Variance Stabilization for Noisy+Estimate Combination in Iterative Poisson Denoising

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***Abstract*—We denoise Poisson images with an iterative algorithm that progressively improves the effectiveness of variance-stabilizing transformations (VST) for Gaussian denoising filters. At each iteration, a combination of the Poisson observations with the denoised estimate from the previous iteration is treated as scaled Poisson data and filtered through a VST scheme. Due to the slight mismatch between a true scaled Poisson distribution and this combination, a special exact unbiased inverse is designed. We present an implementation of this approach based on the BM3D Gaussian denoising filter. With a computational cost at worst twice that of the non-iterative scheme, the proposed algorithm provides significantly better quality, particularly at low SNR, outperforming much costlier state-of-the-art alternatives.**

***Index Terms*—image denoising, photon-limited imaging, Poisson noise, Anscombe transformation, iterative filtering.**

I. Introduction

Denoising of images affected by Poisson noise is commonly executed by: 1) applying a variance stabilizing transformation (VST) to standardize the image noise, 2) denoising the image with an additive white Gaussian noise (AWGN) filter, 3) returning the image to its original range via inverse transformation. The most common VST for this purpose is the Anscombe transformation [1], [2]. Since, at very low counts (*e.g.*, less than one count per pixel, with SNR≪0dB), the Anscombe transformation can be quite inaccurate [3], denoising algorithms specifically designed for Poisson noise [3], [4] were developed to provide better performances than combinations of VST with Gaussian filters.

However, being inexpensive, simple, and independent from the adopted denoising algorithm, the Anscombe transform is still very appealing, and in this letter we propose an iterative algorithm based on the VST framework that is capable of dealing with challenging cases with extremely low SNR, and that outperforms state-of-the-art algorithms, both in terms of image quality and execution time.

At each step we apply the VST approach to a combination of the initial observed image and its most recent estimateto increase the SNR of the signal to be denoised, and consequently to improve the effectiveness of the stabilization and filtering. We analyze the statistics of this combination, which deviate from a Poisson distribution, and introduce the corresponding exact unbiased inverse to be used in this VST framework. We present an implementation of this approach based on the BM3D Gaussian denoising filter [5]. With a computational cost at worst twice that of the non-iterative scheme, the proposed algorithm provides significantly better quality, particularly at low and extremely low SNR, outperforming much costlier state-of-the-art alternatives.

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II. Preliminaries and motivation

Let z be an observed noisy image composed of pixels $z(x)$, $x \in \Omega \subset \mathbb{Z}^2$, modeled as independent realizations of a Poisson process with parameter $y(x) \geq 0$:

$$z(x) \sim \mathcal{P}(y(x)), \quad \mathrm{P}(z(x)\,|\,y(x)) = \begin{cases} \frac{y(x)^{z(x)} e^{-y(x)}}{z(x)!} & z \in \mathbb{N} \cup \{0\} \\ 0 & \text{elsewhere.} \end{cases}$$

The mean and variance of $z(x)$ coincide and are equal to $y(x)$:

$$\mathrm{E}\{z(x)\,|\,y(x)\} = \mathrm{var}\{z(x)\,|\,y(x)\} = y(x)\,.$$

For conciseness, henceforth we will omit x from notation.

Our goal is to compute an estimate $\hat{y}$ of y from z. To this purpose, in the archetypal VST framework, the Anscombe forward transformation a [1] yields an image

$$a(z) = 2\sqrt{z + 3/8}$$

which can be treated as corrupted by AWGN with unit variance. Thus, it can be denoised using any filter Φ designed for AWGN. If the denoising is ideal, we have

$$\Phi\left[a(z)\right] = \mathrm{E}\{a(z)\,|\,y\}\,.$$

The so-called *exact unbiased inverse* of a [2]

$$\mathcal{I}_a^{\mathcal{P}} : \mathrm{E}\{a(z)\,|\,y\} \mapsto \mathrm{E}\{z|y\} = y,$$

is used to return the denoised image to the original range of z, thus yielding an estimate of y:

$$\hat{y} = \mathcal{I}_a^{\mathcal{P}}\left(\Phi\left[a(z)\right]\right).$$

However, for small y, when the SNR is very low, the stabilization is imprecise and the conditional distribution of $a(z)$ is far from the assumed normal, in terms of both scale and shape, leading to ineffective filtering with Φ. This issue has been commonly addressed either by applying VST after binning, i.e. by stabilizing sums of adjacent pixels instead of individual pixels [3], [4], [6]–[10], or by similarly stabilizing transform coefficients [11] (essentially inserting the VST within the denoising method itself). All these stratagems aim at increasing the SNR of the data subject to the VST.

In this letter, we introduce an alternative and more direct way to improve the SNR prior to VST, by combining the noisy observation z with a previously obtained estimate of the noise-free data y, leading to the following simple iterative algorithm.

III. Proposed iterative algorithm

A subscript index denotes a symbol's instance at a particular iteration, *e.g.*, $\hat{y}_i$ is the estimate of y at iteration i.

We initialize the algorithm by setting $\hat{y}_0 = z$. At each iteration $i = 1, \dots, K$ we compute a convex combination of $\hat{y}_{i-1}$ and z

$$\bar{z}_i = \lambda_i z + (1 - \lambda_i)\, \hat{y}_{i-1}, \qquad (1)$$

where $0 < \lambda_i \leq 1$. Provided we can treat $\hat{y}_{i-1}$ as a surrogate for y, we have $\mathrm{E}\{\bar{z}_i|y\} = y = \lambda_i^{-2}\mathrm{var}\{\bar{z}_i|y\}$; thus $\bar{z}_i$ has higher SNR than z for any $\lambda_i < 1$. We then apply a VST f_i to $\bar{z}_i$ and obtain an image $\bar{\bar{z}}_i = f_i(\bar{z}_i)$, which we denoise with a filter Φ for AWGN to obtain a filtered image $D_i = \Phi\left[\bar{\bar{z}}_i\right]$. Assuming $D_i = \mathrm{E}\{f_i(\bar{z}_i)|y\}$, the exact unbiased inverse of f_i, $\mathcal{I}_{f_i}^{\lambda_i} : \mathrm{E}\{f_i(\bar{z}_i)|y\} \mapsto \mathrm{E}\{\bar{z}_i|y\} = y$, brings this image to the original range, yielding

$$\hat{y}_i = \mathcal{I}_{f_i}^{\lambda_i}(D_i)\,,$$

which is either used for the next iteration if $i < K$, or output as final estimate $\hat{y}_K = \hat{y}$.

