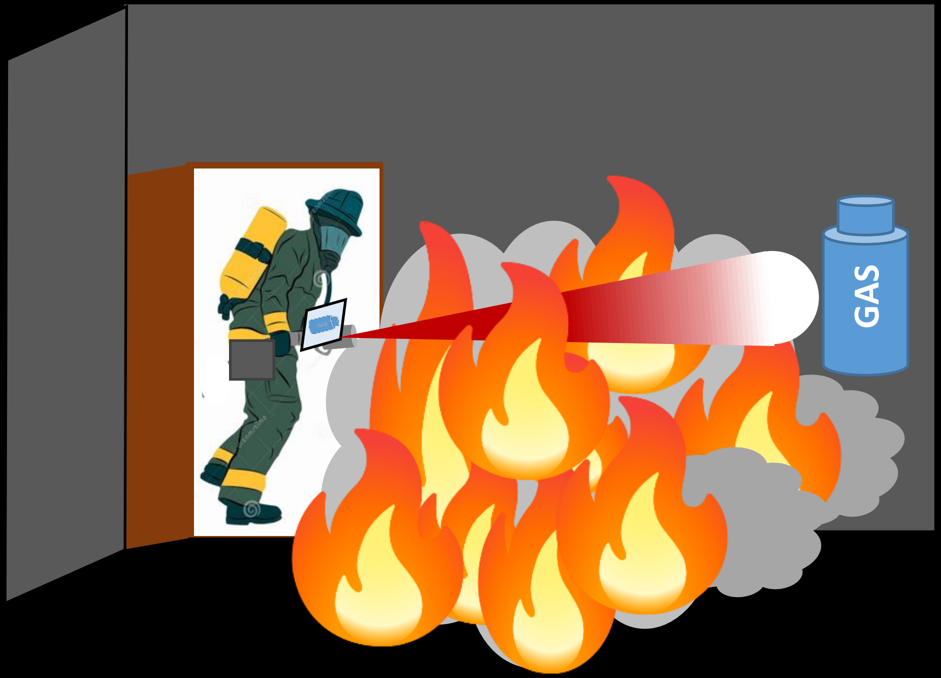
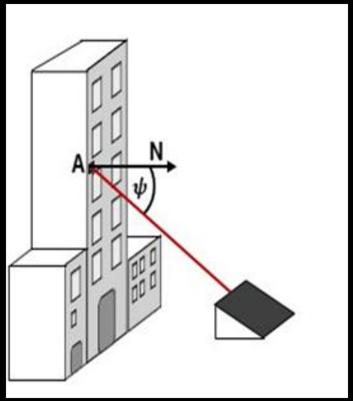
Applicazioni di Olografia Digitale Infrarossa:
‘Visione attraverso fumo e fiamme' e ‘Monitoraggio remote di edifici'



Emergenza antincendio



Eventi sismici

Decadimento naturale

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Massimiliano Locatelli 03.05.2024

UNIVERSITÀ
DEGLI STUDI
FIRENZE

Applicazioni di Olografia Digitale Infrarossa:
‘Visione attraverso fumo e fiamme' e ‘Monitoraggio remote di edifici'

Massimiliano Locatelli massimiliano.locatelli@ino.cnr.it

Istituto Nazionale di Ottica, CNR-INO, Arcetri (FI)

Osservatorio di Arcetri

Indice

1. **Olografia analogica e digitale**
2. **Olografia digitale nell’Infrarosso**
3. **Applicazioni**
    - **Visione attraverso fumo e fiamme**
    - **Monitoraggio remoto di edifici**
4. **Conclusioni**

Olografia Analogica

Olografia nella vita di tutti i giorni

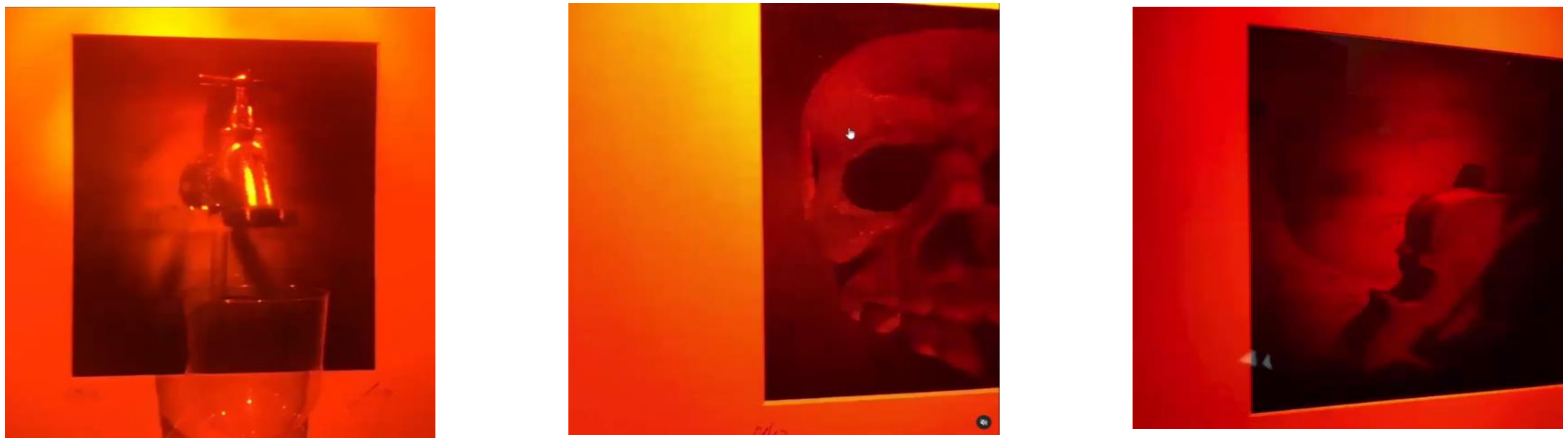
Banconote

Batterie

3.7V
BL-5CA
NOKIA

Carte di credito

Film di fantascienza
(Star Wars, Star Trek, Blade Runner 2049, …)



Ologrammi artistici

Olografia Analogica

L’Olografia, (Gabor 1948) è una tecnica di imaging interferometrico che permette di registrare e, successivamente, ricostruire tutta l’informazione contenuta nel fronte d’onda luminoso proveniente da un oggetto illuminato con radiazione coerente (cioè, in sostanza, illuminato con un laser).

D. Gabor

Dal greco:
ὅλος *holos* (tutto) e γραφή *grafè*, (scrittura)

AMPIEZZA and FASE

D. Gabor – ritratto olografico

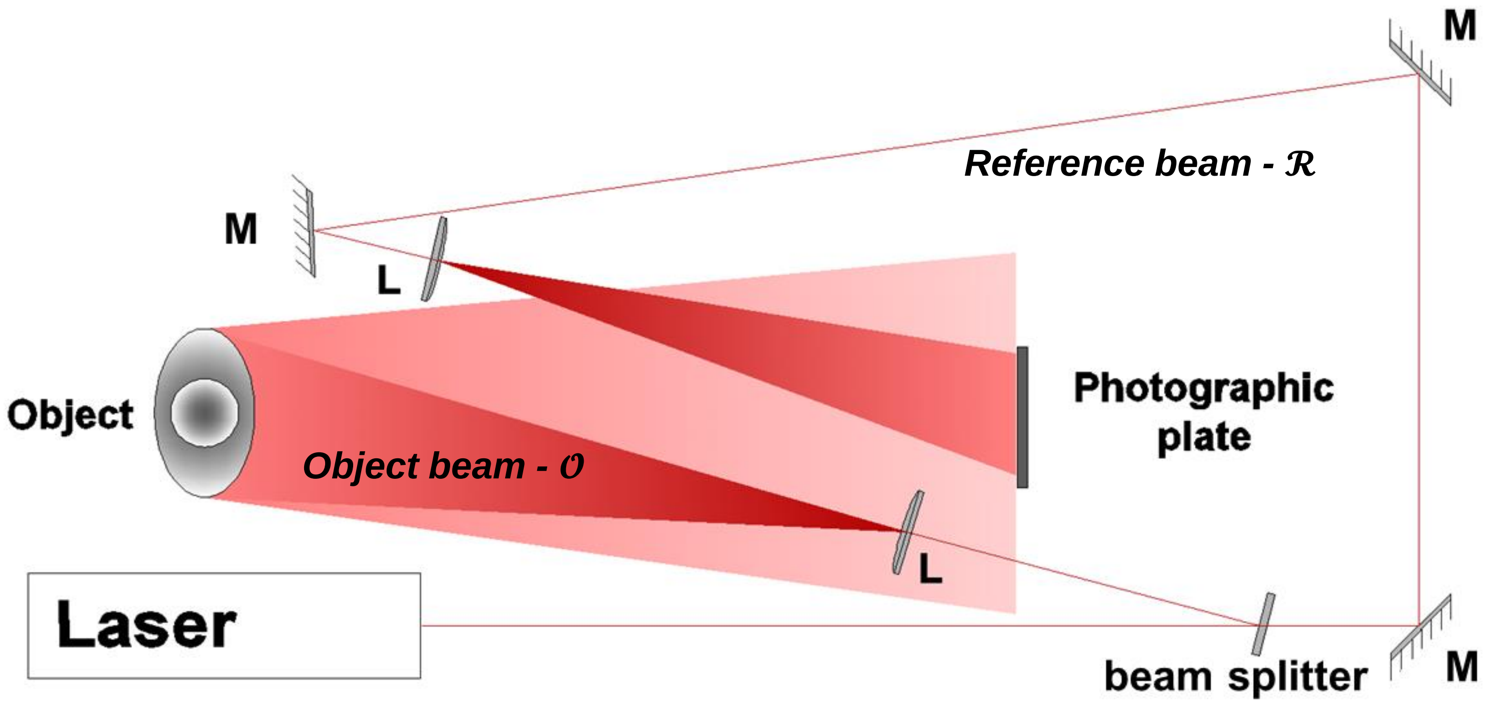
L’olografia è una procedura in due step:

- **Registrazione del fronte d’onda**
- **Ricostruzione del fronte d’onda**

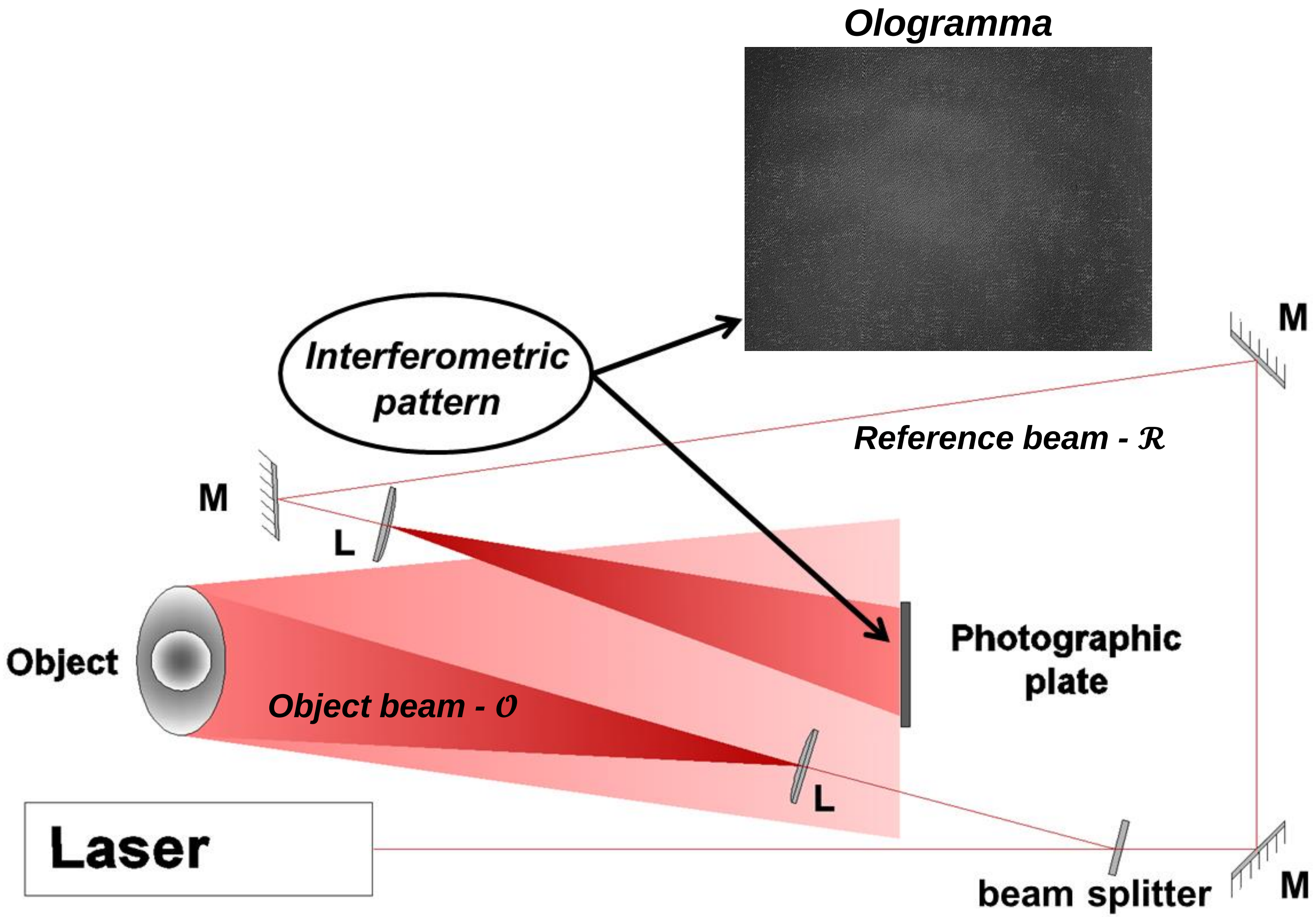
Registrazione del fronte d'onda

Radiazione coerente
Sistema di isolamento dalle vibrazioni

Varie configurazioni:
In trasmissione, in riflessione, fuori asse, in linea, phase shifting, Fourier, …

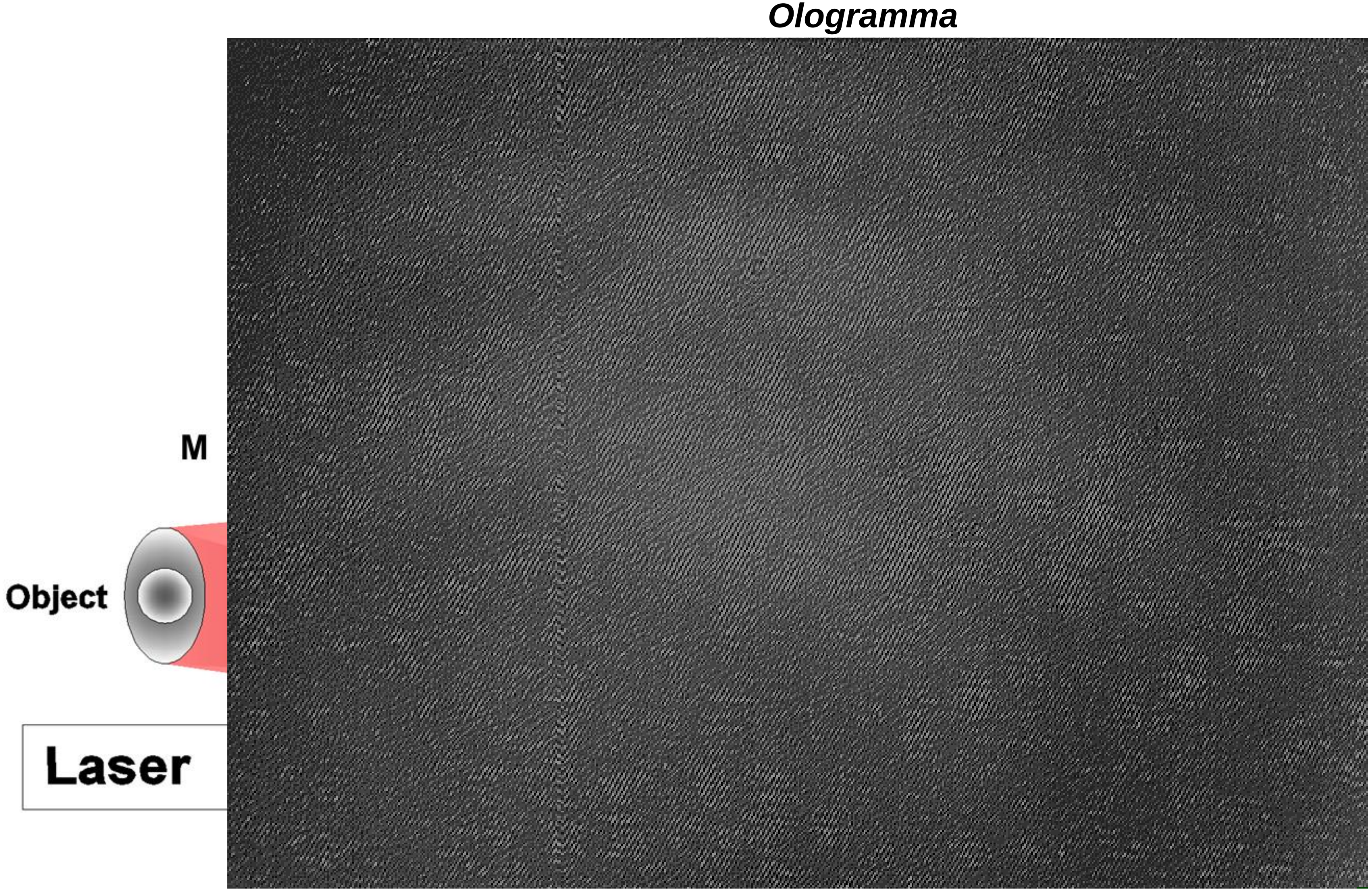

M
Reference beam - $\mathcal{R}$
M
L
Photographic plate
Object
Object beam - $\mathcal{O}$
L
Laser
beam splitter
M

