Dual-wavelength holography for inspection of generally shaped objects in the digital era

3DMC

3D METROLOGY CONFERENCE

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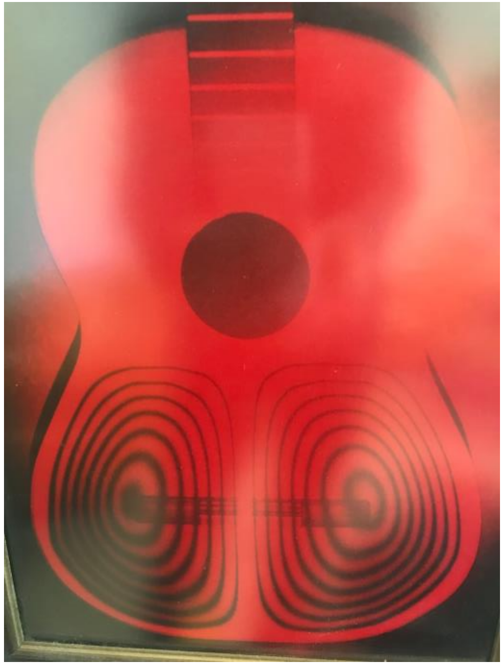
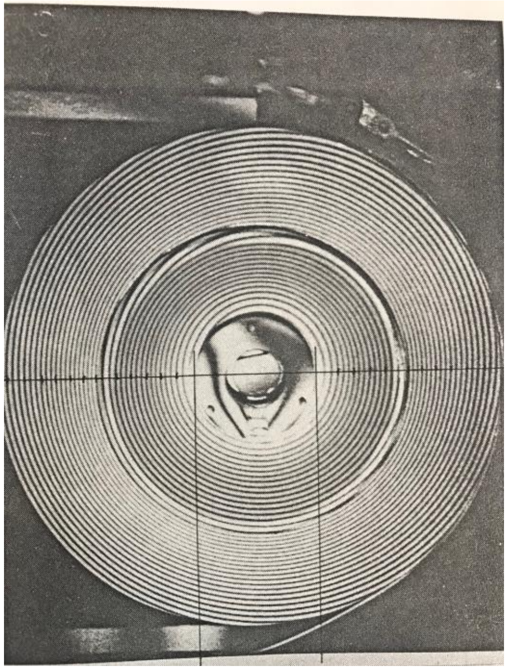
Classic results in DHI



Time-average hologram of a vibrating guitar. Around 1970.



Double-exposure hologram of a deforming granade. 1989.

Striking features:

+ High spatial information density
+ Very high fringe contrast

- A lot of manual work
- Only partly quantitative
- Very sensitive to disturbances

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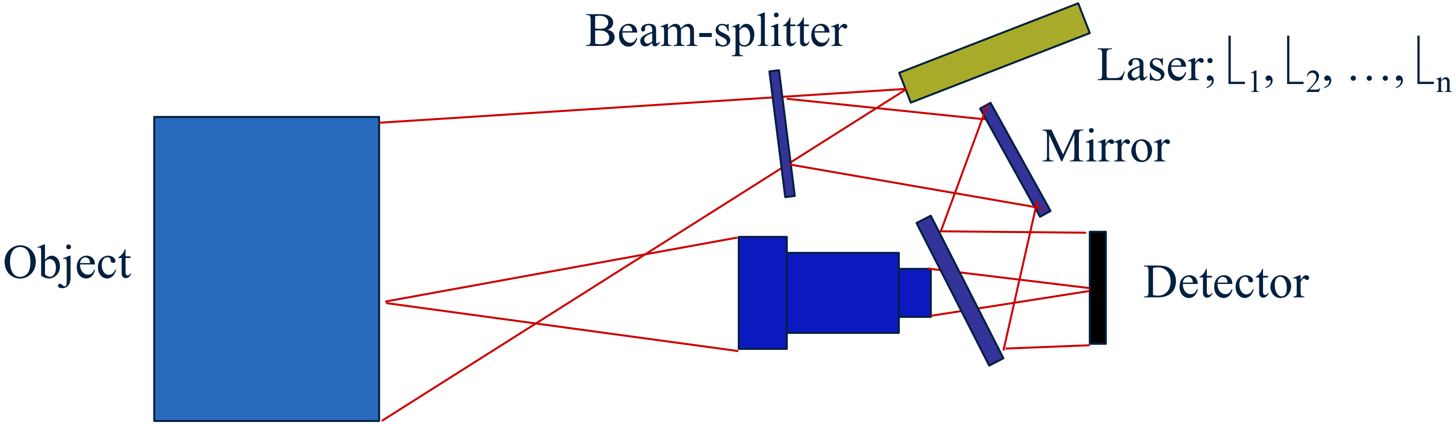
Multi-wavelength



