Texture segmentation based on fractal attributes using convex functional minimization with generalized Stein formalism for automated regularization parameter selection.

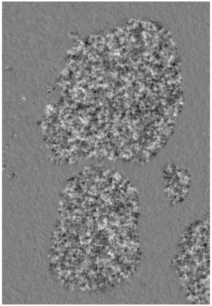
Barbara Pascal

November 27th 2020

Under the supervision of **Patrice Abry** and **Nelly Pustelnik**

Collaboration with **Valérie Vidal** and **Samuel Vaiter**

Image segmentation



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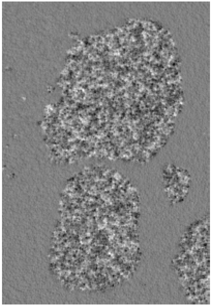

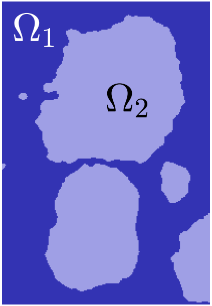

Goal: obtain a partition of the image into K homogeneous regions

$$\Omega = \Omega_1 \bigsqcup \ldots \bigsqcup \Omega_K$$

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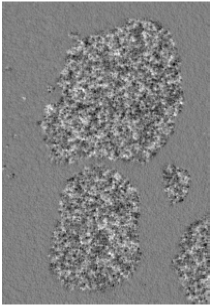

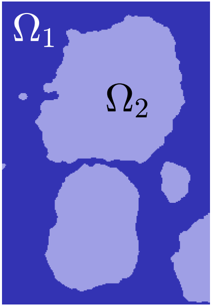

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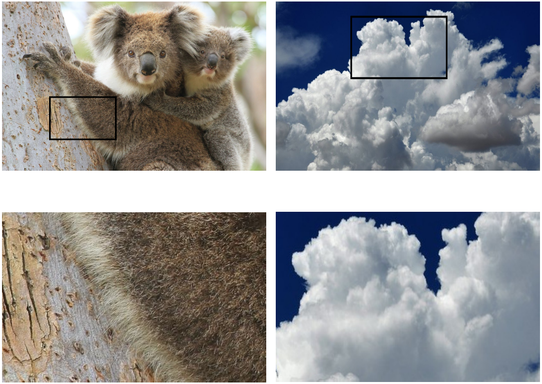

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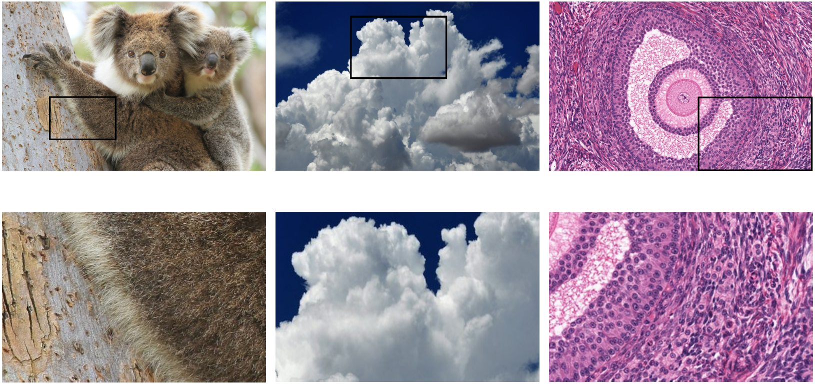

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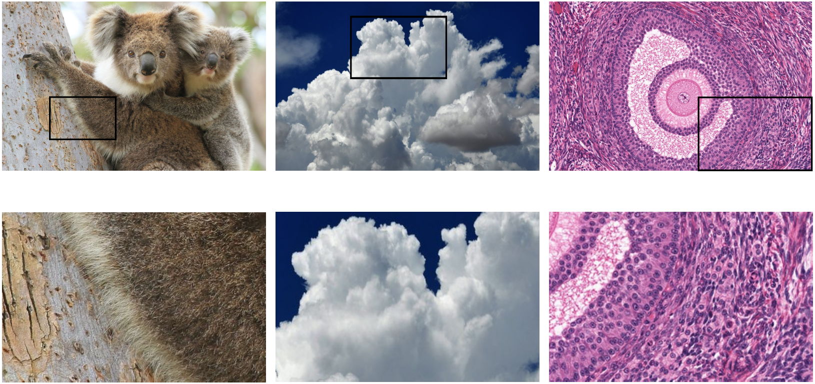
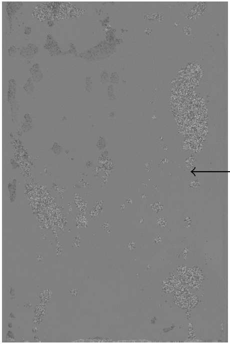


Crucial to describe real-world images

Multiphase flow through porous media

Laboratoire de Physique, ENS Lyon, V. Vidal, T. Busser, (M. Serres, IFPEN)



Solid
foam

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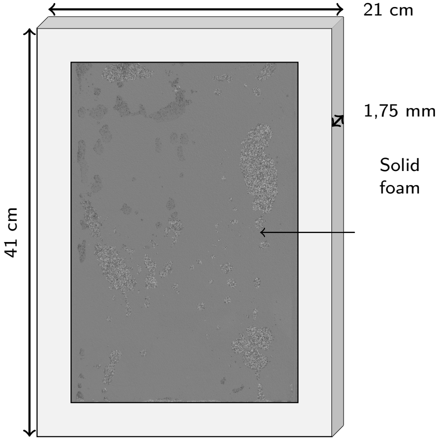

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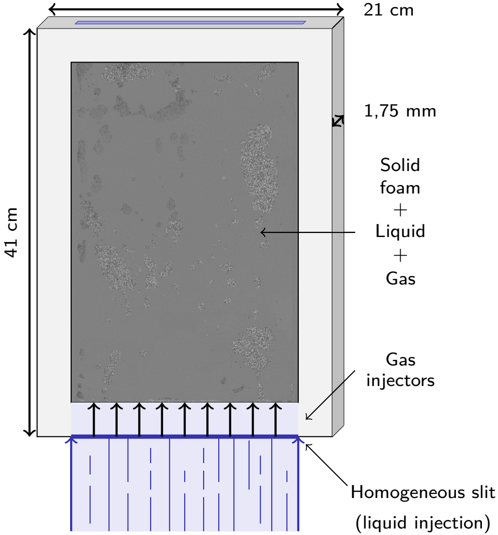

→ 1600 × 1100 pixels
→ video: ∼ 1000 images
→ phase diagram: ∼ 10 flow rates

Presentation outline

1. Texture characterization

[Gabor filters (Dunn, 1995)]
[Local amplitude and frequency (Havlicek, 1996)]
[Spectral histograms (Yuan, 2015)]

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→ fractals attributes

- local variance σ^2
- local regularity h

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2. Design of functionals

[Markov field (Geman, 1984)]
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3. Accelerated minimization algorithms

[Forward-backward (Combettes, 2005)]
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- computation of proximal operators
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4. Hyperparameters tuning

→ SURE under Gaussian correlated noise
- projected estimation error
- quasi-Newton minimization
  ↪ Generalized SUGAR

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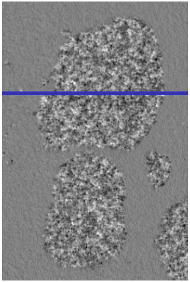
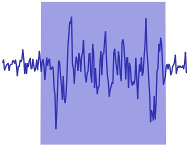
Piecewise monofractal model

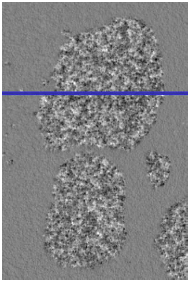


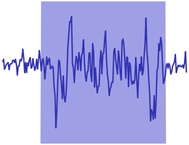


Piecewise monofractal model

Fractals attributes

- variance σ^2 *amplitude of variations*

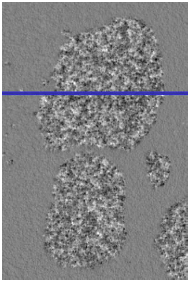


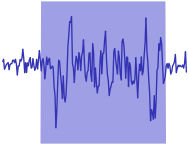


Piecewise monofractal model

Fractals attributes

- variance σ^2 — *amplitude of variations*
- local regularity h — *scale invariance*





Piecewise monofractal model

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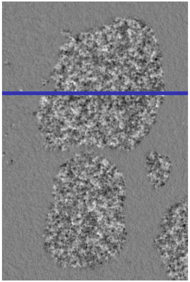
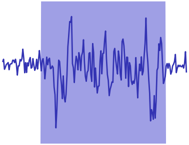
$$|f(x) - f(y)| \leq \sigma(x)|x - y|^{h(x)}$$





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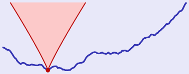
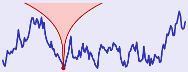
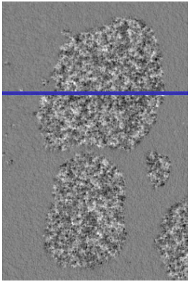
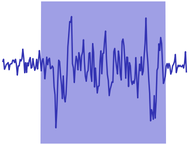


$h(x) \equiv h_1 = 0.9$



$h(x) \equiv h_2 = 0.3$





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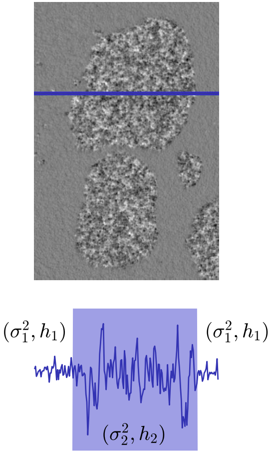
Segmentation

- σ^2 and h piecewise constant



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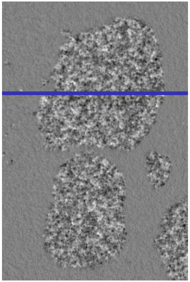
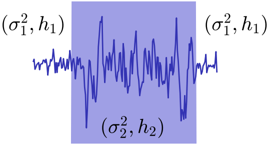
Segmentation

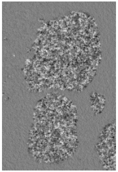
- σ^2 and h piecewise constant
- region Ω_k characterized by (σ_k^2, h_k)





Multiscale analysis

Textured image



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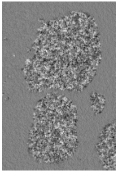
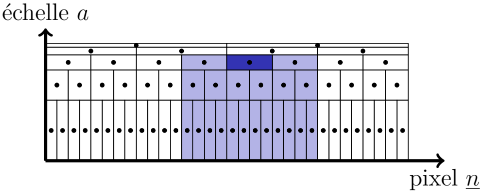


Local maximum of wavelet coefficients: $\mathcal{L}_{a,\cdot}$



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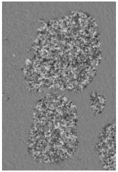

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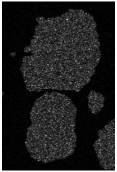

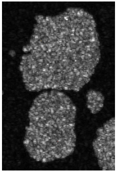

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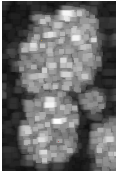

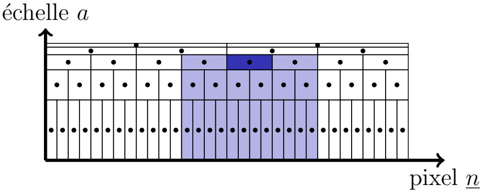

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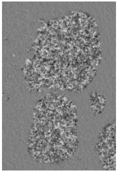

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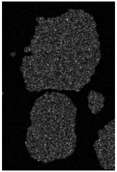

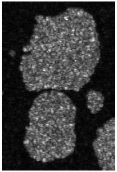

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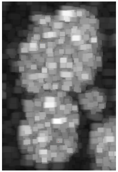

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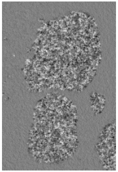

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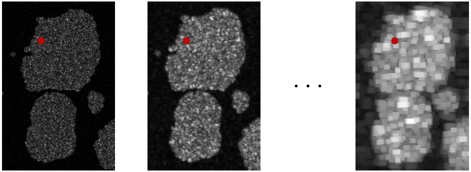