Let us provide further details on the above basic procedure.

A. Forward variance-stabilizing transformation

Consider the scaled variable $\lambda_i^{-2}\bar{z}_i$ and let us model $\hat{y}_{i-1}$ as y. Setting $q_i(t) = \lambda_i t - \frac{1-\lambda_i}{\lambda_i} y$, the conditional probability

$$\mathrm{P}\left(\lambda_i^{-2}\bar{z}_i|y\right) = \begin{cases} \frac{y^{q_i(\lambda_i^{-2}\bar{z}_i)}e^{-y}}{q_i(\lambda_i^{-2}\bar{z}_i)!} & q_i\left(\lambda_i^{-2}\bar{z}_i\right) \in \mathbb{N}\cup\{0\} \\ 0 & \text{elsewhere}\,. \end{cases} \qquad (2)$$

Unless $\lambda_i = 1$, this is *not* a Poisson distribution. However, the mean and variance of $\lambda_i^{-2}\bar{z}_i$ do always coincide:

$$\mathrm{E}\left\{\lambda_i^{-2}\bar{z}_i\middle|y\right\} = \mathrm{var}\left\{\lambda_i^{-2}\bar{z}_i\middle|y\right\} = \lambda_i^{-2}y.$$

Hence, $\lambda_i^{-2}\bar{z}_i$ resembles $\mathcal{P}\left(\lambda^{-2}y\right)$ and indeed one can prove [12] that it is asymptotically stabilized by the Anscombe transformation a. Thus, we set $f_i(\cdot) = a\left(\lambda_i^{-2}(\cdot)\right)$.

B. Exact unbiased inverse transformation

The exact unbiased inverse $\mathcal{I}_{f_i}^{\lambda_i}$ is defined upon (2) as

$$\mathrm{E}\{f_i(\bar{z}_i)|y\} = \sum_{\bar{z}_i : q_i(\lambda_i^{-2}\bar{z}_i) \in \mathbb{N}\cup\{0\}} a\left(\lambda_i^{-2}\bar{z}_i\right) \mathrm{P}\left(\lambda_i^{-2}\bar{z}_i\middle|y\right) \mapsto \mathrm{E}\{\bar{z}_i|y\} = y. \qquad (3)$$

We have $\mathcal{I}_{f_i}^{\lambda_i} \approx \lambda_i^2 \mathcal{I}_a^{\mathcal{P}}$, with $\mathcal{I}_{f_i}^{1} = \mathcal{I}_a^{\mathcal{P}}$ [2]. The appendix describes how to accurately compute (3) in practice.

C. Binning

It is natural to combine the convex combination (1) with a linear binning; this can be especially beneficial at the first iterations, when $\hat{y}_{i-1}$ is a poor estimate of y. Specifically, a binning operator $\mathcal{B}_{h_i}$ can be applied to $\bar{z}_i$, yielding a smaller image where each block (*i.e.* bin) of $h_i \times h_i$ pixels from $\bar{z}_i$ is replaced by a single pixel equal to their sum. $\mathcal{B}_{h_i}$ clearly commutes with (1) and

$$\mathcal{B}_{h_i}[\bar{z}_i] = \lambda_i \mathcal{B}_{h_i}[z] + (1 - \lambda_i)\, \mathcal{B}_{h_i}[\hat{y}_{i-1}]\,.$$

Algorithm 1 Iterative Poisson Image Denoising via VST

$\hat{y}_0 = z$
for $i = 1$ to K **do**
  $\bar{z}_i = \lambda_i z + (1 - \lambda_i)\hat{y}_{i-1}$
  $\bar{\bar{z}}_i = f_i\left(\mathcal{B}_{h_i}[\bar{z}_i]\right)$
  $D_i = \Phi\left[\bar{\bar{z}}_i\right]$
  $\hat{y}_i = \mathcal{B}_{h_i}^{-1}\left[\mathcal{I}_{f_i}^{\lambda_i}(D_i)\right]$
end for
return $\hat{y} = \hat{y}_K$

Algorithm 2 Debinning $\hat{y}_i = \mathcal{B}_{h_i}^{-1}\left[\mathcal{I}_{f_i}^{\lambda_i}(D_i)\right]$

$\hat{y}_{i,0} = 0$
for $j = 1$ to J **do**
  $r_j = \mathcal{I}_{f_i}^{\lambda_i}(D_i) - \mathcal{B}_{h_i}\left[\hat{y}_{i,j-1}\right]$
  $\hat{y}_{i,j} = \max\left\{0,\, \hat{y}_{i,j-1} + \mathcal{U}_{h_i}\left[h^{-2}r_j\right]\right\}$
end for
return $\hat{y}_i = \hat{y}_{i,J}$

Since $\mathcal{B}_{h_i}[z] \sim \mathcal{P}(\mathcal{B}_{h_i}[y]) = \mathcal{P}(\mathrm{E}\{\mathcal{B}_{h_i}[z]|y\})$, and modeling again $\hat{y}_{i-1}$ as y, we have that $\mathcal{B}_{h_i}[\bar{z}_i]$ (resp. $\lambda_i^{-2}\mathcal{B}_{h_i}[\bar{z}_i]$) is subject to the same conditional probability of $\bar{z}_i$ (resp. $\lambda_i^{-2}\bar{z}_i$), which means that the adoption of binning does not interfere with the subsequent VST, denoising, and inverse VST. Thus, we can define $\bar{\bar{z}}_i = f_i\left(\mathcal{B}_{h_i}[\bar{z}_i]\right)$ without modifying f_i .