Dual-Wavelength Holography (DWH)

$$\psi_1(X_1;\lambda_1) = C(X_1;\lambda_1) + iS(X_1;\lambda_1)$$
$$\psi_2(X_2;\lambda_2) = C(X_2;\lambda_2) + iS(X_2;\lambda_2)$$

$$\Lambda = \frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2} \approx \frac{\lambda^2}{\Delta\lambda}$$

B. P. Hildebrand and K. A. Haines, “Multiple-wavelength and multiple source holography applied to contour generation,” *J. Opt. Soc. Am.*, **57**, 155-162 (1967).

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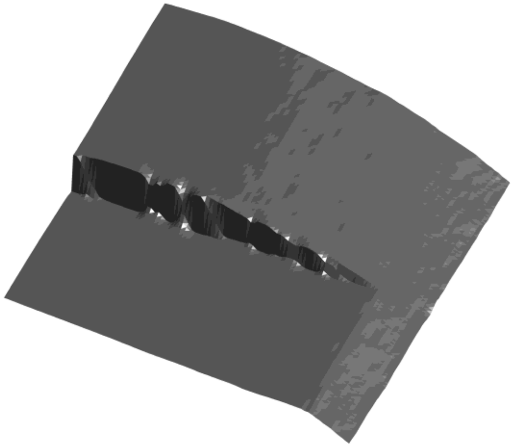
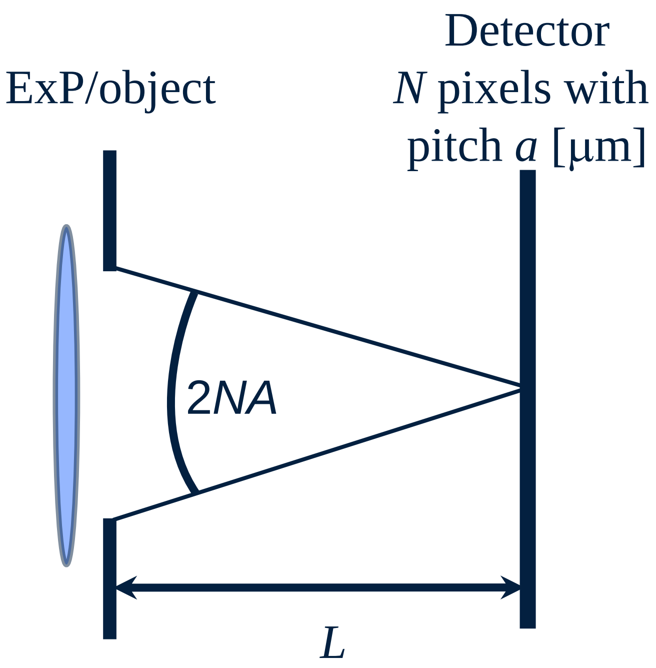
Challenges in DWH

- Resolution
- Absolute distance (discontinuous objects)
- (Ideally pulsed) laser sources that allow single shot detection



