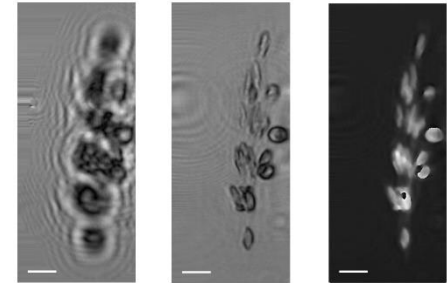
Imaging

Reflecting objects



Changing reconstruction distance z to best focus at $z = d$

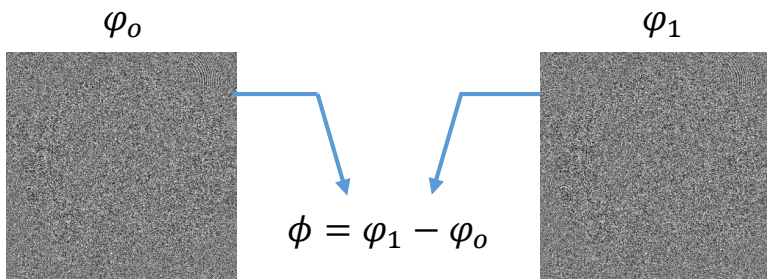
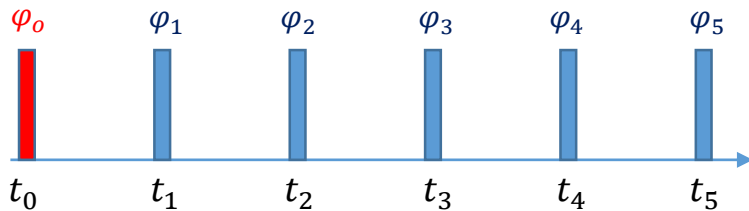
Transparent objects



Digital Holographic Microscope
Quantitative phase imaging

Interferometry

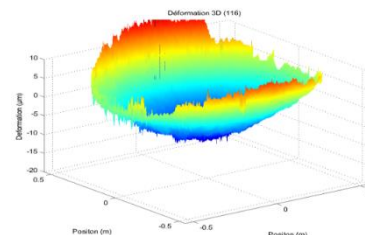
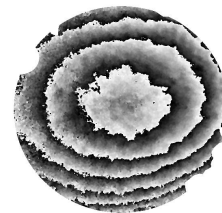
Record time series of holograms



Reflecting objects

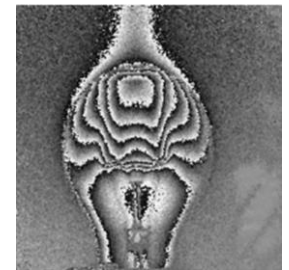
displacements
deformations

$\phi \text{ mod } 2\pi$

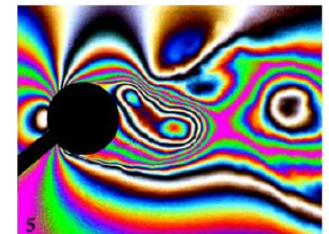


Transparent objects

Refractive index changes



© Desse, Picart



Where long wavelength matters

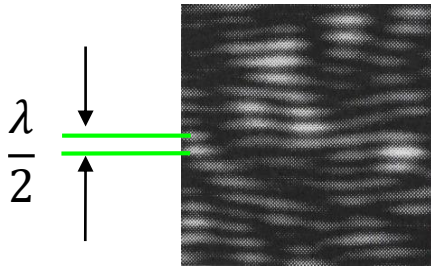
Object size

$$S \sim d \left[\frac{\lambda}{\Delta} \right]$$

d : reconstruction distance
 λ : wavelength
 Δ : pixel size

$$\left[\frac{\lambda}{\Delta} \right]_{10\mu m} \sim 7 \left[\frac{\lambda}{\Delta} \right]_{532nm}$$

Stability of setup

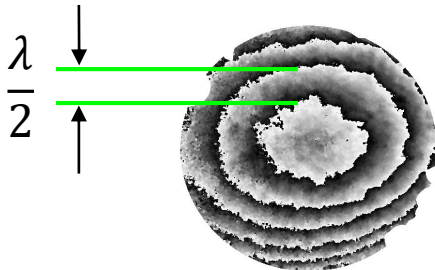


Stability criterion during hologram recording:

Hologram pattern $\{I(u, v)\}$ cannot move by a fraction of wavelength, generally $\frac{\lambda}{10}$

Longer λ allow working in perturbed environments

Measurement range in interferometric metrology



Measurement range :


number of resolvable fringes depends on wavelength

Longer λ allow large displacement or deformation measurements

Transmission of object/matter is function of wavelength

Obviously necessary for inspection/phase measurement of transparent objects

LWIR DH Interferometry

- Application in metrology for European Space Agency 
- ESA needs:
 - Full-field deformations of space reflectors in vacuum-thermal testing
 - Large reflectors: up to 4 m diameter
 - Industrial working conditions
 - Range of deformations: $1\ \mu\text{m}$ – $250\ \mu\text{m}$

LWIR DH
well suited



LWIR DH Interferometry

- Application in metrology for European Space Agency 

M. Georges et al., *Applied Optics* **52**(1), A102-A116 (2013)

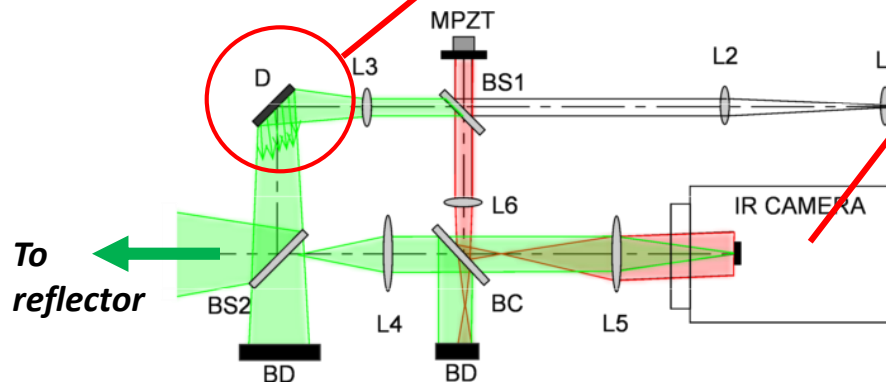
J-F. Vandenrijt et al., *Opt. Eng.* **53**(11), 112309 (2014)