Debinning: An inverse binning operator $\mathcal{B}_{h_i}^{-1}$ is applied after the exact unbiased inversion,

$$\hat{y}_i = \mathcal{B}_{h_i}^{-1}\left[\mathcal{I}_{f_i}^{\lambda_i}(D_i)\right],$$

returning a full-size image estimate $\hat{y}_i$ such that

$$\mathcal{B}_{h_i}[\hat{y}_i] = \mathcal{I}_{f_i}^{\lambda_i}(D_i)\,. \qquad (4)$$

All the above steps are summarized in Algorithm 1 and as

$$\hat{y}_i = \mathcal{B}_{h_i}^{-1}\left[\mathcal{I}_{f_i}^{\lambda_i}(\Phi\left[f_i\left(\mathcal{B}_{h_i}\left[\lambda_i z + (1 - \lambda_i)\hat{y}_{i-1}\right]\right)\right])\right].$$

IV. Implementation and Results

For Φ we adopt the BM3D denoising algorithm [5]; yet, other AWGN filters such as [13]–[20] may be used as well, and also lead to competitive results as shown in the supplementary material [21].

In the debinning step, to compute $\mathcal{B}_{h_i}^{-1}[\mathcal{I}_{f_i}^{\lambda_i}(D_i)]$, $\mathcal{I}_{f_i}^{\lambda_i}(D_i)$ is first divided by h_i^2, *i.e.* by number of pixels in the bin, and upscaled to the size of z via cubic spline interpolation $\mathcal{U}_{h_i}$. To enforce the constraint (4), the output of interpolation is recursively binned by $\mathcal{B}_{h_i}$ and subtracted from the target $\mathcal{I}_{f_i}^{\lambda_i}(D_i)$, giving a residual which is upsampled and accumulated. This subroutine, summarized in Algorithm 2, is an instance of the recursive shaping regularization with nonnegativity [22], [23].

Our current implementation[1] of Algorithm 1 is determined by four parameters: K (number of iterations), λ_K, h_1, h_K (first and last bin sizes); other values of λ_i and h_i are defined as $\lambda_i = 1 - \frac{i-1}{K-1}(1-\lambda_K)$ and $h_i = \max\{h_K, h_1 - 2i + 2\}$. We use

[1] Matlab software available at http://www.cs.tut.fi/~foi/invansc/

Table I
PSNR (dB) DENOISING RESULTS VS [2]–[4], [7], WITH AND WITHOUT 3×3 BINNING. AVERAGES OVER 5 NOISE REALIZATIONS. P^4IP VALUES FROM [7].