Resolution requirements



Off-axis detection + numerical reconstruction:

$$NA < \frac{\lambda}{8a}$$

Resolved

Diffraction field detection + phase-stepping:

$$NA < \frac{\lambda}{4a}$$

Resolved

Image-plane detection + phase-stepping:

$$NA < \sim\frac{\lambda}{2a}$$

Unresolved

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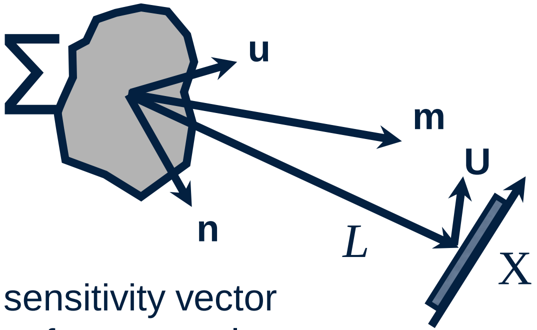
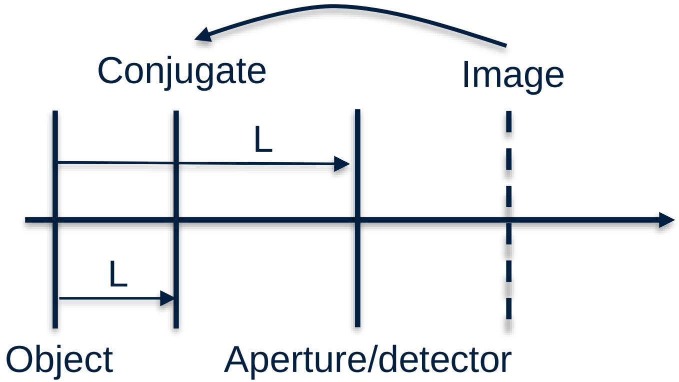
Dynamic speckle properties



m, sensitivity vector
n, surface normal
u, deformation vector
U, speckle motion
ϕ, phase change

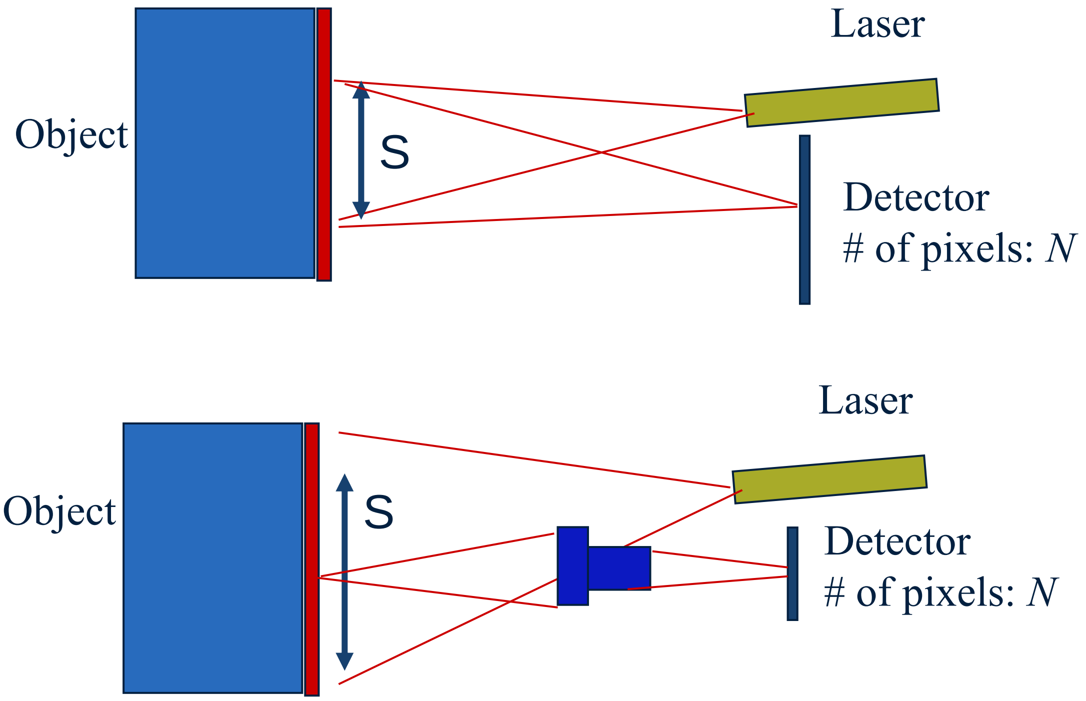


$$\mathbf{U} = \mathbf{u} + Lk^{-1}\nabla\phi$$

The speckles will primarily move in proportion to the gradient of the phase change and defocus distance