Registrazione del fronte d'onda


Ologramma
Interferometric pattern
M
Reference beam - $\mathcal{R}$
M
L
Object
Photographic plate
Object beam - $\mathcal{O}$
L
Laser
beam splitter
M

Olografia Analogica

Registrazione del fronte d'onda

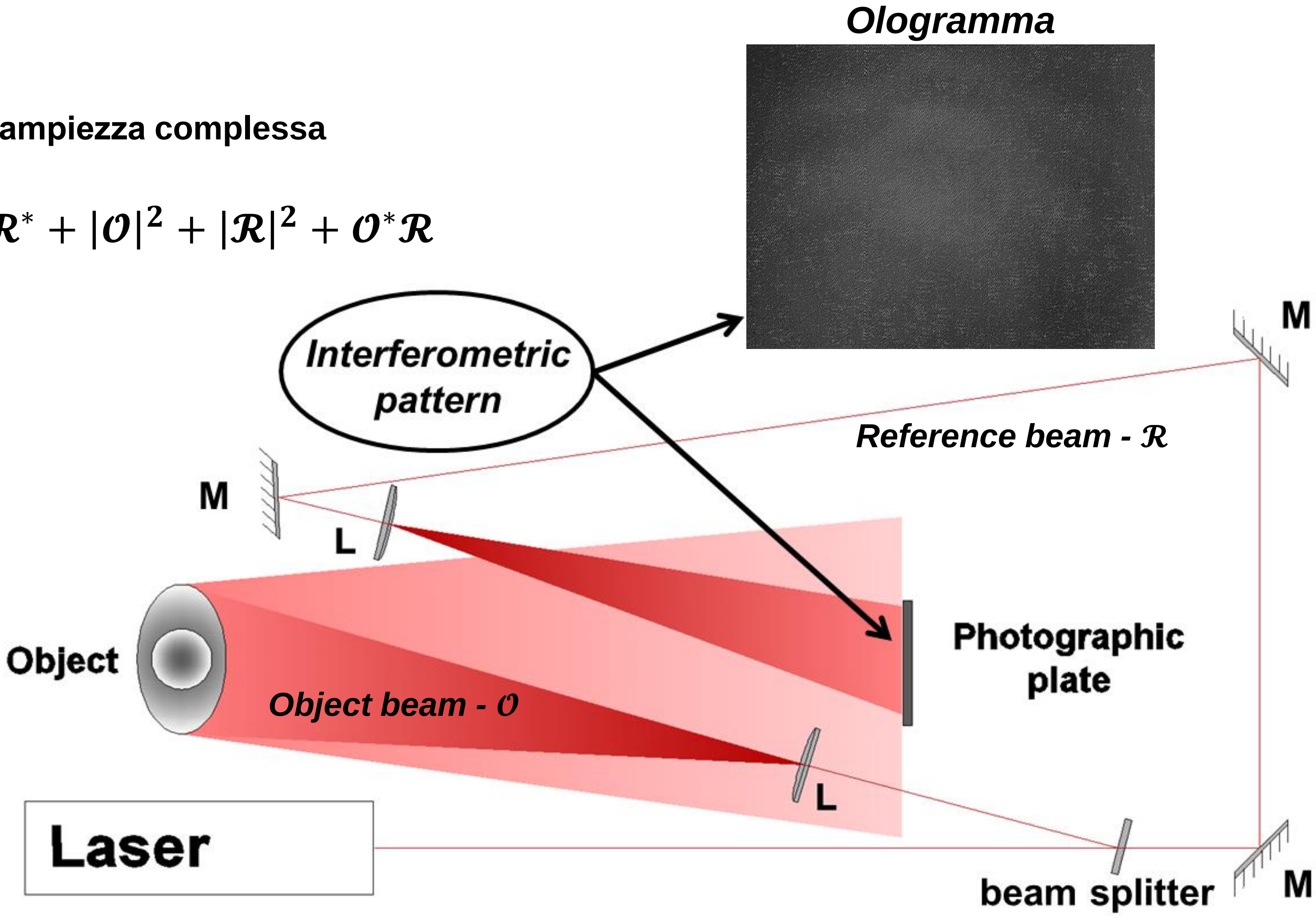

Ologramma
M
Object
Laser

Olografia Analogica

Registrazione del fronte d'onda

Notazione dell'ampiezza complessa

$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

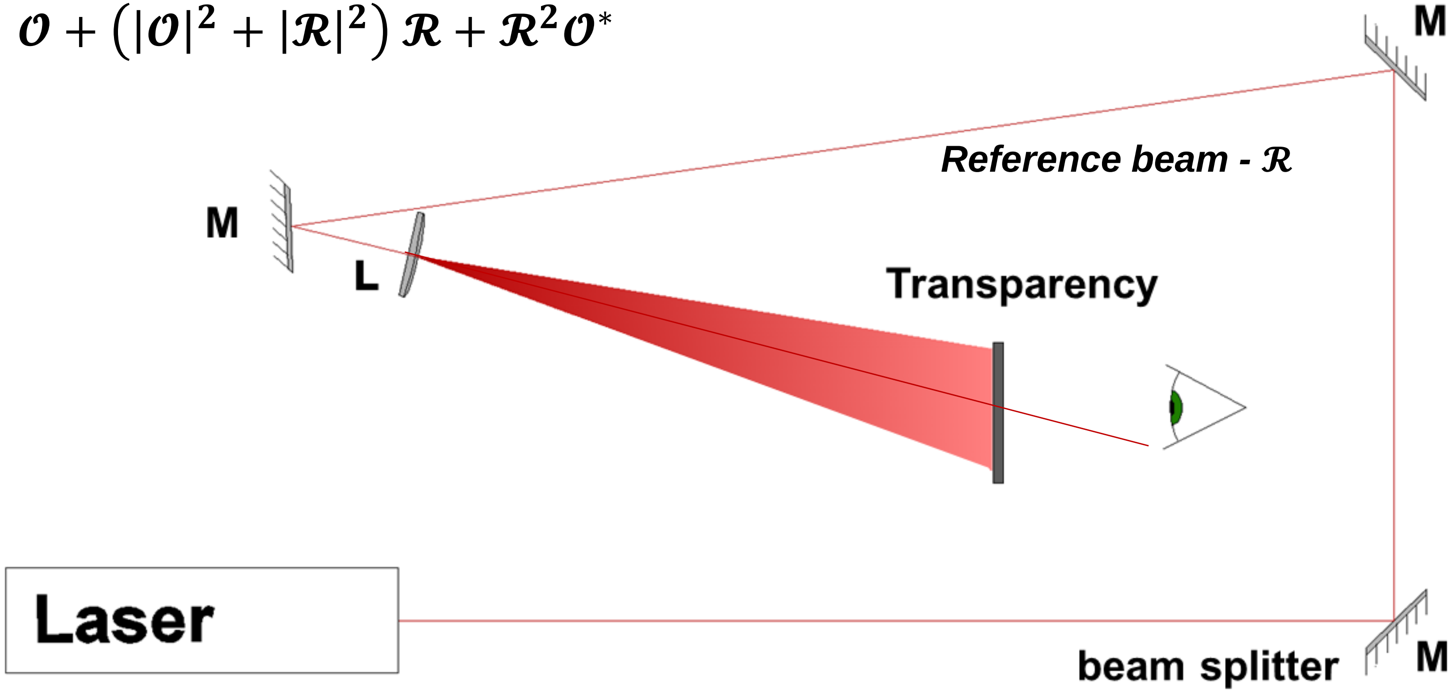

Ologramma
Interferometric pattern
M
Reference beam - $\mathcal{R}$
M
L
Object
Object beam - $\mathcal{O}$
Photographic plate
L
Laser
beam splitter
M

Olografia Analogica

Ricostruzione del fronte d’onda

$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

$$\mathcal{E}^{tot} = \mathcal{R}\mathcal{T} \propto \mathcal{R}\mathcal{I} \propto |\mathcal{R}|^2\,\mathcal{O} + \left(|\mathcal{O}|^2 + |\mathcal{R}|^2\right)\mathcal{R} + \mathcal{R}^2\mathcal{O}^*$$

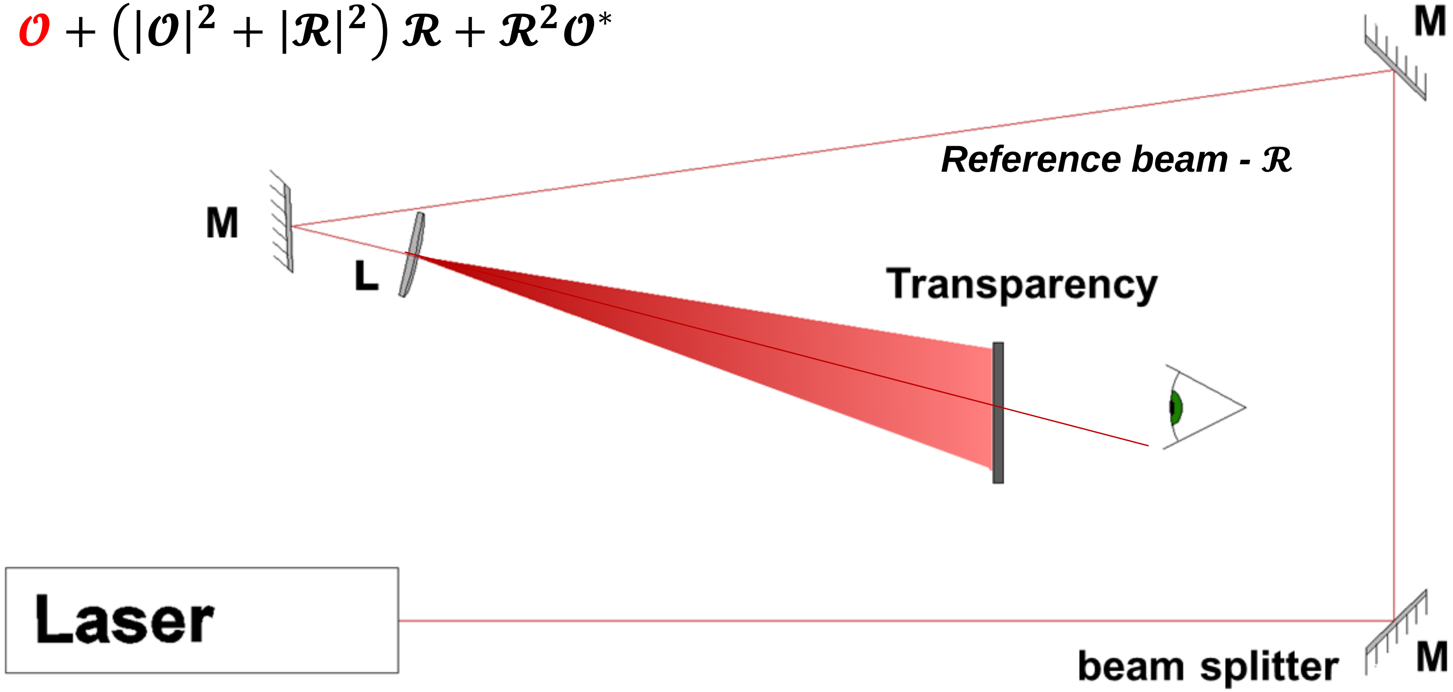

M
Reference beam - $\mathcal{R}$
M
L
Transparency
Laser
beam splitter
M

Olografia Analogica

Ricostruzione del fronte d'onda

$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

$$\mathcal{E}^{tot} = \mathcal{R}\mathcal{T} \propto \mathcal{R}\mathcal{I} \propto |\mathcal{R}|^2\,\mathcal{O} + \left(|\mathcal{O}|^2 + |\mathcal{R}|^2\right)\mathcal{R} + \mathcal{R}^2\mathcal{O}^*$$

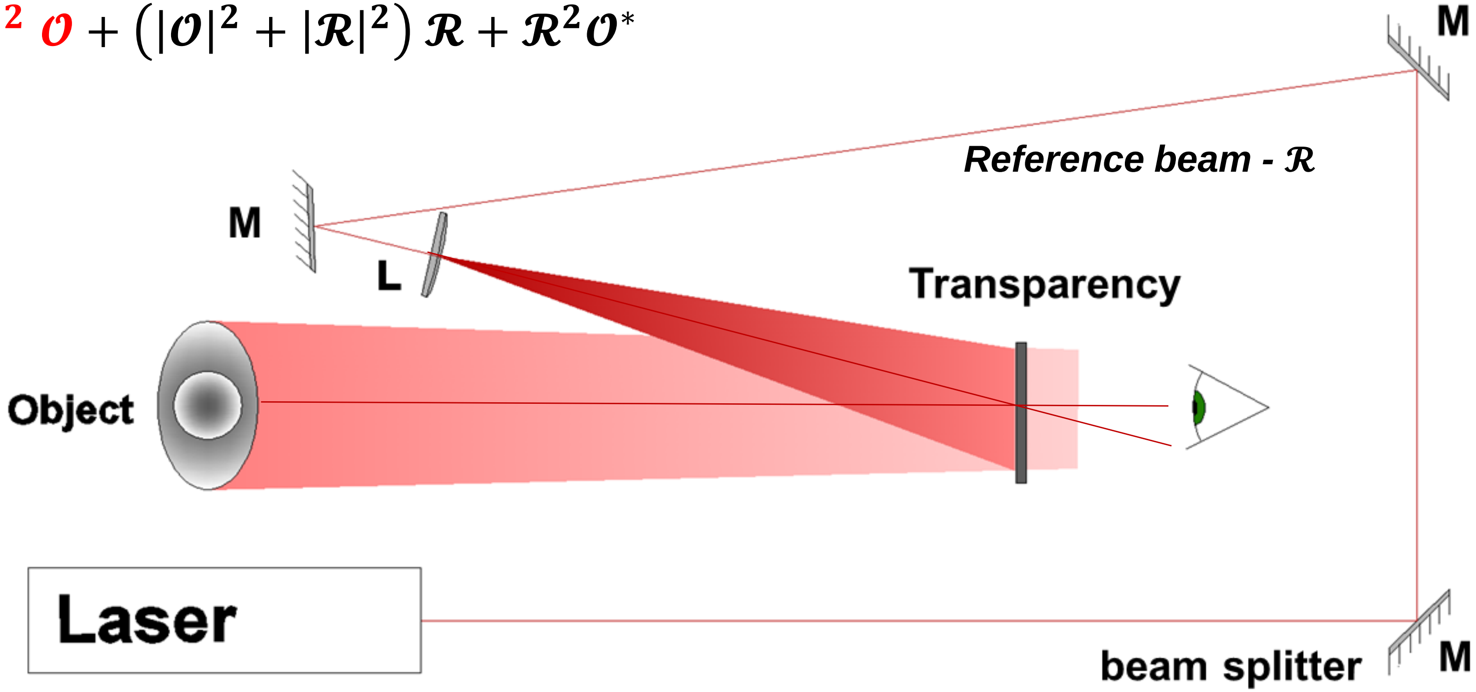

M
Reference beam - $\mathcal{R}$
M
L
Transparency
Laser
beam splitter
M

Olografia Analogica

Ricostruzione del fronte d’onda

$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

$$\mathcal{E}^{tot} = \mathcal{R}\mathcal{T} \propto \mathcal{R}\mathcal{I} \propto |\mathcal{R}|^2\,\mathcal{O} + \left(|\mathcal{O}|^2 + |\mathcal{R}|^2\right)\mathcal{R} + \mathcal{R}^2\mathcal{O}^*$$