Method	Peak	Flag_{256^2}	House_{256^2}	Cam_{256^2}	Man_{512^2}	Bridge_{256^2}	Saturn_{256^2}	Peppers_{256^2}	Boat_{512^2}	Couple_{512^2}	Hill_{512^2}	Time_{256^2}
NLSPCA [3]	0.1	14.60	17.63	16.63	18.35	16.71	20.45	16.17	18.14	18.49	18.80	89s
NLSPCA bin [3]		15.32	**18.66**	17.23	18.41	16.99	18.91	16.22	18.89	18.84	19.47	11s
SPDA [4]		13.51	14.58	14.34	–	14.67	17.57	14.34	–	–	–	8h
SPDA bin [4]		15.27	18.29	16.83	18.72	17.00	21.53	16.15	18.99	18.94	19.39	12min
P^4IP [7]		13.30	18.30	16.88	–	16.45	21.55	16.28	–	–	–	few mins
VST+BM3D [2]		12.38	15.69	15.44	16.95	15.60	18.40	15.15	16.22	16.50	16.79	0.70s
VST+BM3D bin [2]		13.97	18.22	16.99	18.61	16.93	20.09	15.84	18.91	18.62	19.23	0.11s
Proposed		**16.01**	18.48	**17.45**	**18.96**	**17.30**	**21.64**	**16.45**	**19.32**	**19.31**	**19.68**	0.48s
NLSPCA [3]	0.2	16.47	18.63	17.63	19.18	17.56	21.36	17.21	19.14	19.22	19.74	90s
NLSPCA bin [3]		15.63	19.21	17.87	19.12	17.40	19.67	16.69	19.48	19.37	19.99	12s
SPDA [4]		16.65	17.45	16.75	–	16.96	20.67	16.70	–	–	–	5h
SPDA bin [4]		17.41	18.95	17.80	19.73	17.81	22.90	17.25	19.85	19.72	20.36	27min
P^4IP [7]		14.82	19.48	17.82	–	17.54	23.05	17.31	–	–	–	few mins
P^4IP bin [7]		17.26	**19.96**	**18.58**	–	17.54	**23.79**	17.44	–	–	–	~30s
VST+BM3D [2]		13.53	17.79	16.90	18.69	17.12	21.38	16.96	18.23	18.47	18.80	0.69s
VST+BM3D bin [2]		16.85	19.27	17.88	19.82	17.70	22.94	17.19	19.79	19.71	20.09	0.12s
Proposed		**17.49**	19.68	18.40	**19.94**	**18.13**	23.13	**17.54**	**20.09**	**20.03**	**20.48**	0.83s
NLSPCA [3]	0.5	18.61	20.17	19.20	20.59	18.49	22.89	18.69	20.37	20.42	21.14	96s
NLSPCA bin [3]		15.76	20.48	18.26	19.77	18.17	21.65	17.69	20.11	20.01	20.67	19s
SPDA [4]		**20.02**	19.96	18.75	–	18.52	25.37	18.55	–	–	–	4h
SPDA bin [4]		18.40	20.57	18.87	20.70	18.57	**25.93**	18.52	20.84	20.70	21.35	23min
P^4IP [7]		16.50	20.93	19.27	–	18.47	25.19	18.86	–	–	–	few mins
VST+BM3D [2]		15.58	19.61	18.46	20.39	18.26	23.75	18.41	19.99	20.01	20.74	0.71s
VST+BM3D bin [2]		18.19	21.41	19.47	21.15	18.71	25.81	18.78	20.94	20.83	21.72	0.11s
Proposed		18.60	**21.54**	**19.79**	**21.25**	**19.08**	25.78	**19.05**	**21.19**	**21.14**	**21.84**	0.83s
NLSPCA [3]	1	19.68	21.57	20.25	21.46	19.02	24.75	19.50	21.19	21.14	21.94	86s
NLSPCA bin [3]		15.77	20.78	18.40	19.87	18.26	22.83	17.78	20.19	20.11	20.82	16s
SPDA [4]		**22.97**	22.14	20.15	–	19.30	27.05	19.97	–	–	–	5h
SPDA bin [4]		18.99	20.99	19.43	21.15	18.84	27.40	18.93	21.19	20.97	21.50	25min
P^4IP [7]		19.07	22.67	20.54	–	19.31	27.05	20.07	–	–	–	few mins
VST+BM3D [2]		18.46	21.64	20.19	21.62	19.43	25.82	19.71	21.47	21.14	21.92	0.78s
VST+BM3D bin [2]		19.28	22.53	20.69	22.07	19.59	**27.59**	20.22	21.97	21.81	22.72	0.10s
Proposed		19.74	**23.04**	**21.07**	**22.30**	**19.86**	27.27	**20.44**	**22.17**	**22.08**	**22.85**	0.82s
NLSPCA [3]	2	19.70	23.16	20.64	22.37	19.43	26.88	20.48	21.83	21.75	22.68	87s
NLSPCA bin [3]		15.52	20.85	18.35	19.87	18.32	21.27	17.78	20.29	20.21	20.98	12s
SPDA [4]		**24.72**	24.37	21.35	–	20.17	29.13	21.18	–	–	–	6h
SPDA bin [4]		19.26	21.12	19.53	21.66	18.87	28.54	19.17	21.43	21.24	21.94	25min
P^4IP [7]		21.04	**24.65**	21.87	–	20.16	28.93	21.33	–	–	–	few mins
VST+BM3D [2]		20.79	23.79	21.97	23.11	20.49	27.95	**22.02**	22.90	22.65	23.34	0.82s
VST+BM3D bin [2]		19.91	24.10	21.43	23.03	20.36	**29.26**	21.45	22.92	22.84	23.75	0.10s
Proposed		21.18	24.62	**22.25**	**23.40**	**20.69**	28.85	21.93	**23.30**	**23.12**	**23.88**	0.82s
NLSPCA [3]	4	20.15	24.26	20.97	22.93	20.21	27.99	21.07	22.49	22.33	23.51	123s
NLSPCA bin [3]		15.52	20.94	18.27	19.88	18.32	22.02	17.72	20.29	20.25	20.99	13s
SPDA [4]		**25.76**	25.30	21.72	–	20.53	**31.13**	22.20	–	–	–	8h
SPDA bin [4]		19.42	22.07	19.95	22.18	19.26	29.71	20.19	21.76	21.69	22.82	31min
P^4IP [7]		22.49	**26.33**	23.29	–	21.11	30.82	23.88	–	–	–	few mins
VST+BM3D [2]		22.93	25.49	23.82	24.32	21.51	29.41	24.01	24.16	24.10	24.47	0.74s
VST+BM3D bin [2]		20.43	25.49	22.22	23.99	21.13	30.87	22.57	23.92	23.84	24.69	0.10s
Proposed		23.51	26.07	**24.10**	**24.52**	**21.71**	30.38	**24.04**	**24.53**	**24.34**	**24.82**	1.41s

decreasing h_i since binning can cause loss of image details and it becomes progressively less useful when λ_i gets larger and the role of $\hat{y}_{i-1}$ dominates in improving the SNR of the VST input. Obviously, $\mathcal{B}_1$ and $\mathcal{B}_1^{-1}$ are identity operators.

The Poisson image z is the only input to our algorithm; the parameters K, λ_K, h_1, h_K are adaptively selected based on the quantiles of z, following a training [21] over 6 images not included in the experiments test dataset; we fix $J = 9$.

PSNR (dB) results of the proposed algorithm and [2]–[4], [7], as well as their versions with binning, are reported in Table I. Table II gives a separate comparison with [8], over the different dataset of 256×256 downscaled images adopted by its authors. The tables demonstrate the superior overall performance of the proposed algorithm, also confirmed by visual inspection of the examples in Figure 1.

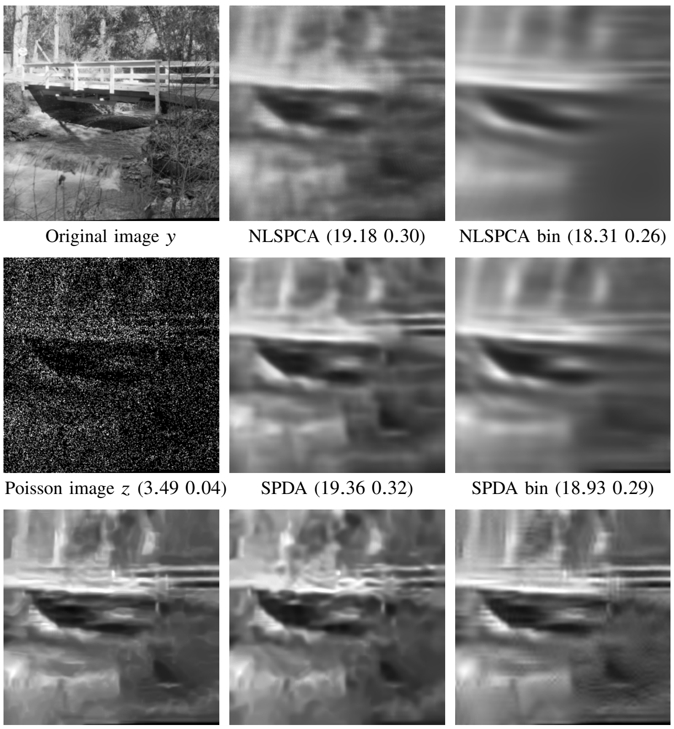
The complexity of Algorithm 1 is dominated by the filter Φ and possibly by the debinning operators $\mathcal{B}_{h_i}^{-1}$. The overall execution time depends especially on the number of iterations K and on h_K, which sets the size of the largest image to be filtered by Φ; all our results have $K \leq 4$. Table I and Table II report also the average execution times for 256×256 images. We ran the proposed algorithm and [2]–[4] on a single thread of a 3.4-GHz Intel i7 CPU; the runtimes for [7], [8] are taken from the respective articles, where [8] uses a 3.3-GHz Intel i7, and [7] also uses an Intel i7. The proposed algorithm and [2] are significantly less expensive than any of the other methods.