M. Sjodahl, "Dynamic properties of multispectral speckles in digital holography and image correlation," *Opt. Eng.* **52**, 101908 (2013).

Coherent limit



Microstructural limit:

$$\Delta\lambda < \lambda_c$$

Deformation limit:

$$\frac{\nabla\phi}{2\pi} < \frac{N}{4S}$$

For shape measurement:

$$S < \frac{N\Lambda}{8\tan\theta}$$

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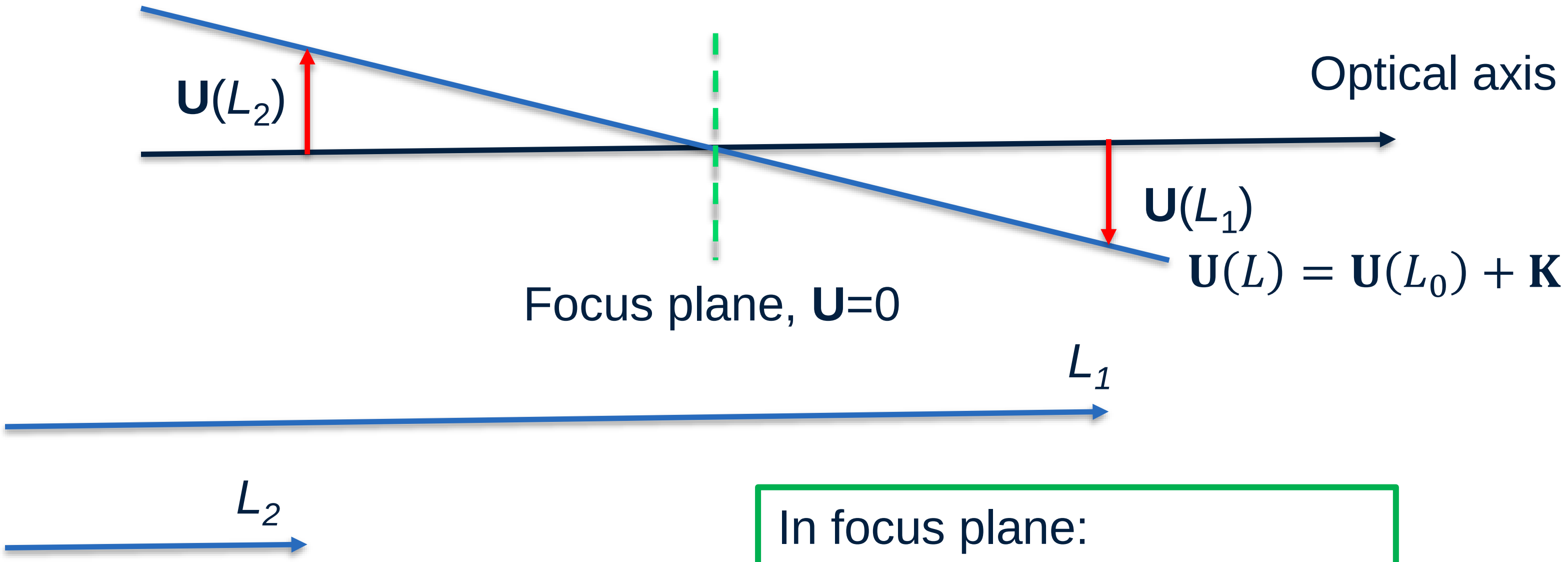
True focus plane (absolute distance)



$$\mathbf{U}(L) = \mathbf{U}(L_0) + \mathbf{K}(L - L_0)$$

In focus plane:

- Best accuracy
- Correct lateral dimension

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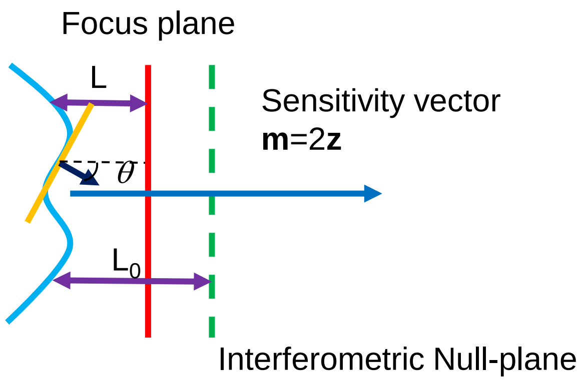
Evaluation criteria for shape measurement



$$\psi_1^*\psi_2 \rightarrow \phi$$
$$I_1 = |\psi_1|^2, I_2 = |\psi_2|^2$$
$$\langle \Delta I_1 \Delta I_2 \rangle \rightarrow \gamma(0)$$
$$\langle \Delta I_1(X_1) \Delta I_2(X_2) \rangle \rightarrow \mathbf{U}, \gamma(\mathbf{U})$$

Phase difference: $L_0 = C + \frac{\phi\Lambda}{4\pi}$

High precision, low trueness because of wrapping

Speckle correlation:

High trueness, lower precision

$$\Longrightarrow \tan\theta = \frac{\mathbf{K}\Lambda}{2\lambda} \quad \text{and} \quad \mathbf{U} = 0, \gamma(0) = \gamma(\mathbf{U}) \rightarrow \text{surface}$$

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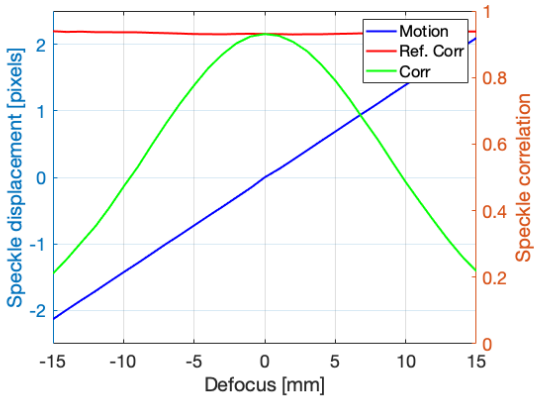
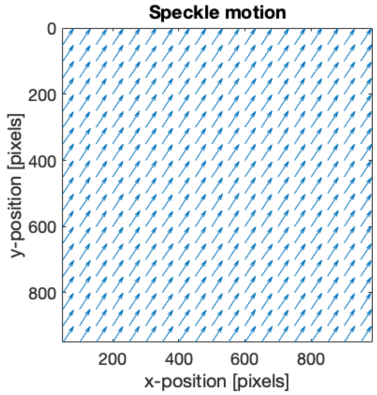
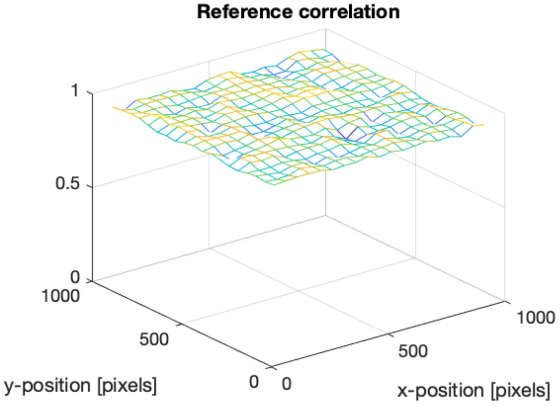
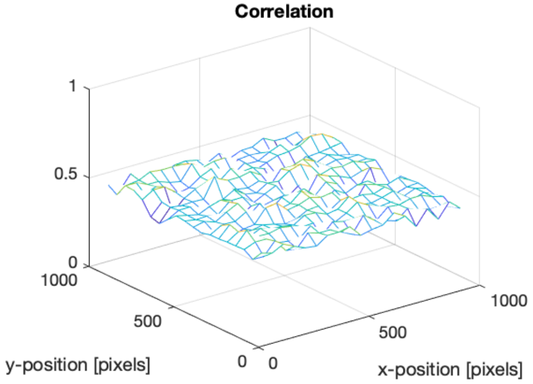
Results from a tilted plane