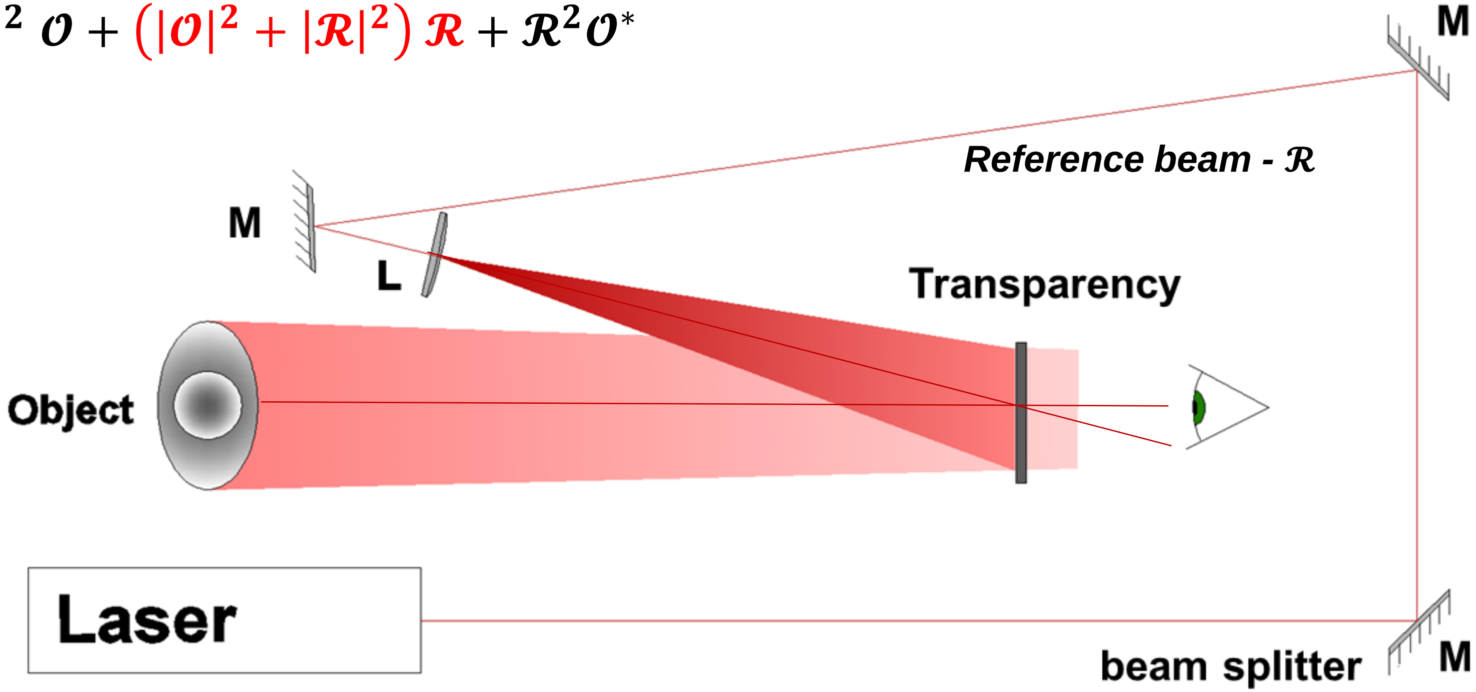

M
Reference beam - $\mathcal{R}$
M
L
Transparency
Object
Laser
beam splitter
M

Olografia Analogica

Ricostruzione del fronte d'onda

$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

$$\mathcal{E}^{tot} = \mathcal{R}\mathcal{T} \propto \mathcal{R}\mathcal{I} \propto |\mathcal{R}|^2\,\mathcal{O} + \left(|\mathcal{O}|^2 + |\mathcal{R}|^2\right)\mathcal{R} + \mathcal{R}^2\mathcal{O}^*$$

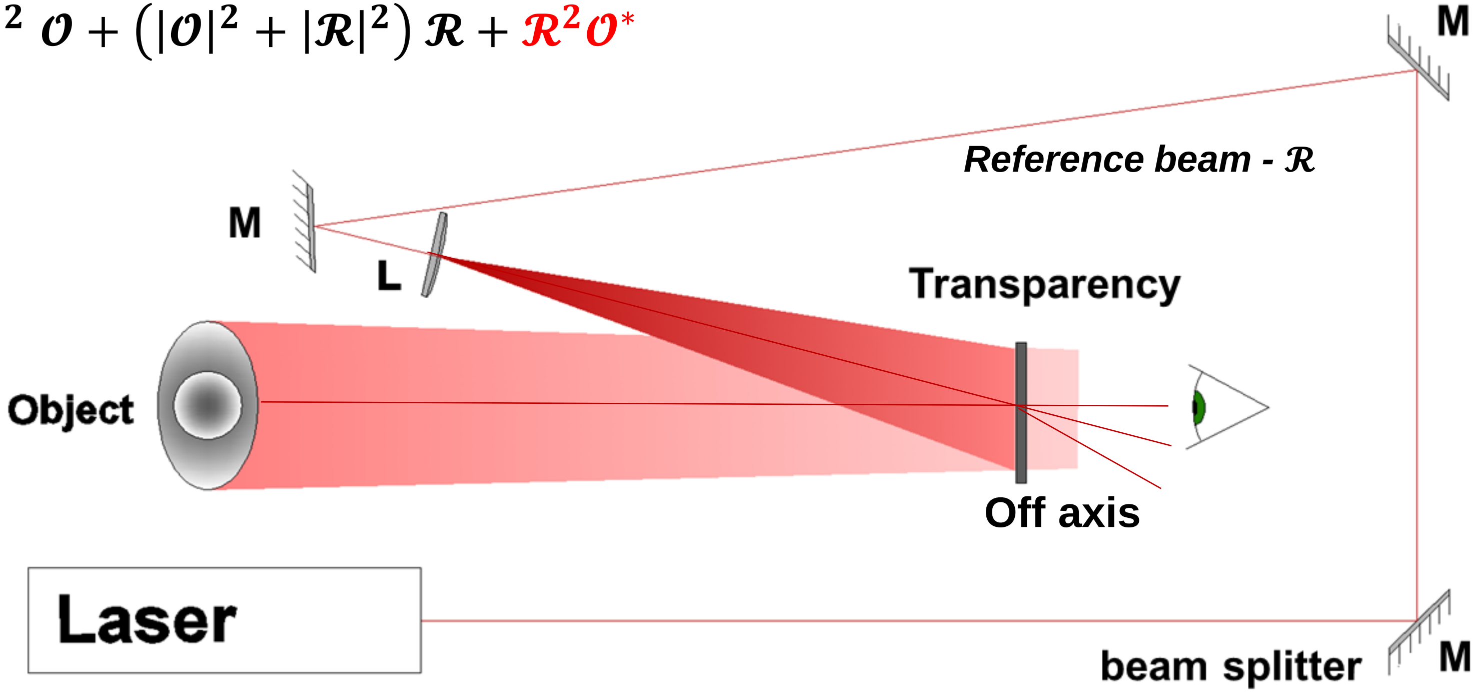

M
Reference beam - $\mathcal{R}$
M
L
Transparency
Object
Laser
beam splitter
M

Olografia Analogica

Ricostruzione del fronte d’onda

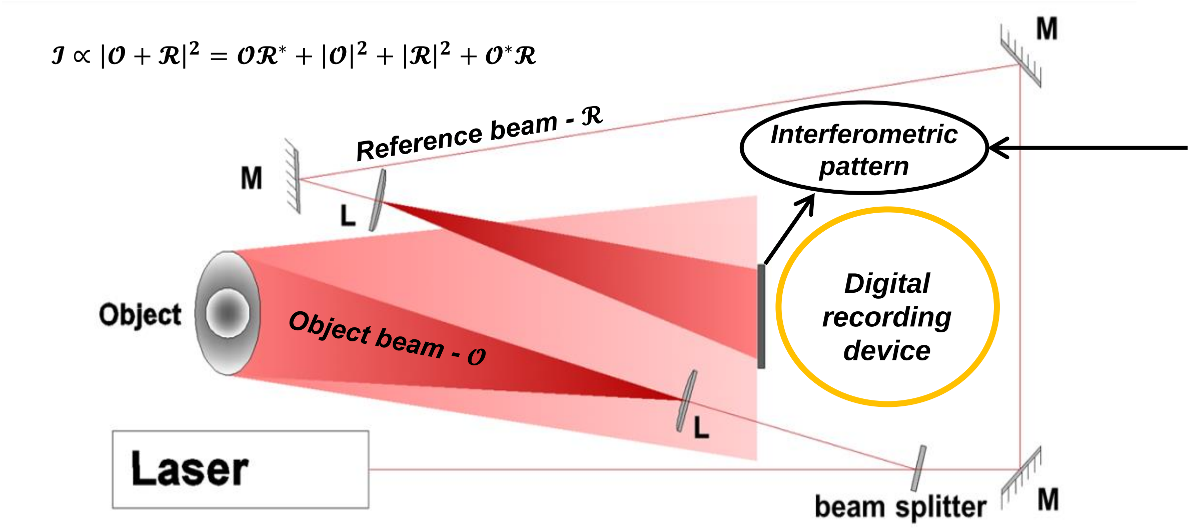
$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

$$\mathcal{E}^{tot} = \mathcal{R}\mathcal{T} \propto \mathcal{R}\mathcal{I} \propto |\mathcal{R}|^2\,\mathcal{O} + \left(|\mathcal{O}|^2 + |\mathcal{R}|^2\right)\mathcal{R} + \mathcal{R}^2\mathcal{O}^*$$


M
Reference beam - $\mathcal{R}$
M
L
Transparency
Object
Off axis
Laser
beam splitter
M

Olografia Digitale

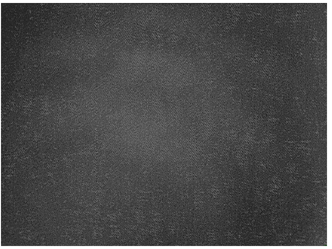
Registrazione del fronte d'onda



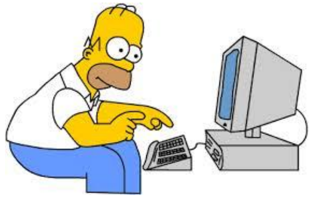
$$\mathcal{I} \propto |\mathcal{O}+\mathcal{R}|^2 = \mathcal{O}\mathcal{R}^* + |\mathcal{O}|^2 + |\mathcal{R}|^2 + \mathcal{O}^*\mathcal{R}$$

M
Reference beam - $\mathcal{R}$
M
L
Object
Object beam - $\mathcal{O}$
L
Laser
beam splitter
M
Interferometric pattern
Digital recording device

Ologramma



Ricostruzione numerica del fronte d'onda

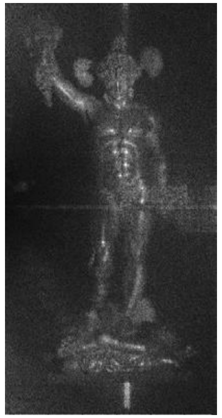


Integrale di Rayleigh – Sommerfeld

$$\mathcal{O}\,(x_R, y_R) = \frac{1}{i\lambda} \iint_{-\infty}^{+\infty} \mathcal{R}(x_H, y_H) H(x_H, y_H) \frac{e^{i\frac{2\pi}{\lambda}\rho}}{\rho}\, dx_H dy_H$$

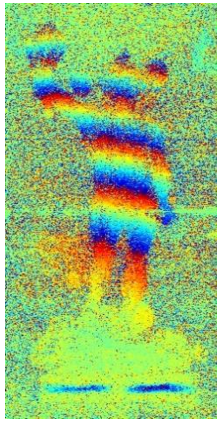
1 FFT (Metodo di Fresnel)

Immagine di ampiezza



$$I(x_R, y_R) = \mathcal{O}(x_R, y_R)\, \mathcal{O}^*(x_R, y_R)$$

Immagine di fase



$$\phi(x_R, y_R) = \tan^{-1}\left(\frac{Im\{\mathcal{O}(x_R, y_R)\}}{Re\{\mathcal{O}(x_R, y_R)\}}\right)$$

Olografia Digitale Infrarossa

Maggiore lunghezza d'onda →

Minore sensibilità alle vibrazioni

Maggiore campo di vista

$$FOV = 2\,sin^{-1}\left(\frac{\lambda}{4d_p}\right) \overset{small\ angles}{\approx} \frac{\lambda}{2d_p}$$

Laser CO_2 →

Alta potenza → **Irraggiamento efficiente**

Alta coerenza → **Irraggiamento remoto**

Video ologrammi di scene dinamiche di grandi dimensioni da remoto anche fuori dal laboratorio.

Allaria … - Digital holography at 10.6 μ m - Opt. Commun. 215, 257–262 (2003).

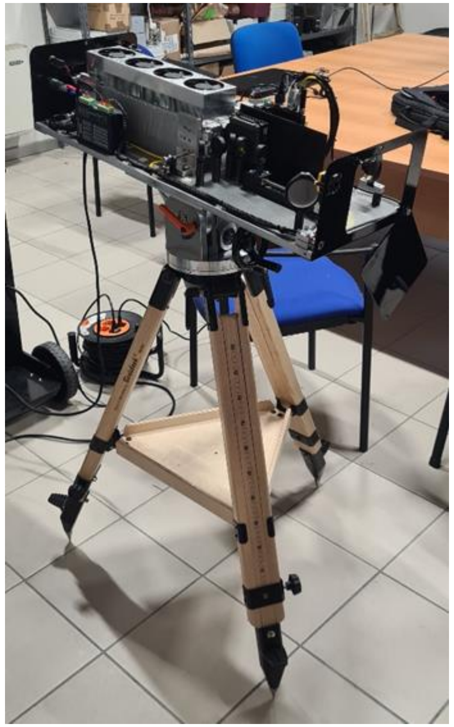
Olografia Digitale Infrarossa

Apparato sperimentale

IR laser source
Air cooled CO2 Laser
10.6 µm wavelength
40 W power

IR detector (with no lens)
Dali IRTech ZE 1920 HD 1920 X 1080
15 µm pixel pitch - 50 Hz frame rate

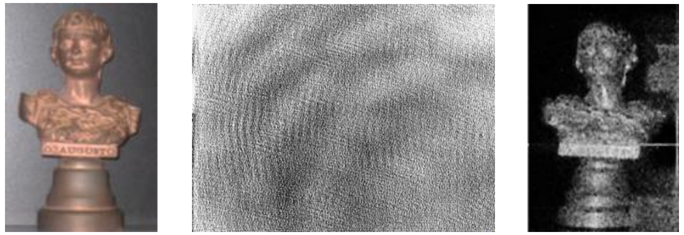
IR optics
Zn-Se lenses and BS
Gold coated mirrors



Prototipo attuale

Olografia Digitale Infrarossa

Ologrammi IR

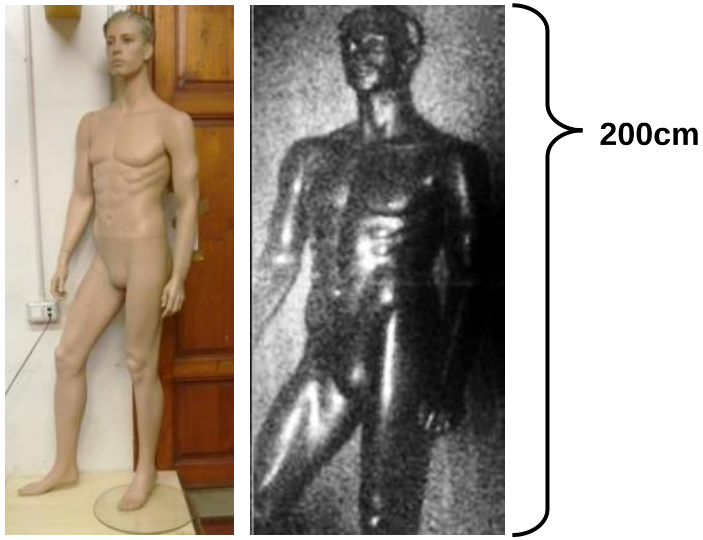


Oggeto

Ologramma

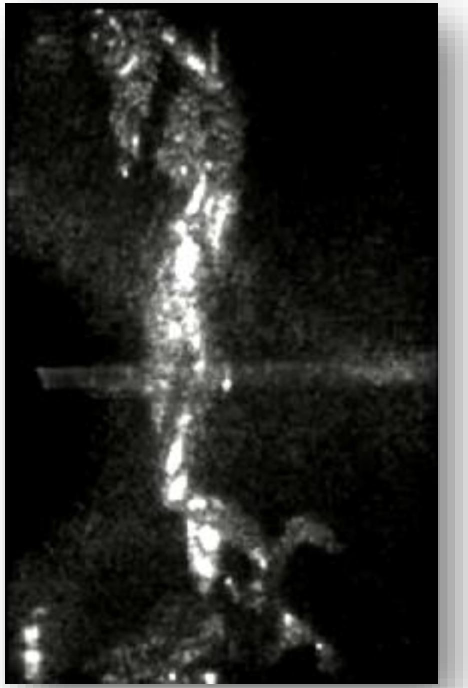
Immagine
di ampiezza

Grande campo di vista



Ologrammi a dimensione umana

Bassa sensibiltà alle vibrazioni



Video ologramma

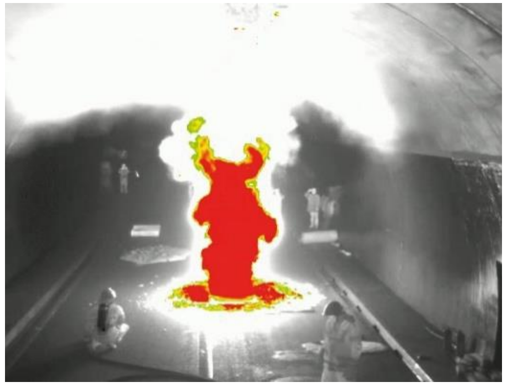
Bassa sensibilità alle vibrazioni + Grande campo di vista

