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

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Light Conference, July 16-18, 2019, Changchun, China

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

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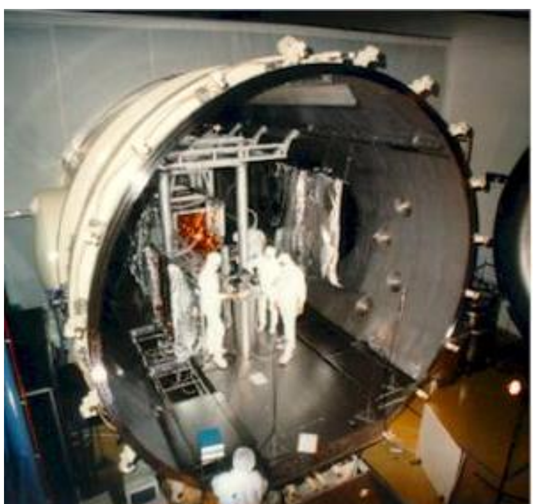
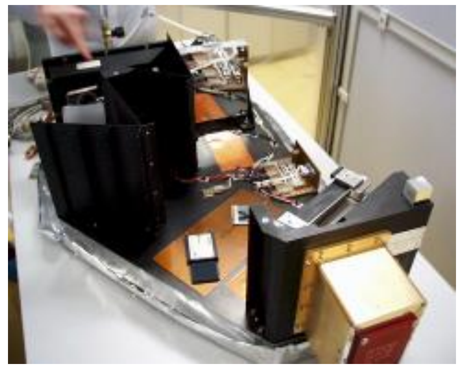
Optics for Space

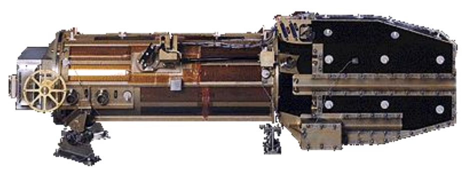
Center of Excellence for Optics of esa

Testing of space payloads in vacuum-thermal chambers



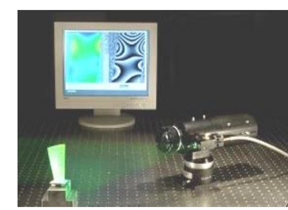
Development of optical space instrumentation

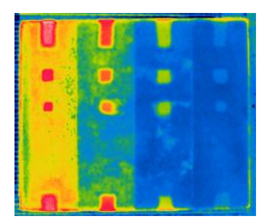


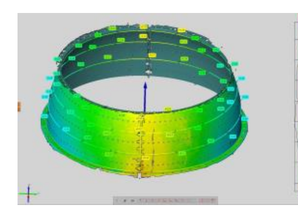


Development of Advanced Technologies

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







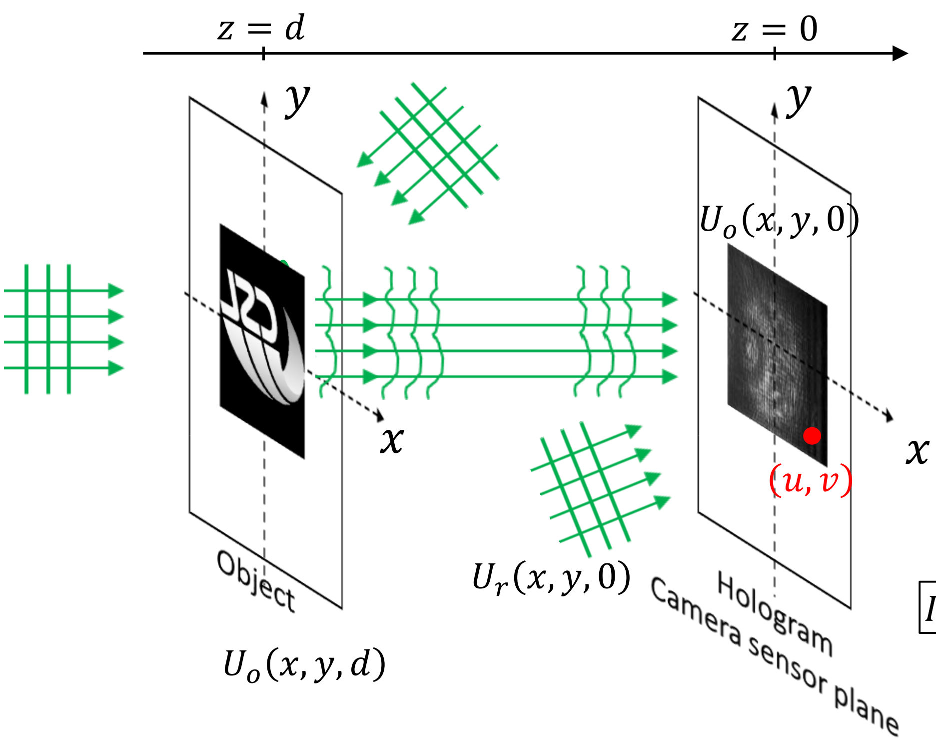
Summary

- 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



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

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

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

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

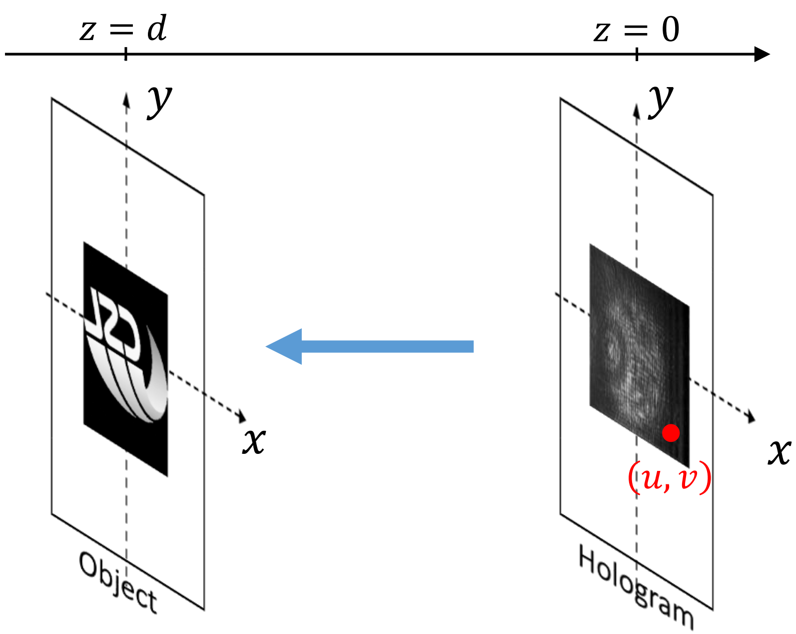
$$\boxed{I(u,v) = I_{av}(u,v)\left[1 + m(u,v)\cos\left(\varphi_r(u,v) - \varphi_o(u,v)\right)\right]}$$

Hologram intensity at point $(\boldsymbol{u},\boldsymbol{v})$

Holography

▪ Digital Holography principle - 2

Step 2: Reconstruction by scalar diffraction theory



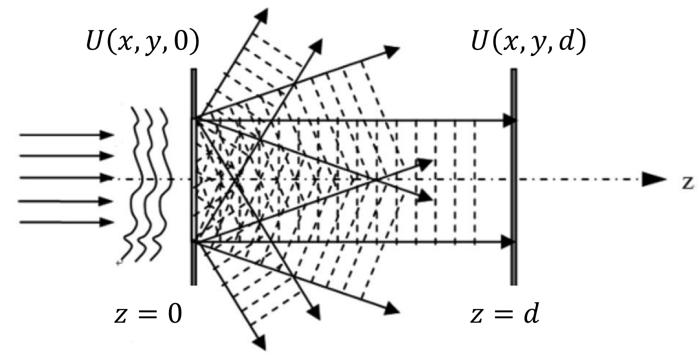
?