Diffuser

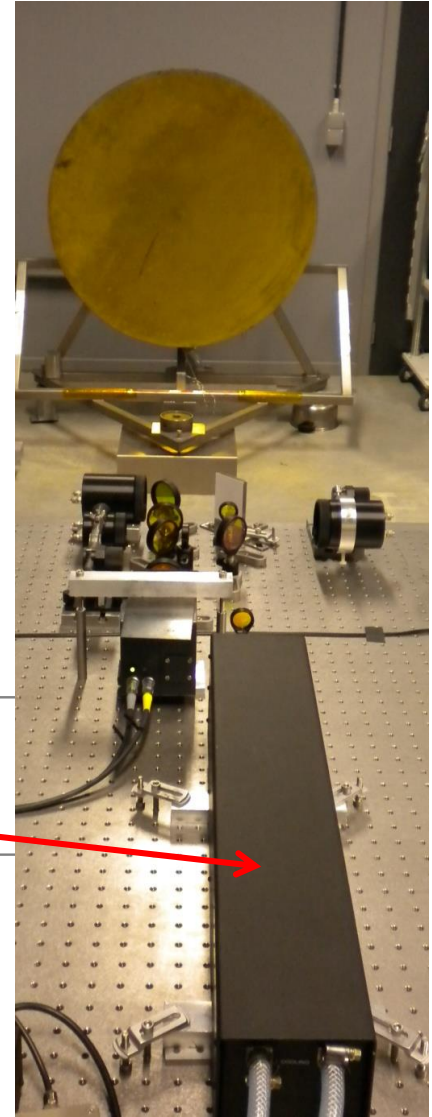


Uncooled μ -bolometer
640x480 pixels
Pixel Pitch: 25 μm
Frame rate 60 Hz
16 bits



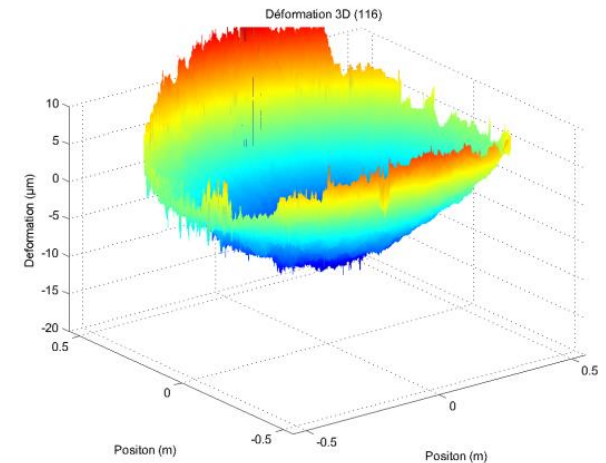
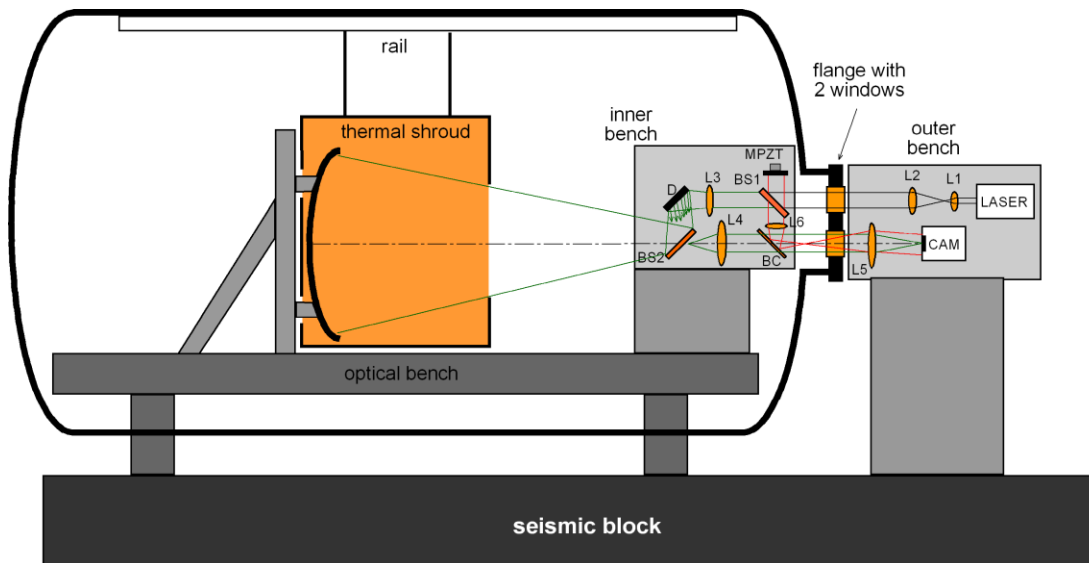
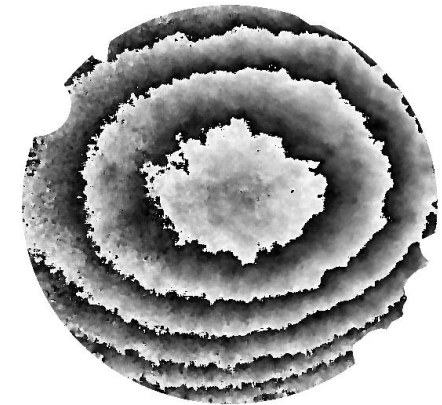
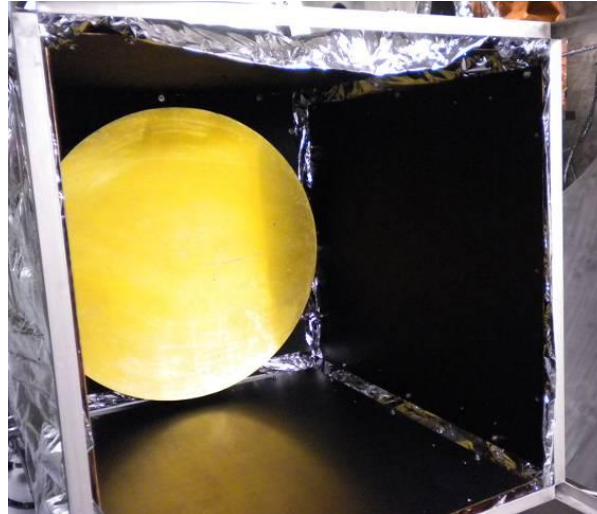
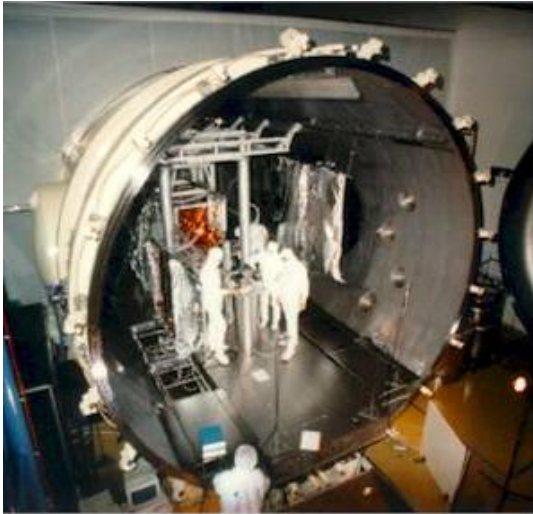
CO₂ LASER