Ologramma di un essere umano

FINE
PRIMO TEMPO

Visone attraverso fumo e fiamme

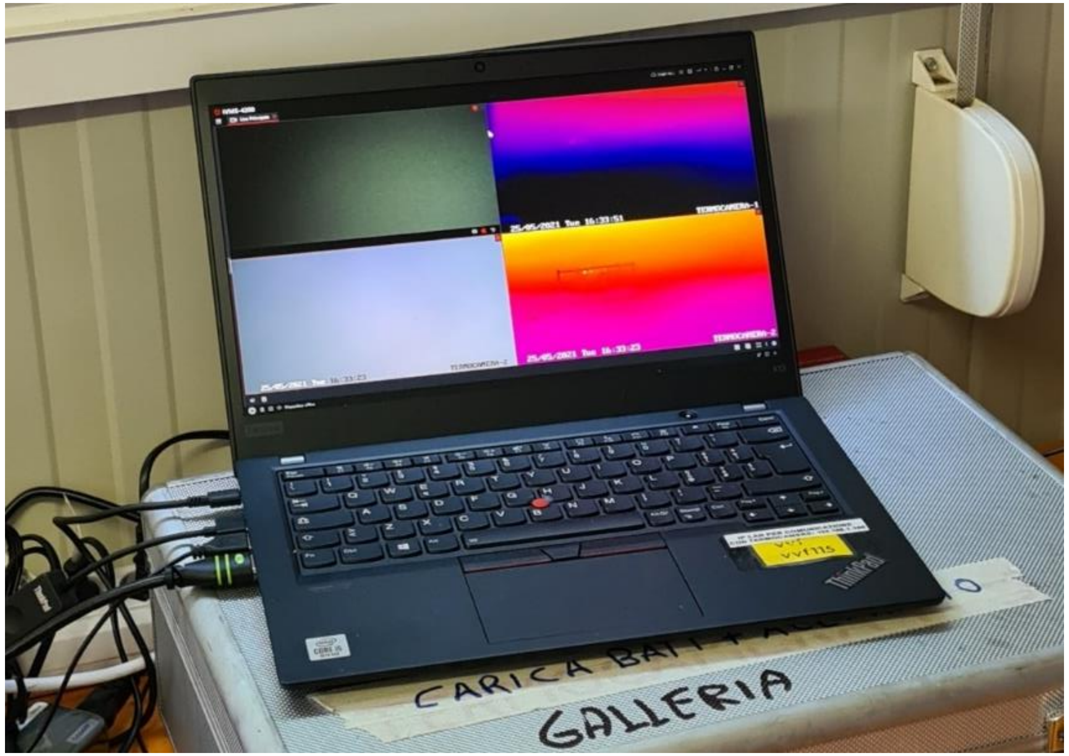
Termo-camera
In ambiente saturo di fumo



Termo-camera
in una scena di fuoco

Visone attraverso fumo e fiamme

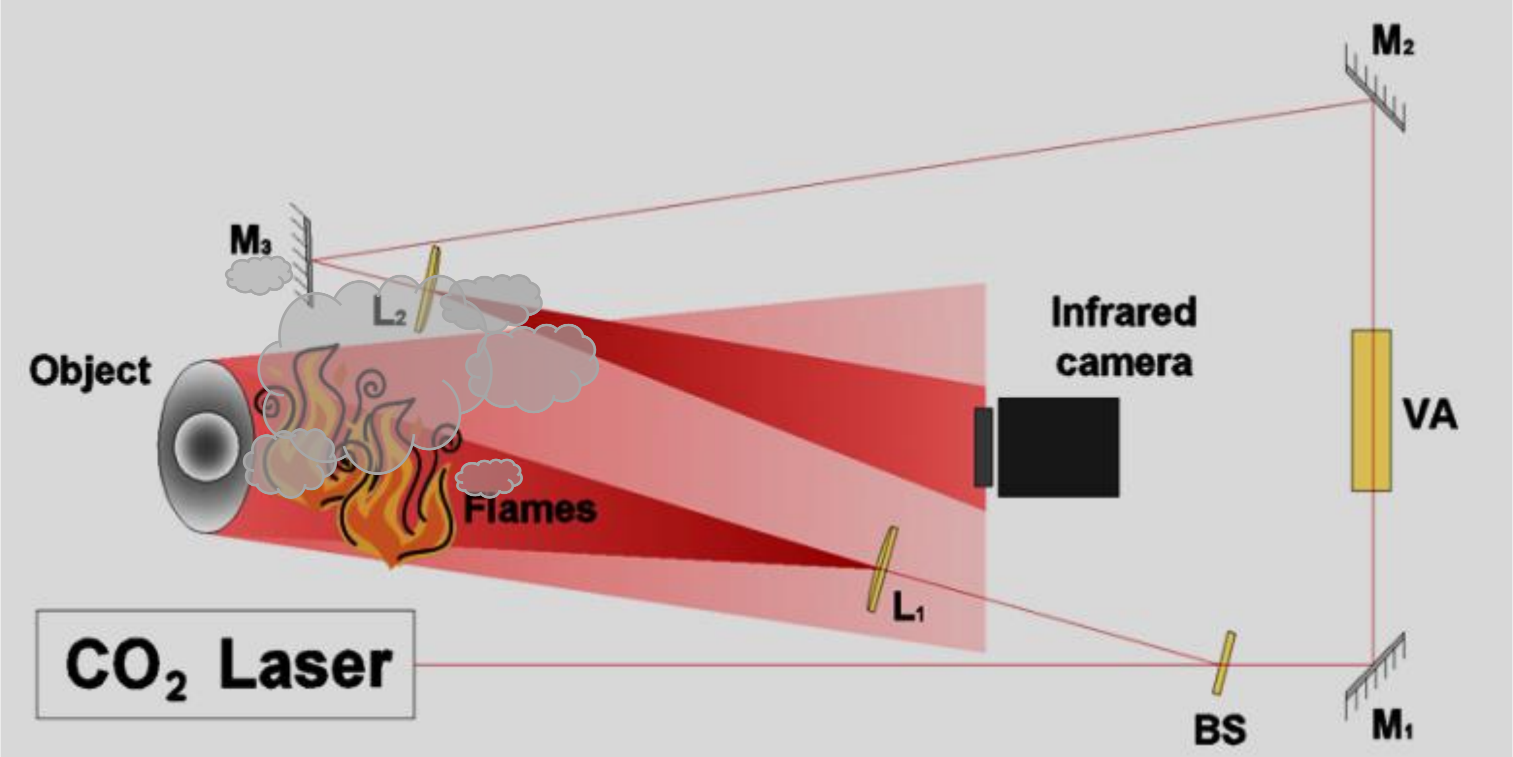
Il problema da risolvere


CARICA BATT
GALLERIA

2 Camere nel visibile + 2 termo camere

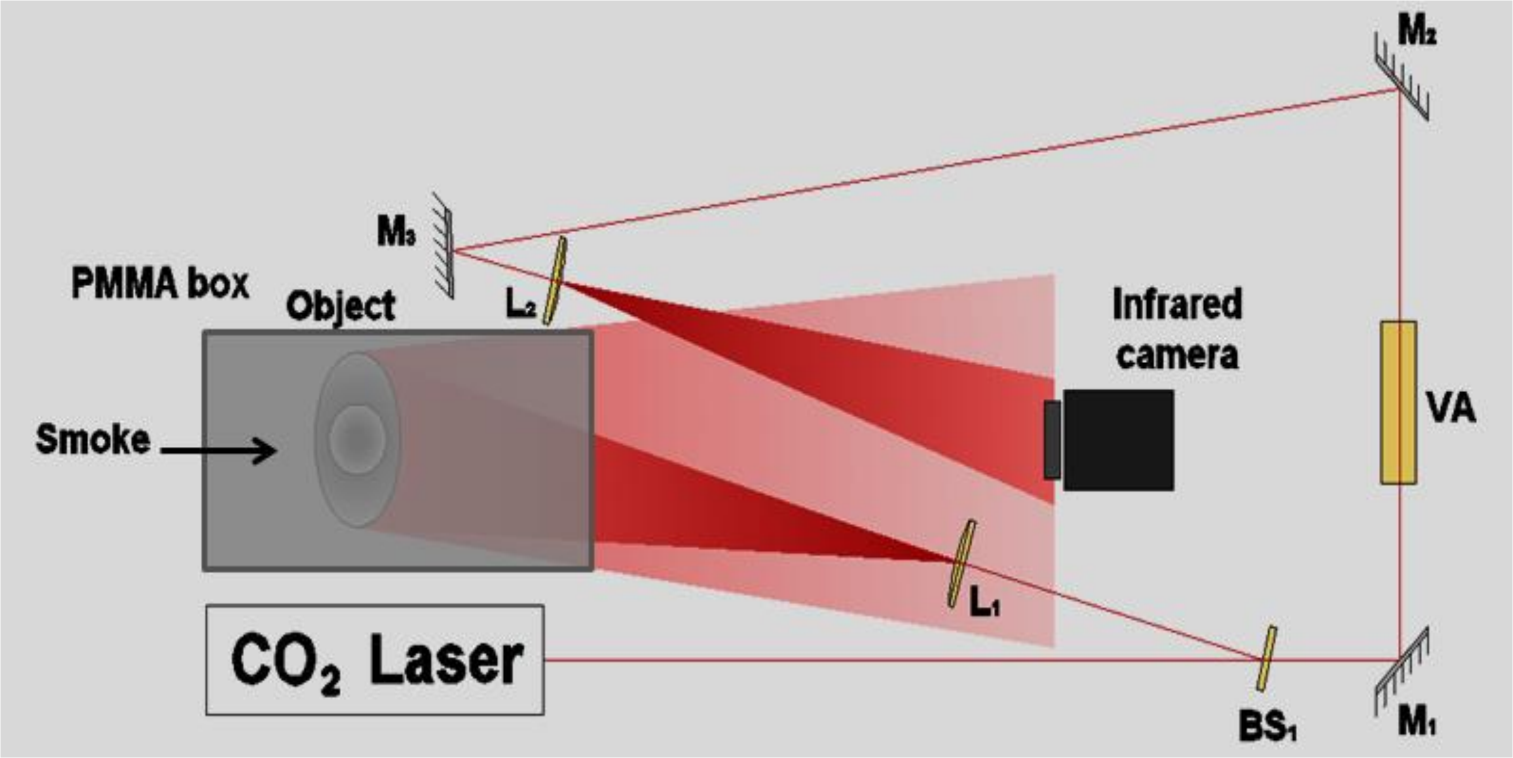
Corpo Nazionale dei Vigili del Fuoco
(Montelibretti)
Test di incendio in galleria

Visone attraverso fumo e fiamme

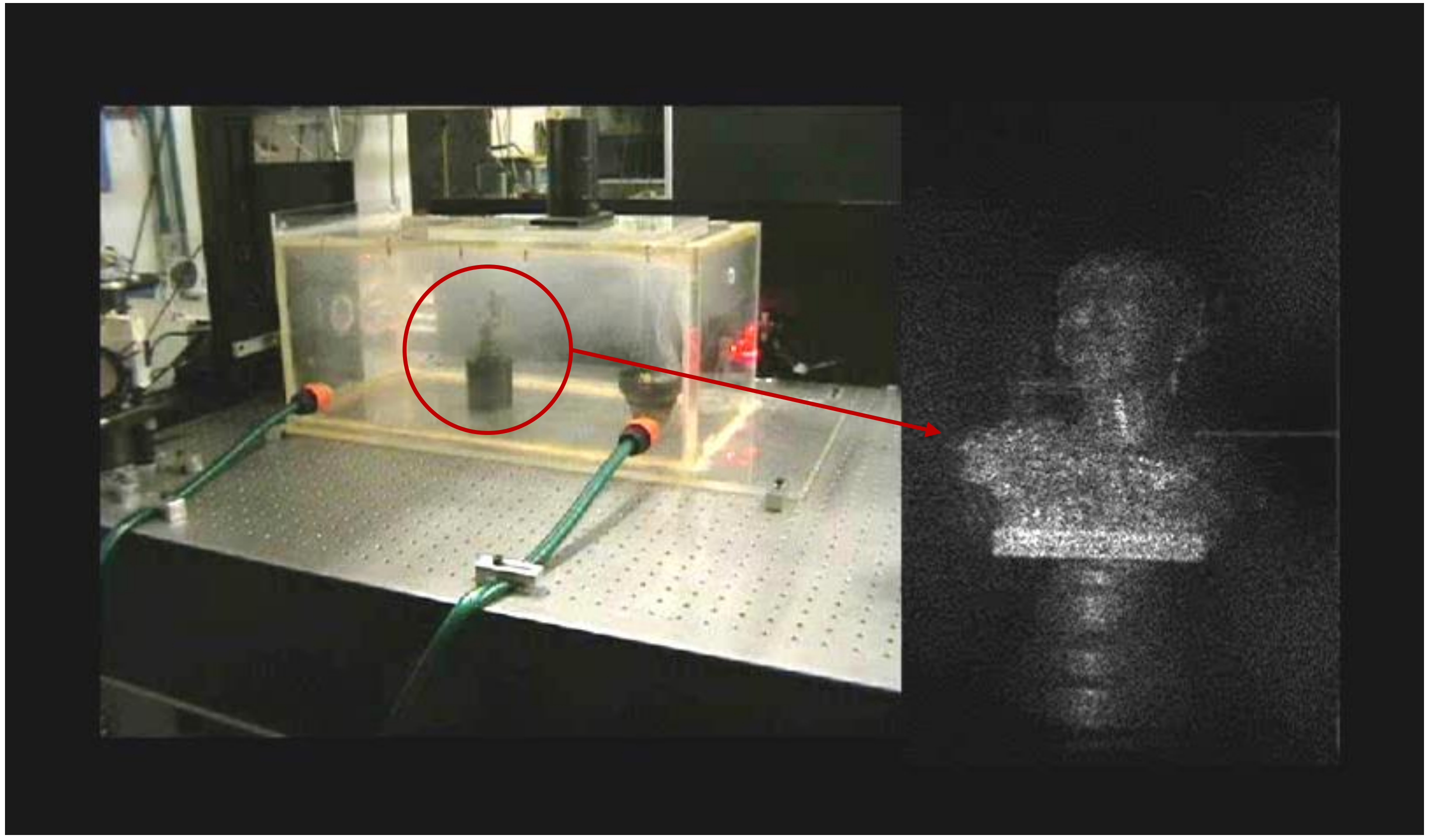

M2
M3
L2
Infrared camera
Object
VA
Flames
L1
CO2 Laser
BS
M1

Locatelli … "Imaging live humans through smoke and flames using far-infrared digital holography" Opt. Express 21, 5379-5390 (2013)