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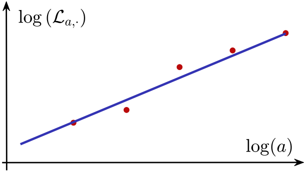

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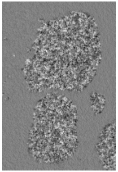

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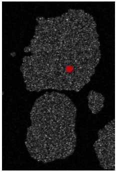

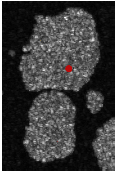

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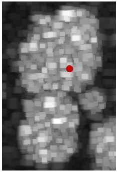

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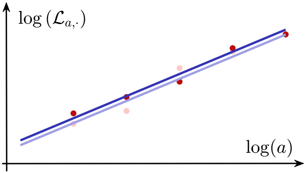

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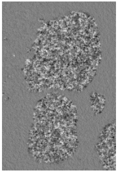

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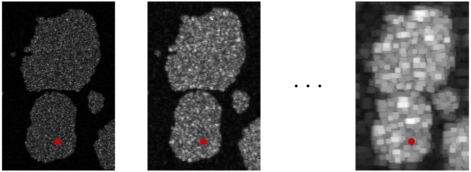

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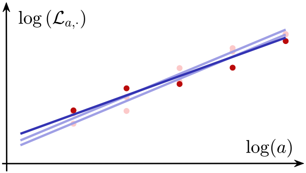

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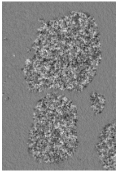

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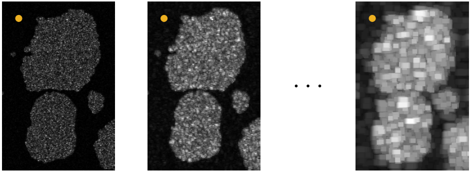
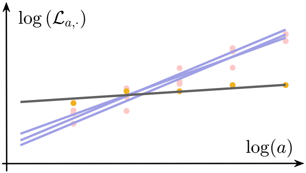


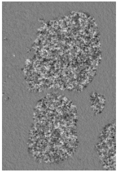
Proposition *(Jaffard, 2004), (Wendt, 2008)*

$$\log\left(\mathcal{L}_{a,\cdot}\right) \underset{a\to 0}{\simeq} \log(a) \underbrace{\boldsymbol{h}}_{\text{regularity}} + \underbrace{\boldsymbol{v}}_{\substack{\propto \log(\boldsymbol{\sigma}^2) \\ \text{(variance)}}}$$



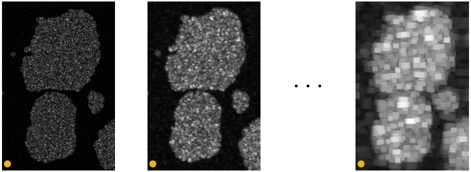
Multiscale analysis

Textured image



Local maximum of wavelet coefficients: $\mathcal{L}_{a,\cdot}$

Scale $a = 2^1$ $a = 2^2$ $\cdots$ $a = 2^5$



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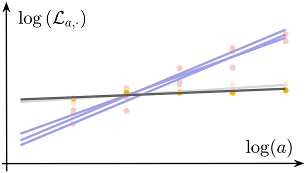
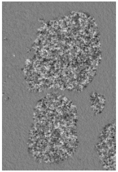


Multiscale analysis

Textured image



Local maximum of wavelet coefficients: $\mathcal{L}_{a,\cdot}$

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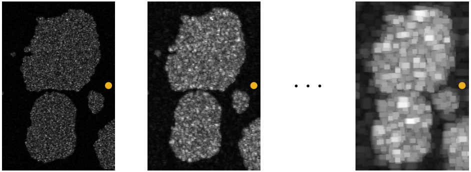

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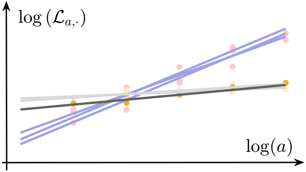
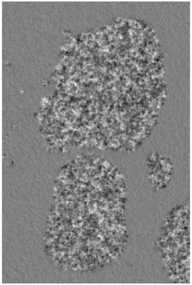


Direct punctual estimation

Linear regression $\log(\mathcal{L}_{a,\cdot}) \simeq \log(a) \underbrace{\boldsymbol{h}}_{\text{regularity}} + \underbrace{\boldsymbol{v}}_{\propto \log(\boldsymbol{\sigma}^2)}$

Textured image



Direct punctual estimation

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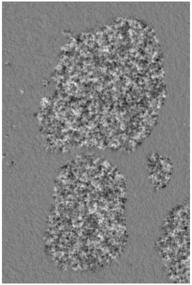
$$\left(\widehat{\boldsymbol{h}}^{\mathrm{LR}}, \widehat{\boldsymbol{v}}^{\mathrm{LR}}\right) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_{a=a_{\min}}^{a_{\max}} \left\| \log(\mathcal{L}_{a,\cdot}) - \log(a)\boldsymbol{h} - \boldsymbol{v} \right\|^2$$

Textured image



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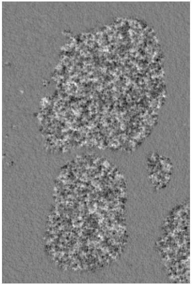
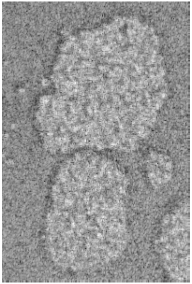
Textured image



Local regularity $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

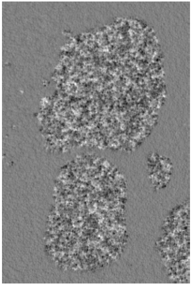
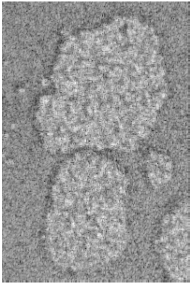
Local power $\widehat{\boldsymbol{v}}^{\mathrm{LR}}$



Direct punctual estimation

Linear regression $\underbrace{\mathbb{E}\log\left(\mathcal{L}_{a,\cdot}\right)}_{\text{expected value}} = \log(a)\underbrace{\bar{\boldsymbol{h}}}_{\text{regularity}} + \underbrace{\bar{\boldsymbol{v}}}_{\propto\log(\boldsymbol{\sigma}^2)}$

$$\left(\widehat{\boldsymbol{h}}^{\mathrm{LR}}, \widehat{\boldsymbol{v}}^{\mathrm{LR}}\right) = \underset{\boldsymbol{h},\boldsymbol{v}}{\mathrm{argmin}} \sum_{a=a_{\min}}^{a_{\max}} \left\|\log\left(\mathcal{L}_{a,\cdot}\right) - \log(a)\boldsymbol{h} - \boldsymbol{v}\right\|^2$$

Textured image	Local regularity $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$	Local power $\widehat{\boldsymbol{v}}^{\mathrm{LR}}$
		

$\longrightarrow$ large estimation variance

A posteriori regularization

Linear regression $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

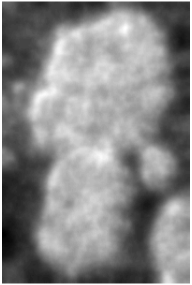
A posteriori regularization

Filter smoothing (linear)

$$\left(\mathbf{I} + \lambda \mathbf{D}^\top \mathbf{D}\right)^{-1} \widehat{\boldsymbol{h}}^{\mathrm{LR}}$$

Linear regression $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

Lissage



A posteriori regularization

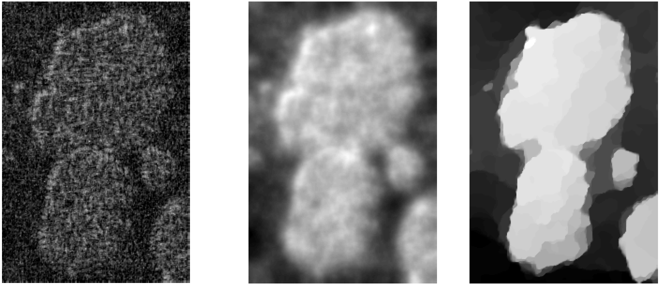
Filter smoothing (linear)

$$\left(\mathbf{I} + \lambda \mathbf{D}^\top \mathbf{D}\right)^{-1} \widehat{\boldsymbol{h}}^{\mathrm{LR}}$$

ROF denoising (nonlinear)

$$\underset{\boldsymbol{h}}{\operatorname{argmin}} \; \|\boldsymbol{h} - \widehat{\boldsymbol{h}}^{\mathrm{LR}}\|^2 + \lambda \|\mathbf{D}\boldsymbol{h}\|_{2,1}$$

Linear regression $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ | Lissage | ROF



A posteriori regularization

Filter smoothing (linear)

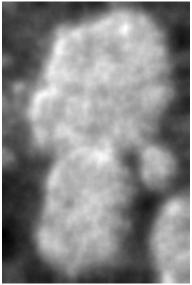
$$\left(\mathbf{I} + \lambda \mathbf{D}^\top \mathbf{D}\right)^{-1} \widehat{\boldsymbol{h}}^{\mathrm{LR}}$$

ROF denoising (nonlinear)

$$\underset{\boldsymbol{h}}{\operatorname{argmin}} \, \|\boldsymbol{h} - \widehat{\boldsymbol{h}}^{\mathrm{LR}}\|^2 + \lambda \|\mathbf{D}\boldsymbol{h}\|_{2,1}$$

Linear regression $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

Lissage



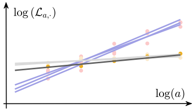
ROF

$\longrightarrow$ cumulative estimation variance and regularization bias

Functionals with either free or co-localized contours

$$\sum_a \underbrace{\|\log \mathcal{L}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}}$$

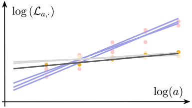
→ fidelity to the log-linear model



Functionals with either free or co-localized contours

$$\sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \quad + \quad \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

$\rightarrow$ fidelity to the log-linear model



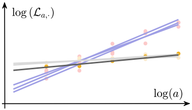
$\rightarrow$ favors piecewise constancy

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model

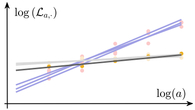
→ favors piecewise constancy



Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model



→ favors piecewise constancy

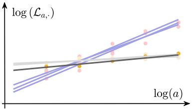
Finite differences $\mathbf{D}_1\boldsymbol{x}$ (horizontal), $\mathbf{D}_2\boldsymbol{x}$ (vertical) in each pixel

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \;+\; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model

→ favors piecewise constancy



Finite differences $\mathbf{D}\boldsymbol{x} = [\mathbf{D}_1\boldsymbol{x}, \mathbf{D}_2\boldsymbol{x}]$

Free: $\boldsymbol{h}$, $\boldsymbol{v}$ are **independently** piecewise constant

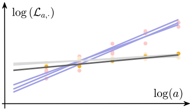
$$\mathcal{Q}_{\mathrm{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha) = \alpha\|\mathbf{D}\boldsymbol{h}\|_{2,1} + \|\mathbf{D}\boldsymbol{v}\|_{2,1}$$

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model

→ favors piecewise constancy



Finite differences $\mathbf{D}\boldsymbol{x} = [\mathbf{D}_1\boldsymbol{x}, \mathbf{D}_2\boldsymbol{x}]$

Free: $\boldsymbol{h}$, $\boldsymbol{v}$ are **independently** piecewise constant

$$\mathcal{Q}_{\mathrm{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha) = \alpha\|\mathbf{D}\boldsymbol{h}\|_{2,1} + \|\mathbf{D}\boldsymbol{v}\|_{2,1}$$

Co-localized: $\boldsymbol{h}$, $\boldsymbol{v}$ are **concomitantly** piecewise constant

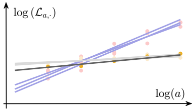
$$\mathcal{Q}_{\mathrm{C}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha) = \|[\alpha\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}]\|_{2,1}$$

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \quad \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \quad + \quad \lambda \, \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model

→ favors piecewise constancy



Disjoint contours

$\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$

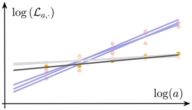
Common contours

$\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \quad \underbrace{\sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \quad + \quad \lambda\, \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