λ : 10.6 μm
Power: 8 Watts



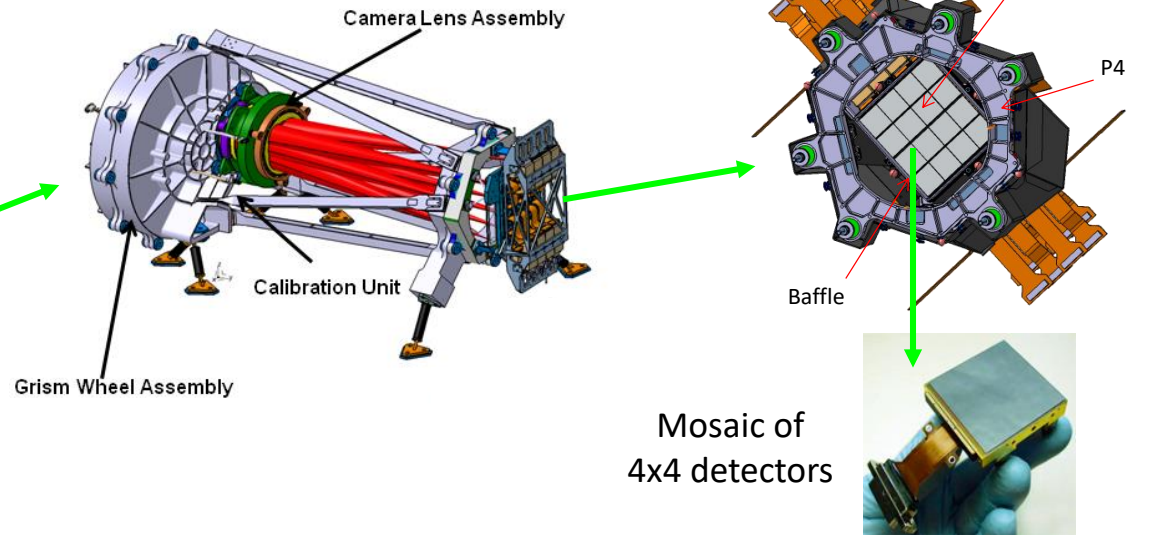
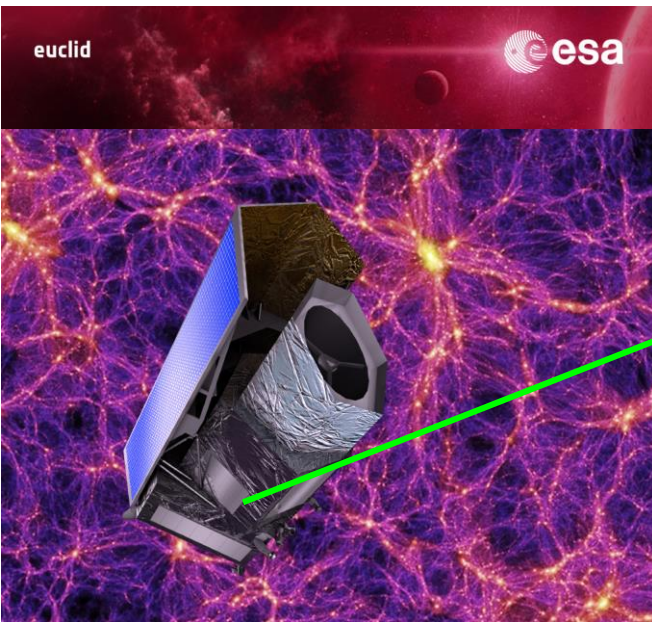
LWIR DH Interferometry

