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Image reconstruction from in-line holograms using inverse problems recipes: tutorial

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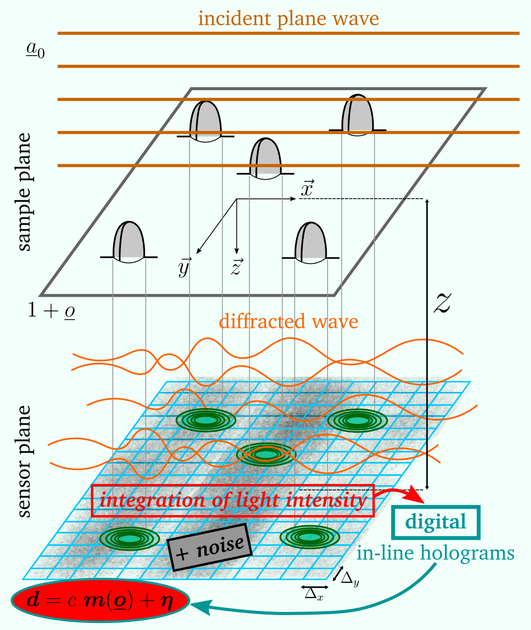
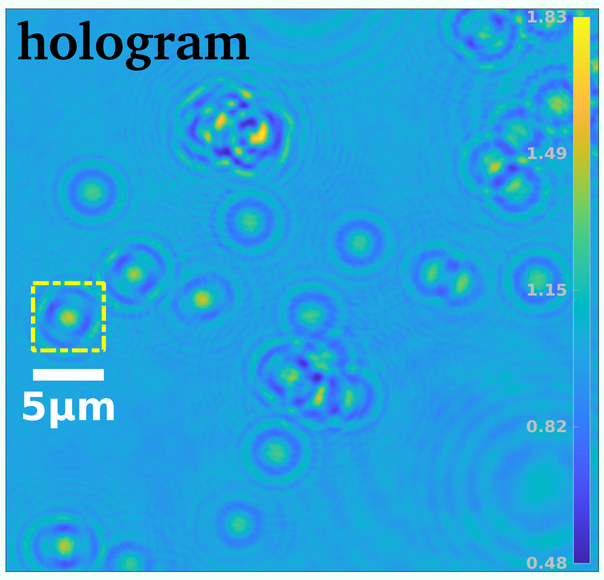
Abstract

We present our tutorial [1] for building **inverse problems** based image reconstruction strategies in **digital in-line holography (DH)**, starting from the identification of the connections with the well known **alternated projections** strategies. **In-line DH is of great interest for optical microscopy dedicated to biology, as it constitutes a robust, efficient and label-free tool for imaging transparent living samples.**

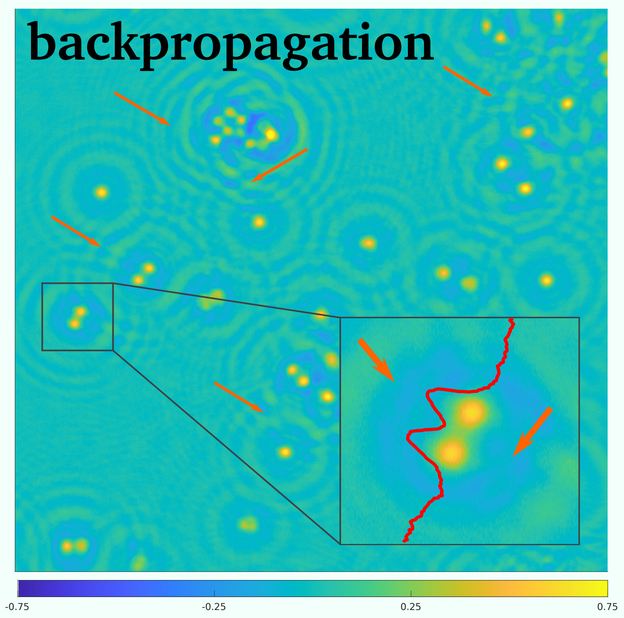
Digital Holography (DH) and the phase retrieval problem



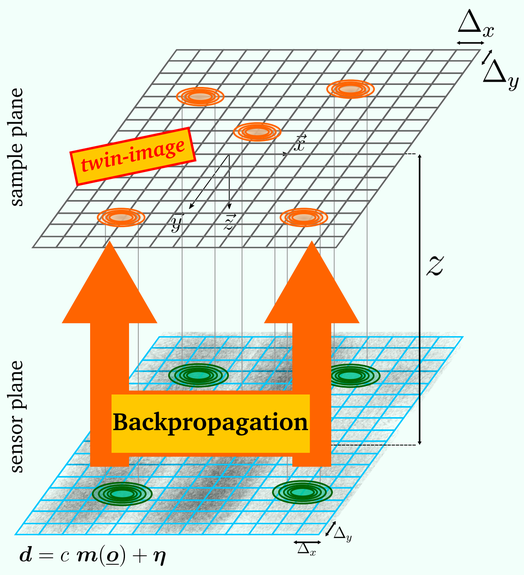
$$d = c\, m(o) + \eta = c\, |1 + H_z\, o|^2 + \eta$$



polystyrene beads in immersion oil
- illumination wavelength: $\lambda = 532$nm
- refractive index of the medium: $n_0 = 1.52$
- pixel size: $\Delta_x = \Delta_y = 2.2\mu$m