Least-Squares → fidelity to the log-linear model



Total Variation → favors piecewise constancy

Disjoint contours

$\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\quad$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$

$\mathcal{Q}_{\mathsf{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 4$

Common contours

$\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\quad$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$

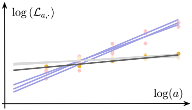
$\mathcal{Q}_{\mathsf{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 4$

Functionals with either free or co-localized contours

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

→ fidelity to the log-linear model

→ favors piecewise constancy



Disjoint contours

Common contours

$\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$ $\boldsymbol{h} \in \mathbb{R}^{2\times 2}$ $\boldsymbol{v} \in \mathbb{R}^{2\times 2}$

Disjoint contours:

$\mathcal{Q}_{\mathrm{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 4$

$\mathcal{Q}_{\mathrm{C}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 2 + \sqrt{2} \simeq 3.4$

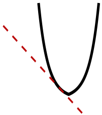
Common contours:

$\mathcal{Q}_{\mathrm{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 4$

$\mathcal{Q}_{\mathrm{C}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; 1) = 2\sqrt{2} \simeq 2.8$

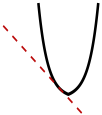
Functionals minimization

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \underbrace{\sum_a \|\log \mathcal{L}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \ + \ \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



Functionals minimization

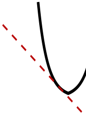
$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



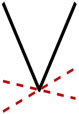
- gradient descent $\boldsymbol{x}^{n+1} = \boldsymbol{x}^n - \tau \nabla \varphi(\boldsymbol{x}^n)$

Functionals minimization

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \;\; \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \;+\; \underbrace{\lambda\, \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth

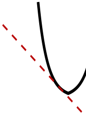


- gradient descent $\boldsymbol{x}^{n+1} = \boldsymbol{x}^n - \tau \nabla\varphi(\boldsymbol{x}^n)$
- implicit subgradient descent: proximal point algorithm

$$\boldsymbol{x}^{n+1} = \boldsymbol{x}^n - \tau \boldsymbol{u}^n,\;\; \boldsymbol{u}^n \in \partial\varphi(\boldsymbol{x}^{n+1}) \;\Leftrightarrow\; \boldsymbol{x}^{n+1} = \mathrm{prox}_{\tau\varphi}(\boldsymbol{x}^n)$$

Functionals minimization

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \;\; \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



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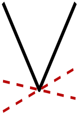

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- splitting proximal algorithm

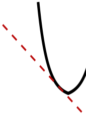
$$\boldsymbol{y}^{n+1} = \operatorname{prox}_{\sigma(\lambda\mathcal{Q})^*}\left(\boldsymbol{y}^n + \sigma \mathbf{D}\bar{\boldsymbol{x}}^n\right)$$

$$\boldsymbol{x}^{n+1} = \operatorname{prox}_{\tau\|\mathcal{L}-\Phi\cdot\|_2^2}\left(\boldsymbol{x}^n - \tau \mathbf{D}^\top \boldsymbol{y}^{n+1}\right), \qquad \Phi : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$$

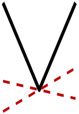
$$\bar{\boldsymbol{x}}^{n+1} = 2\boldsymbol{x}^{n+1} - \boldsymbol{x}^n$$

Functionals minimization

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth



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- splitting proximal algorithm $\quad \mathrm{prox}_{\tau\varphi}(\boldsymbol{x}) = \underset{\boldsymbol{u}}{\mathrm{argmin}} \frac{1}{2}\|\boldsymbol{x} - \boldsymbol{u}\|^2 + \tau\varphi(\boldsymbol{u})$

$$\boldsymbol{y}^{n+1} = \mathrm{prox}_{\sigma(\lambda\mathcal{Q})^*}\left(\boldsymbol{y}^n + \sigma \mathbf{D}\bar{\boldsymbol{x}}^n\right)$$

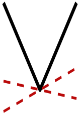
$$\boldsymbol{x}^{n+1} = \mathrm{prox}_{\tau\|\mathcal{L} - \boldsymbol{\Phi}\cdot\|_2^2}\left(\boldsymbol{x}^n - \tau \mathbf{D}^\top \boldsymbol{y}^{n+1}\right), \qquad \boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$$

$$\bar{\boldsymbol{x}}^{n+1} = 2\boldsymbol{x}^{n+1} - \boldsymbol{x}^n$$

Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \;+\; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

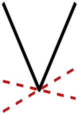
nonsmooth



Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

nonsmooth

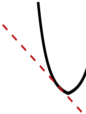


Ex. Mixed norm: for $\boldsymbol{z} = [\boldsymbol{z}_1; \ldots; \boldsymbol{z}_I]$

$$\mathcal{Q}(\boldsymbol{z}) = \|\boldsymbol{z}\|_{2,1} = \sum_{\underline{n}\in\Omega} \sqrt{\sum_{i=1}^{I} z_i^2(\underline{n})} = \sum_{\underline{n}\in\Omega} \|\boldsymbol{z}(\underline{n})\|_2$$

Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \underbrace{\sum_{a} \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



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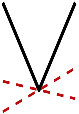


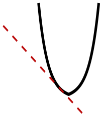
Ex. **Mixed norm:** for $\boldsymbol{z} = [\boldsymbol{z}_1; \dots; \boldsymbol{z}_I]$

$$\mathcal{Q}(\boldsymbol{z}) = \|\boldsymbol{z}\|_{2,1} = \sum_{\underline{n}\in\Omega} \sqrt{\sum_{i=1}^{I} z_i^2(\underline{n})} = \sum_{\underline{n}\in\Omega} \|\boldsymbol{z}(\underline{n})\|_2$$

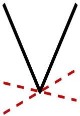
$$\boldsymbol{p} = \mathrm{prox}_{\lambda\|\cdot\|_{2,1}}(\boldsymbol{z}) \quad \Leftrightarrow \quad p_i(\underline{n}) = \max\left(0, 1 - \frac{\lambda}{\|\boldsymbol{z}(\underline{n})\|_2}\right) z_i(\underline{n})$$

Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



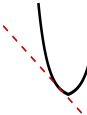
nonsmooth



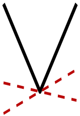
Least-Squares: $\|\log \boldsymbol{\mathcal{L}} - \boldsymbol{\Phi}(\boldsymbol{h}, \boldsymbol{v})\|^2, \quad \boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$

Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \sum_{a} \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth



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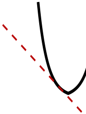
Proposition *(Pascal, 2019)*

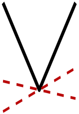
$$(\widetilde{\boldsymbol{h}}, \widetilde{\boldsymbol{v}}) = \text{prox}_{\tau\|\boldsymbol{\mathcal{L}}-\boldsymbol{\Phi}\cdot\|^2}(\boldsymbol{h}, \boldsymbol{v}) \iff (\widetilde{\boldsymbol{h}}, \widetilde{\boldsymbol{v}}) = \left(\mathbf{I} + \tau\boldsymbol{\Phi}^\top\boldsymbol{\Phi}\right)^{-1}\left((\boldsymbol{h}, \boldsymbol{v}) + \tau\boldsymbol{\Phi}^\top \log \boldsymbol{\mathcal{L}}\right)$$

Computation of proximal operators

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \sum_a \underbrace{\|\log \mathcal{L}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \;+\; \lambda\, \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth



Least-Squares: $\|\log \mathcal{L} - \boldsymbol{\Phi}(\boldsymbol{h}, \boldsymbol{v})\|^2, \quad \boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$

Proposition *(Pascal, 2019)*

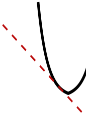
Let $S_m = \sum_a \log^m(a)$, $\mathcal{D} = (1 + \tau S_2)(1 + \tau S_0) - \tau^2 S_1^2$, $\mathcal{T} = \sum_a \log \mathcal{L}_a$ and $\mathcal{G} = \sum_a \log(a) \log \mathcal{L}_a$, alors

$$(\widetilde{\boldsymbol{h}}, \widetilde{\boldsymbol{v}}) = \mathrm{prox}_{\tau\|\mathcal{L} - \boldsymbol{\Phi}\cdot\|^2}(\boldsymbol{h}, \boldsymbol{v}) \iff (\widetilde{\boldsymbol{h}}, \widetilde{\boldsymbol{v}}) = \left(\mathbf{I} + \tau \boldsymbol{\Phi}^\top \boldsymbol{\Phi}\right)^{-1} \left((\boldsymbol{h}, \boldsymbol{v}) + \tau \boldsymbol{\Phi}^\top \log \mathcal{L}\right)$$

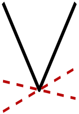
$$\iff \begin{cases} \widetilde{\boldsymbol{h}} = \mathcal{D}^{-1}\left((1 + \tau S_0)(\tau \mathcal{G} + \boldsymbol{h}) - \tau S_1(\tau \mathcal{T} + \boldsymbol{v})\right) \\ \widetilde{\boldsymbol{v}} = \mathcal{D}^{-1}\left((1 + \tau S_2)(\tau \mathcal{T} + \boldsymbol{v}) - \tau S_1(\tau \mathcal{G} + \boldsymbol{h})\right) \end{cases}$$

Accelerated algorithm based on strong-convexity

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \underbrace{\sum_{a} \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \ + \ \lambda \ \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth

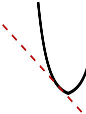


Primal-dual algorithm *(Chambolle, 2011)*

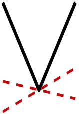
δ: duality gap, $\delta(\boldsymbol{x}^n, \boldsymbol{y}^n) \underset{n\to\infty}{\longrightarrow} 0$

Accelerated algorithm based on strong-convexity

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



nonsmooth



Primal-dual algorithm *(Chambolle, 2011)*

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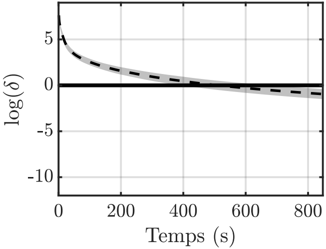
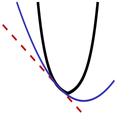


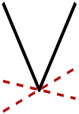
Convexity properties

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \sum_a \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



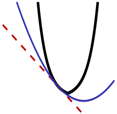
$\boldsymbol{\mu}$-strongly convex

nonsmooth



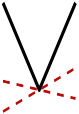
Convexity properties

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \; + \; \lambda \, \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



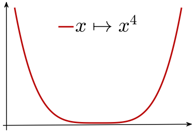
μ-strongly convex

nonsmooth

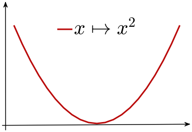


Strong-convexity

- φ μ-strongly convex iff $\varphi - \frac{\mu}{2}\|\cdot\|^2$ convex



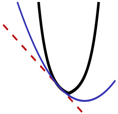
✓ strictly convex
✗ non strongly convex



✓ strictly convex
✓ 1-strongly convex

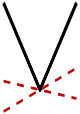
Convexity properties

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



$\boldsymbol{\mu}$-strongly convex

nonsmooth

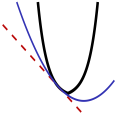


Strong-convexity

- φ $\boldsymbol{\mu}$-strongly convex iff $\varphi - \frac{\boldsymbol{\mu}}{2}\|\cdot\|^2$ convex
- φ $\mathcal{C}^2$ with Hessian matrix $\boldsymbol{H}\varphi \succeq 0 \implies \boldsymbol{\mu} = \min \mathrm{Sp}(\boldsymbol{H}\varphi)$

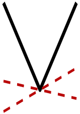
Convexity properties

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



μ-strongly convex

nonsmooth



Strong-convexity

- φ μ-strongly convex iff $\varphi - \frac{\mu}{2}\|\cdot\|^2$ convex
- φ $\mathcal{C}^2$ with Hessian matrix $\boldsymbol{H}\varphi \succeq 0 \implies \mu = \min \mathrm{Sp}(\boldsymbol{H}\varphi)$

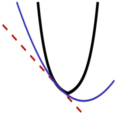
Proposition *(Pascal, 2019)*

$\sum_a \|\log \boldsymbol{\mathcal{L}} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2$ est μ-strongly convex.