- Application in metrology for European Space Agency 



LWIR DH Interferometry

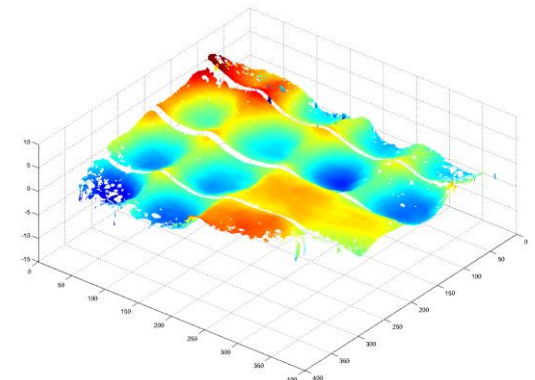
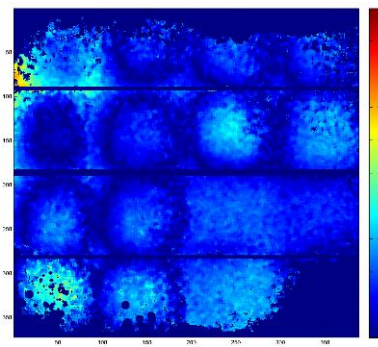
- Application in metrology for European Space Agency 



Measure during vacuum-cryogenic test:

- Deformation of each detector
- Deformation of ensemble
- Rigid body motions of each detector
- Large rigid body motion of ensemble

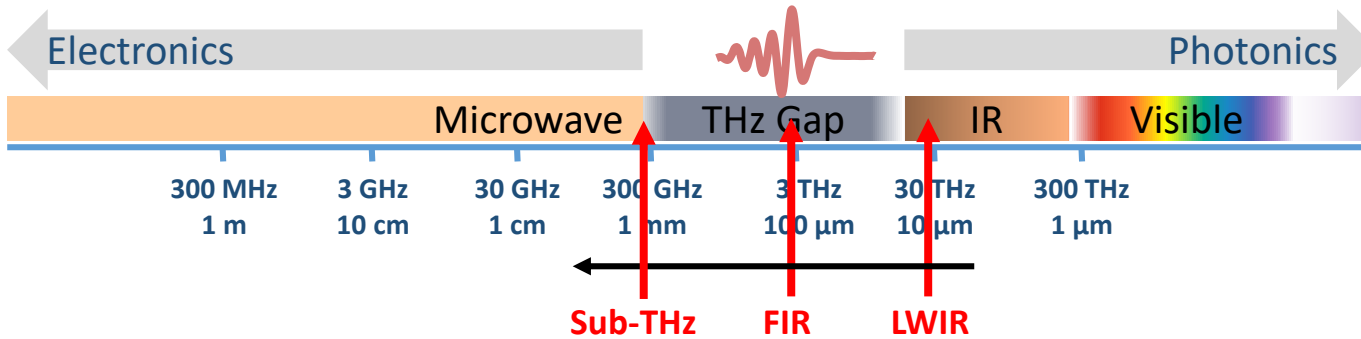
In the range of LWIR DHI



Terahertz Digital Holography

■ Motivation:

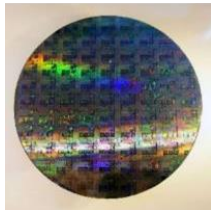
- Application in defect detection (NDI) in materials transparent
- Digital holography allows reconstruction at different depths numerically based on single shot



Transfer our knowledge from LWIR to THz

Materials transparent in THz

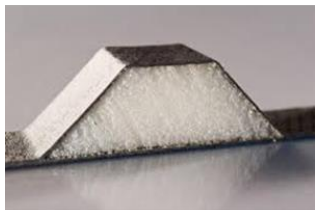
Silicon



Plastics, teflon,...



Foams



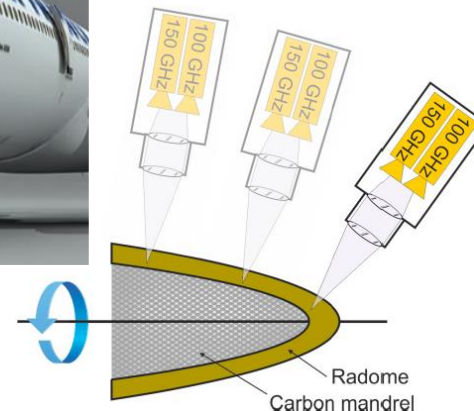
(Rohacell)

Paints & varnishes



Radome (glass fiber composite)

Material transparent in sub-THz



State of art: scanning

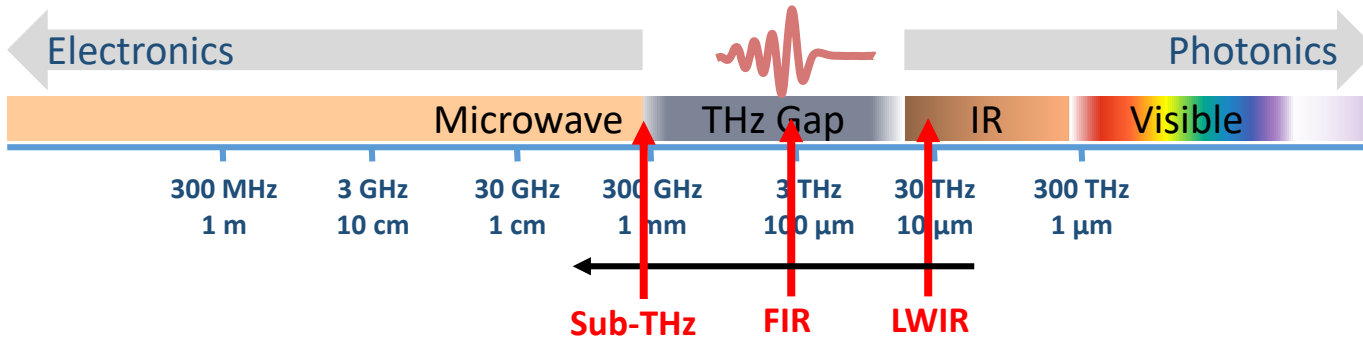


© Fraunhofer ITWM

Terahertz Digital Holography

■ Motivation:

- Application in defect detection (NDI) in plastics/composites
- Digital holography allows reconstruction at different depths numerically based on single shot



Transfer our knowledge from LWIR to THz

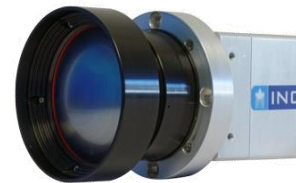
Gas laser



P=500 mW @ $\lambda=118.8 \mu\text{m}$ (2.5 THz)

Uncooled microbolometer array cameras

Optimized FIR camera



384x288
35 μm pitch

LWIR camera

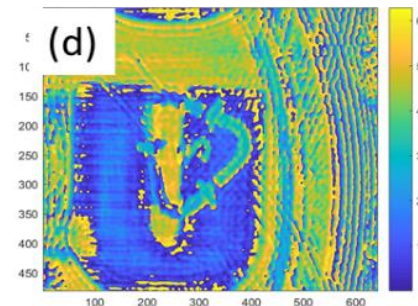
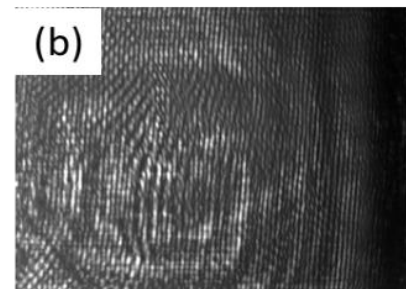
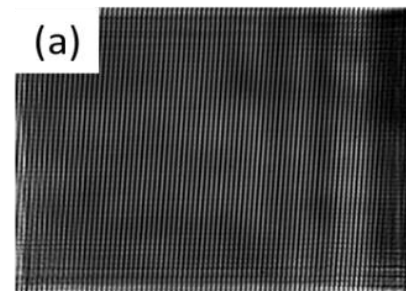
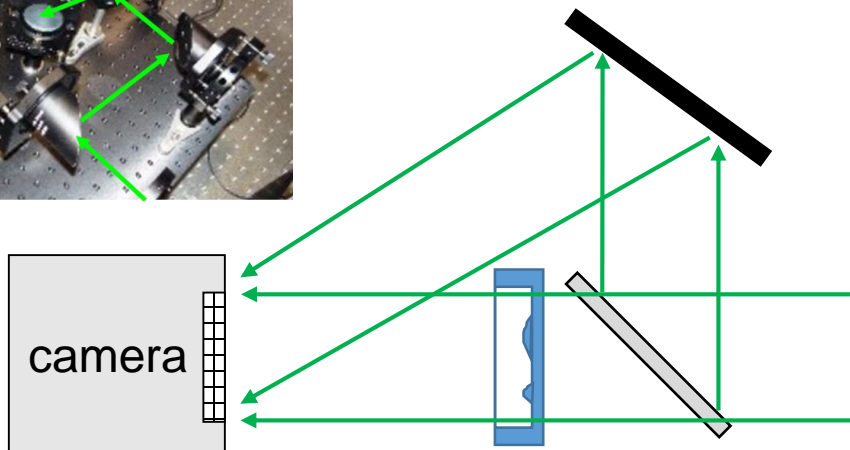
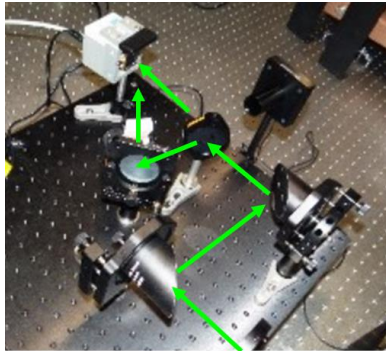


640x480
17 μm pitch

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

Terahertz Digital Holography

- **Validity of paraxial approximation at FIR**
 - Object must be very close to the sensor (a few cm)
 - Reconstruction by S-FFT feasible but lateral resolution very poor
- **Solution: Use rigorous Angular Spectrum Method (ASM)**
 - Size of reconstructed object = size of detector
 - Lateral resolution proportional to distance object-sensor d
- **Set-up:**



Terahertz Digital Holography

■ Improve resolution

- Decrease distance d
- Problem : occlusion of reference beam by object
- Large angles : difficult and occlusion by camera frame