Visone attraverso FUMO e fiamme


M2
M3
PMMA box
Object
L2
Infrared camera
Smoke
VA
L1
CO2 Laser
BS1
M1

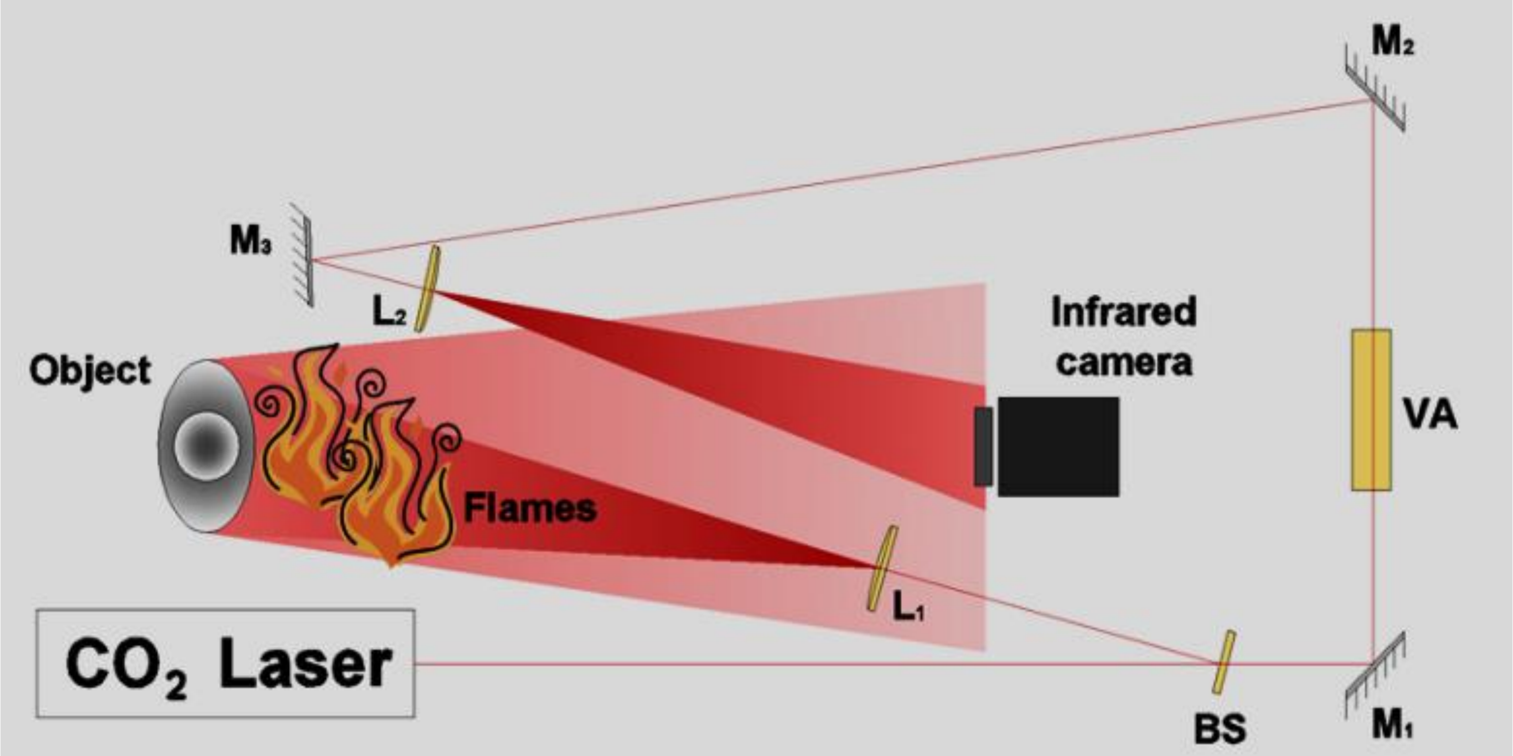
Visone attraverso FUMO e fiamme



Video nel visibile

Video olografico nell’Infrarosso

Visone attraverso fumo e FIAMME


M₂
M₃
L₂
Infrared camera
Object
VA
Flames
L₁
CO₂ Laser
BS
M₁

Visone attraverso fumo e FIAMME

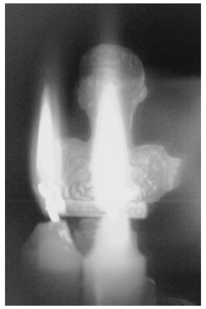


Immagine termica

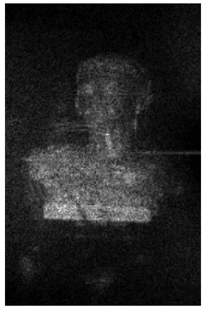


Immagine olografica

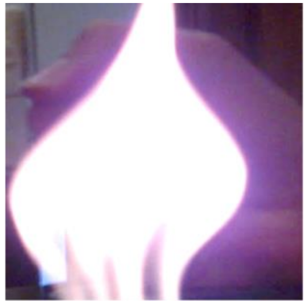


Immagine Nel visibile

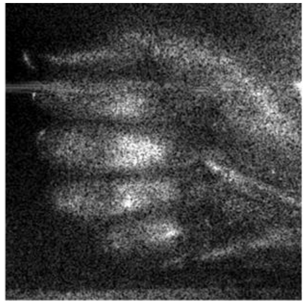


Immagine olografica

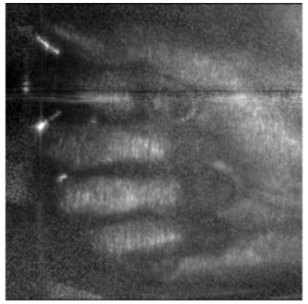


Immagine Olografica (riduzione del rumore)

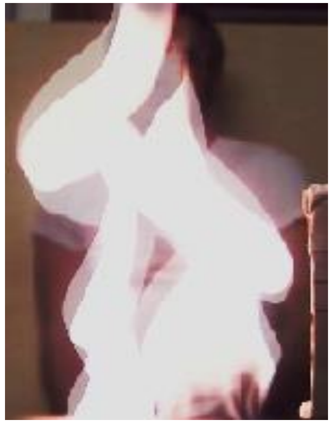


Immagine nel visibile

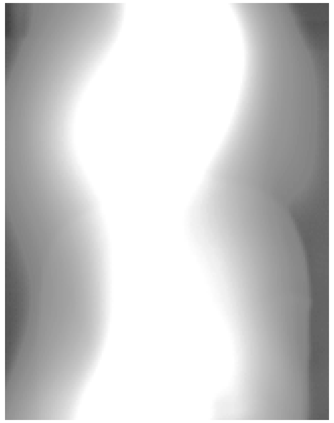


Immagine termica

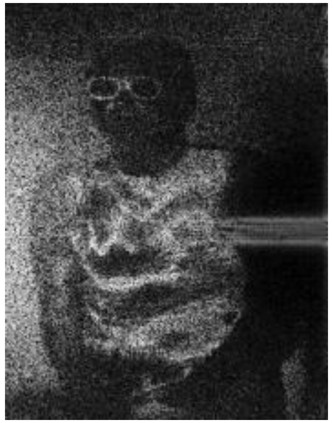
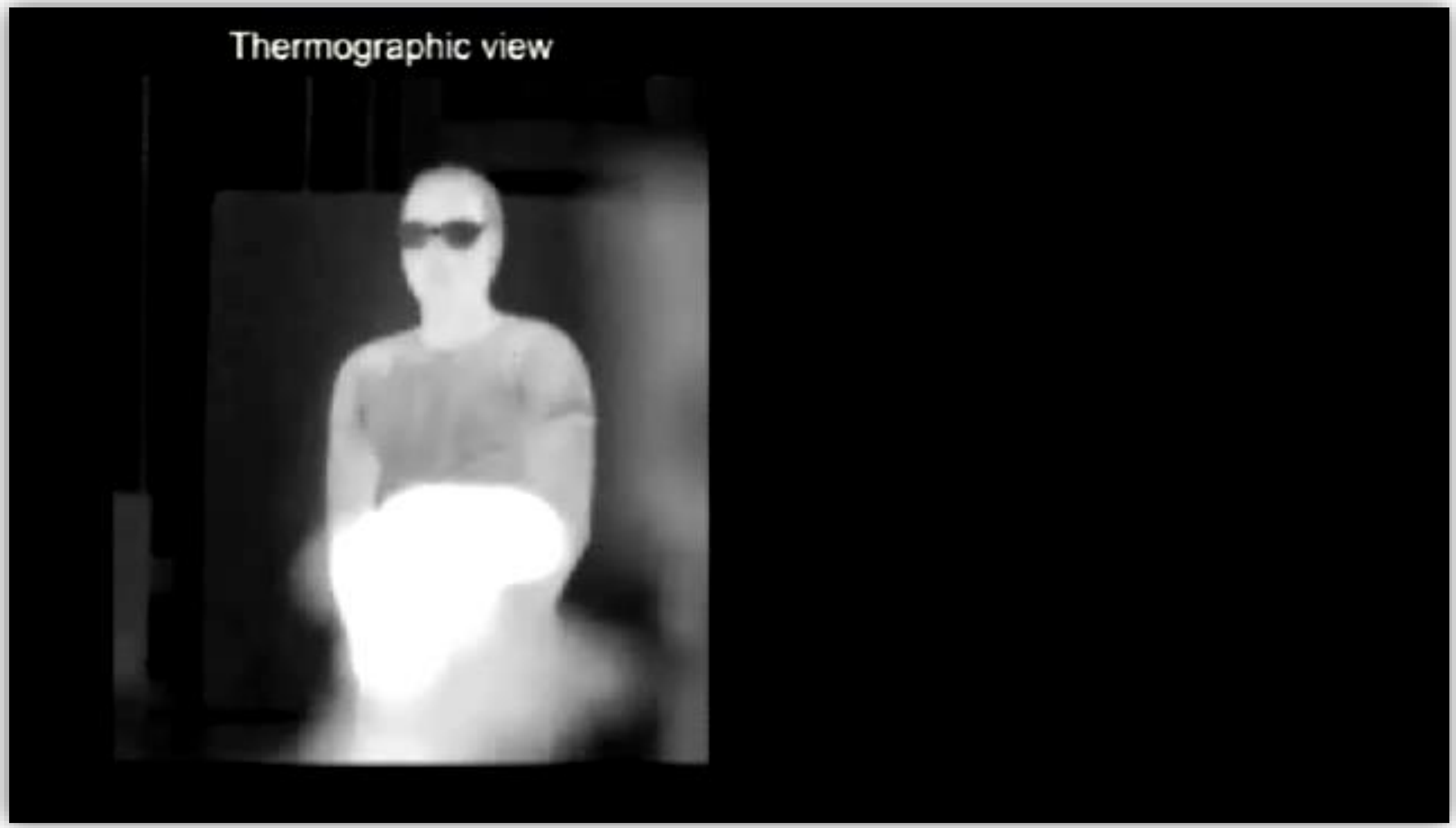


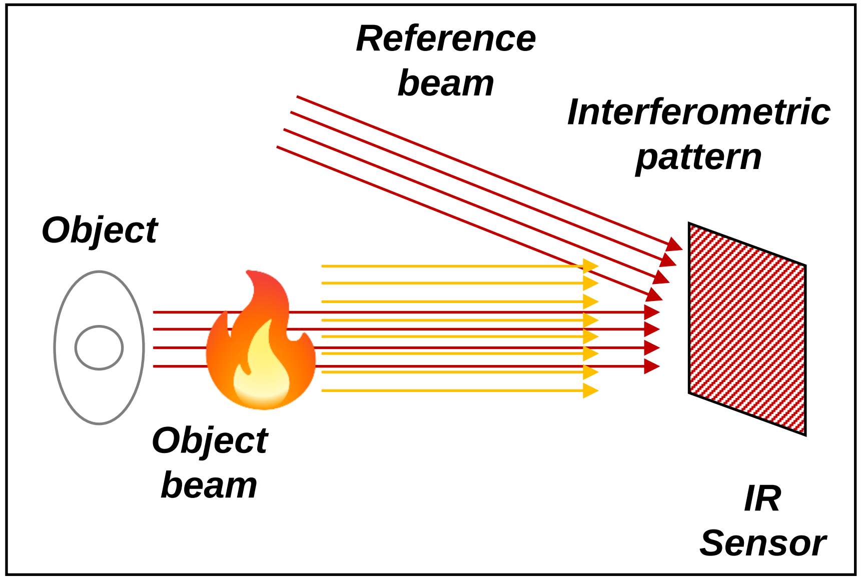
Immagine olografica

Visone attraverso fumo e FIAMME


Thermographic view

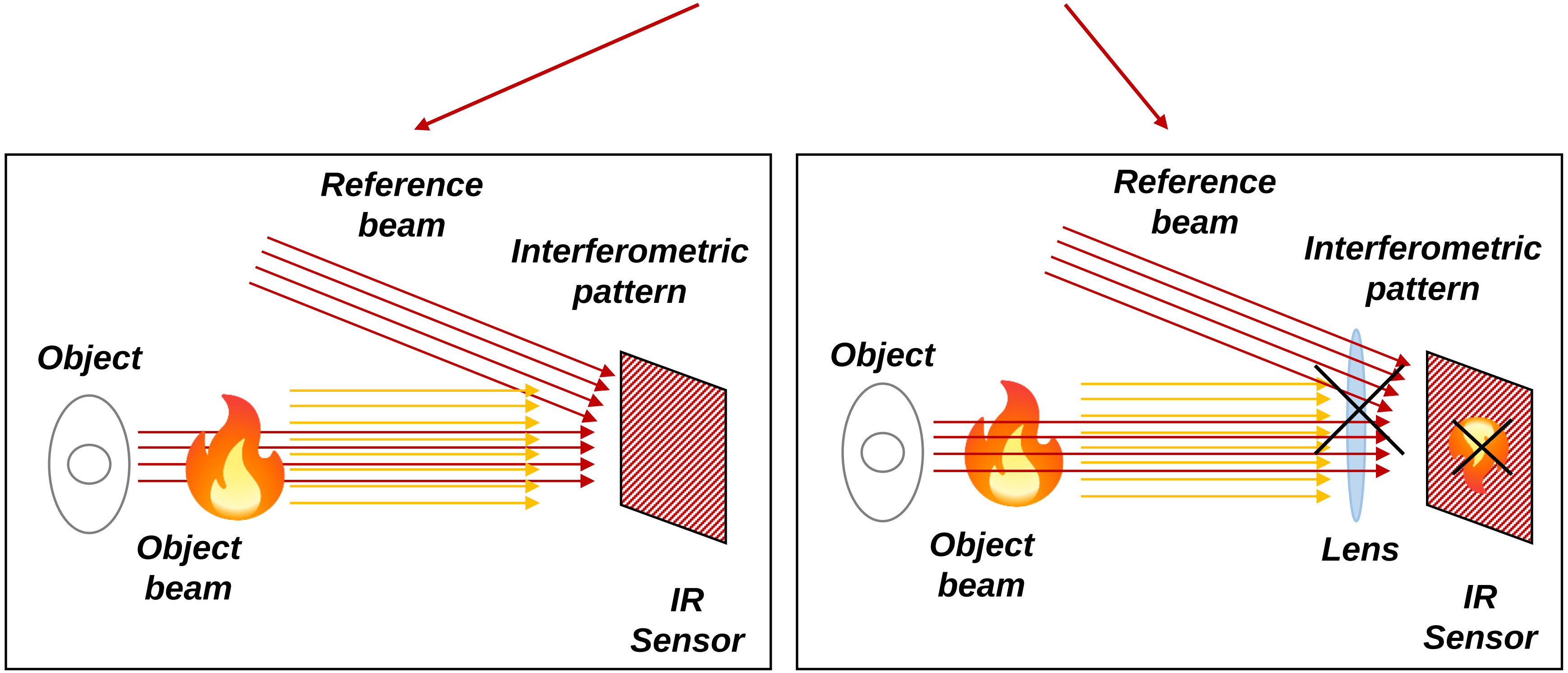
Visone attraverso fumo e FIAMME

Sistema di imaging INTERFEROMETRICO e SENZA LENTI (LENSLESS)

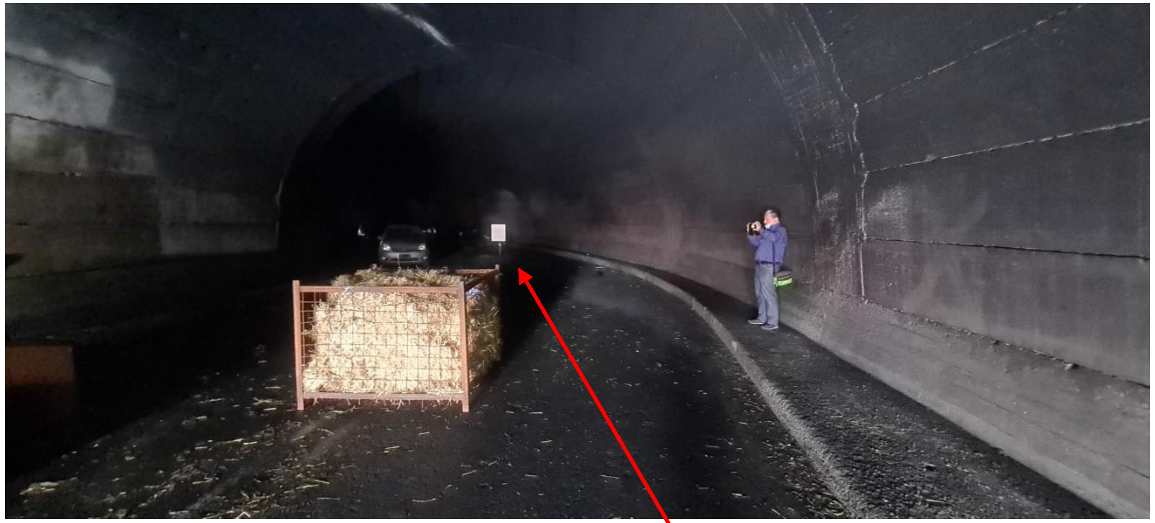

Reference beam
Interferometric pattern
Object
Object beam
IR Sensor

Visone attraverso fumo e FIAMME

Sistema di imaging INTERFEROMETRICO e SENZA LENTI (LENSLESS)


Reference beam
Interferometric pattern
Object
Object beam
IR Sensor
Reference beam
Interferometric pattern
Object
Object beam
Lens
IR Sensor

Visone attraverso fumo e fiamme



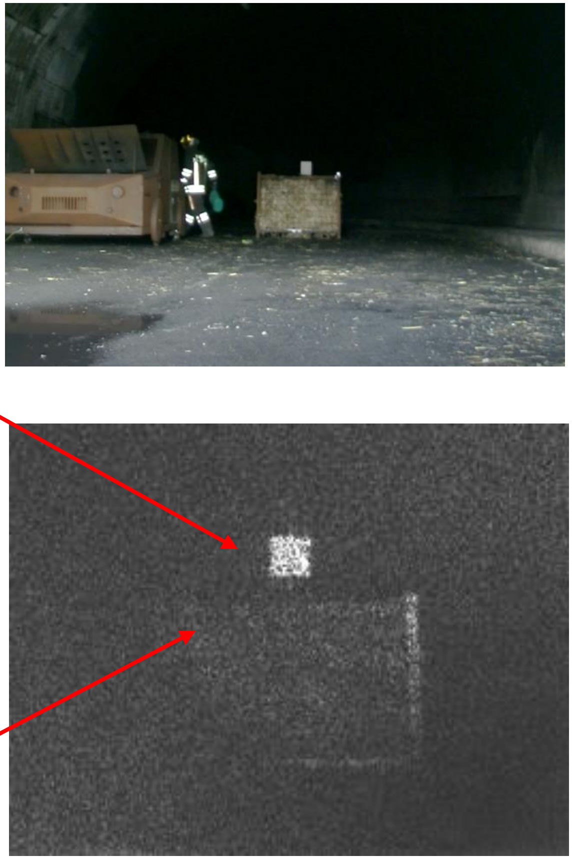
Target

Sistema
olografico

Scenario: incendio in galleria
Combustibile: paglia
Target: piastra metallica(24cm x 29cm)
Distanza di lavoro: 25m (Sistema laser-target)