$a_{\min} = 2^1$, $a_{\max}$	2^2	2^3	2^4	2^5	2^6
$\mu = \min \mathrm{Sp}\left(2\boldsymbol{\Phi}^\top \boldsymbol{\Phi}\right)$	0.29	**0.72**	1.20	1.69	2.20

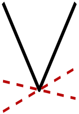
Accelerated algorithm based on strong-convexity

$$\operatorname*{minimize}_{\boldsymbol{h},\boldsymbol{v}} \ \underbrace{\sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \ + \ \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$



μ-strongly convex

nonsmooth



Accelerated Primal-dual algorithm *(Chambolle, 2011)*

for $n = 0, 1, \ldots$ $\qquad \boldsymbol{x} = (\boldsymbol{h}, \boldsymbol{v})$

$$\boldsymbol{y}^{n+1} = \operatorname{prox}_{\sigma_n (\lambda \mathcal{Q})^*} \left(\boldsymbol{y}^n + \sigma_n \mathbf{D} \bar{\boldsymbol{x}}^n\right)$$

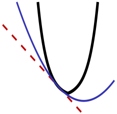
$$\boldsymbol{x}^{n+1} = \operatorname{prox}_{\tau_n \|\boldsymbol{\mathcal{L}} - \boldsymbol{\Phi} \cdot\|_2^2} \left(\boldsymbol{x}^n - \tau_n \mathbf{D}^\top \boldsymbol{y}^{n+1}\right)$$

$$\theta_n = \sqrt{1 + 2\mu\tau_n}, \quad \tau_{n+1} = \tau_n / \theta_n, \quad \sigma_{n+1} = \theta_n \sigma_n$$

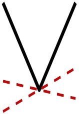
$$\bar{\boldsymbol{x}}^{n+1} = \boldsymbol{x}^{n+1} + \theta_n^{-1} \left(\boldsymbol{x}^{n+1} - \boldsymbol{x}^n\right)$$

Algorithme accéléré par forte-convexité

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_a \underbrace{\|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

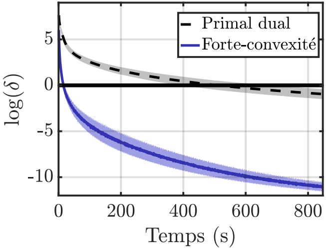


μ-strongly convex nonsmooth



Accelerated Primal-dual algorithm *(Chambolle, 2011)*

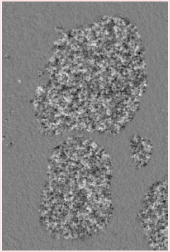
δ: duality gap, $\delta(\boldsymbol{x}^n, \boldsymbol{y}^n) \underset{n\to\infty}{\longrightarrow} 0$



Segmentation *via* iterated thresholding

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \sum_{a} \underbrace{\|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

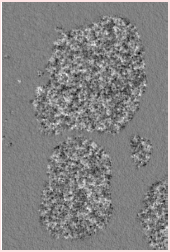
Textured image



Segmentation *via* iterated thresholding

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \ \underbrace{\sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} + \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

Textured image

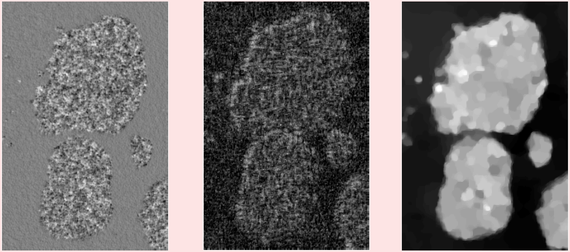


Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

Segmentation *via* iterated thresholding

$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \; \underbrace{\sum_a \|\log \mathcal{L}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \;+\; \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

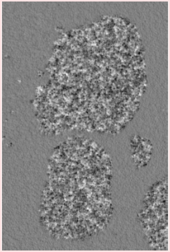
Textured image | Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ | Co-localized contours $\widehat{\boldsymbol{h}}^{\mathrm{C}}$



Segmentation *via* iterated thresholding

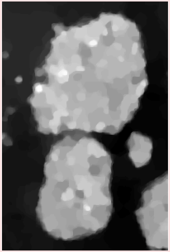
$$\underset{\boldsymbol{h},\boldsymbol{v}}{\text{minimize}} \quad \underbrace{\sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2}_{\textbf{Least-Squares}} \quad + \quad \lambda \underbrace{\mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)}_{\textbf{Total Variation}}$$

Textured image



Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

Co-localized contours $\widehat{\boldsymbol{h}}^{\mathrm{C}}$



Threshold estimate† $T\widehat{\boldsymbol{h}}^{\mathrm{C}}$

† *(Cai, 2013)*

State-of-the-art methods for texture segmentation

Threshold-ROF on $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

(Nafornita, 2014), (Pustelnik, 2016)

$$\underset{\boldsymbol{h}}{\operatorname{argmin}} \ \|\boldsymbol{h} - \widehat{\boldsymbol{h}}^{\mathrm{LR}}\|^2 + \lambda \|\mathbf{D}\boldsymbol{h}\|_{2,1}$$

Only based on regularity $\boldsymbol{h}$.

State-of-the-art methods for texture segmentation

Threshold-ROF on $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

(Nafornita, 2014), (Pustelnik, 2016)

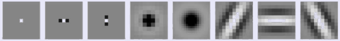
$$\underset{\boldsymbol{h}}{\operatorname{argmin}} \; \|\boldsymbol{h} - \widehat{\boldsymbol{h}}^{\mathrm{LR}}\|^2 + \lambda \|\mathbf{D}\boldsymbol{h}\|_{2,1}$$

Lin. reg. | ROF | Threshold

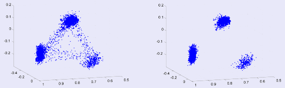
Only based on regularity $\boldsymbol{h}$.

Factorization based segmentation[†] *(Yuan, 2015)*

(i) local histograms



(ii) matrix factorization



(a) (b)

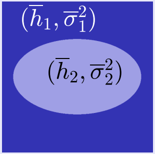
Fig. 2. Scatterplot of features in subspace. (a) Scatterplot of features projected onto the 3-d subspace. (b) Scatterplot after removing features with high edgeness.

[†] https://sites.google.com/site/factorizationsegmentation/

Compared segmentation performance on synthetic textures

Piecewise monofractal texture synthesis *(Pascal, 2019)*

- mask: $\Omega = \Omega_1 \sqcup \Omega_2$,
- attributes: $(\overline{h}_k, \overline{\sigma}_k^2)_{k=1,2}$



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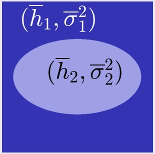
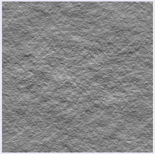
Ex. $\bar{h}_1 = 0.5,\ \bar{\sigma}_1^2 = 0.6$
$\bar{h}_2 = 0.6,\ \bar{\sigma}_2^2 = 0.7$





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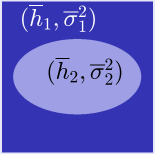
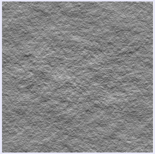
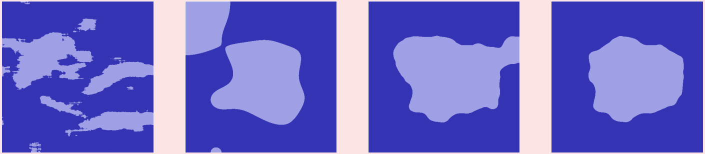




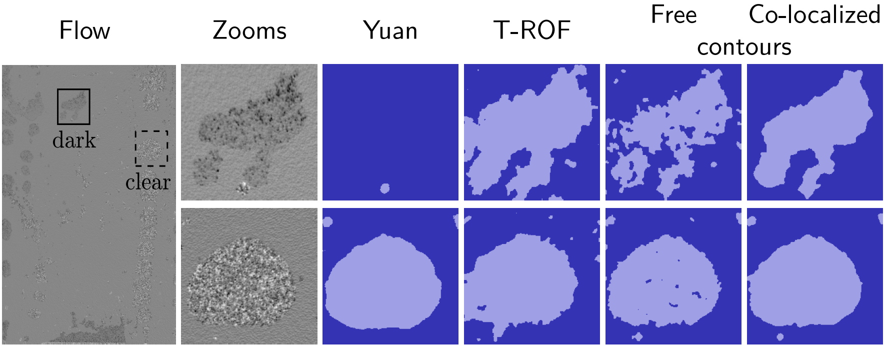
Averaged segmentation performances over 5 realizations

Yuan	T-ROF	free contours	co-localized contours

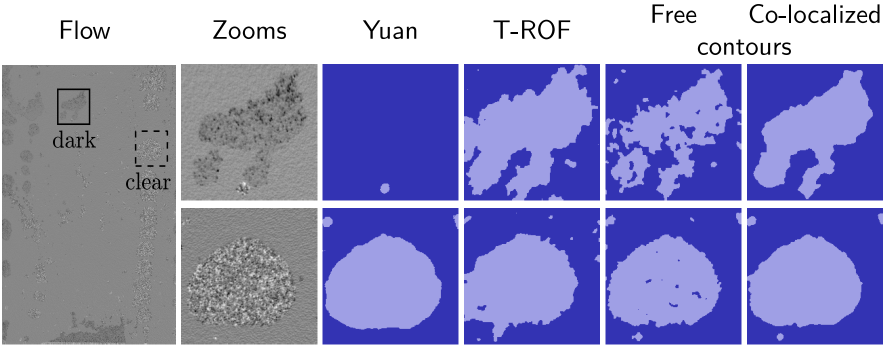


$71.1 \pm 1.3\%$	$78.5 \pm 1.1\%$	$90.2 \pm 1.9\%$	$91.1 \pm 1.5\%$

Low activity: $Q_{\mathrm{G}} = 300\mathrm{mL/min}$ - $Q_{\mathrm{L}} = 300\mathrm{mL/min}$



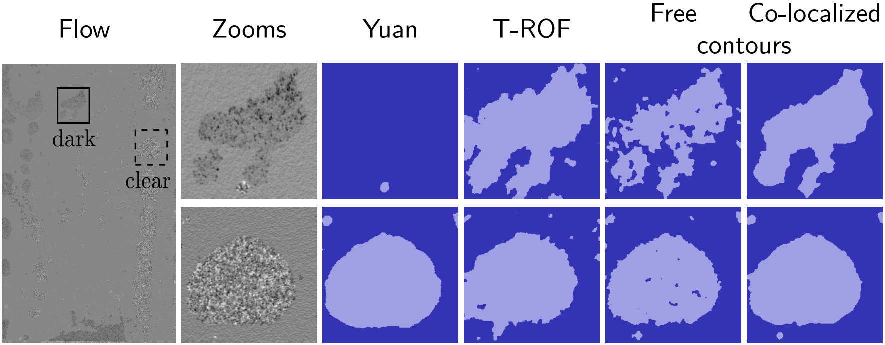
Low activity: $Q_{\mathrm{G}} = 300\mathrm{mL/min}$ - $Q_{\mathrm{L}} = 300\mathrm{mL/min}$



Liquid: $h_{\mathrm{L}} = 0.4$

Gas: $h_{\mathrm{G}} = 0.9$

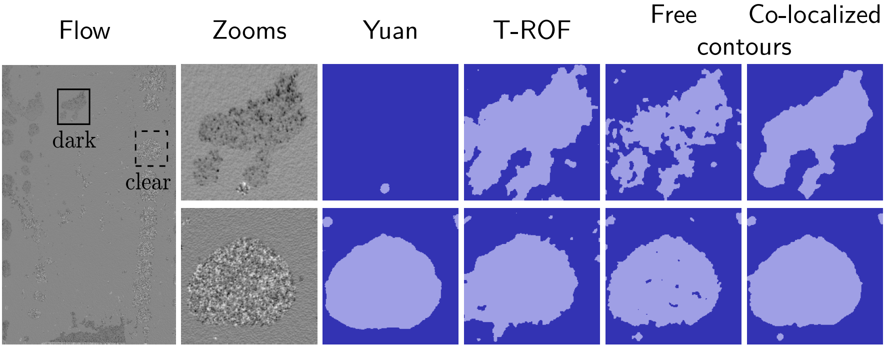
Low activity: $Q_\mathrm{G} = 300\mathrm{mL/min}$ - $Q_\mathrm{L} = 300\mathrm{mL/min}$