- propagation distance: $z = 12.5\mu$m
- refractive index of the beads: $n_b = 1.59$
- magnification factor: mag $= 56.7$

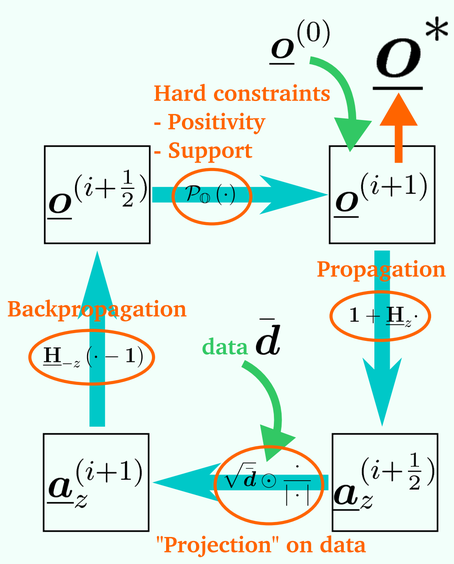


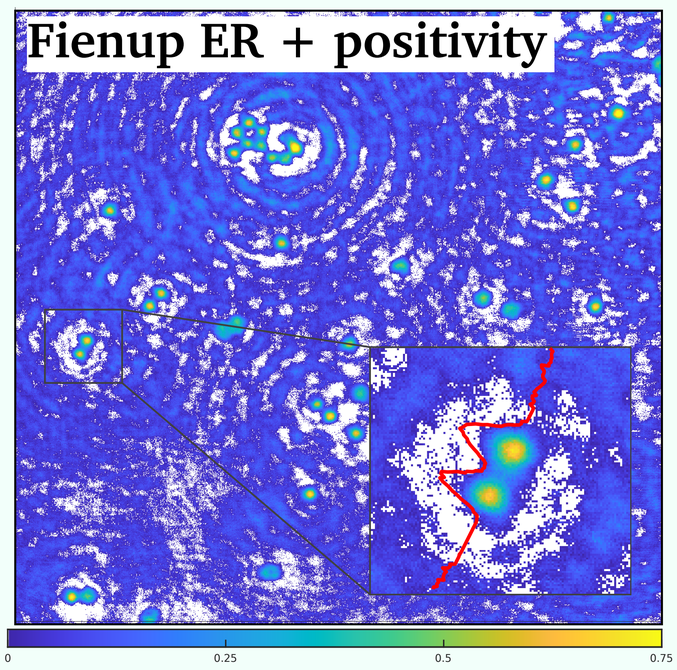
$$o^{backprop} = H_{-z}(\bar{d} - 1) \text{ s.t. } H_z H_{-z} \approx I$$

Alternated projections

➟ Iterative procedure involving a projection step on a feasible domain $o \in \mathbb{O}$ (e.g. positive values of the phase-shift / support constraint) to reduce/suppress twin-image artifacts [2].

➟ a popular instance is the **Fienup's Error Reduction algorithm (Fienup ER)**:





$$o^{(i+1)} \approx \mathcal{P}_{\mathbb{O}}\left[o^{(i)} - \underbrace{H_z^{\dagger}\left(\frac{a_z^{(i+1/2)}}{|a_z^{(i+1/2)}|} \odot \left(|a_z^{(i+1/2)}| - \sqrt{\bar{d}} \right) \right)}_{\nabla \mathcal{G}(o^{(i)})} \right]$$

↳ **gradient descent step** of the **data-fidelity** criterion $\mathcal{G}$ at current point $o^{(i)}$.

↳ **projection step** $\mathcal{P}_{\mathbb{O}}$ **on the domain $\mathbb{O}$, called proximal mapping of the indicator function $\iota_{\mathbb{O}}$ at point $o^{(i+1/2)}$.**

This resolution method is an instance of the ISTA algorithm (Iterative Shrinkage Thresholding Algorithm), a proximal gradient method.