V. DISCUSSION AND CONCLUSIONS

We presented an iterative VST framework for Poisson denoising. The iterative combination with a previous estimate refines

Table II
PSNR (dB) denoising results versus those reported in [8]. Averages over 5 noise realizations.

Method	Peak	Peppers_{256^2}	Bridge_{256^2}	Boat_{256^2}	Couple_{256^2}	Hill_{256^2}	Mandrill_{256^2}	Man_{256^2}	Time_{256^2}
MMSE est [8]	1	20.38	19.55	20.24	20.26	20.98	18.43	20.49	~14min
Proposed		**20.44**	**19.86**	**20.65**	**20.47**	**21.23**	**18.56**	**20.50**	0.82s
MMSE est [8]	2	**22.26**	20.65	21.28	21.22	22.05	18.98	21.60	~14min
Proposed		21.93	**20.69**	**21.46**	**21.40**	**22.32**	**19.14**	**21.62**	0.82s
MMSE est [8]	4	23.92	21.60	22.32	22.26	23.23	19.56	**22.79**	~14min
Proposed		**24.04**	**21.71**	**22.53**	**22.52**	**23.29**	**19.65**	22.75	1.41s



Original image y — NLSPCA (19.18 0.30) — NLSPCA bin (18.31 0.26)
Poisson image z (3.49 0.04) — SPDA (19.36 0.32) — SPDA bin (18.93 0.29)
Proposed (**19.81 0.36**) — VST+BM3D (19.43 0.34) — VST+BM3D bin (19.59 0.34)

Figure 1. Denoising of *Bridge* at peak 1. PSNR (dB) and SSIM [24] of $\hat{y}$ are given in brackets. For clarity, z is visualized on a compressed range.

the stabilization and helps to cope with extreme low-SNR cases, in which a standard VST approach [2] underperforms even when endowed with binning.

To analyze the importance of embedding the VST framework within the iterations, in Table III we compare our results from Table I with those by a simplified version of Algorithm 1, where the VST is *external* to the loop: f_i and $\mathcal{I}_{f_i}^{\lambda_i}$ are replaced by identity operators and a and $\mathcal{I}_a^{\mathcal{P}}$ are applied outside of the algorithm. The significant gain in the table confirms that the improvement over [2] is not a mere consequence of a better denoising due to iterative filtering at multiple scales.

Also P^4IP [7] relies on iterative AWGN filtering to denoise the Poisson z. In contrast to P^4IP, which formulates an optimization problem to be solved upon convergence of ADMM [25] iterations, each iteration of Algorithm 1 attacks the Poisson denoising problem directly, so any $\hat{y}_k$ can be treated as an estimate of y, with $\hat{y}_1$ already coinciding with [2]. This results in a more efficient, stable, and substantially faster procedure, where Φ (*e.g.*, BM3D) is used as explicit denoiser for AWGN with variance 1 set by the VST without need of empirical tuning.

Table III
PSNR gain (average over all images in Table I) of Algorithm 1 over its simplification with *external* VST (see Section V).

Peak	0.1	0.2	0.5	1	2	4
PSNR (dB) gain	0.64	0.66	0.38	0.22	0.11	0.13

The proposed algorithm achieves state-of-the-art quality in only a tiny fraction of the time required by competitive algorithms.

Appendix: Computing the exact unbiased inverse

As in [2], we compute $\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\,|y\right\}$ numerically over a finite grid of values of y and λ_i, from which we interpolate $\mathcal{I}_{f_i}^{\lambda_i}$ (3) at values within the grid range. Outside of the grid range, we leverage the available implementation [2] of the exact unbiased inverse for Poisson $\mathcal{I}_a^{\mathcal{P}}:\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}\mapsto\lambda_i^{-2}y$, where $\lambda_i^{-2}\zeta\sim\mathcal{P}(\lambda_i^{-2}y)$, through the composition

$$\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}\longmapsto\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}\longmapsto\lambda_i^{-2}y\longmapsto y. \tag{5}$$

To deal with the first of the three mappings (5), we study the difference between $\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}$ and $\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}$. For $p\sim\mathcal{P}(\mu)$, the mean of a generic $g(p)=2\sqrt{(p+d)/\gamma}$ is [1], [26]

$$\mathrm{E}\{g(p)\,|\mu\}=2\sqrt{\tfrac{\mu+d}{\gamma}}\Big(1-\tfrac{1}{8}\tfrac{\mu}{(\mu+d)^2}+ \tag{6}$$
$$+\tfrac{1}{16}\tfrac{\mu}{(\mu+d)^3}-\tfrac{5}{128}\tfrac{3\mu^2+\mu}{(\mu+d)^4}+O\left(\mu^{-3}\right)\Big).$$

It yields $\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}$ when $\mu=y$, $\gamma=\lambda_i$, $d=\frac{1-\lambda_i}{\lambda_i}y+\frac{3}{8}\lambda_i$, and $\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}$ when $\mu=\lambda^{-2}y$, $\gamma=1$, $d=\frac{3}{8}$. Then

$$\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}-\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}=\tfrac{\lambda_i^2(\lambda_i-1)}{8}y^{-\frac{3}{2}}+O\left(y^{-\frac{5}{2}}\right), \tag{7}$$

which is however expressed as a function of y, while (5) requires a function of $\mathrm{E}\left\{a(\lambda^{-2}\bar{z})\middle|y\right\}$. From (6), we can approximate large y as

$$y=\left(\tfrac{\lambda_i}{2}\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}\right)^2+O(1)\,. \tag{8}$$