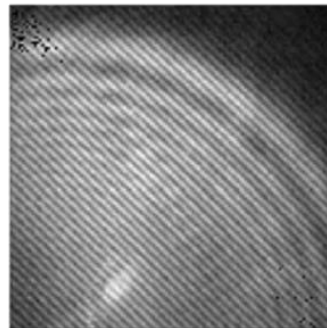
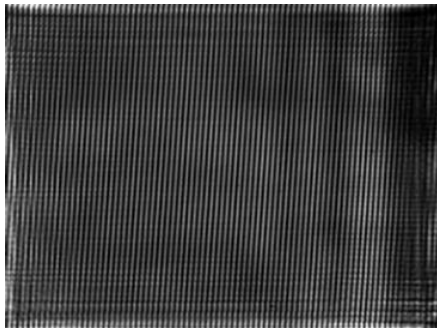
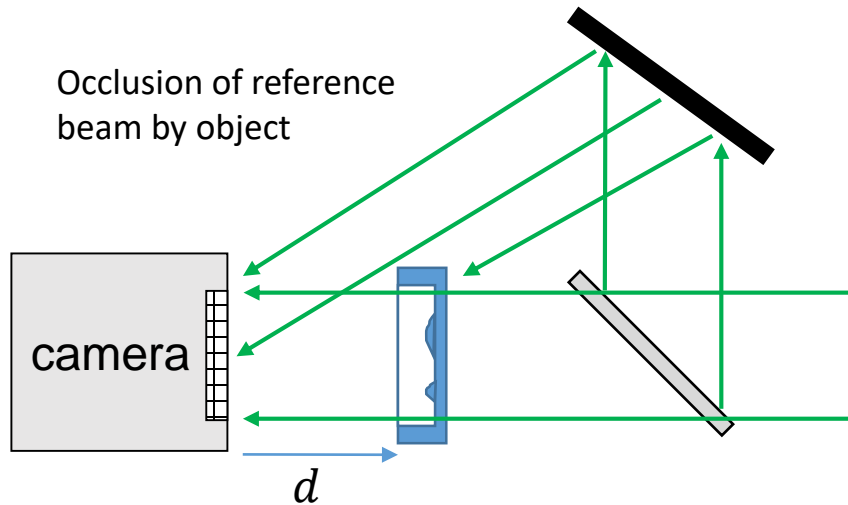
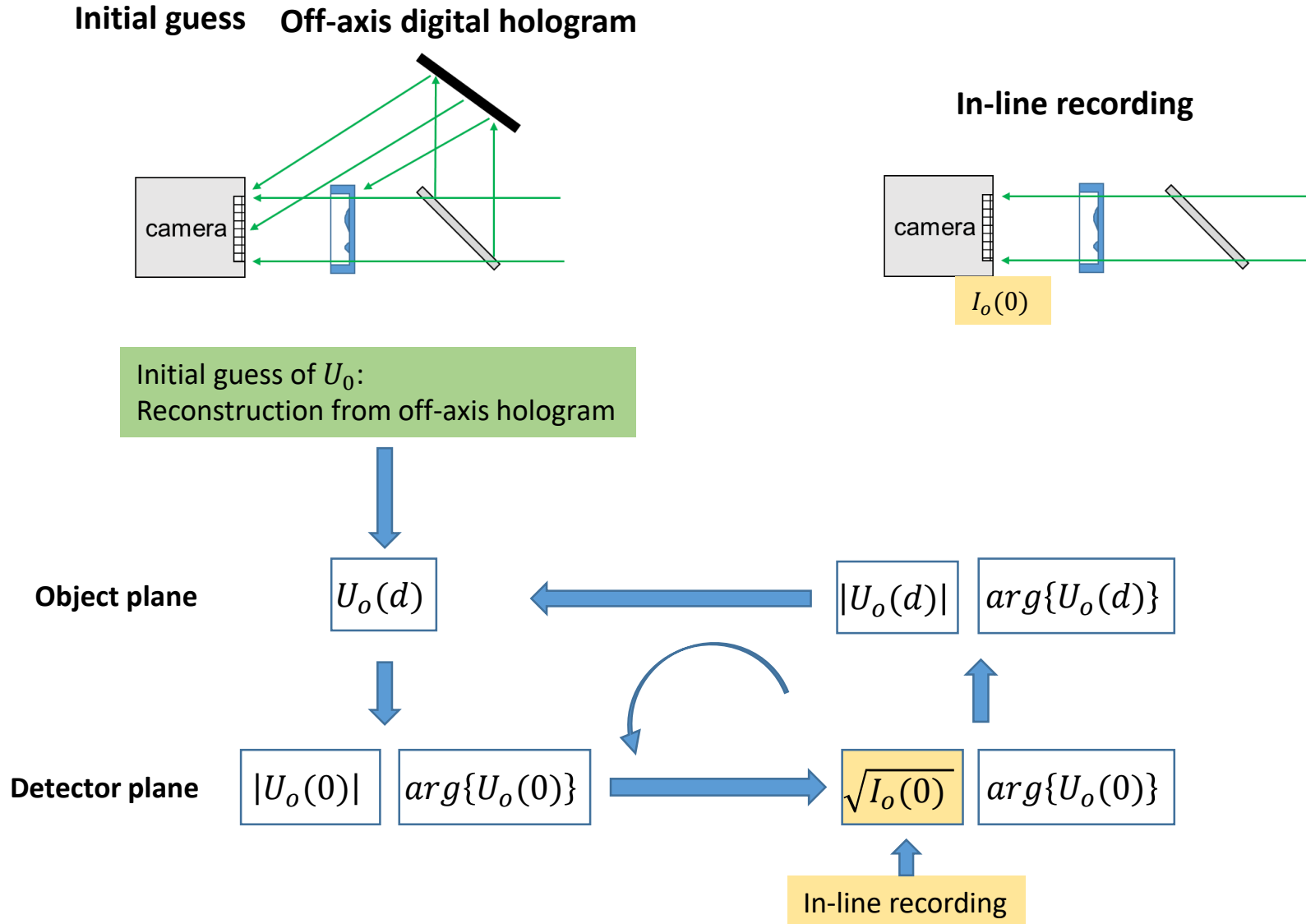


Image degradation !