$U_o(x, y, d)$ ← $\{I(u, v)\}$

Hologram intensity

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

Rigorous : *Angular Spectrum Method (ASM)*



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

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

Paraxial approximation: distance d >> object size

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

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

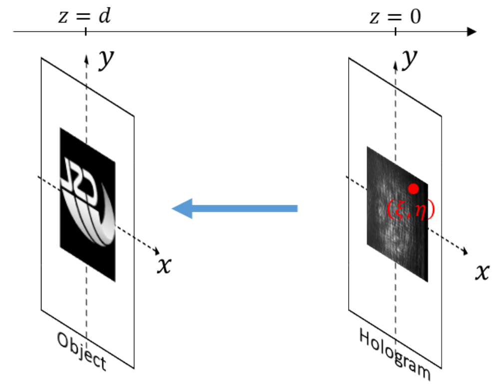
- Digital Holography principle - 3

Reconstruction by Fresnel lensless DH principle

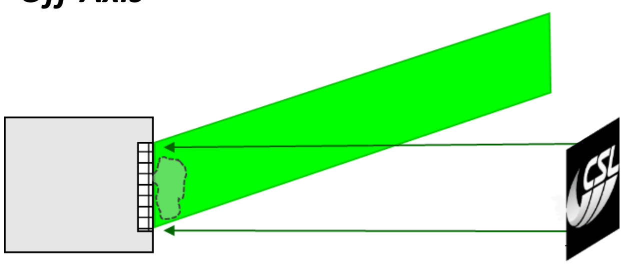
$$U(x,y,d) \div \iint I(u,v)U_r(u,v)\exp\left[-i\frac{\pi}{\lambda d}(u^2+v^2)\right]\exp\left[i\frac{2\pi}{\lambda d}(xu+yv)\right]dudv$$

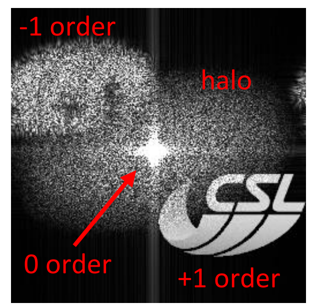
$$\mathcal{F}\left\{I(u,v)U_r(u,v)\exp\left[-i\frac{\pi}{\lambda d}(u^2+v^2)\right]\right\}$$

"S-FFT"



Off-Axis

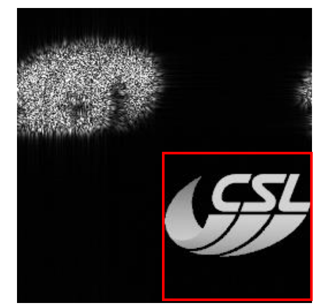




$U(x,y,d)$

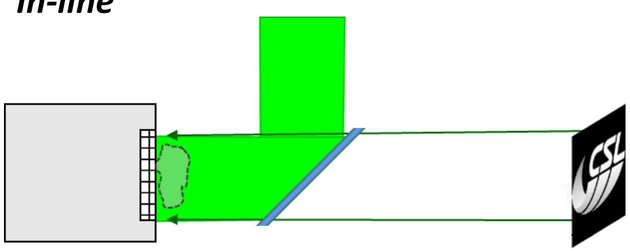
Preliminary capture of separated beams

Suppress unwanted orders



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

In-line



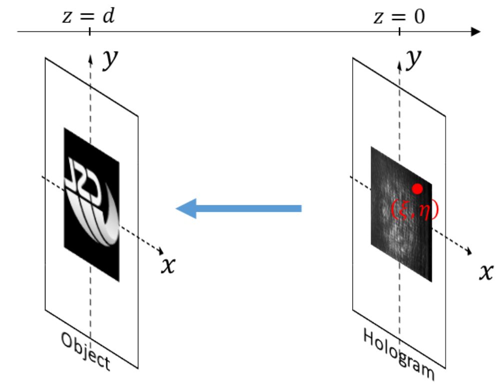
Phase-shifting (4 acquisitions)

Extract object image

Resolution: full

Holography

- Digital Holography principle - 3



Reconstruction by Fresnel lensless DH principle

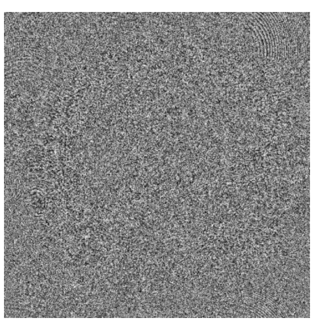
$$U(x,y,d) \div \underbrace{\iint I(u,v)U_r(u,v)\exp\left[-i\frac{\pi}{\lambda d}(u^2+v^2)\right]\exp\left[i\frac{2\pi}{\lambda d}(xu+yv)\right]dudv}$$

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

"S-FFT"

Amplitude

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



Phase

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

Applications

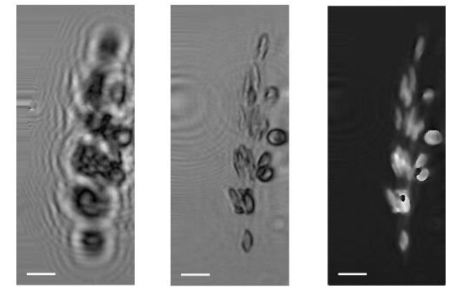
- Imaging

Reflecting objects

© Picart

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

Transparent objects



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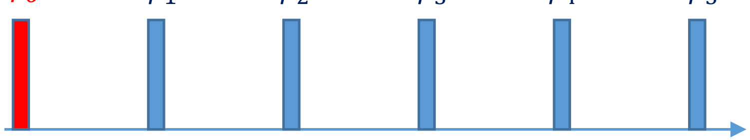
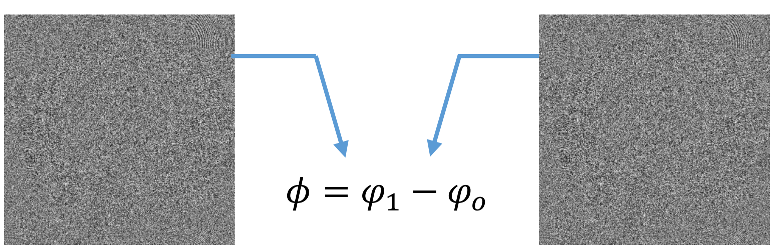
Digital Holographic Microscope
Quantitative phase imaging