Visone attraverso fumo e fiamme

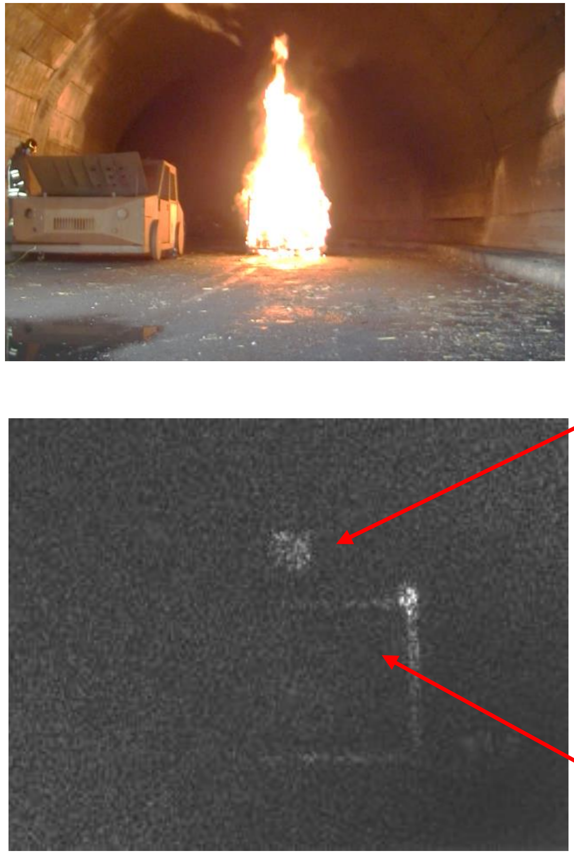
VVFF Montelibretti – incendio in galleria



Target

Contenitore
metallico con
paglia

Video olografico in
assenza di fumo e fiamme



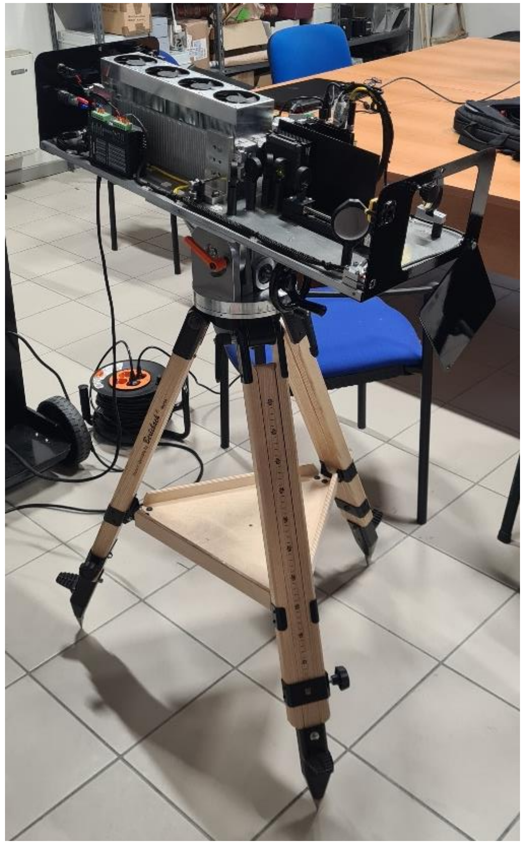
Target

Contenitore
metallico

Video olografico in presenza
di fumo e fiamme

Visone attraverso fumo e fiamme

Prototipo attuale

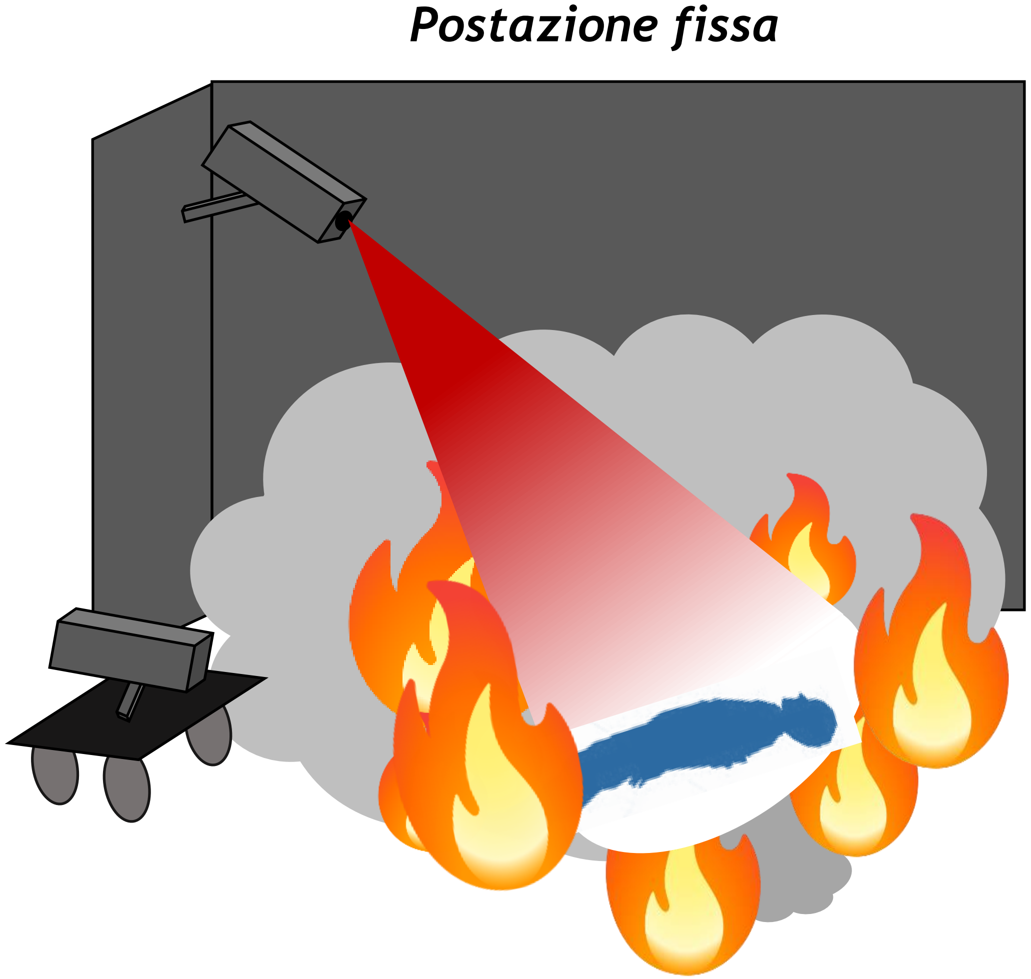


Source: Laser CO2, air cooled, radiofrequecy pumped
Wavelength: 10.6 micron
Power: 40W

Sensor: microbolometric (Asi)
Resolution: 1920 x 1080
Pixel pitch: 15 micron

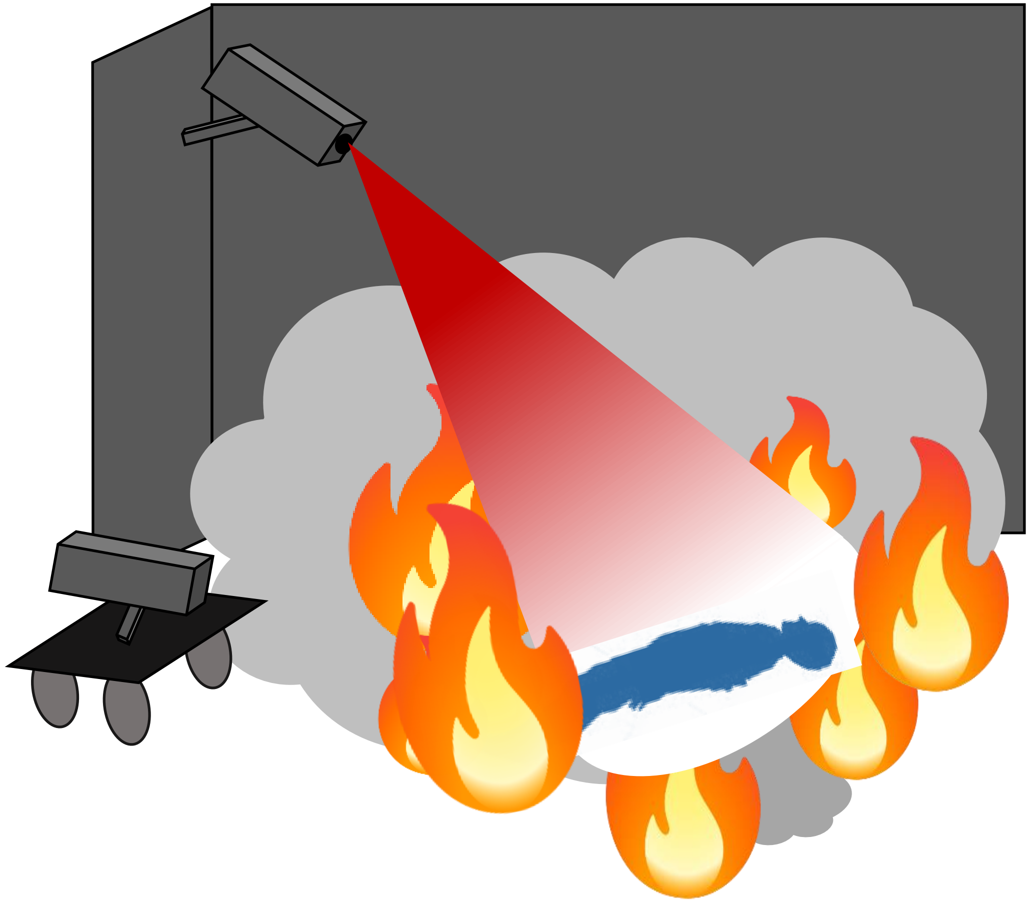
Working distance: 50m (max)

Visone attraverso fumo e fiamme

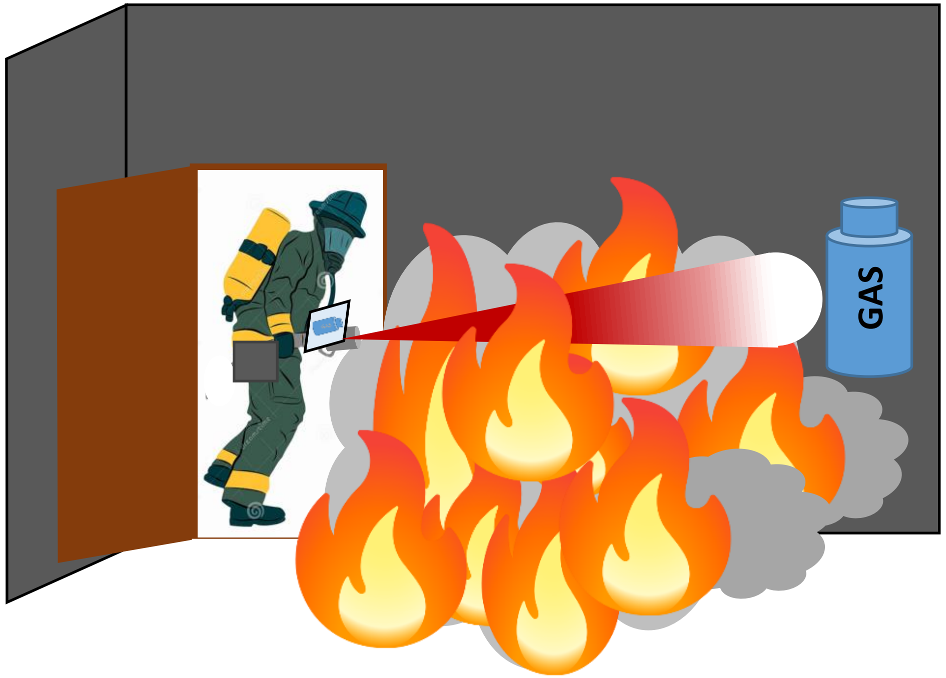

Postazione fissa

Visone attraverso fumo e fiamme

Postazione fissa

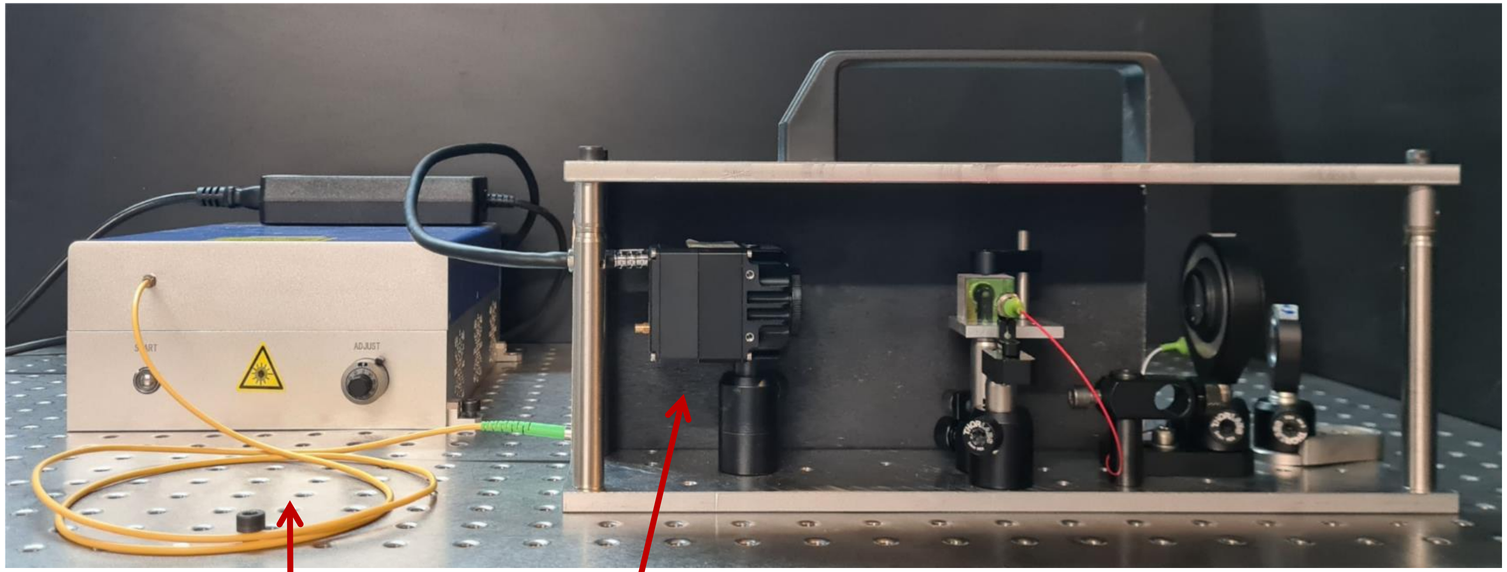


Dispositivo portatile



Visone attraverso fumo e fiamme

SWIR Digital Holography (1.55 μm)



SWIR fiber coupled laser

SWIR InGaAs detector

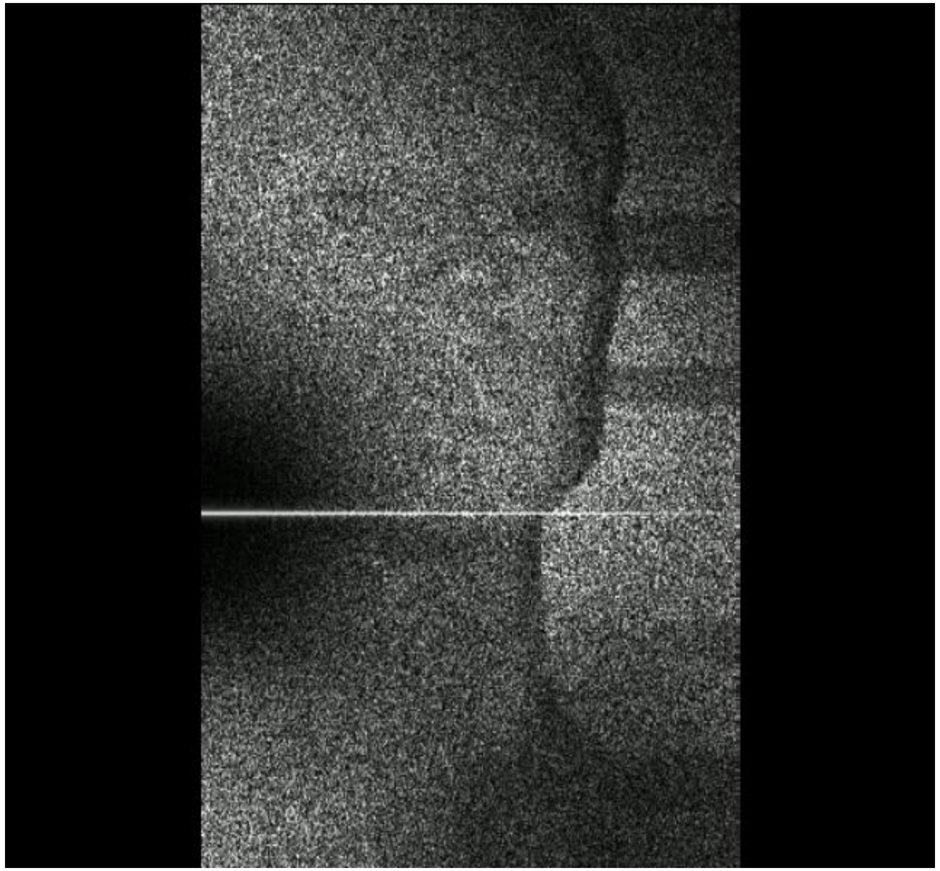
Interferometric system

Vantaggi dello SWIR range

- Range utilizzato per le telecomunicazioni
- Sicurezza laser
- Laser compatti e robusti, accoppiabili in fibra
- Immagini ad alta risoluzione
- Sensori InGaAs ad alta sensibilità
  - Bassa potenza laser
  - Portabilità