Recorded holograms with occlusion

Terahertz Digital Holography

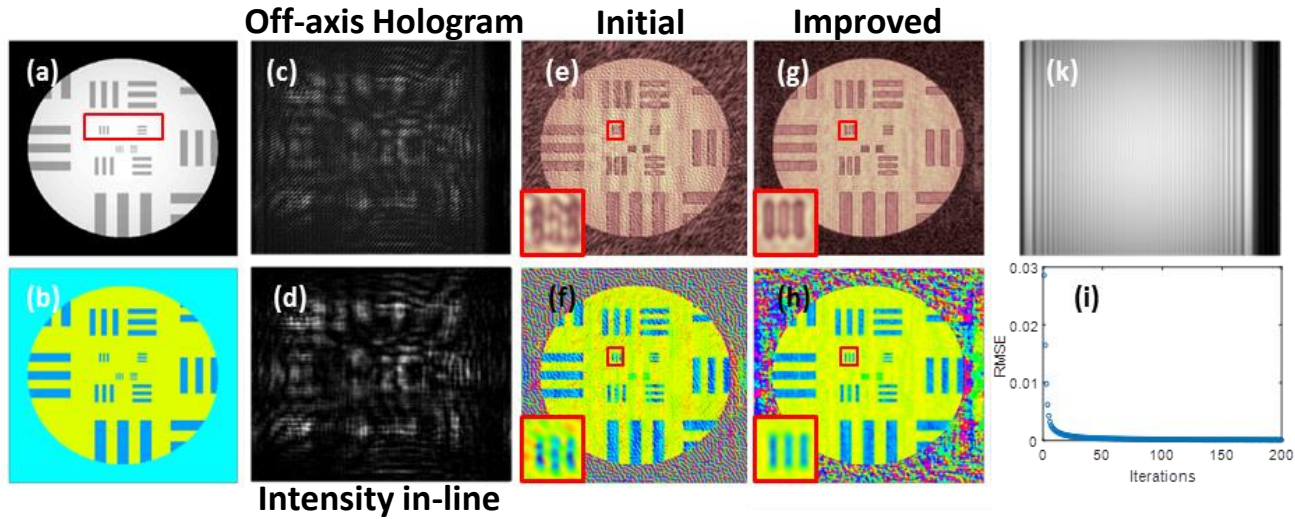
- Use of phase retrieval to recover image and improve resolution



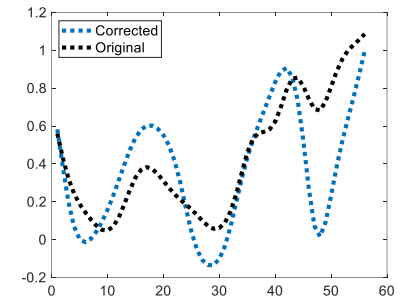
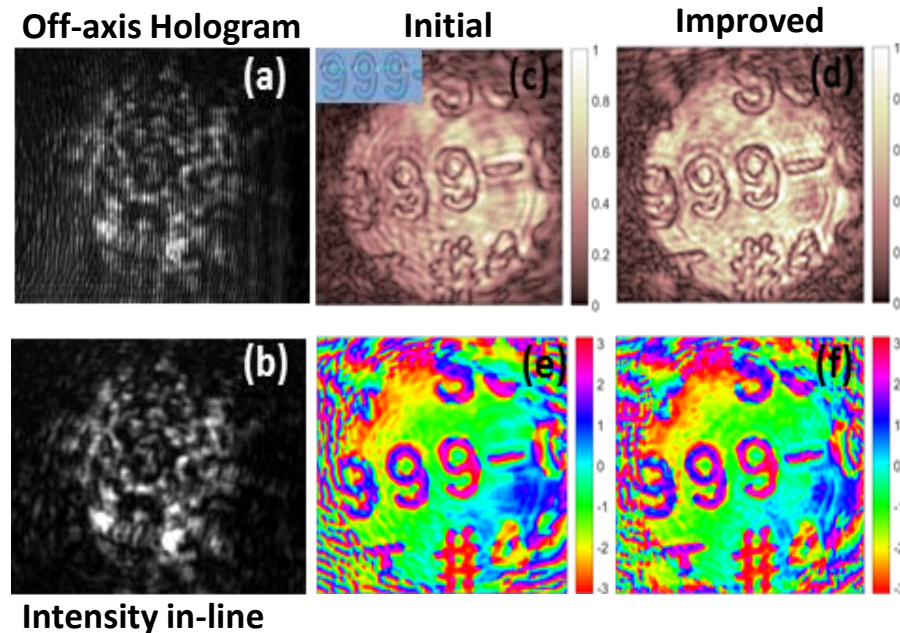
Terahertz Digital Holography

- Use of phase retrieval to recover image and improve resolution

Simulated



Experimental

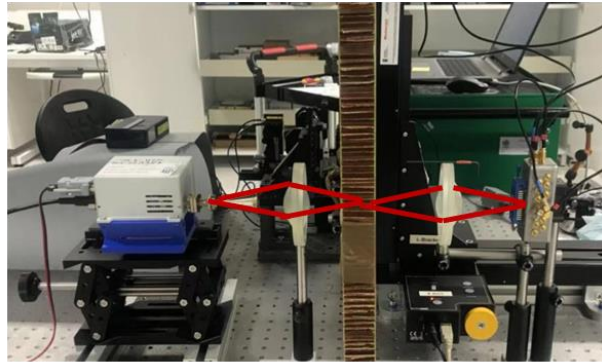


$$\rho_H = 114.7 \mu\text{m} \leftrightarrow \lambda = 118.8 \mu\text{m}$$

$$\rho_V = 152.9 \mu\text{m}$$

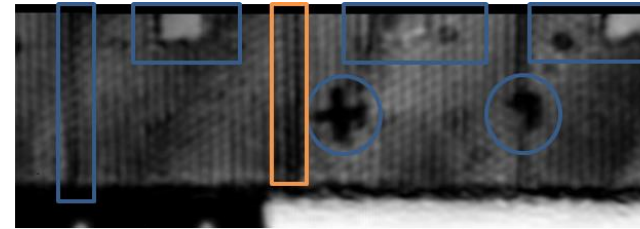
Terahertz Digital Holography

- Many composite materials are not transparent enough at FIR
- Move to sub-THz (1 mm wavelength) Collaboration with CENTERA Poland
 - Other detectors/sources
 - No cameras - Single point detectors or line sensors (FET)
- Transparency test with true aerospace materials