Liquid: $h_\mathrm{L} = 0.4$ $\sigma^2_\mathrm{dark} = 10^{-2}$

Gas: $h_\mathrm{G} = 0.9$

Low activity: $Q_{\mathrm{G}} = 300\text{mL}/\text{min}$ - $Q_{\mathrm{L}} = 300\text{mL}/\text{min}$



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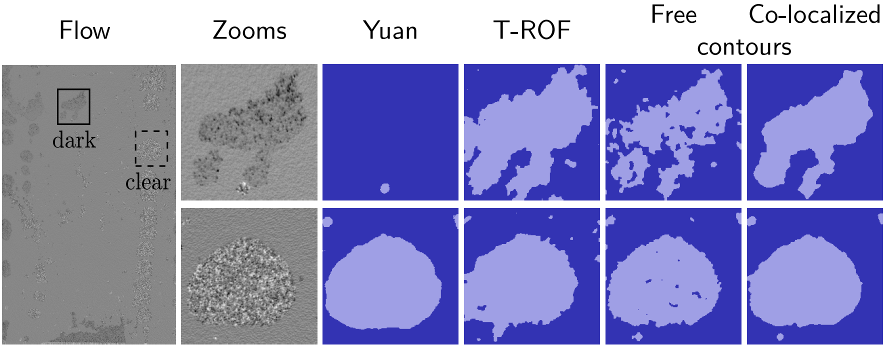
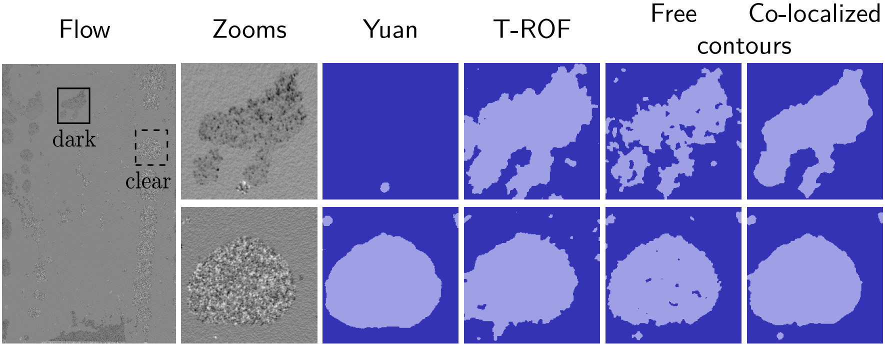


Liquid: $h_{\mathrm{L}} = 0.4$ $\quad \sigma^2_{\mathrm{dark}} = 10^{-2}$

Gas: $h_{\mathrm{G}} = 0.9$ $\quad \sigma^2_{\mathrm{dark}} = 10^{-2}$ (dark bubbles)

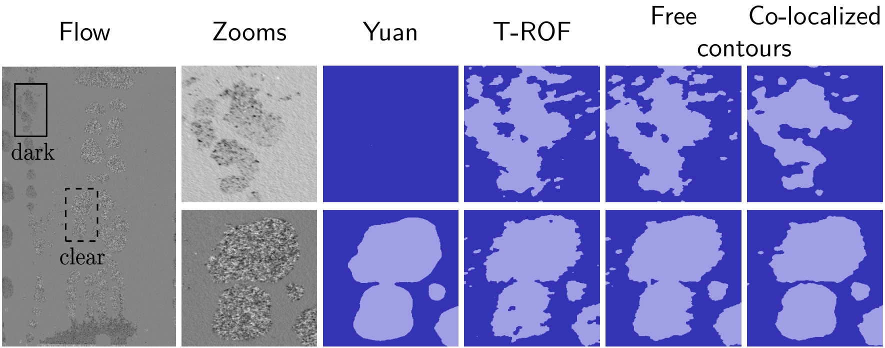
Low activity: $Q_{\mathrm{G}} = 300\text{mL/min}$ - $Q_{\mathrm{L}} = 300\text{mL/min}$



Liquid: $h_{\mathrm{L}} = 0.4 \qquad \sigma^2_{\mathrm{dark}} = 10^{-2}$

Gas: $h_{\mathrm{G}} = 0.9$ | $\sigma^2_{\mathrm{dark}} = 10^{-2}$ (dark bubbles)
$\sigma^2_{\mathrm{bright}} = 10^{-1}$ (bright bubbles)

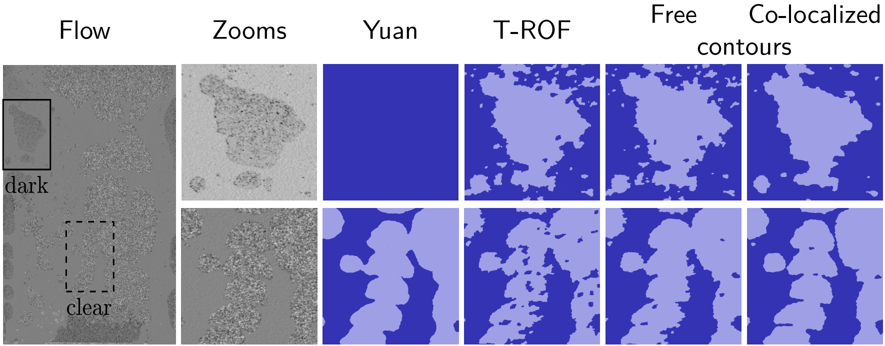
Transition: $Q_{\mathrm{G}} = 400\mathrm{mL}/\mathrm{min}$ - $Q_{\mathrm{L}} = 700\mathrm{mL}/\mathrm{min}$



Liquid: $h_{\mathrm{L}} = 0.4 \qquad \sigma^2_{\mathrm{dark}} = 10^{-2}$

Gas: $h_{\mathrm{G}} = 0.9$ | $\sigma^2_{\mathrm{dark}} = 10^{-2}$ (dark bubbles)
$\sigma^2_{\mathrm{bright}} = 10^{-1}$ (bright bubbles).

High activity: $Q_{\mathrm{G}} = 1200\text{mL/min}$ - $Q_{\mathrm{L}} = 300\text{mL/min}$

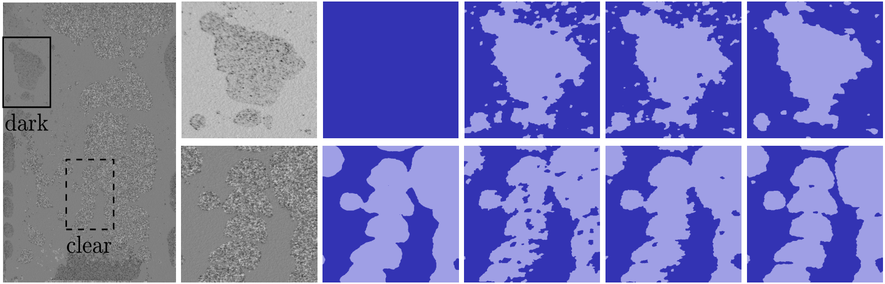


Liquid: $h_{\mathrm{L}} = 0.4 \qquad \sigma^2_{\mathrm{dark}} = 10^{-2}$

Gas: $h_{\mathrm{G}} = 0.9 \quad \Big| \quad \sigma^2_{\mathrm{dark}} = 10^{-2}$ (dark bubbles), $\sigma^2_{\mathrm{bright}} = 10^{-1}$ (bright bubbles).

High activity: $Q_{\mathrm{G}} = 1200\text{mL}/\text{min}$ - $Q_{\mathrm{L}} = 300\text{mL}/\text{min}$

Flow	Zooms	Yuan	T-ROF	Free	Co-localized
				contours	



Computational load		1s	12s	700s	**2100s**

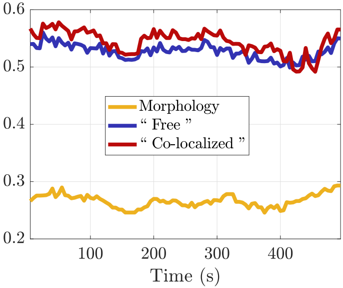
Liquid: $h_{\mathrm{L}} = 0.4$ $\quad \sigma^2_{\mathrm{dark}} = 10^{-2}$

Gas: $h_{\mathrm{G}} = 0.9$ $\quad \left| \begin{array}{ll} \sigma^2_{\mathrm{dark}} = 10^{-2} & \text{(dark bubbles)} \\ \sigma^2_{\mathrm{bright}} = 10^{-1} & \text{(bright bubbles).} \end{array} \right.$

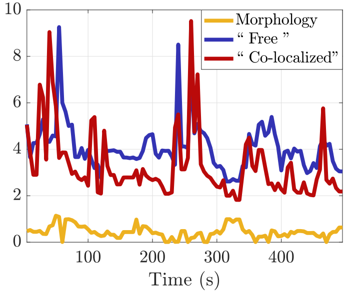
Multiphase flow through porous media

Laboratoire de Physique, ENS Lyon, V. Vidal, T. Busser, (M. Serres, IFPEN)

Gas fraction in the cell



Interface perimeter



Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_{a} \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

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Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$

$(\lambda, \alpha) = (0, 0)$

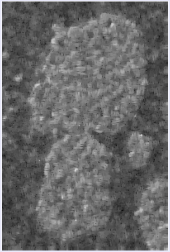
Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_{a} \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ Co-localized contours estimate $\widehat{\boldsymbol{h}}^{\mathrm{C}}$

$(\lambda, \alpha) = (0, 0)$

$(\lambda, \alpha) = (0.5, 0.5)$



too small

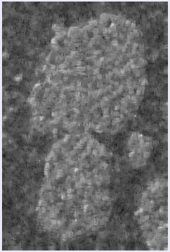
Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ — Co-localized contours estimate $\widehat{\boldsymbol{h}}^{\mathrm{C}}$

$(\lambda, \alpha) = (0, 0)$

$(\lambda, \alpha) = (0.5, 0.5)$



too small

$(\lambda, \alpha) = (500, 500)$

too large

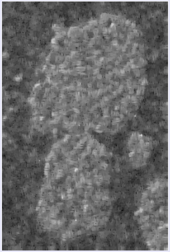
Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\mathcal{L}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ — Co-localized contours estimate $\widehat{\boldsymbol{h}}^{\mathrm{C}}$

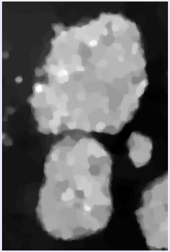
$(\lambda, \alpha) = (0, 0)$

$(\lambda, \alpha) = (0.5, 0.5)$



too small

$(\lambda^\dagger, \alpha^\dagger) = (11.5, 0.8)$



optimal

$(\lambda, \alpha) = (500, 500)$

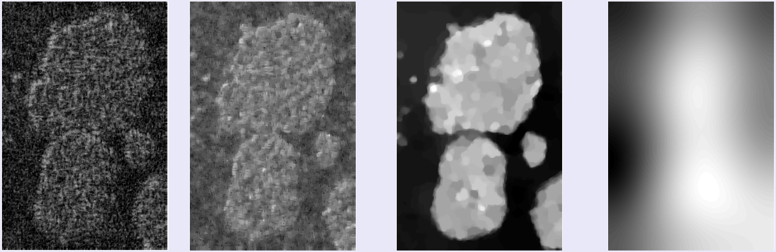
too large

Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\mathcal{L}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \mathcal{L}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ Co-localized contours estimate $\widehat{\boldsymbol{h}}^{\mathrm{C}}$

$(\lambda, \alpha) = (0, 0)$ $(\lambda, \alpha) = (0.5, 0.5)$ $(\lambda^\dagger, \alpha^\dagger) = (11.5, 0.8)$ $(\lambda, \alpha) = (500, 500)$



too small optimal too large

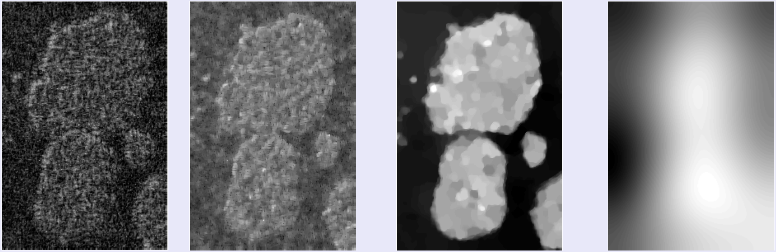
What *optimal* means?