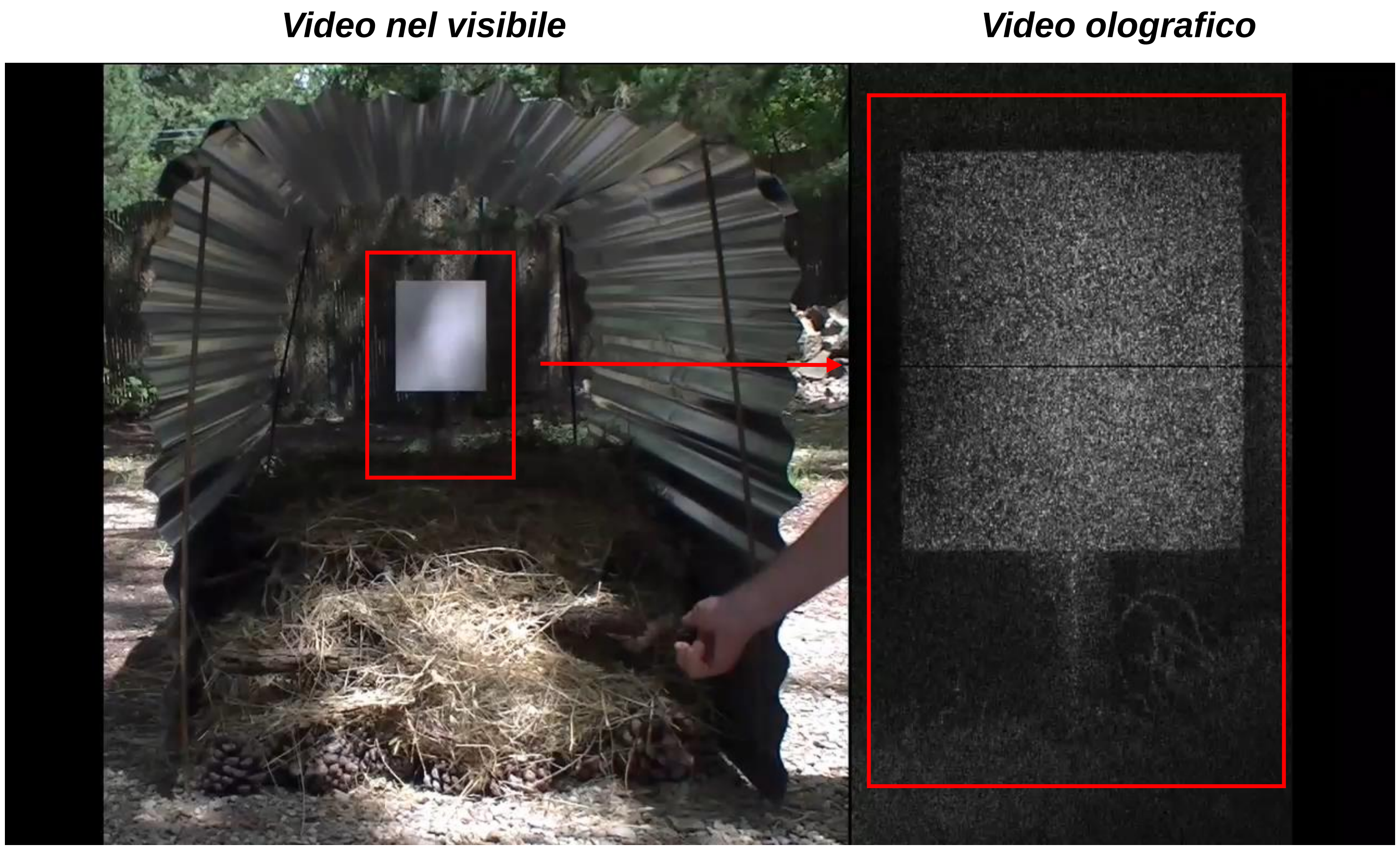
Visone attraverso fumo e fiamme

Ricostruzione video olografica - modalità torcia



Visone attraverso fumo e fiamme

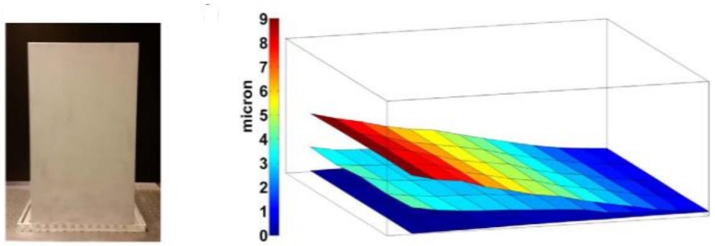
Test in scenario di incendio realistico


Video nel visibile
Video olografico

M. Locatelli, … "SWIR digital holography and imaging through smoke and flames: unveiling the invisible," Opt. Express 31, 42090-42098 (2023) https://doi.org/10.1364/OE.501602

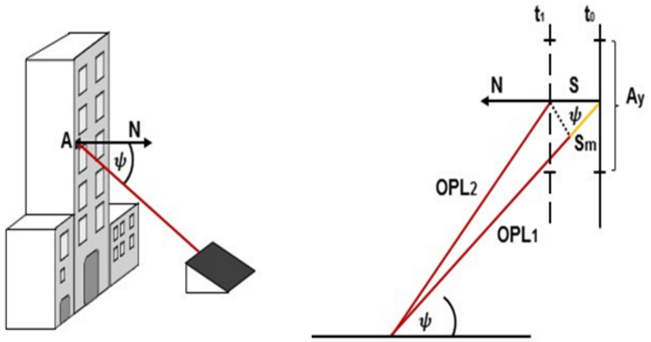
Monitoraggio remoto di edifici

Deformazione - Spostamento



IR

AMPIEZZA e FREQUENZA
dei modi normali di oscillazione di strutture edili



Monitoraggio sistematico

Eventi sismici

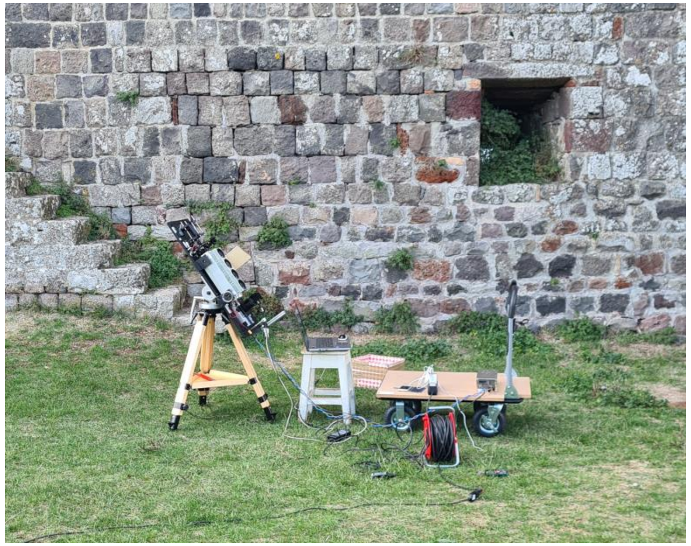
Decadimento naturale

Vulnerabilità sismica
Stato di conservazione

Poggi, … "Remote monitoring of building oscillation modes by means of real-time Mid Infrared Digital Holography“ Scientific Reports 6, 23688 (2016)

Monitoraggio remoto di edifici

Rocca di Radicofani

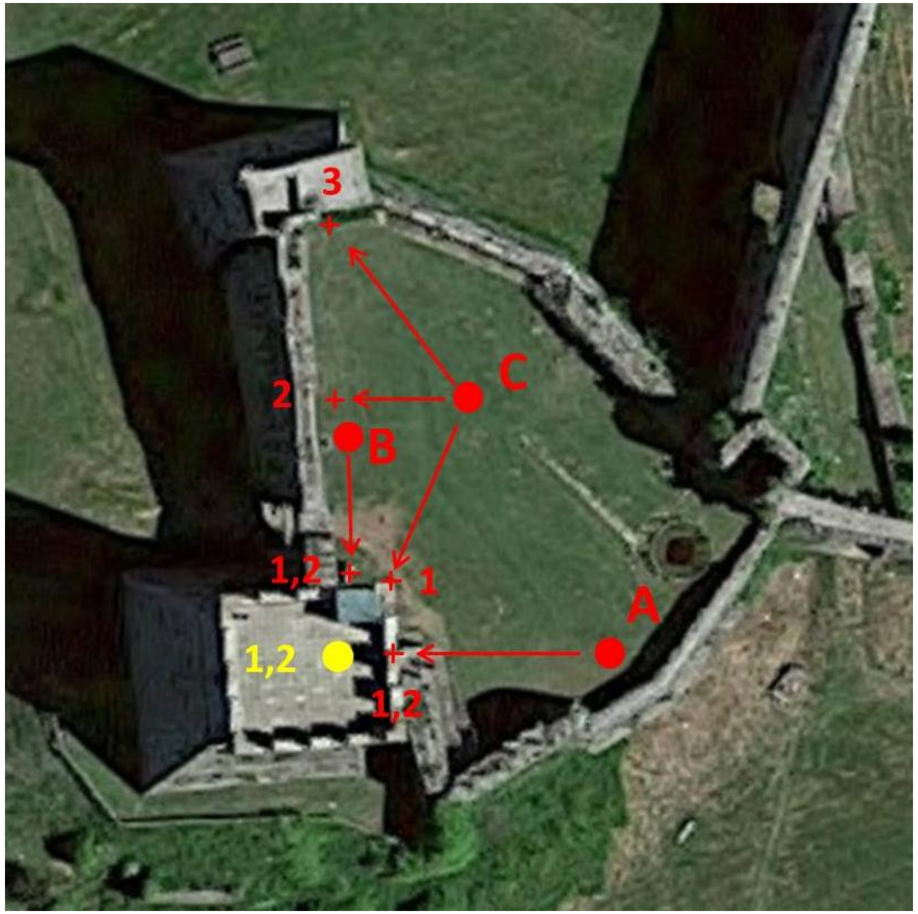


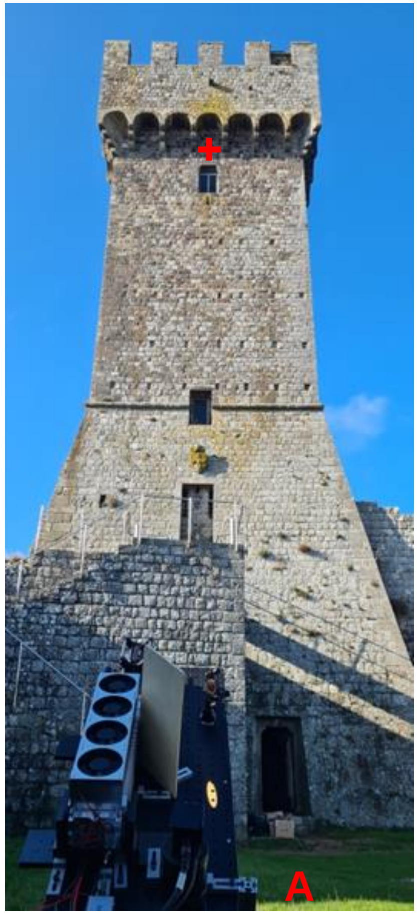
Laser 40W air-cooled (DAVI)

Monitoraggio remoto di edifici

Postazioni e punti di misura

- ● Sismometri
- ● Postazioni di misura olografiche
- + Punti di misura olografici