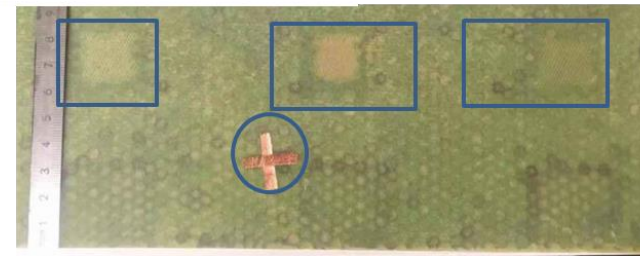
Focal plane Imaging
Pitch 0,5mm

Front
(source side)



Metal holder with 2 holes

Air



Back
(detector side)



Terahertz Digital Holography

- Scanning hologram with single point detectors
- Digital holography validation

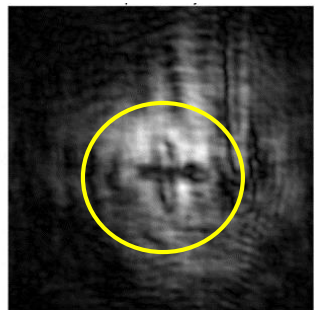
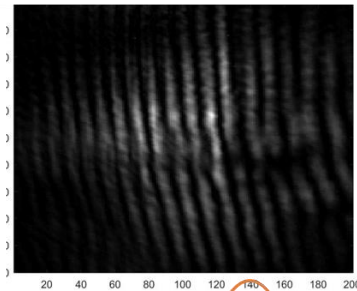
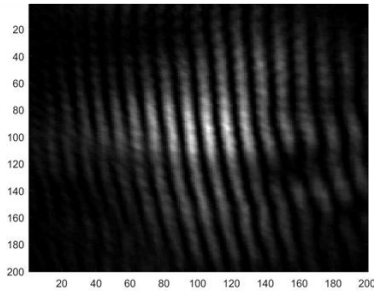
Amplitude object: metallic cross

Phase object: plastic stick

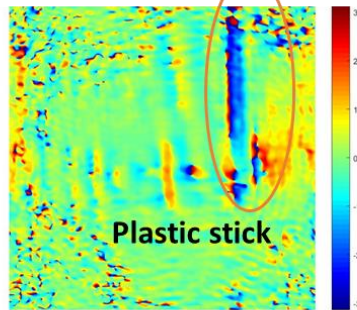


Without object

With object

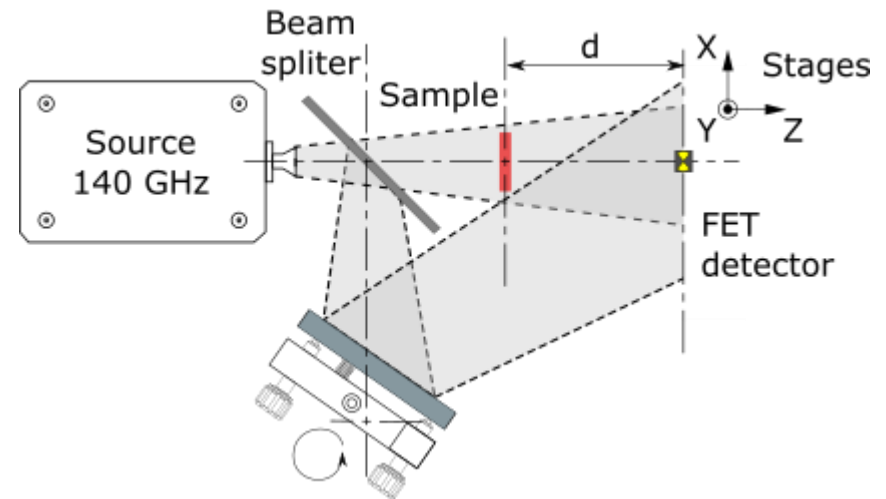


Object amplitude



Phase difference

Setup



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

Conclusion – Discussion

■ LWIR digital holography

- Large deformation of space structures in industrial environment
- Large objects

■ THz digital holography

- FIR: development of techniques (improvement of resolution)
- Sub-THz: first steps for composites NDI
- In future: line-scanning

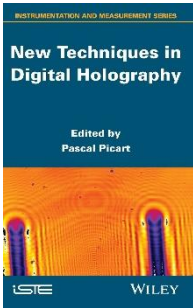
■ Improvement of DH

- Use of DH principle and all associated post-processing
- From FIR to sub-THz
- State-of-art in lensless imaging techniques
 - EMPA, Switzerland
 - Beijing Univ. Technology, China
 - CSL, Belgium

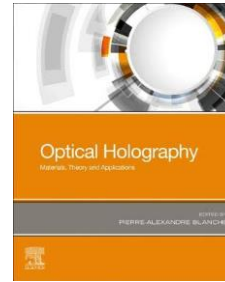
Phase retrieval
Numerical auto-focusing
Synthetic aperture
Compressed sensing
...

“THz coherent lensless imaging techniques – A Review”
L. Valzania, Y. Zhao, L. Rong, D. Wang, M. Georges,
E. Hack, P. Zolliker (submitted)

Further readings



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



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

Announcement

SPIE PHOTONICS EUROPE

2020

Photonics Europe

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PE120	Tissue Optics and Photonics (Tuchin, Blondel, Zalevsky)	29

APPLICATIONS OF PHOTONIC TECHNOLOGY

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PE124	Photosensitive Materials and their Applications (McLeod, Pascual Villalobos, Tomita, Sheridan)	33

WORKSHOPS ON EMERGING TOPICS

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WS202	Synthesis of Photonics and Plasmonics at the Mesoscale (Lecler, Astratov, Minin)	35
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WS204	6th annual Sino-French "Photonics and Optoelectronics" PHOTONET International Research Network Workshop (Blondel, Gralak, Peucheret, Zhang, Gao, Bai)	36

謝謝

Thanks for your
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