➟ **Fienup ER** is an **Inverse Problems** approach that uses a particular optimization strategy for minimizing the following criterion:

$$o^* = \arg\min_{o} \underbrace{\left\| |1 + H_z\, o| - \sqrt{\bar{d}} \right\|_2^2}_{\text{data-fidelity } \mathcal{G}(o) \text{ (smooth)}} + \underbrace{\iota_{\mathbb{O}}(o)}_{\mathcal{H}(o) \text{ (non smooth)}}$$

Towards inverse approaches

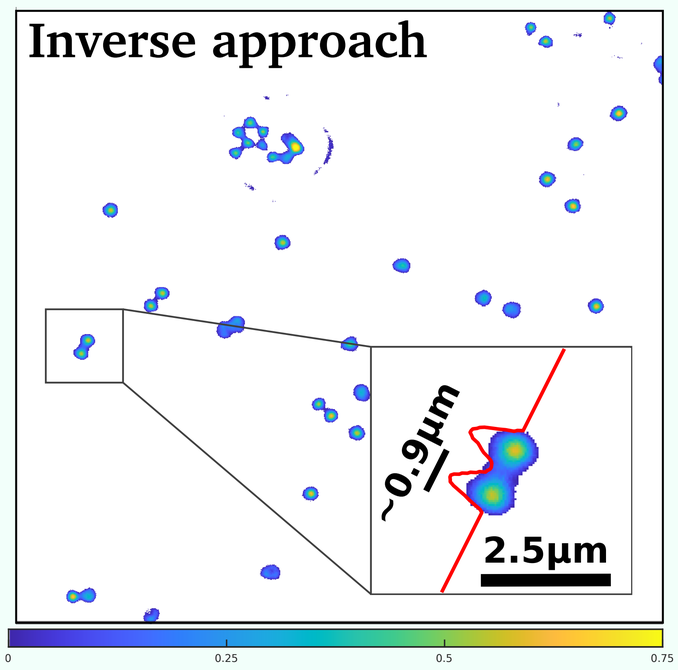
Alternating projections methods such Fienup ER can then benefit from the Inverse Problems framework to gain flexibility and reconstruction quality.

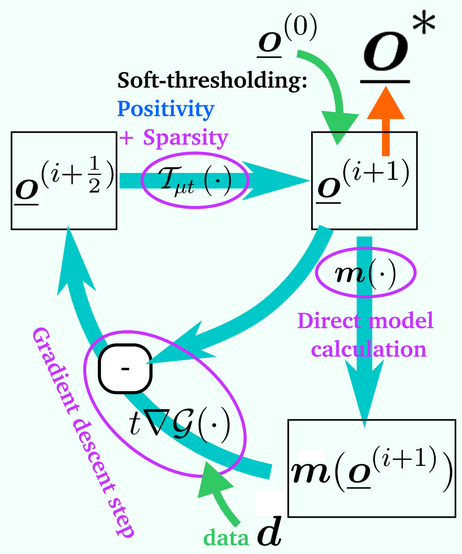
↳ More appropriate **direct image formation model $m(o)$**.
➪ **auto-calibration** of model parameters made possible.

↳ Taking into account **data uncertainties** (statistical considerations about the **noise η** in the criterion).

↳ Inclusion of **more sophisticated non smooth and smooth regularizers**: sparsity constraints (ℓ_1, TV / non smooth), image gradient smoothing (Tikhonov, edge-preserving / smooth).

$$o^* = \arg\min_{o \geq 0} \underbrace{\left\| c^*\, m(o) - d \right\|_W^2 + \mu_{TV} \sum_q \sqrt{\|\nabla_q o\|_2^2 + \epsilon^2}}_{\mathcal{G}(o) \text{ (smooth)}} + \underbrace{\mu_{l_1} \|o\|_1}_{\mathcal{H}(o) \text{ (non smooth)}}$$





➟ Others optimization methods than **ISTA** are possible: **FISTA** ("accelerated" ISTA), **L-BFGS-B** (smooth criterions), etc.

Conclusion & perspectives

➟ **Inverse problems** constitute a rigorous framework for solving image reconstruction and/or parameter estimation tasks in **Digital Holography (DH)**.

➟ **Inverse problems** make possible the extension of classical **2D DH** to deal with **multi-dimensional** and **multi-variate data**: fully-3D (diffractive tomography), multi-spectral, polarimetric data, etc.

A **Matlab™** code for **2D DH reconstruction** is available for download at this link: `https://github.com/fabienmomey/Inline_Hologram_Reconstruction_by_Regularized_Inversion.git`

References

[1] Momey, F., Denis, L., Olivier, T., and Fournier, C., "From Fienup's phase retrieval techniques to regularized inversion for in-line holography: tutorial," J. Opt. Soc. Am. A 36, D62-D80 (2019).
[2] Fienup, J. R., "Phase retrieval algorithms: a comparison," Appl. Opt., 21, 2758–2769 (1982).