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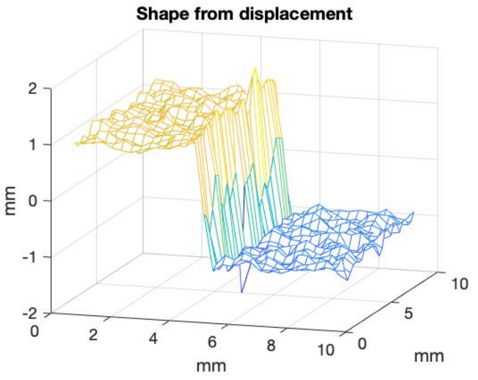
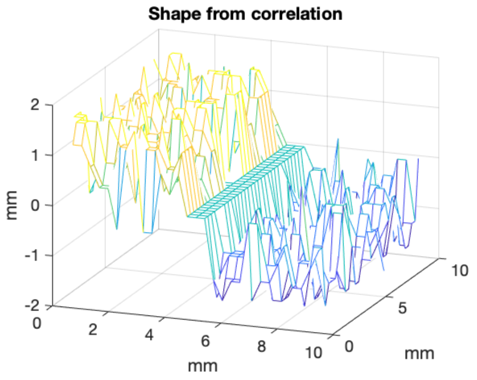
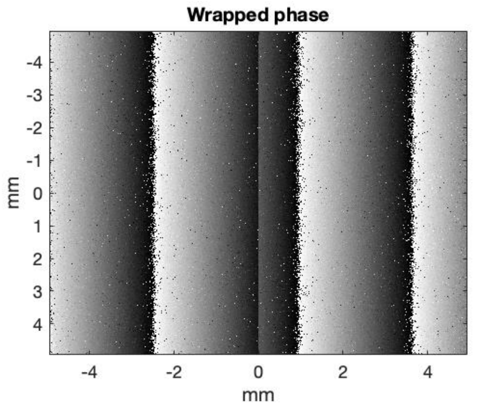
Results from a 2 mm jump