3
C
2
B
1,2
1
A
1,2
1,2



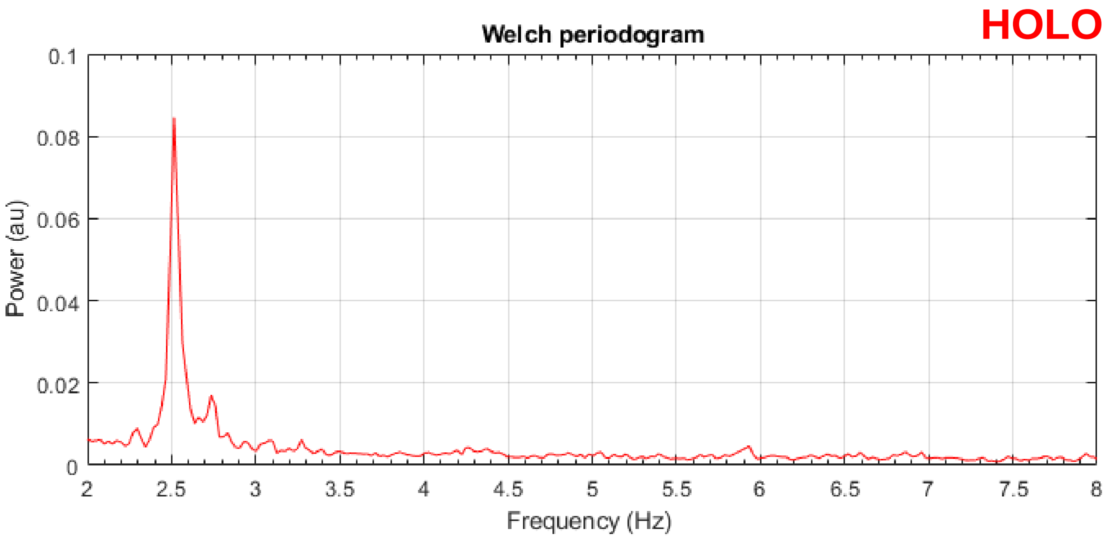
Monitoraggio remoto di edifici

Spostamenti e frequenze di oscillazione

A

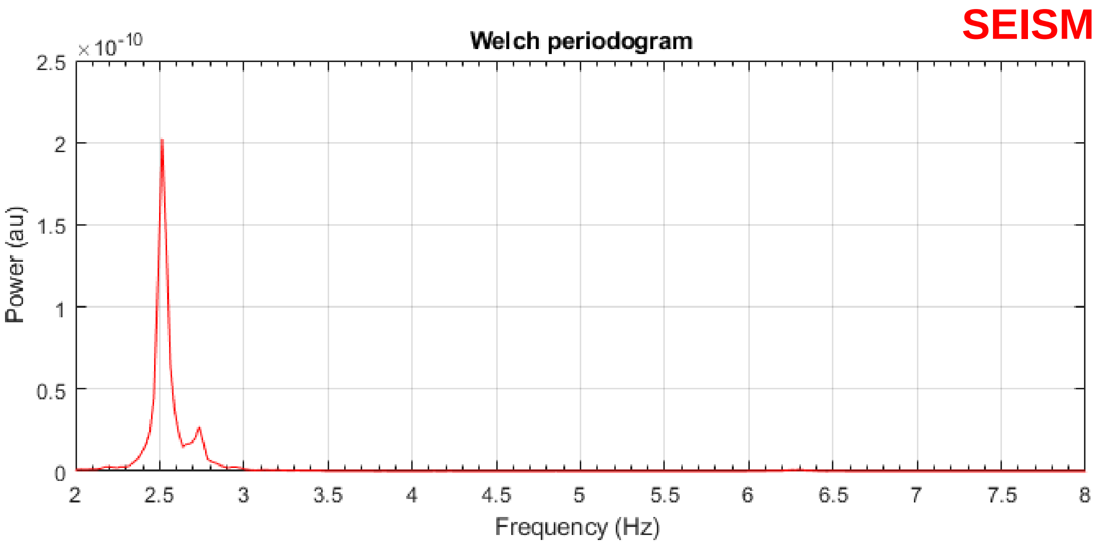
A(μm): σ = 0.33; max = 2.43

F(Hz): 2.54 - 2.73

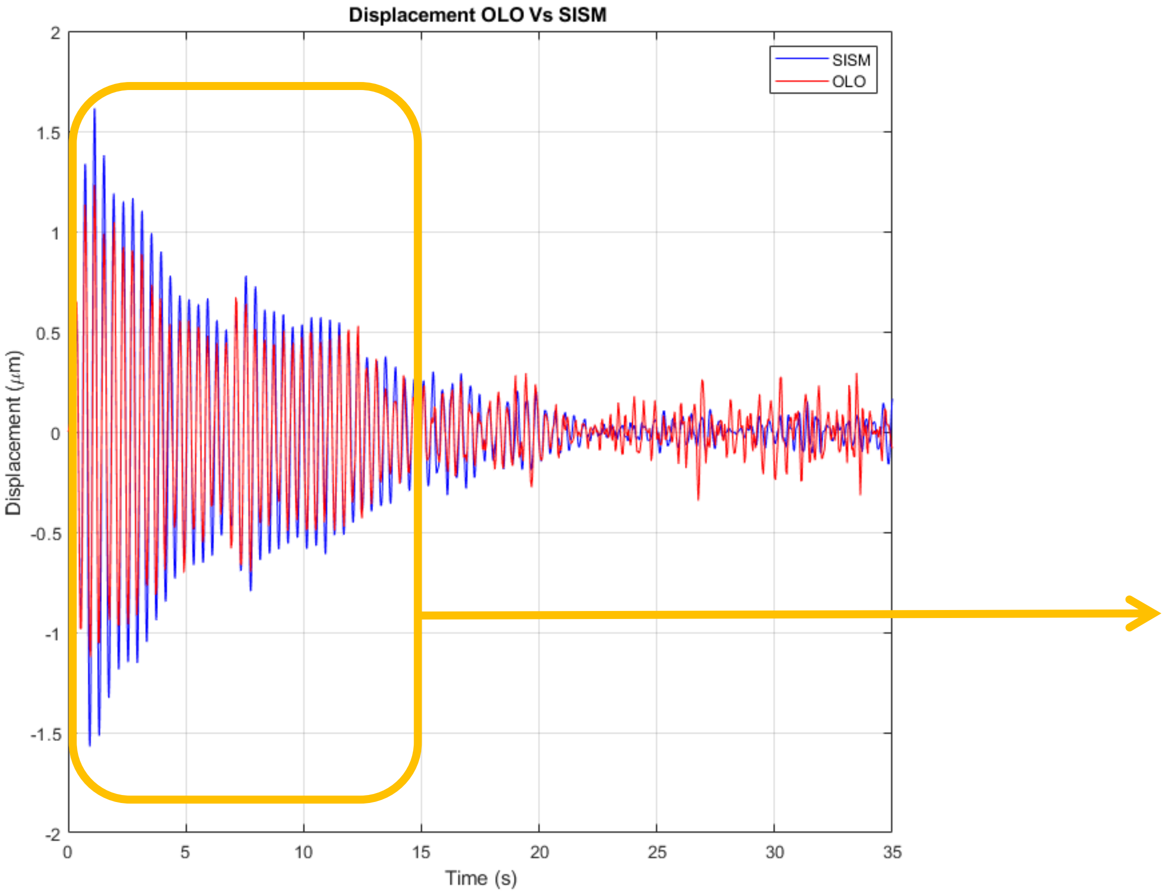


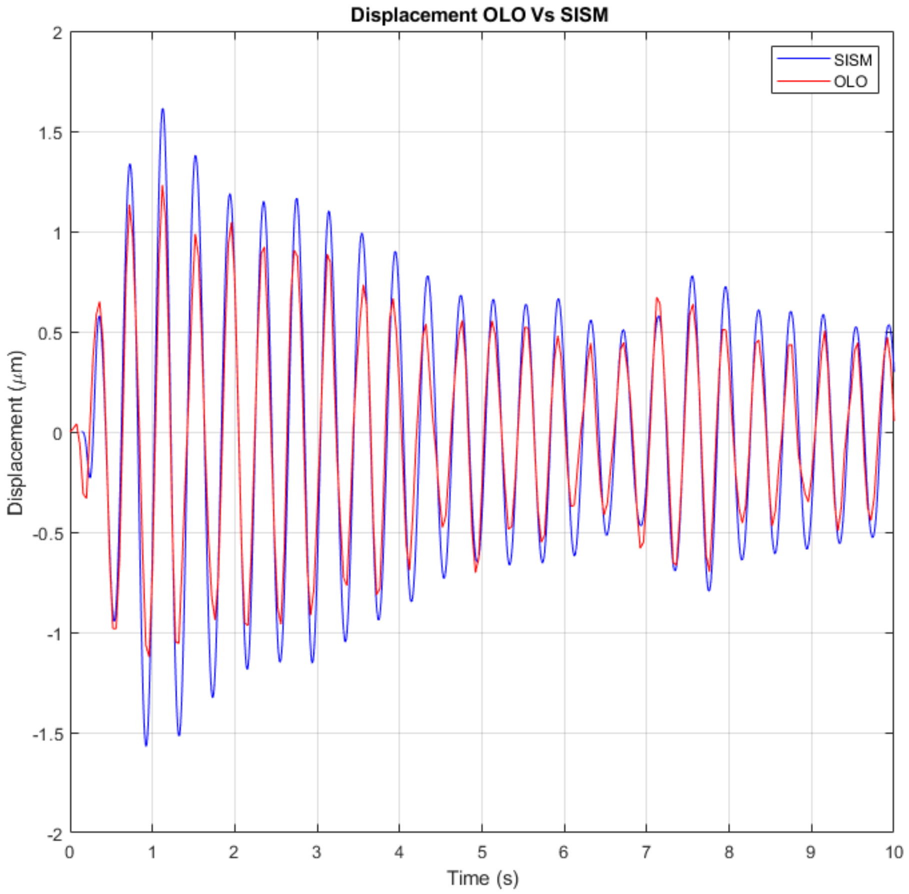
A(μm): σ = 0.29; max = 2.47

F(Hz): 2.54 - 2.73



Spostamenti OLO Vs SEISMOMETRIC





Monitoraggio remoto di edifici

Palazzo Medici Riccardi
(Firenze)

2021/09/13 12:31

Santa Caterina Church
(Massa Carrara)

Rocca di Radicofani
(Siena)

Villa Sforzesca
(Grosseto)

Castell'Azzara palazzo comunale
(Grosseto)

Monitoraggio remoto di edifici

Prospettive future

Ingegneria civile

- Edifici, mura
- Ponti e viadotti
- Elementi architettonici (cornici, terrazze, stemmi, formelle, ...)

Beni culturali

- Statue
- Affreschi, pitture su tavola, …

Ambiente e territorio

- Fronti rocciosi
- Monitoraggio piante ad alto fusto

Prototipo attuale

Monitoraggio remoto di edifici

Monitoraggio piante ad alto fusto

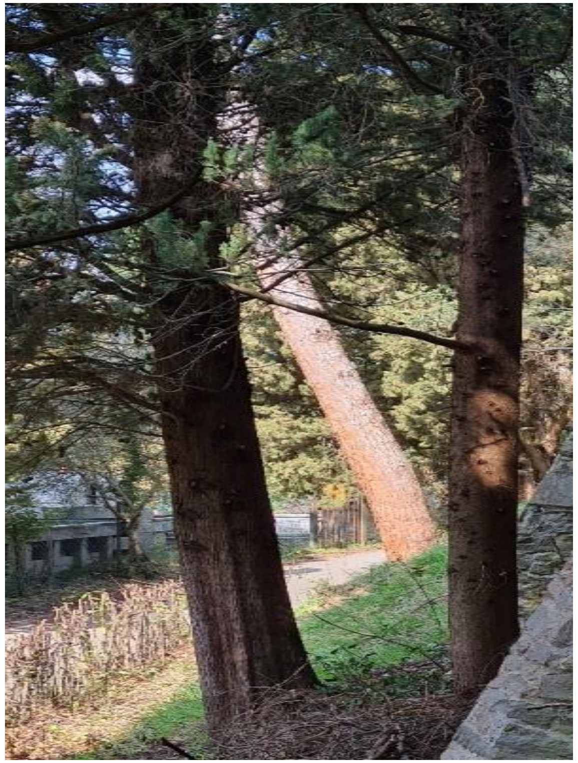


Immagine nel visibile

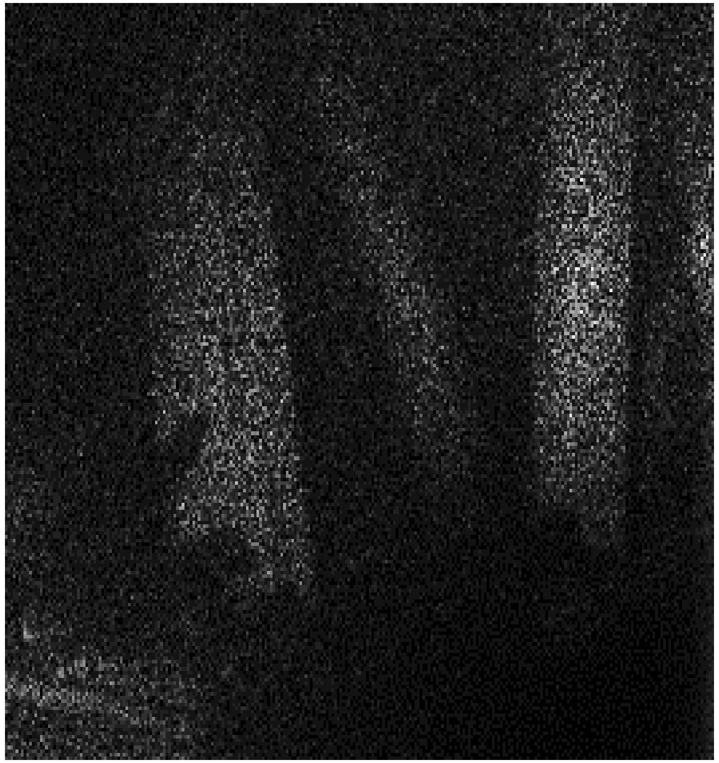


Immagine d’ampiezza

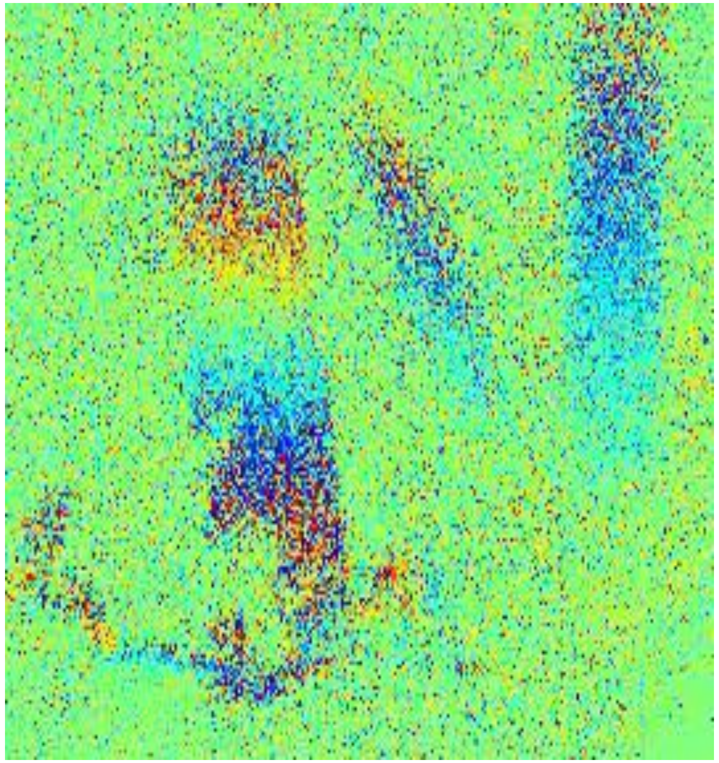
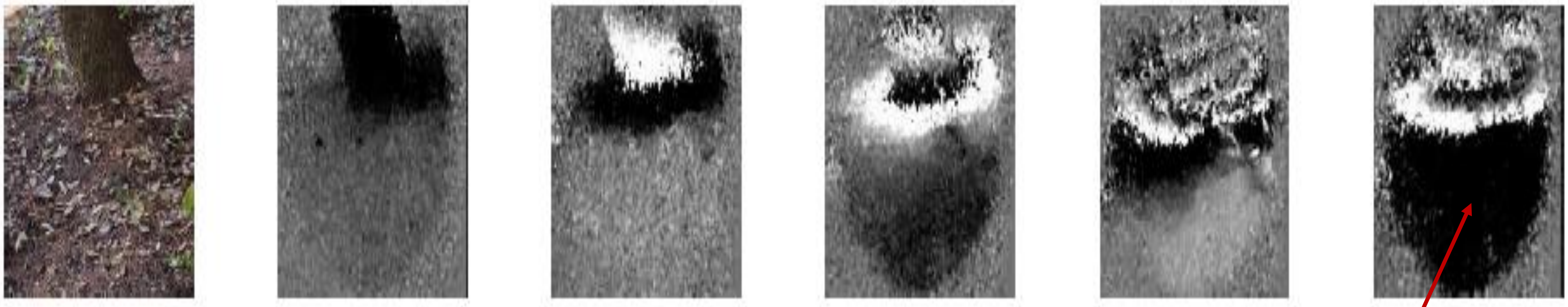


Immagine di fase

Monitoraggio remoto di edifici

Monitoraggio piante ad alto fusto

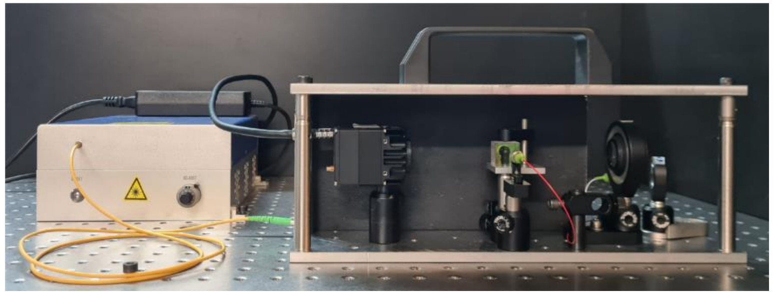


Terreno d'ancoraggio

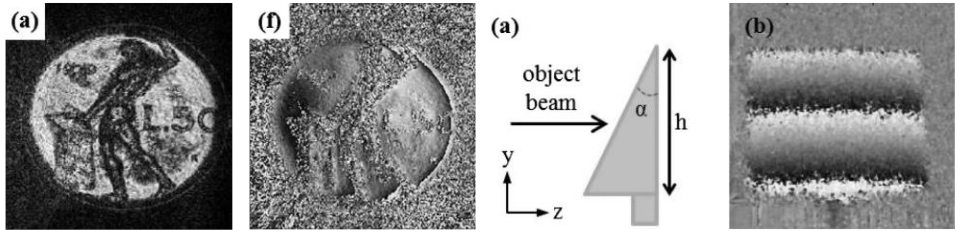
Conclusioni

LWIR DH

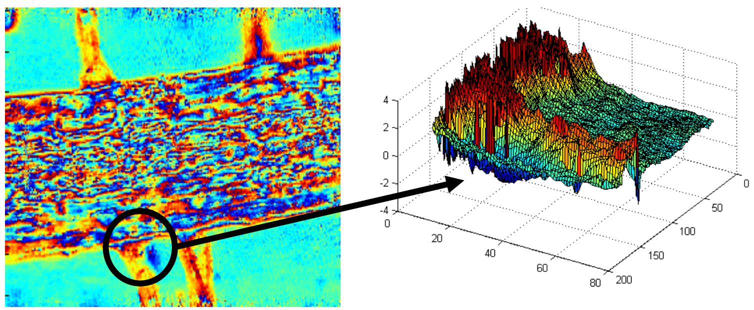
SWIR DH



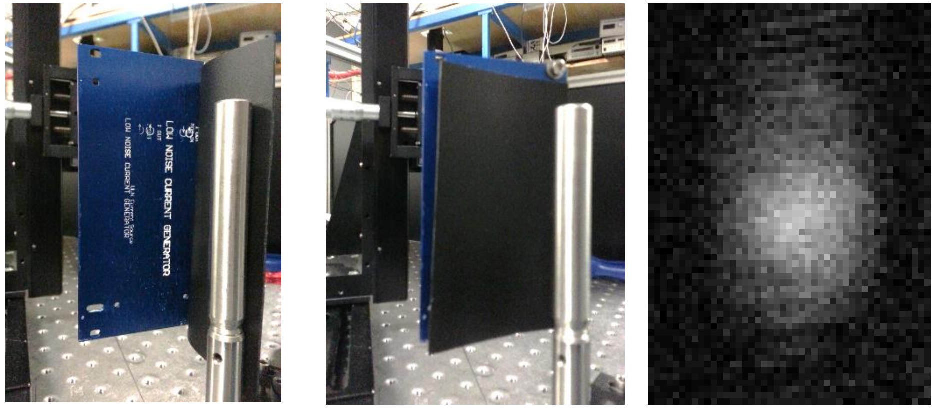
MidIR DH


(a)
(f)
(a)
object beam
α
h
y
z
(b)

Visible DH



THZ DH



Grazie