- Interferometry

Record time series of holograms

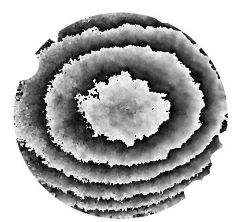


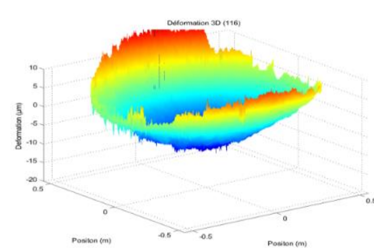


Reflecting objects

displacements
deformations

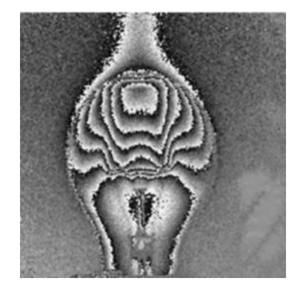
ϕ mod2π





Transparent objects

Refractive index changes



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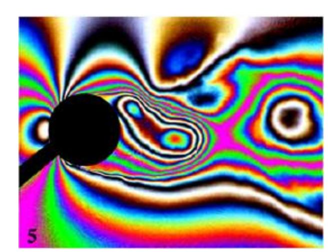


Where long wavelength matters

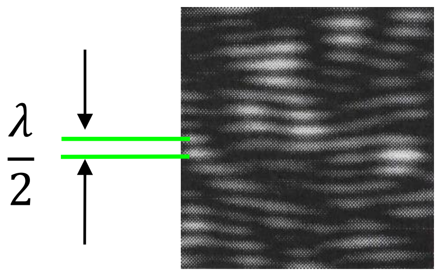
- Object size

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

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

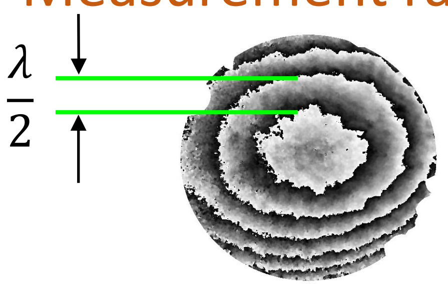


Stability criterion during hologram recording:

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
- 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 µm – 250 µm

LWIR DH well suited

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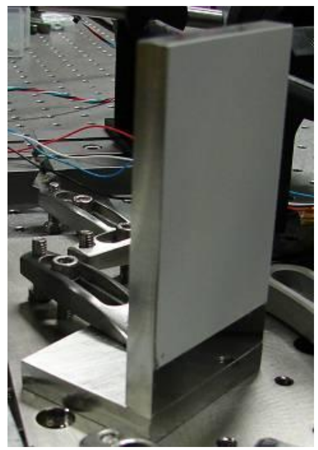
LWIR DH Interferometry

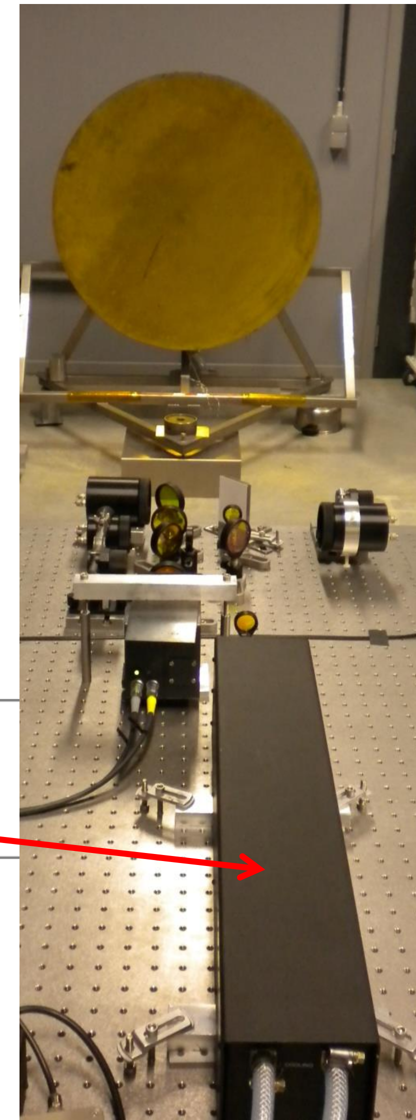
- Application in metrology for European Space Agency

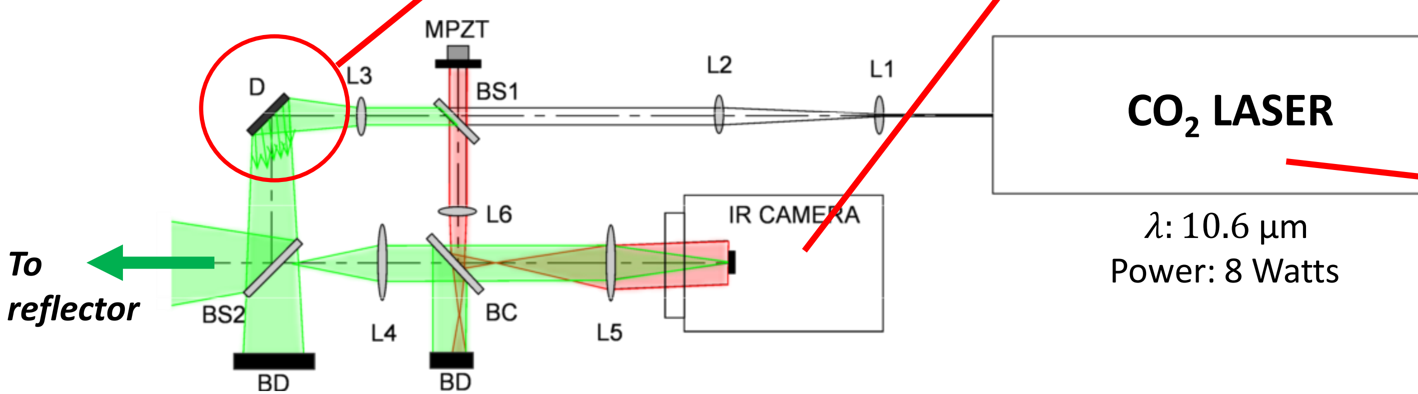
M. Georges et al., Applied Optics ***52****(1), A102-A116 (2013)*
J-F. Vandenrijt et al., Opt. Eng. ***53****(11), 112309 (2014)*