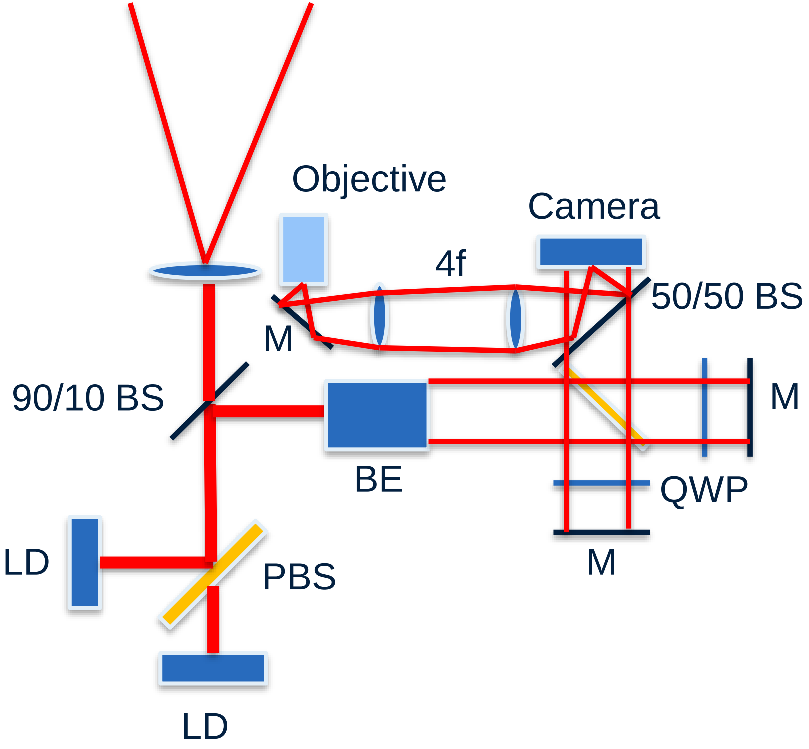


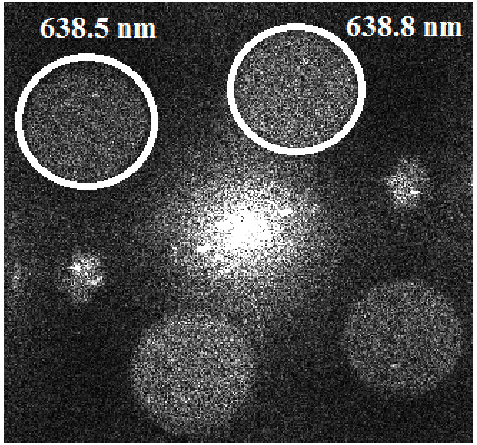




Correlation window: 64X64 pixels, speckle size: 4 pixels

Simultaneous acquisitions





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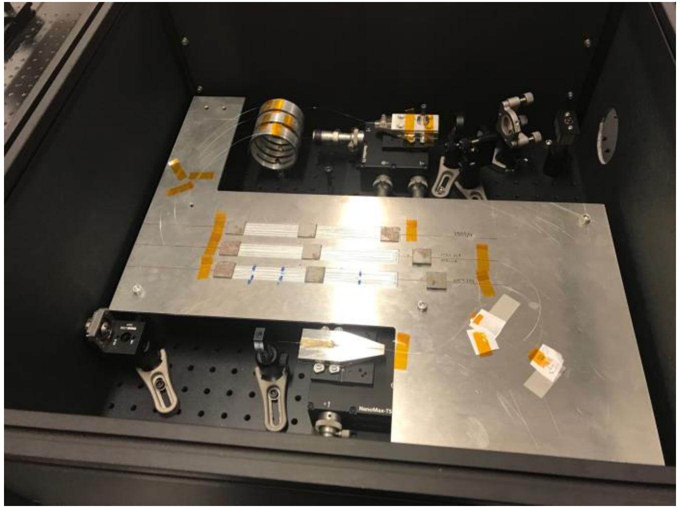
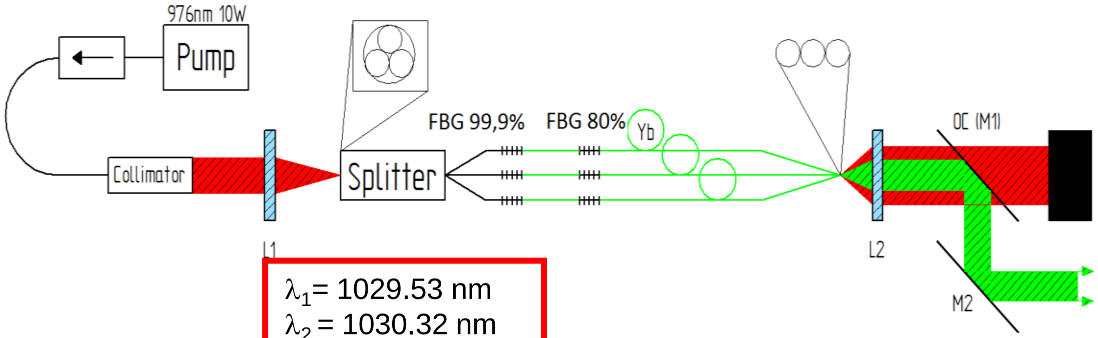
Specially built pulsed laser





λ_1= 1029.53 nm
λ_2 = 1030.32 nm
λ_3 = 1031.31 nm

P=3 x 40 mW

S. Tjornhammar, FK. Eklof, ZW. Yu, D. Khodadad, E. Hallstig, M. Sjodahl and F. Laurell, “Multiwavelength laser designed for single-frame digital holography,” *Appl. Opt.*, **55**, 7517-7521 (2016).