On substituting (8) into (7) we obtain

$$\mathrm{E}\left\{a(\lambda_i^{-2}\zeta)\middle|y\right\}-\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}= \tag{9}$$
$$=\tfrac{\lambda_i-1}{\lambda_i}\left(\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}\right)^{-3}+O\left(\mathrm{E}\left\{a(\lambda_i^{-2}\bar{z}_i)\middle|y\right\}\right)^{-4}.$$

Outside of the grid range we can discard the higher-order terms from (9) and compute $\mathcal{I}_{f_i}^{\lambda_i}(D_i)$ using $\mathcal{I}_a^{\mathcal{P}}$ [2] as

$$\mathcal{I}_{f_i}^{\lambda_i}(D_i)=\lambda_i^2\,\mathcal{I}_a^{\mathcal{P}}\Big(D_i+\tfrac{\lambda_i-1}{\lambda_i}D_i^{-3}\Big)\,.$$

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Supplementary to the manuscript "Variance Stabilization for Noisy+Estimate Combination in Iterative Poisson Denoising"

Lucio Azzari and Alessandro Foi

SUPPL.I. CONVEX COMBINATION AND VARIANCE STABILIZATION

Here we show that the increase of SNR due to the convex combination (Equation 1, in the manuscript) results in a direct improvement of the stabilization by the Anscombe transformation.

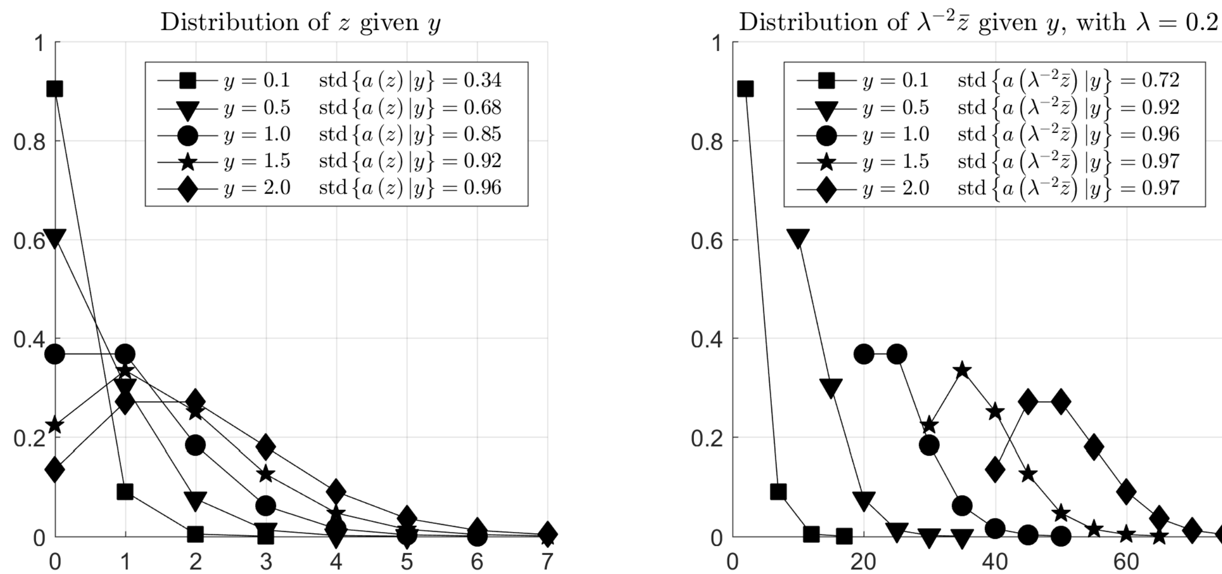

Figure Suppl.I.1. Effect of convex combination on the data distributions and on the standard deviation of the stabilized data.

The plot at the left in Figure Suppl.I.1 shows the Poisson distributions $\mathrm{P}(z|y)$ with mean and variance $y = 0.1, 0.5, 1, 1.5, 2$. At the right, we show the distributions $\mathrm{P}\left(\lambda_i^{-2}\bar{z}_i|y\right)$ (Equation 2 in the manuscript) of the data obtained after the convex combination with $\lambda = 0.2$. Note how the convex combination results in a shift of the distributions towards higher mean values and how the overlap between different distributions is reduced. Because of this reduced overlap, different distribution can benefit from the different slopes of the Anscombe transformation at the corresponding locations; this leads to a significantly more accurate stabilization. In particular, in the legends we report the standard deviations of the stabilized distributions, which for the combined data is much closer to the target value 1.

SUPPL.II. EXPERIMENTS WITH DIFFERENT GAUSSIAN DENOISING FILTERS

Our manuscript reports extensive Poisson denoising results obtained by the proposed iterative VST framework, adopting the Block-Matching and 3D collaborative filtering (BM3D) algorithm [Suppl.1] as the specific Gaussian denoising filter used inside the iterations. Here we report the corresponding results obtained upon replacing BM3D by each of the following Gaussian denoising filters: BM3D with Shape-Adaptive Principal Components Analysis (SAPCA) [Suppl.2], Pointwise Shape-Adaptive Discrete Cosine Transform filter (SADCT) [Suppl.3], Non-Local Means (NLM) [Suppl.4], Anisotropic Foveated Non-Local Means (FOVNLM) [Suppl.5], Structure-Adaptive Filtering for Image Restoration (SAFIR) [Suppl.6], Bayesian Least Squares - Gaussian Scale Mixture (BLSGSM) [Suppl.7], K-SVD algorithm (KSVD) [Suppl.8], Non-Local Means via Smooth Patch Ordering (NLMPO) [Suppl.9].