Regularization parameters selection

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Lin. reg. $\widehat{\boldsymbol{h}}^{\mathrm{LR}}$ Co-localized contours estimate $\widehat{\boldsymbol{h}}^{\mathrm{C}}$

$(\lambda, \alpha) = (0, 0)$ $(\lambda, \alpha) = (0.5, 0.5)$ $(\lambda^\dagger, \alpha^\dagger) = (11.5, 0.8)$ $(\lambda, \alpha) = (500, 500)$



too small optimal too large

What *optimal* means? How to determine $\lambda^\dagger$ and $\alpha^\dagger$?

Parameter tuning (Grid search)

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\mathcal{L}; \lambda, \alpha) = \underset{\boldsymbol{h}, \boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \mathcal{L}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

$\boldsymbol{h}$: *discriminant*, $\boldsymbol{v}$: *auxiliary*

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$\boldsymbol{h}$: *discriminant*, $\boldsymbol{v}$: *auxiliary*

$\bar{\boldsymbol{h}}$: *true* regularity

$$\mathcal{R}(\lambda, \alpha) = \left\|\widehat{\boldsymbol{h}}(\mathcal{L}; \lambda, \alpha) - \bar{\boldsymbol{h}}\right\|^2$$

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$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\mathrm{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

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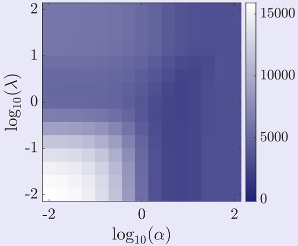

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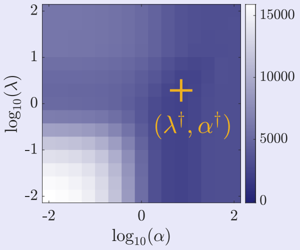

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$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

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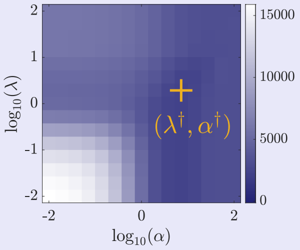

$\bar{\boldsymbol{h}}$: unknown!

?

Parameter tuning (Grid search)

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

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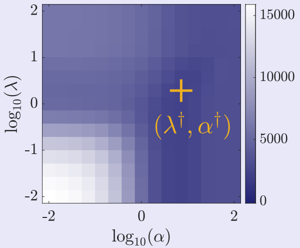

$\bar{\boldsymbol{h}}$: unknown!

?

Stein Unbiased Risk Estimate
(SURE)

Stein Unbiased Risk Estimate (Principe)

Observations $\boldsymbol{y} = \bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}}$: truth and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \rho^2 \mathbf{I})$

Stein Unbiased Risk Estimate (Principe)

Observations $\boldsymbol{y} = \bar{\boldsymbol{x}} + \zeta \in \mathbb{R}^P$, $\bar{\boldsymbol{x}}$: truth and $\zeta \sim \mathcal{N}(\mathbf{0}, \rho^2 \mathbf{I})$

Parametric estimator $(\boldsymbol{y}; \lambda) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda)$

Ex. $$\widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda) = \begin{cases} \left(\mathbf{I} + \lambda \mathbf{D}^\top \mathbf{D}\right)^{-1} \boldsymbol{y} & \text{(linear)} \\ \operatorname*{argmin}_{\boldsymbol{x}} \|\boldsymbol{y} - \boldsymbol{x}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{x}) & \text{(nonlinear)} \end{cases}$$

Stein Unbiased Risk Estimate (Principe)

Observations $\boldsymbol{y} = \bar{\boldsymbol{x}} + \zeta \in \mathbb{R}^P$, $\bar{\boldsymbol{x}}$: truth and $\zeta \sim \mathcal{N}(\mathbf{0}, \rho^2 \mathbf{I})$

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Quadratic error $R(\lambda) \triangleq \mathbb{E}_\zeta \|\widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda) - \bar{\boldsymbol{x}}\|^2 \overset{?}{=} \mathbb{E}_\zeta \widehat{R}(\boldsymbol{y}; \lambda)$ $\bar{\boldsymbol{x}}$ unknown

Stein Unbiased Risk Estimate (Principe)

Observations $\boldsymbol{y} = \bar{\boldsymbol{x}} + \zeta \in \mathbb{R}^P$, $\bar{\boldsymbol{x}}$: truth and $\zeta \sim \mathcal{N}(\mathbf{0}, \rho^2 \mathbf{I})$

Parametric estimator $(\boldsymbol{y}; \lambda) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda)$

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Quadratic error $R(\lambda) \triangleq \mathbb{E}_\zeta \|\widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda) - \bar{\boldsymbol{x}}\|^2 \overset{?}{=} \mathbb{E}_\zeta \widehat{R}(\boldsymbol{y}; \lambda)$ $\bar{\boldsymbol{x}}$ unknown

Theorem *(Stein, 1981)*

Let $(\boldsymbol{y}; \lambda) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda)$ an estimator of $\bar{\boldsymbol{x}}$

- weakly differentiable w.r.t. $\boldsymbol{y}$,
- such that $\zeta \mapsto \langle \widehat{\boldsymbol{x}}(\bar{\boldsymbol{x}} + \zeta; \lambda), \zeta \rangle$ is integrable w.r.t. $\mathcal{N}(\mathbf{0}, \rho^2 \mathbf{I})$.

$$\widehat{R}(\boldsymbol{y}; \lambda) \triangleq \|\widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda) - \boldsymbol{y}\|^2 + 2\rho^2 \operatorname{tr}\left(\partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}(\boldsymbol{y}; \lambda)\right) - \rho^2 P$$
$$\Longrightarrow R(\lambda) = \mathbb{E}_\zeta[\widehat{R}(\boldsymbol{y}; \lambda)].$$

Generalized *Stein Unbiased Risk Estimate*

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

Generalized *Stein Unbiased Risk Estimate*

Observations $\boldsymbol{y} = \Phi\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\Phi : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

E.g. the estimators $\widehat{\boldsymbol{h}}(\mathcal{L}; \lambda, \alpha)$ with free or co-localized contours

$\log \boldsymbol{\mathcal{L}} = \Phi(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \boldsymbol{\zeta}$

$\Phi : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$

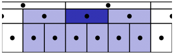
Generalized *Stein Unbiased Risk Estimate*

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

E.g. the estimators $\widehat{\boldsymbol{h}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha)$ with free or co-localized contours

$\log \boldsymbol{\mathcal{L}} = \boldsymbol{\Phi}(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \boldsymbol{\zeta}$ $\qquad$ $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$\boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$



Generalized *Stein Unbiased Risk Estimate*

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

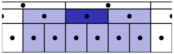
E.g. the estimators $\widehat{\boldsymbol{h}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha)$ with free or co-localized contours

$\log \boldsymbol{\mathcal{L}} = \boldsymbol{\Phi}(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \boldsymbol{\zeta}$

$\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

$\mathcal{R} = \|\widehat{\boldsymbol{h}} - \bar{\boldsymbol{h}}\|^2$

$\boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$



$\boldsymbol{\Pi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto (\boldsymbol{h}, \boldsymbol{0})$

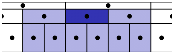
Generalized *Stein Unbiased Risk Estimate*

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P, \quad \bar{\boldsymbol{x}} \in \mathbb{R}^N, \ \boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

E.g. the estimators $\widehat{\boldsymbol{h}}(\mathcal{L}; \lambda, \alpha)$ with free or co-localized contours

$\log \mathcal{L} = \boldsymbol{\Phi}(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \boldsymbol{\zeta}$ $\qquad$ $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$ $\qquad$ $\mathcal{R} = \|\widehat{\boldsymbol{h}} - \bar{\boldsymbol{h}}\|^2$

$\boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$



$\boldsymbol{\Pi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto (\boldsymbol{h}, \boldsymbol{0})$

Projected estimation error $\quad R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P, \quad \bar{\boldsymbol{x}} \in \mathbb{R}^N, \ \boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \| \boldsymbol{\Pi} \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{\Pi} \bar{\boldsymbol{x}} \|^2$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$$R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$$

$$= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

$$\begin{aligned} R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\ &= \mathbb{E}_{\boldsymbol{\zeta}} \left\| \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}}) \right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\ &= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \end{aligned}$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \mathcal{S})$

$$\begin{aligned} R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\ &= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\ &= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\ &= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \end{aligned}$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right]
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

$$\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_\zeta \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_\zeta \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_\zeta \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_\zeta \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_\zeta \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_\zeta \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right]
\end{aligned}$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\| \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top \boldsymbol{\Phi})^{-1} \boldsymbol{\Phi}^\top \boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \bar{\boldsymbol{x}}) \right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top \boldsymbol{\Phi})^{-1} \boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2 \langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta} \rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2 \langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta} \rangle - 2 \langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta} \rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2 \langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta} \rangle - 2 \langle \mathbf{A}(\boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta}), \mathbf{A}\boldsymbol{\zeta} \rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right]
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_\zeta \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_\zeta \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_\zeta \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_\zeta \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_\zeta \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_\zeta \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_\zeta \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A} \qquad \boldsymbol{\zeta}\ , \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right]
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A} \qquad \boldsymbol{\zeta}\;, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\mathbb{E}_{\boldsymbol{\zeta}} \left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}\boldsymbol{\zeta}\|^2
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P, \quad \bar{\boldsymbol{x}} \in \mathbb{R}^N, \ \boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A} \quad \boldsymbol{\zeta}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\mathbb{E}_{\boldsymbol{\zeta}} \left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - \operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \mathcal{S})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\zeta} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\zeta} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\zeta} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\zeta} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\zeta} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\zeta} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\zeta} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A} \qquad \boldsymbol{\zeta}\ , \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\zeta} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\mathbb{E}_{\zeta}\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - \underbrace{\operatorname{tr}\left(\mathbf{A}\mathcal{S}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$$\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A} \qquad \boldsymbol{\zeta}\ , \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \underbrace{\mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2}_{\text{accessible}} + 2\mathbb{E}_{\boldsymbol{\zeta}} \langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - \underbrace{\operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P, \quad \bar{\boldsymbol{x}} \in \mathbb{R}^N, \ \boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \| \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\| \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle \mathbf{A} \qquad \boldsymbol{\zeta}\ , \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2 \right] \\
&= \underbrace{\mathbb{E}_{\boldsymbol{\zeta}} \| \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2}_{\text{accessible}} + 2\mathbb{E}_{\boldsymbol{\zeta}} \langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - \underbrace{\operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \mathcal{S})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A} \quad \boldsymbol{\zeta}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \underbrace{\mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2}_{\text{accessible}} + 2\mathbb{E}_{\boldsymbol{\zeta}}\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - \underbrace{\operatorname{tr}\left(\mathbf{A}\mathcal{S}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}
$$

$$
\mathbb{E}_{\boldsymbol{\zeta}}\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle = \mathbb{E}_{\boldsymbol{\zeta}}\left\langle \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}} \left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - 2\left\langle \mathbf{A} \qquad \boldsymbol{\zeta}\ , \mathbf{A}\boldsymbol{\zeta}\right\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \underbrace{\mathbb{E}_{\boldsymbol{\zeta}} \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2}_{\text{accessible}} + 2\mathbb{E}_{\boldsymbol{\zeta}} \left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle - \underbrace{\operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}
$$

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{\zeta}} \left\langle \mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle &= \mathbb{E}_{\boldsymbol{\zeta}} \left\langle \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\right\rangle \\
&= \int \left\langle \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta};\lambda), \mathbf{A}\boldsymbol{\zeta}\right\rangle \exp\left(-\frac{\boldsymbol{\zeta}^\top\boldsymbol{\mathcal{S}}^{-1}\boldsymbol{\zeta}}{2}\right) \mathrm{d}\boldsymbol{\zeta}
\end{aligned}
$$