Diffuser



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

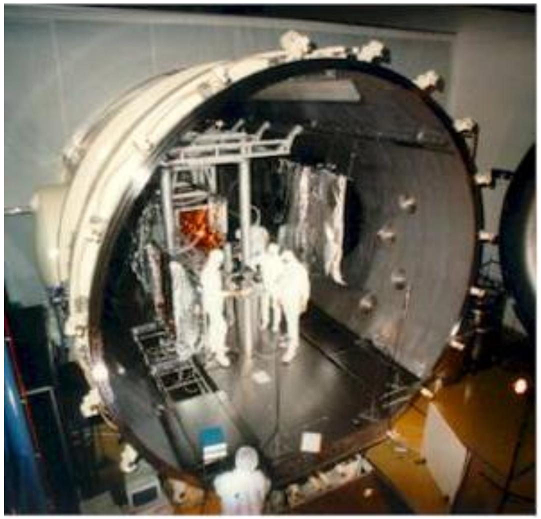


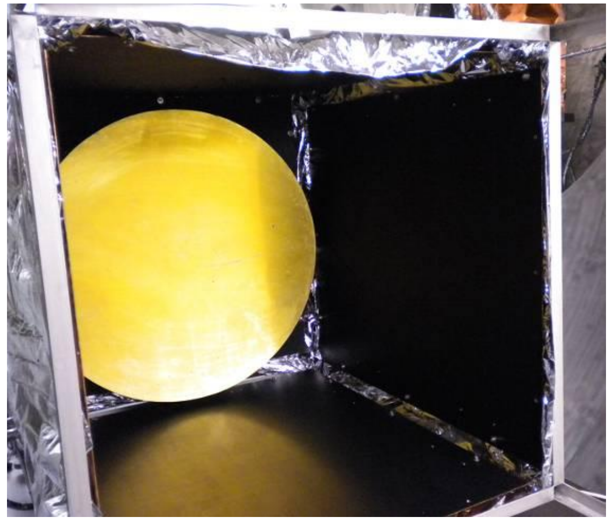


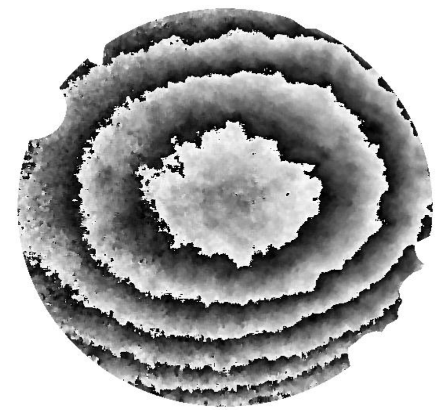
λ: 10.6 µm
Power: 8 Watts

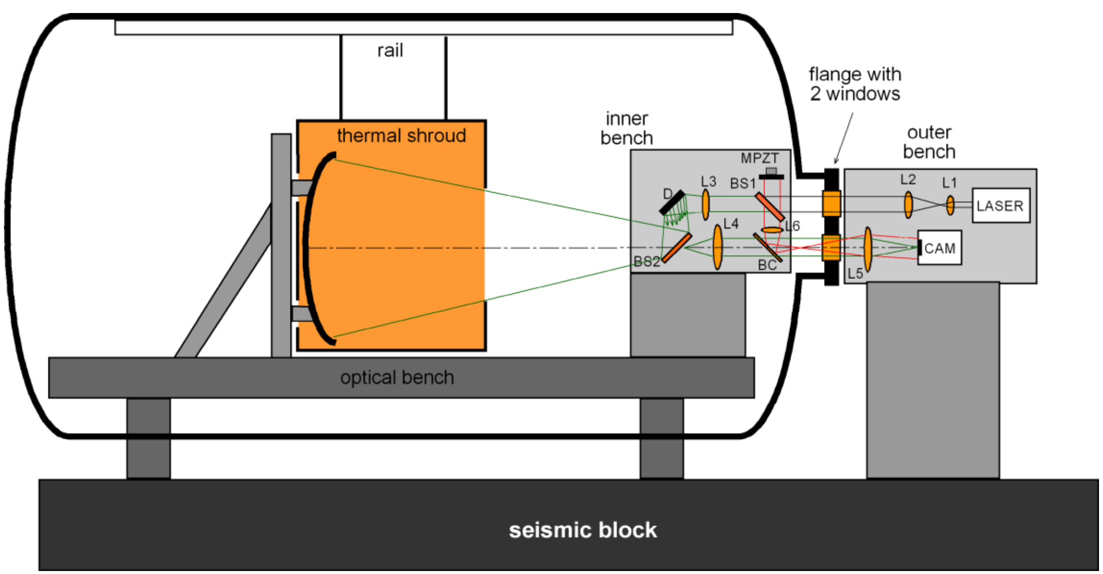
LWIR DH Interferometry

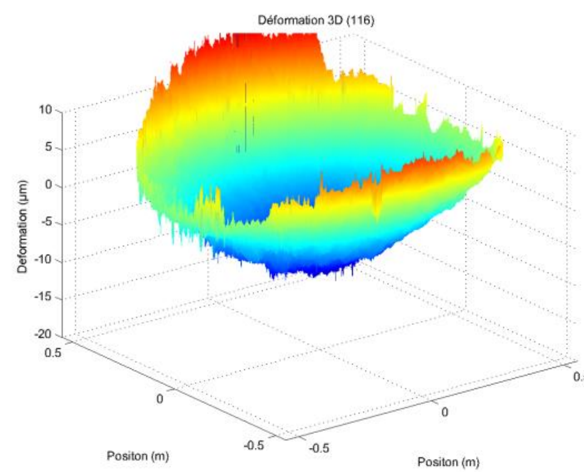
- Application in metrology for European Space Agency





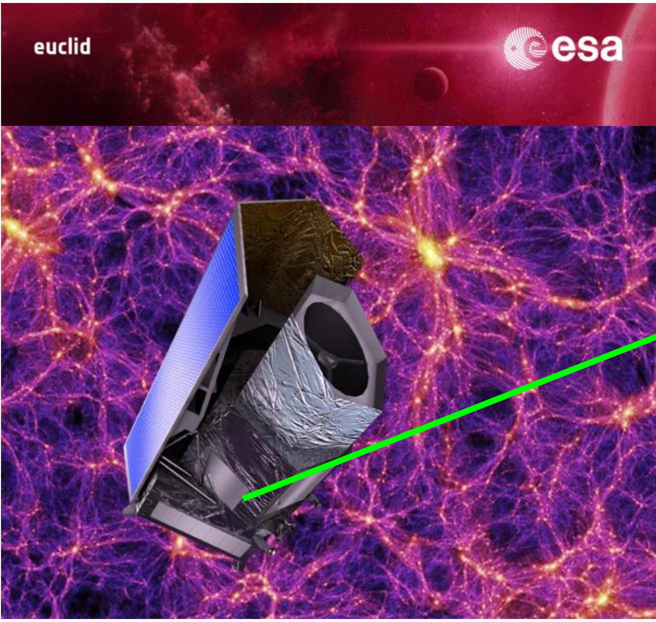


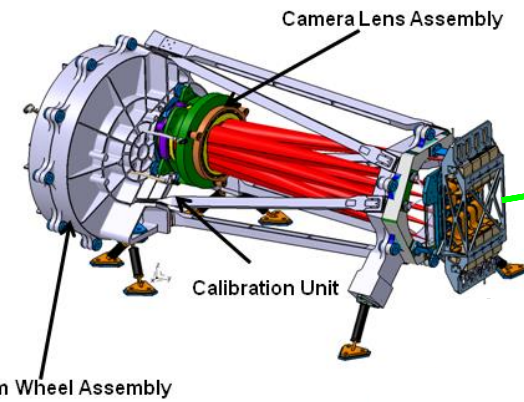


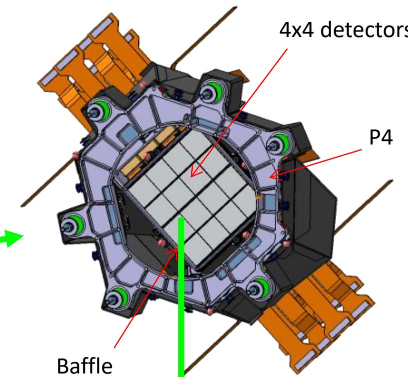


LWIR DH Interferometry

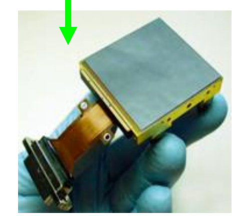
- Application in metrology for European Space Agency