Table Suppl.II.1 and Table Suppl.II.2 show that the presented framework gives excellent results consistently over these diverse set of Gaussian denoisers. In fact, most of these results are superior to those by state-of-the-art Poisson filters considered in Table I and Table II of the manuscript. A few examples are visualized in Figure Suppl.III.1.

Table Suppl.II.1
PSNR (dB) DENOISING RESULTS OF THE PROPOSED FRAMEWORK ADOPTING DIFFERENT AWGN DENOISERS. THE NOISY IMAGES ARE THE SAME OF TABLE I IN THE MANUSCRIPT.

Method	Peak	Flag_{256^2}	House_{256^2}	Cam_{256^2}	Man_{512^2}	Bridge_{256^2}	Saturn_{256^2}	Peppers_{256^2}	Boat_{512^2}	Couple_{512^2}	Hill_{512^2}
BM3D [Suppl.1]	0.1	16.01	**18.48**	17.45	18.96	**17.30**	21.64	16.45	19.32	**19.31**	**19.68**
SAPCA [Suppl.2]		15.88	18.02	**17.59**	**18.99**	17.25	21.78	**16.52**	19.35	19.24	19.66
SADCT [Suppl.3]		13.94	18.41	17.42	18.89	17.16	20.62	16.32	**19.41**	19.21	19.63
NLM [Suppl.4]		13.24	17.94	17.32	18.52	16.73	21.19	15.95	18.79	18.79	19.25
FOVNLM [Suppl.5]		13.72	18.03	17.51	18.61	16.98	21.40	16.10	19.13	18.91	19.25
SAFIR [Suppl.6]		14.24	18.48	16.97	18.55	16.99	20.73	16.19	19.15	18.90	19.38
BLSGSM [Suppl.7]		13.18	17.72	16.47	18.72	16.89	20.80	16.08	19.06	19.00	19.52
KSVD [Suppl.8]		14.94	18.07	17.03	18.38	16.89	20.55	15.91	19.18	18.81	18.94
NLMPO [Suppl.9]		**16.12**	18.09	17.44	18.67	17.16	**21.80**	16.26	19.29	19.12	19.40
BM3D [Suppl.1]	0.2	17.49	19.68	**18.40**	**19.94**	**18.13**	23.13	17.54	20.09	**20.03**	**20.48**
SAPCA [Suppl.2]		17.35	19.52	18.34	19.88	18.02	23.09	**17.60**	19.92	19.90	20.32
SADCT [Suppl.3]		15.30	19.41	18.29	19.82	18.00	21.72	17.35	**20.16**	19.97	20.48
NLM [Suppl.4]		13.89	18.74	17.81	19.32	17.39	22.18	16.86	19.40	19.41	19.91
FOVNLM [Suppl.5]		14.81	19.00	18.25	19.51	17.60	22.93	17.08	19.79	19.62	19.92
SAFIR [Suppl.6]		16.18	**19.72**	18.16	19.79	17.79	22.54	17.38	19.99	19.82	20.20
BLSGSM [Suppl.7]		14.71	18.76	17.51	19.68	17.81	21.93	17.13	19.91	19.84	20.38
KSVD [Suppl.8]		17.23	18.81	18.14	19.36	17.54	22.28	16.98	19.80	19.59	19.95
NLMPO [Suppl.9]		**18.28**	19.55	18.27	19.70	17.81	**23.44**	17.35	19.72	19.78	20.06
BM3D [Suppl.1]	0.5	18.60	21.54	19.79	21.25	**19.08**	25.78	19.05	21.19	**21.14**	**21.84**
SAPCA [Suppl.2]		18.46	21.54	**19.91**	**21.26**	19.03	25.72	**19.21**	**21.19**	21.08	21.78
SADCT [Suppl.3]		17.01	21.07	19.80	21.18	19.03	23.81	19.01	21.18	21.05	21.82
NLM [Suppl.4]		16.97	20.31	19.41	20.82	18.43	25.37	18.50	20.73	20.57	21.09
FOVNLM [Suppl.5]		17.63	21.01	19.78	21.14	18.71	25.53	18.75	20.96	20.76	21.31
SAFIR [Suppl.6]		18.92	21.23	19.59	21.17	18.80	24.98	18.94	21.04	20.93	21.62
BLSGSM [Suppl.7]		16.48	20.42	18.84	20.92	18.80	24.15	18.67	20.96	20.85	21.64
KSVD [Suppl.8]		18.74	21.08	19.71	21.07	18.82	24.87	18.95	21.09	20.87	21.37
NLMPO [Suppl.9]		**19.41**	**21.72**	19.90	21.26	18.95	**26.16**	19.01	21.05	20.94	21.63
BM3D [Suppl.1]	1	19.74	23.04	21.07	22.30	**19.86**	27.27	20.44	22.17	**22.08**	**22.85**
SAPCA [Suppl.2]		19.54	23.05	**21.17**	**22.36**	19.86	27.39	**20.57**	**22.28**	22.08	22.83
SADCT [Suppl.3]		18.44	22.51	20.94	22.20	19.82	25.48	20.40	22.06	21.97	22.79
NLM [Suppl.4]		17.89	21.50	20.46	21.85	19.33	26.95	19.86	21.56	21.41	22.07
FOVNLM [Suppl.5]		18.93	22.30	20.93	22.19	19.54	27.07	20.18	21.88	21.68	22.31
SAFIR [Suppl.6]		20.36	22.90	20.87	22.26	19.65	26.72	20.42	21.94	21.86	22.67
BLSGSM [Suppl.7]		17.53	21.92	19.96	21.93	19.59	25.51	19.98	21.90	21.75	22.62
KSVD [Suppl.8]		20.19	22.26	20.83	22.04	19.67	26.59	20.34	21.90	21.67	22.40
NLMPO [Suppl.9]		**20.67**	**23.07**	21.09	22.24	19.70	**27.87**	20.36	21.94	21.81	22.63
BM3D [Suppl.1]	2	21.18	24.62	22.25	23.40	**20.69**	28.85	21.93	23.30	**23.12**	23.88
SAPCA [Suppl.2]		20.86	**24.65**	**22.35**	**23.46**	20.67	29.10	**22.18**	**23.38**	23.12	**23.88**
SADCT [Suppl.3]		19.97	23.94	22.02	23.27	20.57	27.20	21.89	23.03	22.93	23.78
NLM [Suppl.4]		18.89	22.84	21.37	22.85	20.12	28.28	21.22	22.41	22.28	23.05
FOVNLM [Suppl.5]		20.30	23.82	21.99	23.20	20.31	28.65	21.66	22.80	22.59	23.34
SAFIR [Suppl.6]		21.74	24.64	22.17	23.35	20.42	28.66	22.09	23.13	22.91	23.79
BLSGSM [Suppl.7]		18.47	23.30	21.00	22.93	20.38	27.08	21.16	22.88	22.73	23.61
KSVD [Suppl.8]		21.49	23.52	21.73	22.92	20.30	28.27	21.52	22.63	22.42	23.31
NLMPO [Suppl.9]		**21.84**	24.64	22.22	23.21	20.38	**29.67**	21.82	23.05	22.77	23.61
BM3D [Suppl.1]	4	23.51	26.07	24.10	24.52	**21.71**	30.38	24.04	**24.53**	**24.34**	**24.82**
SAPCA [Suppl.2]		22.85	25.77	**24.11**	**24.57**	21.69	30.80	24.25	24.52	24.33	24.77
SADCT [Suppl.3]		21.69	25.46	23.66	24.41	21.61	28.96	23.91	24.27	24.15	24.82
NLM [Suppl.4]		20.81	23.88	22.79	23.89	21.04	29.10	23.18	23.51	23.28	24.02
FOVNLM [Suppl.5]		21.65	25.07	23.61	24.27	21.28	29.97	23.74	24.08	23.70	24.35
SAFIR [Suppl.6]		23.11	26.38	23.99	24.56	21.48	30.70	**24.25**	24.46	24.17	24.80
BLSGSM [Suppl.7]		20.16	24.81	22.38	24.06	21.41	28.76	22.91	24.10	23.89	24.62
KSVD [Suppl.8]		23.58	24.50	23.35	24.00	21.22	29.32	23.51	23.85	23.48	24.24
NLMPO [Suppl.9]		**23.97**	**26.40**	24.11	24.38	21.40	**31.41**	24.14	24.37	24.06	24.62