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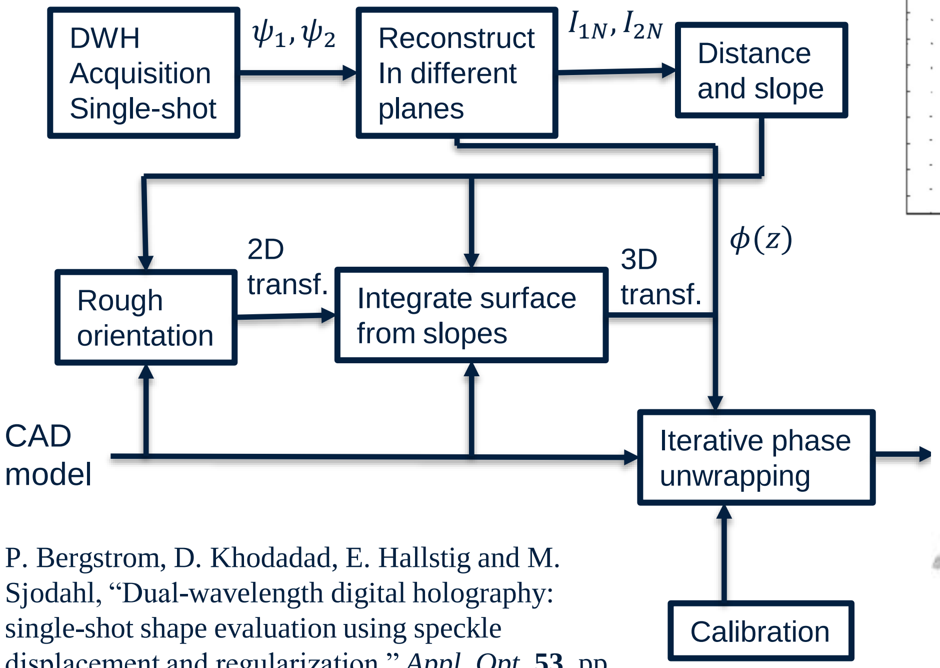
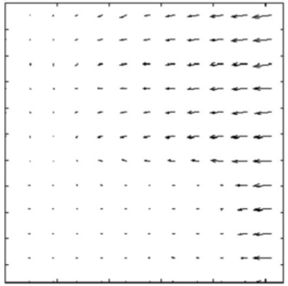
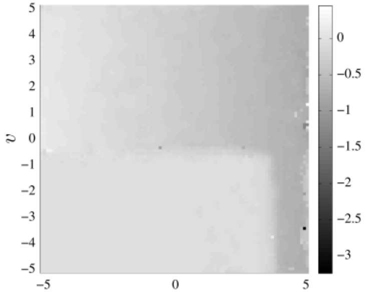
Calculation procedure

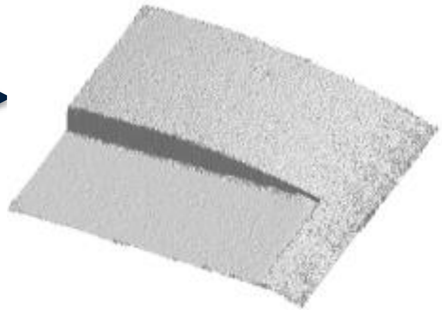




Slope field



Integrated surface



P. Bergstrom, D. Khodadad, E. Hallstig and M. Sjodahl, "Dual-wavelength digital holography: single-shot shape evaluation using speckle displacement and regularization," *Appl. Opt.* **53**, pp. 123-131 (2014).

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