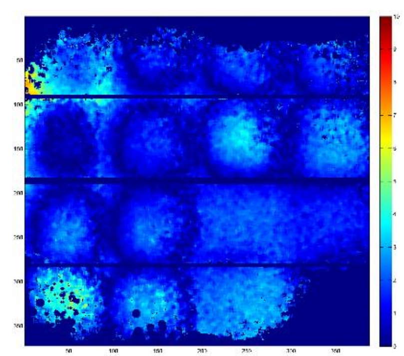
Mosaic of
4x4 detectors

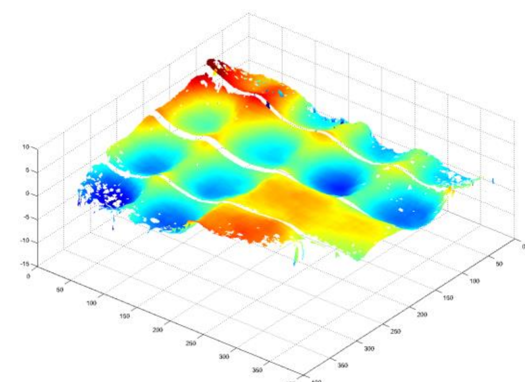


Measure during vacuum-cryogenic test:

- 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



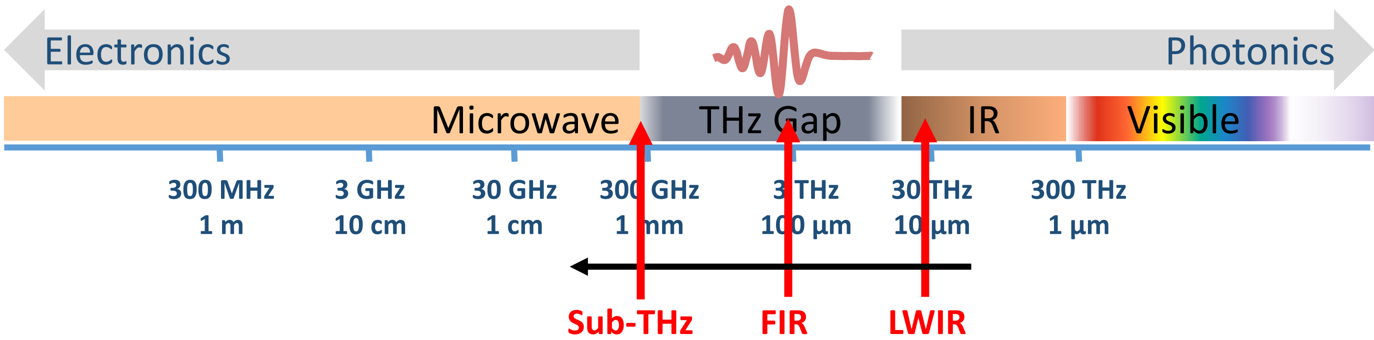


J-F. Vandenrijt et al., Appl. Opt. ***55****(12), 121723 (2016)*

Terahertz Digital Holography

▪ Motivation:

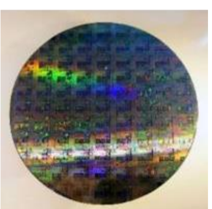
- Application in defect detection (NDI) in materials transparent
- Digital holography allows reconstruction at different depths numerically based on single shot



Transfer our knowledge from LWIR to THz

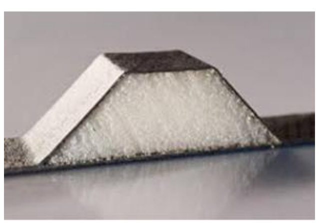
Materials transparent in THz

Silicon



Plastics, teflon,...

Foams

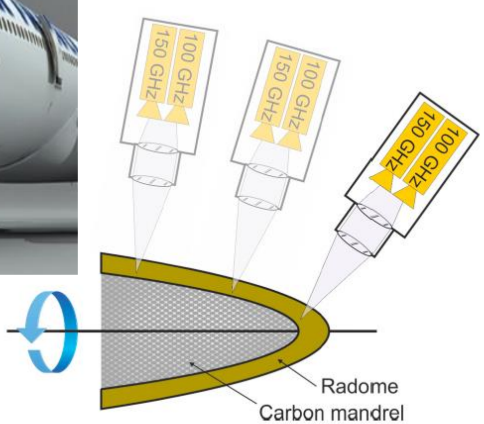


(Rohacell)

Paints & varnishes

Radome (glass fiber composite)

Material transparent in sub-THz

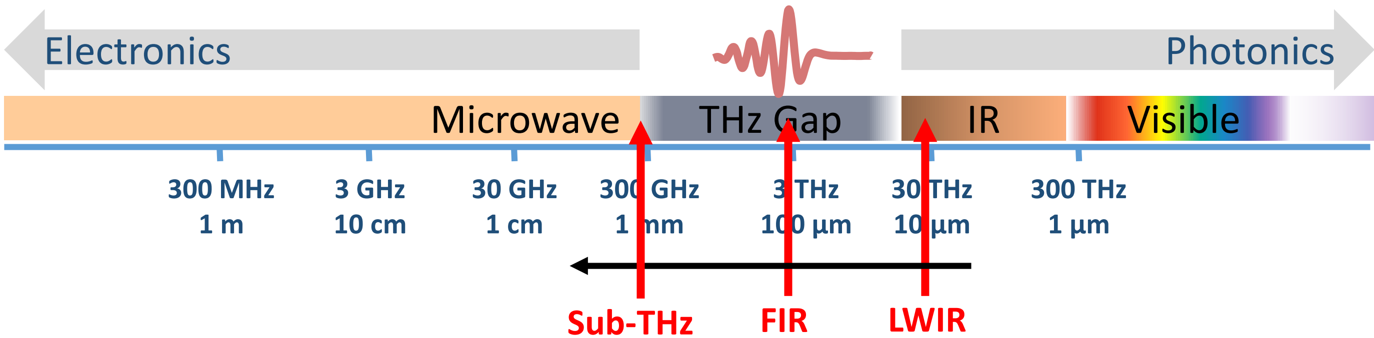


State of art: scanning

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 @ λ=118.8 µm (2.5 THz)