Generalized *Stein Unbiased Risk Estimate* (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

$$
\begin{aligned}
R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) &\triangleq \mathbb{E}_{\boldsymbol{\zeta}}\|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\left\|\boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top\boldsymbol{\Phi}(\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \bar{\boldsymbol{x}})\right\|^2 \qquad \mathbf{A} \triangleq \boldsymbol{\Pi}(\boldsymbol{\Phi}^\top\boldsymbol{\Phi})^{-1}\boldsymbol{\Phi}^\top \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{y} - \boldsymbol{\Phi}\bar{\boldsymbol{x}})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y} + \boldsymbol{\zeta})\|^2 \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}), \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle\mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle\mathbf{A}\boldsymbol{y}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \mathbb{E}_{\boldsymbol{\zeta}}\left[\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\langle\mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - 2\langle\mathbf{A} \qquad \boldsymbol{\zeta}, \mathbf{A}\boldsymbol{\zeta}\rangle + \|\mathbf{A}\boldsymbol{\zeta}\|^2\right] \\
&= \underbrace{\mathbb{E}_{\boldsymbol{\zeta}}\|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y})\|^2}_{\text{accessible}} + 2\mathbb{E}_{\boldsymbol{\zeta}}\langle\mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle - \underbrace{\mathrm{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)}_{\text{accessible}}
\end{aligned}
$$

$$
\begin{aligned}
\mathbb{E}_{\boldsymbol{\zeta}}\langle\mathbf{A}\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle &= \mathbb{E}_{\boldsymbol{\zeta}}\langle\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}), \mathbf{A}\boldsymbol{\zeta}\rangle \\
&= \int \langle\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta};\lambda), \mathbf{A}\boldsymbol{\zeta}\rangle \exp\left(-\frac{\boldsymbol{\zeta}^\top\boldsymbol{\mathcal{S}}^{-1}\boldsymbol{\zeta}}{2}\right)\mathrm{d}\boldsymbol{\zeta} \\
\text{(Gen. I.b.P.)} &= \mathbb{E}_{\boldsymbol{\zeta}}\mathrm{tr}\left(\boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\partial_{\boldsymbol{y}}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right)
\end{aligned}
$$

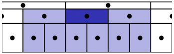
Stein Unbiased Risk Estimate généralisé

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

E.g. the estimators $\widehat{\boldsymbol{h}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha)$ with free or co-localized contours

$\log \boldsymbol{\mathcal{L}} = \boldsymbol{\Phi}(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \boldsymbol{\zeta}$ $\qquad$ $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$ $\qquad$ $\mathcal{R} = \|\widehat{\boldsymbol{h}} - \bar{\boldsymbol{h}}\|^2$

$\boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$



$\boldsymbol{\Pi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto (\boldsymbol{h}, \mathbf{0})$

Projected estimation error $\quad R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$

Theorem *(Pascal, 2020)*

Let $(\boldsymbol{y}; \boldsymbol{\Lambda}) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda})$ an estimator of $\bar{\boldsymbol{x}}$

- weakly differentiable w.r.t. $\boldsymbol{y}$,
- such that $\boldsymbol{\zeta} \mapsto \langle \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\bar{\boldsymbol{x}} + \boldsymbol{\zeta}; \lambda), \mathbf{A}\boldsymbol{\zeta} \rangle$ is integrable w.r.t. $\mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$.

$$\widehat{R}(\boldsymbol{\Lambda}) \triangleq \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\mathrm{tr}\left(\boldsymbol{\mathcal{S}}\mathbf{A}^\top \boldsymbol{\Pi} \partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda})\right) - \mathrm{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)$$

$$\Longrightarrow R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) = \mathbb{E}_{\boldsymbol{\zeta}}[\widehat{R}(\boldsymbol{\Lambda})].$$

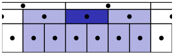
Stein Unbiased Risk Estimate généralisé

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \zeta \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\zeta \sim \mathcal{N}(\mathbf{0}, \mathcal{S})$

E.g. the estimators $\widehat{h}(\mathcal{L}; \lambda, \alpha)$ with free or co-localized contours

$\log \boldsymbol{\mathcal{L}} = \boldsymbol{\Phi}(\bar{\boldsymbol{h}}, \bar{\boldsymbol{v}}) + \zeta$ $\quad$ $\zeta \sim \mathcal{N}(\mathbf{0}, \mathcal{S})$ $\quad$ $\mathcal{R} = \|\widehat{\boldsymbol{h}} - \bar{\boldsymbol{h}}\|^2$

$\boldsymbol{\Phi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto \{\log(a)\boldsymbol{h} + \boldsymbol{v}\}_a$



$\boldsymbol{\Pi} : (\boldsymbol{h}, \boldsymbol{v}) \mapsto (\boldsymbol{h}, \mathbf{0})$

Projected estimation error $\quad R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_\zeta \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$

Theorem *(Pascal, 2020)*

Let $(\boldsymbol{y}; \boldsymbol{\Lambda}) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda})$ an estimator of $\bar{\boldsymbol{x}}$

- weakly differentiable w.r.t. $\boldsymbol{y}$,
- such that $\zeta \mapsto \langle \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\bar{\boldsymbol{x}} + \zeta; \lambda), \mathbf{A}\zeta \rangle$ is integrable w.r.t. $\mathcal{N}(\mathbf{0}, \mathcal{S})$.

$$\widehat{R}(\boldsymbol{\Lambda}) \triangleq \|\mathbf{A}(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda}) - \boldsymbol{y})\|^2 + 2\mathrm{tr}\left(\mathcal{S}\mathbf{A}^\top \boldsymbol{\Pi} \partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda})\right) - \mathrm{tr}\left(\mathbf{A}\mathcal{S}\mathbf{A}^\top\right)$$

$$\Longrightarrow R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) = \mathbb{E}_\zeta[\widehat{R}(\boldsymbol{\Lambda})].$$

Computation of the degrees of freedom

Degrees of freedom $\mathrm{dof} \triangleq \mathrm{tr}\left(\boldsymbol{\mathcal{S}}\mathbf{A}^\top \boldsymbol{\Pi} \partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}(\boldsymbol{y}; \boldsymbol{\Lambda})\right)$

Computation of the degrees of freedom

Degrees of freedom $\mathrm{dof} \triangleq \mathrm{tr}\left(\boldsymbol{\mathcal{S}}\mathbf{A}^\top \boldsymbol{\Pi}\partial_{\boldsymbol{y}}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right)$

- **Monte Carlo strategy** (MC) **Large size matrix M** $\in \mathbb{R}^{P\times P}$

$$\mathrm{tr}(\mathbf{M}) = \mathbb{E}_{\boldsymbol{\varepsilon}}\left\langle \mathbf{M}\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}\right\rangle, \quad \boldsymbol{\varepsilon} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I}_P)$$

Computation of the degrees of freedom

Degrees of freedom $\quad \mathrm{dof} \triangleq \mathrm{tr}\left(\mathcal{S}\mathbf{A}^\top \mathbf{\Pi}\partial_{\boldsymbol{y}}\widehat{\boldsymbol{x}}(\boldsymbol{y};\mathbf{\Lambda})\right)$

- **Monte Carlo strategy** (MC) — **Large size matrix M** $\in \mathbb{R}^{P\times P}$

$$\mathrm{tr}(\mathbf{M}) = \mathbb{E}_{\boldsymbol{\varepsilon}}\left\langle \mathbf{M}\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}\right\rangle, \quad \boldsymbol{\varepsilon} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I}_P)$$

- **Finite Differences** (FD) — **Inaccessible Jacobian matrix**

$$\partial_{\boldsymbol{y}}\widehat{\boldsymbol{x}}\left[\varepsilon\right] \underset{\nu\to 0}{\simeq} \frac{1}{\nu}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\varepsilon;\mathbf{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\mathbf{\Lambda})\right)$$

Computation of the degrees of freedom

Degrees of freedom $\quad \mathrm{dof} \triangleq \mathrm{tr}\left(\boldsymbol{\mathcal{S}}\mathbf{A}^\top \boldsymbol{\Pi} \partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right)$

- **Monte Carlo strategy** (MC) **Large size matrix $\mathbf{M} \in \mathbb{R}^{P\times P}$**

$$\mathrm{tr}(\mathbf{M}) = \mathbb{E}_{\boldsymbol{\varepsilon}} \langle \mathbf{M}\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}\rangle, \quad \boldsymbol{\varepsilon} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I}_P)$$

- **Finite Differences** (FD) **Inaccessible Jacobian matrix**

$$\partial_{\boldsymbol{y}} \widehat{\boldsymbol{x}}[\boldsymbol{\varepsilon}] \underset{\nu\to 0}{\simeq} \frac{1}{\nu}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right)$$

Proposition *(Pascal, 2020)*

Let $(\boldsymbol{y};\boldsymbol{\Lambda}) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})$ an estimator of $\bar{\boldsymbol{x}}$

- uniformly Lipschitz continuous w.r.t. $\boldsymbol{y}$,
- such that $\forall \boldsymbol{\Lambda} \in \mathbb{R}^L$, $\widehat{\boldsymbol{x}}(\mathbf{0}_P;\boldsymbol{\Lambda}) = \mathbf{0}_N$. Then

$$\mathbb{E}_{\boldsymbol{\zeta}}[\mathrm{dof}] = \lim_{\nu\to 0} \mathbb{E}_{\boldsymbol{\zeta},\boldsymbol{\varepsilon}}\left[\frac{1}{\nu}\left\langle \boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right), \boldsymbol{\varepsilon}\right\rangle\right]$$

Stein Unbiased Risk Estimate (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P, \quad \bar{\boldsymbol{x}} \in \mathbb{R}^N, \ \boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{\mathcal{S}})$

Projected estimation error $R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \|\boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$

Generalized Finite Difference Monte Carlo SURE

$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}}) \triangleq \left\|\mathbf{A}\left(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}\right)\right\|^2 + \frac{2}{\nu}\left\langle \boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right), \boldsymbol{\varepsilon}\right\rangle - \operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)$$

Stein Unbiased Risk Estimate (Computation)

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

Projected estimation error $R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) \triangleq \mathbb{E}_{\boldsymbol{\zeta}} \| \boldsymbol{\Pi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{\Pi}\bar{\boldsymbol{x}}\|^2$

Generalized Finite Difference Monte Carlo SURE

$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}}) \triangleq \left\|\mathbf{A}\left(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}\right)\right\|^2 + \frac{2}{\nu}\left\langle \boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right), \boldsymbol{\varepsilon}\right\rangle - \operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)$$

Theorem *(Pascal, 2020)*

Let $(\boldsymbol{y};\boldsymbol{\Lambda}) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})$ an estimator of $\bar{\boldsymbol{x}}$

- uniformly Lipschitz continuous w.r.t. $\boldsymbol{y}$,
- such that $\forall \boldsymbol{\Lambda} \in \mathbb{R}^L$, $\widehat{\boldsymbol{x}}(\boldsymbol{0}_P;\boldsymbol{\Lambda}) = \boldsymbol{0}_N$. Then

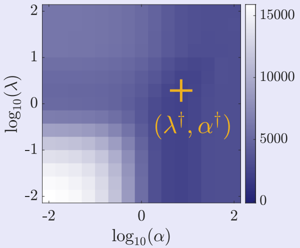
$$R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) = \lim_{\nu\to 0} \mathbb{E}_{\boldsymbol{\zeta},\boldsymbol{\varepsilon}}\left[\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}})\right]$$

Parameter tuning (Grid search)

$$\left(\widehat{\boldsymbol{h}}, \widehat{\boldsymbol{v}}\right)(\boldsymbol{\mathcal{L}}; \lambda, \alpha) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_a \|\log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

$\bar{\boldsymbol{h}}$: *true* regularity

$$\mathcal{R}(\lambda, \alpha) = \left\| \widehat{\boldsymbol{h}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha) - \bar{\boldsymbol{h}} \right\|^2$$



$\bar{\boldsymbol{h}}$: unknown!