Uncooled microbolometer array cameras

Optimized FIR camera

384×288
35 µm pitch

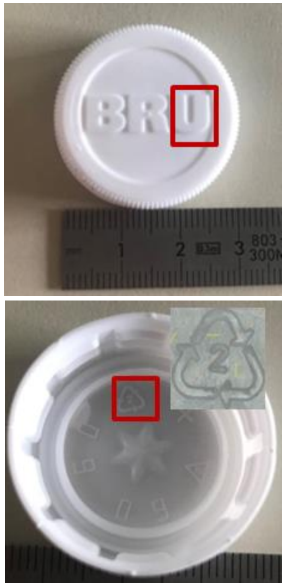
LWIR camera

640x480
17 µm pitch

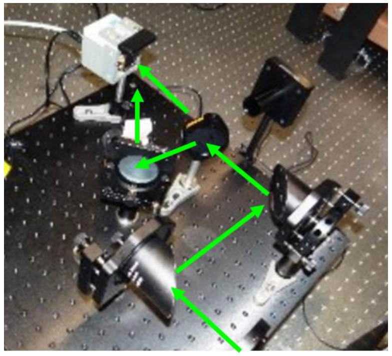
LWIR camera has good response in FIR !!
(Without lens…)

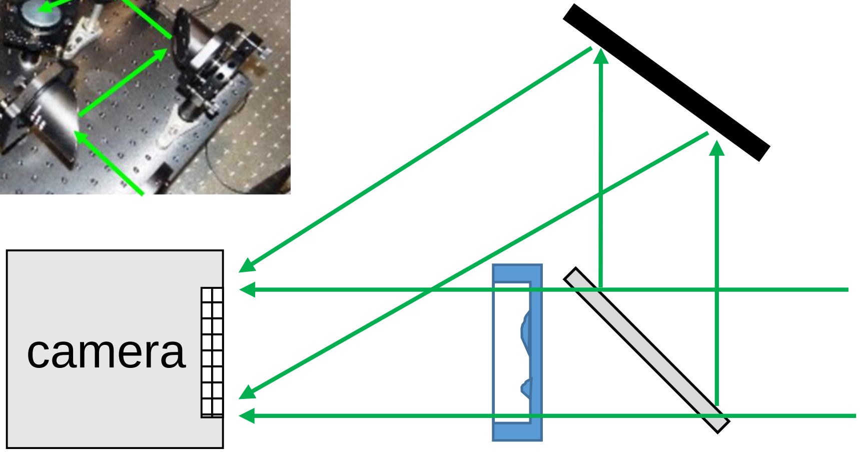
Terahertz Digital Holography

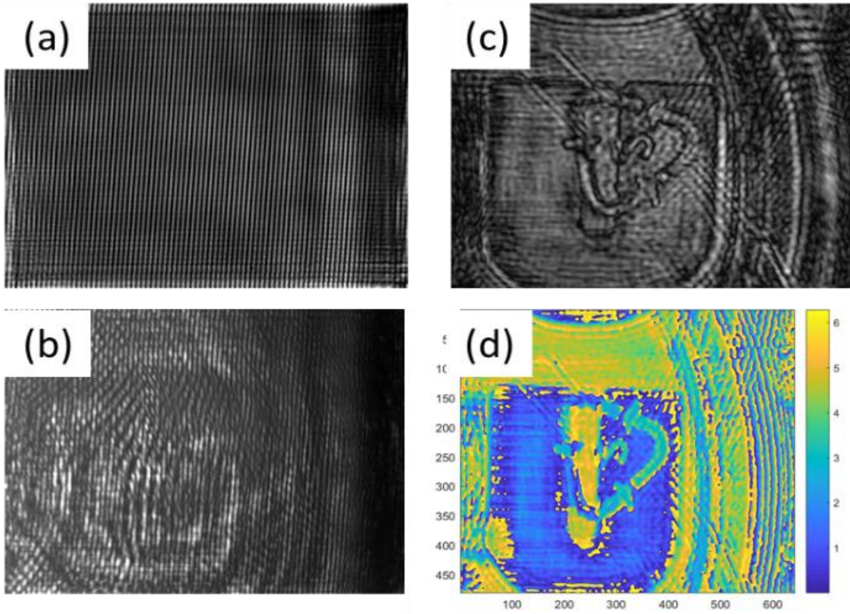
- Validity of paraxial approximation at FIR
  - Object must be very close to the sensor (a few cm)
  - Reconstruction by S-FFT feasible but lateral resolution very poor
- Solution: Use rigorous Angular Spectrum Method (ASM)
  - Size of reconstructed object = size of detector
  - Lateral resolution proportional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



- Set-up:

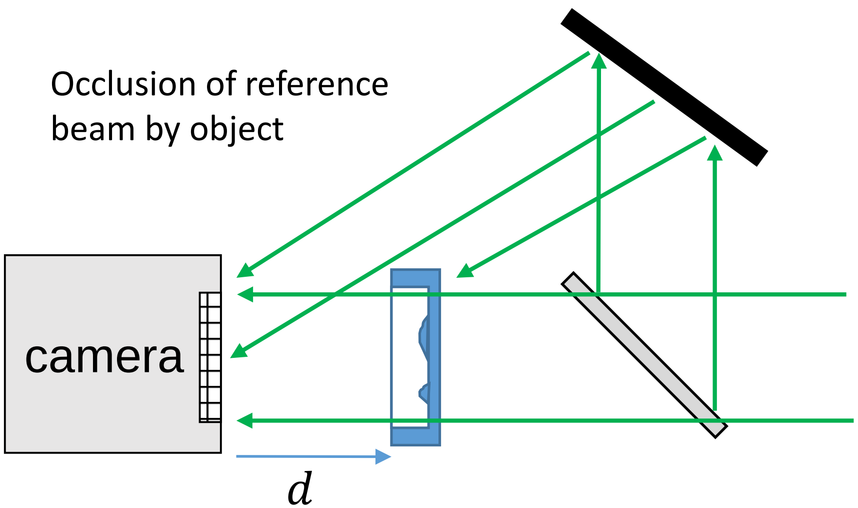


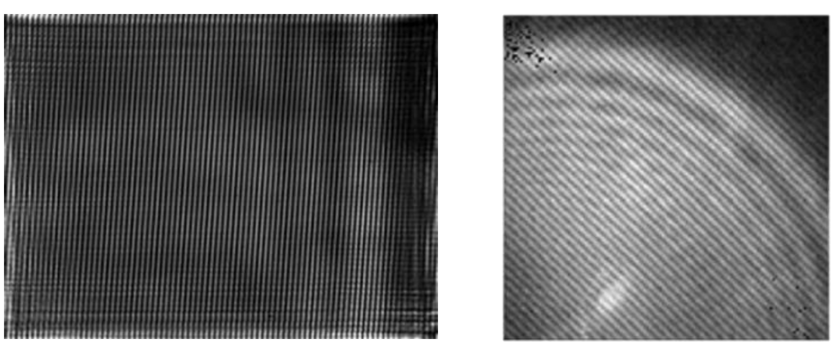




Terahertz Digital Holography

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



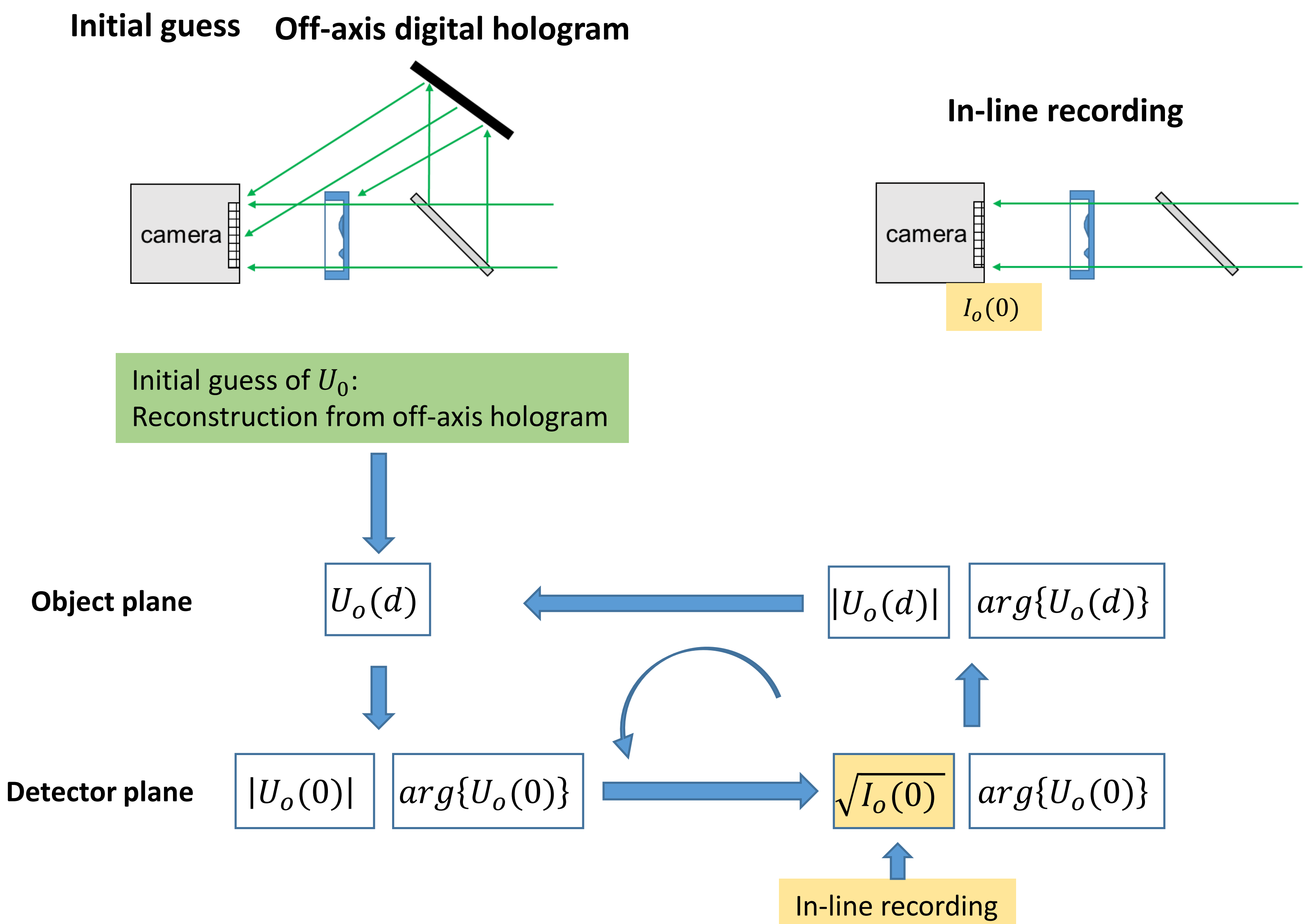


Recorded holograms with occlusion

Image degradation !