$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha | \boldsymbol{\mathcal{S}})$$

Parameter tuning (Grid search)

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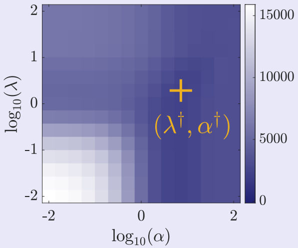

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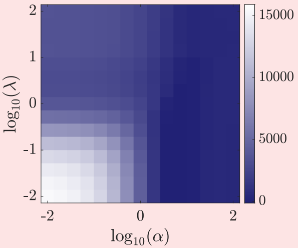
$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha | \boldsymbol{\mathcal{S}})$$



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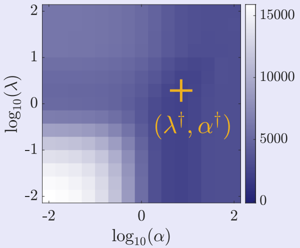

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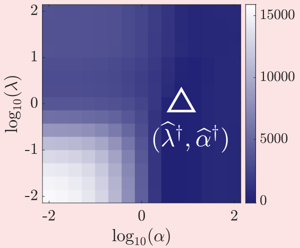

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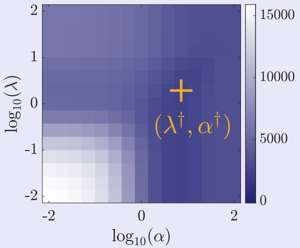

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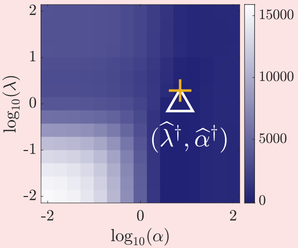
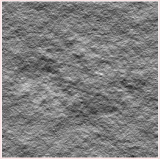
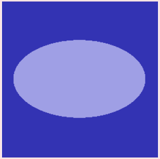


Grid search selection of regularization parameters

$$\left(\widehat{\boldsymbol{h}}^{\mathsf{F}}, \widehat{\boldsymbol{v}}^{\mathsf{F}}\right)(\boldsymbol{\mathcal{L}}; \boldsymbol{\Lambda}) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_{a} \|\log \boldsymbol{\mathcal{L}}_{a,.} - \log(a)\boldsymbol{h} - \boldsymbol{v}\|^2 + \lambda \mathcal{Q}_{\mathsf{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

Example





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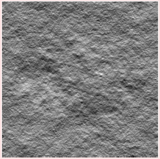
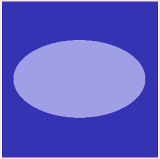
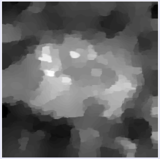




$\widehat{\boldsymbol{h}}^{\mathrm{F}}(\boldsymbol{\mathcal{L}}; \lambda^\dagger, \alpha^\dagger)$ (grid)



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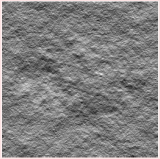

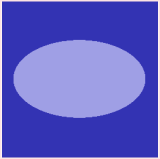

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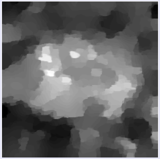

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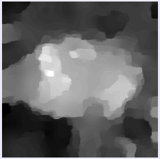

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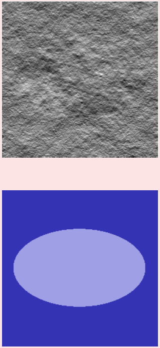

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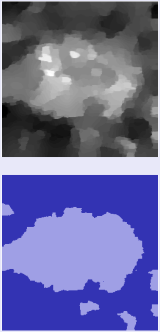
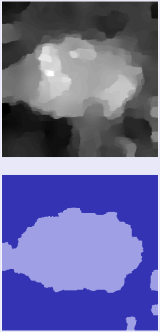


$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \widehat{\lambda}^{\dagger}, \widehat{\alpha}^{\dagger})$ (grid)



$15 \times 15 =$ **225** parameters $\longrightarrow$ grid search is very costly!

Automatic minimization of Generalized SURE

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P \times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

Generalized FDMC SURE $\lim_{\nu \to 0} \mathbb{E}_{\boldsymbol{\zeta},\boldsymbol{\varepsilon}} \widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y}; \boldsymbol{\Lambda} \,|\, \boldsymbol{\mathcal{S}}) = R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda})$

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But : $\underset{\boldsymbol{\Lambda}}{\text{minimize}} \ \widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y}; \boldsymbol{\Lambda} \,|\, \boldsymbol{\mathcal{S}})$ for given $\boldsymbol{y}$, $\boldsymbol{\mathcal{S}}$

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Broyden-Fletcher-Goldfarb-Shanno Quasi-Newton *(Nocedal, 2006)*

for $t = 0, 1, \ldots$

$\boldsymbol{d}^{[t]} = -\boldsymbol{H}^{[t]}\partial_{\boldsymbol{\Lambda}}\widehat{R}(\boldsymbol{\Lambda}^{[t]})$ *descent direction*

$\alpha^{[t]} \in \underset{\alpha\in\mathbb{R}}{\text{Argmin}}\ \widehat{R}(\boldsymbol{\Lambda}^{[t]} + \alpha\boldsymbol{d}^{[t]})$ *line search*

$\boldsymbol{\Lambda}^{[t+1]} = \boldsymbol{\Lambda}^{[t]} + \alpha^{[t]}\boldsymbol{d}^{[t]}$

$\boldsymbol{u}^{[t]} = \partial_{\boldsymbol{\Lambda}}\widehat{R}(\boldsymbol{\Lambda}^{[t+1]}) - \partial_{\boldsymbol{\Lambda}}\widehat{R}(\boldsymbol{\Lambda}^{[t]})$ *gradient increment*

$\boldsymbol{H}^{[t+1]} = \text{BFGS}(\boldsymbol{H}^{[t]}, \boldsymbol{d}^{[t]}, \boldsymbol{u}^{[t]})$ *"inverse Hessian" update*

Automatic minimization of Generalized SURE

Observations $\boldsymbol{y} = \boldsymbol{\Phi}\bar{\boldsymbol{x}} + \boldsymbol{\zeta} \in \mathbb{R}^P$, $\bar{\boldsymbol{x}} \in \mathbb{R}^N$, $\boldsymbol{\Phi} : \mathbb{R}^{P\times N}$ and $\boldsymbol{\zeta} \sim \mathcal{N}(\boldsymbol{0}, \boldsymbol{\mathcal{S}})$

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Stein Unbiased GrAdient Risk estimate

Generalized FDMC SURE

$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}}) = \left\|\mathbf{A}\left(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}\right)\right\|^2 + \frac{2}{\nu}\left\langle \boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\left(\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right), \boldsymbol{\varepsilon}\right\rangle - \operatorname{tr}\left(\mathbf{A}\boldsymbol{\mathcal{S}}\mathbf{A}^\top\right)$$

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Generalized Finite Difference Monte Carlo SUGAR

$$\partial_{\boldsymbol{\Lambda}}\widehat{R}_{\nu,\varepsilon}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}}) = 2\left(\mathbf{A}\boldsymbol{\Phi}\partial_{\boldsymbol{\Lambda}}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right)^\top\mathbf{A}\left(\boldsymbol{\Phi}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda}) - \boldsymbol{y}\right) + \frac{2}{\nu}\left\langle \boldsymbol{\mathcal{S}}\mathbf{A}^\top\boldsymbol{\Pi}\left(\partial_{\boldsymbol{\Lambda}}\widehat{\boldsymbol{x}}(\boldsymbol{y}+\nu\boldsymbol{\varepsilon};\boldsymbol{\Lambda}) - \partial_{\boldsymbol{\Lambda}}\widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})\right), \boldsymbol{\varepsilon}\right\rangle$$

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Theorem *(Pascal, 2020)*

Let $(\boldsymbol{y};\boldsymbol{\Lambda}) \mapsto \widehat{\boldsymbol{x}}(\boldsymbol{y};\boldsymbol{\Lambda})$ an estimator of $\bar{\boldsymbol{x}}$

- uniformly Lipschitz continuous w.r.t. $\boldsymbol{y}$
- such that $\forall \boldsymbol{\Lambda} \in \mathbb{R}^L$, $\widehat{\boldsymbol{x}}(\boldsymbol{0}_P;\boldsymbol{\Lambda}) = \boldsymbol{0}_N$,
- uniformly L-Lipschitz continuous w.r.t. $\boldsymbol{\Lambda}$, L ind. of $\boldsymbol{y}$. Then

$$\partial_{\boldsymbol{\Lambda}} R_{\boldsymbol{\Pi}}(\boldsymbol{\Lambda}) = \lim_{\nu\to 0}\mathbb{E}_{\boldsymbol{\zeta},\boldsymbol{\varepsilon}}\left[\partial_{\boldsymbol{\Lambda}}\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{y};\boldsymbol{\Lambda}\,|\,\boldsymbol{\mathcal{S}})\right]$$

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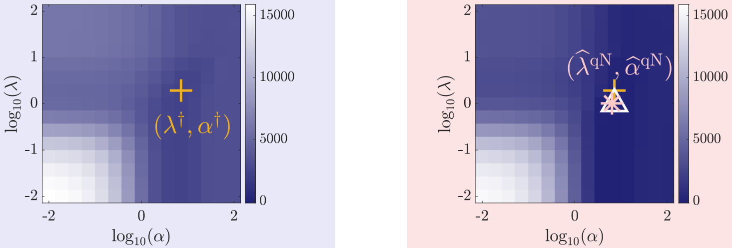
$\bar{\boldsymbol{h}}$: unknown!

$$\widehat{R}_{\nu,\boldsymbol{\varepsilon}}(\boldsymbol{\mathcal{L}}; \lambda, \alpha | \boldsymbol{\mathcal{S}})$$



Automated selection of regularization parameters

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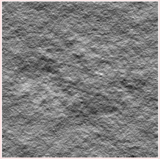
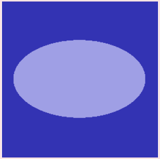
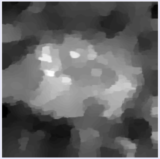
Example





$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \lambda^\dagger, \alpha^\dagger)$ (grid)



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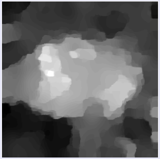

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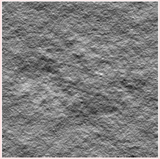
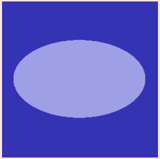
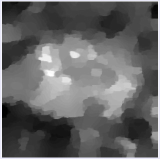
Example

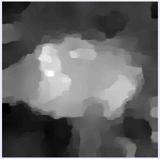




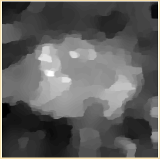
$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \lambda^{\dagger}, \alpha^{\dagger})$ (grid)



$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \widehat{\lambda}^{\dagger}, \widehat{\alpha}^{\dagger})$ (grid)



$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \widehat{\lambda}^{\mathsf{qN}}, \widehat{\alpha}^{\mathsf{qN}})$ (quasi-Newton)



Automated selection of regularization parameters

$$\left(\widehat{\boldsymbol{h}}^{\mathsf{F}}, \widehat{\boldsymbol{v}}^{\mathsf{F}}\right)(\boldsymbol{\mathcal{L}}; \boldsymbol{\Lambda}) = \underset{\boldsymbol{h},\boldsymbol{v}}{\operatorname{argmin}} \sum_{a} \| \log \boldsymbol{\mathcal{L}}_{a,\cdot} - \log(a)\boldsymbol{h} - \boldsymbol{v} \|^2 + \lambda \mathcal{Q}_{\mathsf{F}}(\mathbf{D}\boldsymbol{h}, \mathbf{D}\boldsymbol{v}; \alpha)$$

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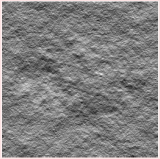

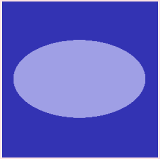

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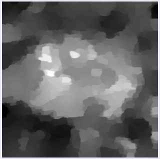
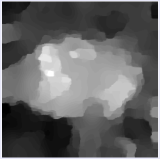


$\widehat{\boldsymbol{h}}^{\mathsf{F}}(\boldsymbol{\mathcal{L}}; \widehat{\lambda}^\dagger, \widehat{\alpha}^\dagger)$ (grid)



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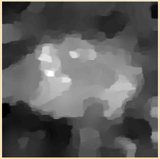

40 calls of the estimator v.s. **225** over a grid

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⟶ **In progress**: automated analysis of temporal series of images from multiphase flow experiments [Ann. Telecom, 2020]