Terahertz Digital Holography

- Use of phase retrieval to recover image and improve resolution

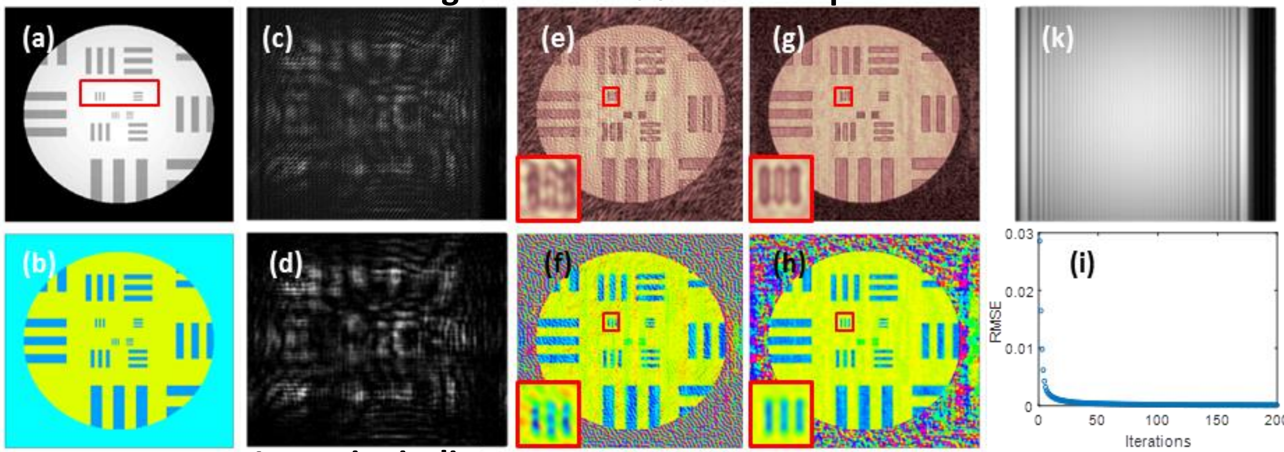


Terahertz Digital Holography

- Use of phase retrieval to recover image and improve resolution

Simulated

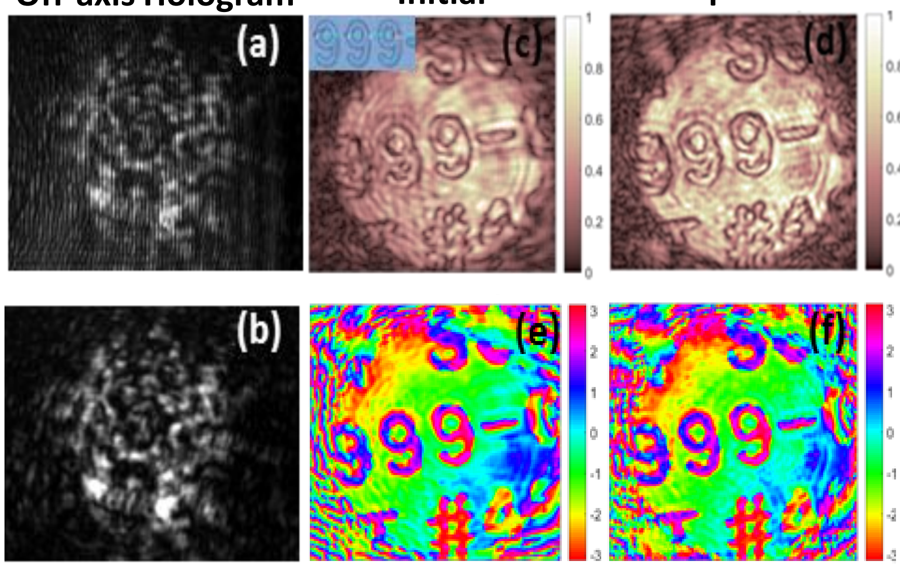
Off-axis Hologram | Initial | Improved



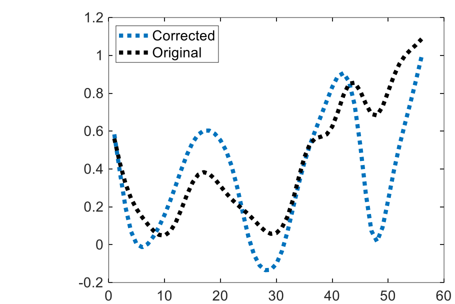
Intensity in-line

Experimental

Off-axis Hologram | Initial | Improved



Intensity in-line



Resolution: $\rho = \frac{\lambda d}{N\Delta}$

ρ_H = **114.7 µm** ⇔ $\lambda = 118.8\ \mu m$

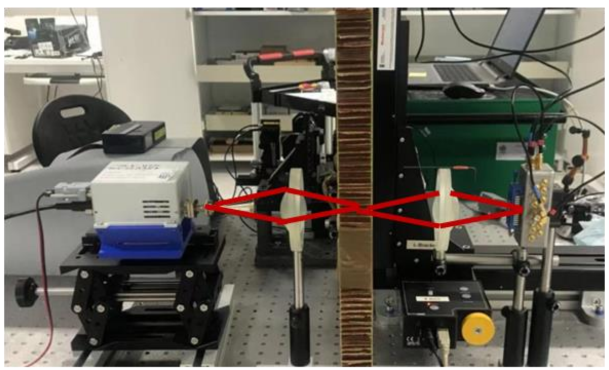
$\rho_V = 152.9\ \mu m$

Terahertz Digital Holography

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

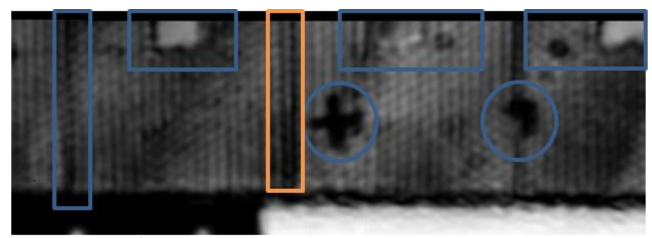
Collaboration with CENTERA Poland

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



Focal plane Imaging

Pitch 0,5mm

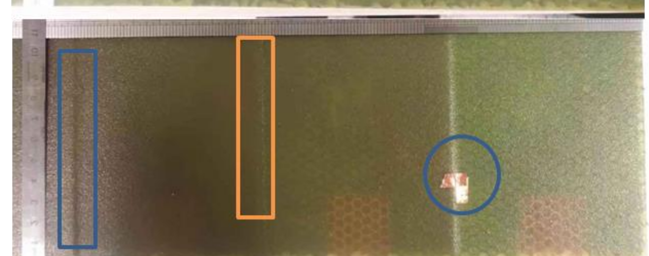


Metal holder with 2 holes

Air

Front
(source side)

Back
(detector side)

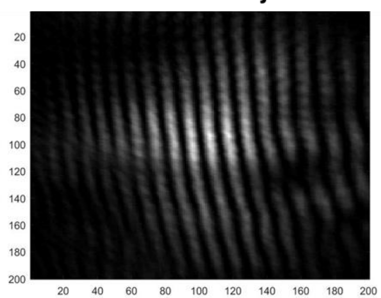


Terahertz Digital Holography

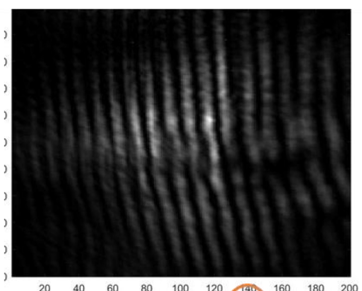
- Scanning hologram with single point detectors
- Digital holography validation

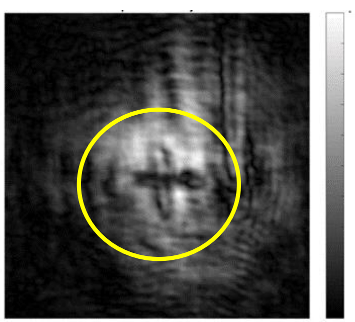
Amplitude object: metallic cross
Phase object: plastic stick

Without object

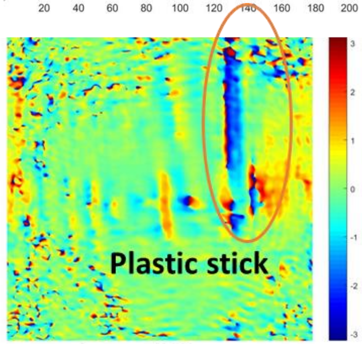


With object



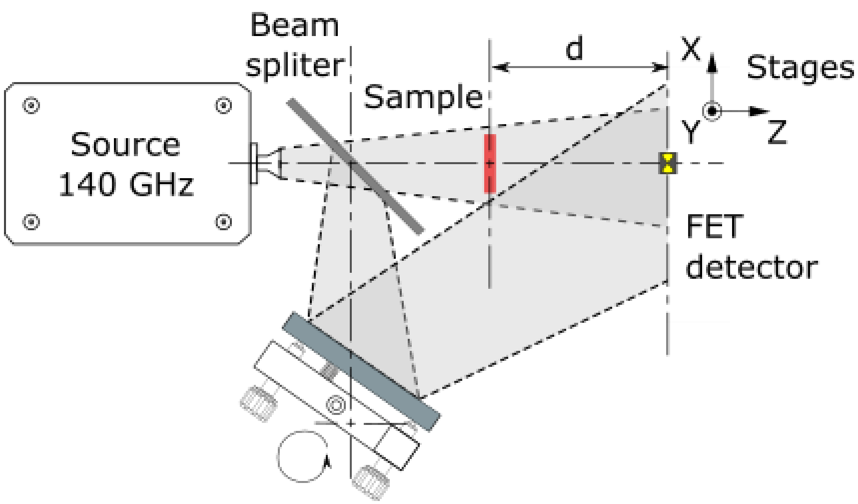


Object amplitude



Phase difference

Setup



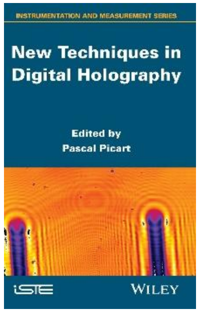
- 100 mm*100 mm hologram
- pitch: 0,5mm
- 2 hours scan

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
    - Phase retrieval
    - Numerical auto-focusing
    - Synthetic aperture
    - Compressed sensing
    - …
  - From FIR to sub-THz
  - State-of-art in lensless imaging techniques
    - EMPA, Switzerland
    - Beijing Univ. Technology, China
    - CSL, Belgium

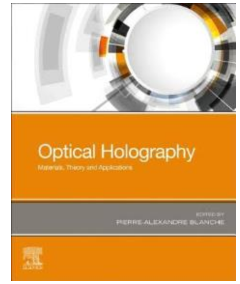
“THz coherent lensless imaging techniques – A Review”
L. Valzania, Y. Zhao, L. Rong, D. Wang, M. Georges,
E. Hack, P. Zolliker (submitted)

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

Strasbourg (FR), March 29-April 2, 2020

謝謝

Thanks for your attention !

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