SUPPL.III. PARAMETER TRAINING AND ADAPTIVE SELECTION

As mentioned in Section IV of the manuscript, our implementation of the algorithm has four parameters, namely K, λ_K, h_1, and h_K. We have tested multiple combinations of values for these parameters over a training set of 6 images and for different peak values. We remark that none of these images has any overlap with the test images in the manuscript. For each peak, we selected the set of parameter values that yields the highest PSNR average over the training images at that particular peak. We also compute the 21 uniform 5% quantiles of each noisy image, and model the quantile distribution of a generic training image at each peak as a 21-dimensional multivariate normal, whose mean and diagonal covariance are given by the sample means and by the sample variances of the 21 quantiles over all training images at that peak. Thus, for each peak, we have a set of four selected parameter values, and the sample means and sample variances of the image quantiles at that peak. All these data, for all peaks, are stored in a look-up table. Our idea is to leverage the quantile distribution as a proxy for the peak, from which to identify an appropriate set of parameter values for any given input image not found in the training set.

Table Suppl.II.2
PSNR (dB) DENOISING RESULTS OF THE PROPOSED FRAMEWORK ADOPTING DIFFERENT AWGN DENOISERS. THE NOISY IMAGES ARE THE SAME OF TABLE II IN THE ORIGINAL MANUSCRIPT.

Method	Peak	Peppers_{256^2}	Bridge_{256^2}	Boat_{256^2}	Couple_{256^2}	Hill_{256^2}	Mandrill_{256^2}	Man_{256^2}
BM3D [Suppl.1]	0.1	16.45	**17.30**	**17.91**	17.86	18.43	16.84	17.21
SAPCA [Suppl.2]		**16.52**	17.25	17.75	**17.91**	**18.48**	16.60	**17.23**
SADCT [Suppl.3]		16.32	17.16	17.75	17.73	18.21	**16.87**	17.15
NLM [Suppl.4]		15.95	16.73	17.33	17.52	17.95	16.63	16.83
FOVNLM [Suppl.5]		16.10	16.98	17.59	17.57	18.04	16.47	16.92
SAFIR [Suppl.6]		16.19	16.99	17.65	17.36	18.05	16.71	16.80
BLSGSM [Suppl.7]		16.08	16.89	17.16	17.60	17.78	16.66	16.83
KSVD [Suppl.8]		15.91	16.89	17.40	17.34	17.37	16.67	16.65
NLMPO [Suppl.9]		16.26	17.16	17.65	17.45	18.12	16.62	17.07
BM3D [Suppl.1]	0.2	17.54	**18.13**	**18.74**	**18.62**	**19.16**	17.36	18.17
SAPCA [Suppl.2]		**17.60**	18.02	18.64	18.53	19.10	17.23	**18.19**
SADCT [Suppl.3]		17.35	18.00	18.64	18.46	19.04	**17.44**	18.10
NLM [Suppl.4]		16.86	17.39	17.92	18.13	18.64	17.22	17.69
FOVNLM [Suppl.5]		17.08	17.60	18.27	18.20	18.60	17.13	17.78
SAFIR [Suppl.6]		17.38	17.79	18.41	18.25	18.89	17.32	17.84
BLSGSM [Suppl.7]		17.13	17.81	18.17	18.34	18.85	17.15	17.86
KSVD [Suppl.8]		16.98	17.54	18.36	18.08	18.42	17.17	17.62
NLMPO [Suppl.9]		17.35	17.81	18.64	18.30	18.90	17.38	17.91
BM3D [Suppl.1]	0.5	19.05	**19.08**	19.80	**19.65**	**20.40**	18.08	19.48
SAPCA [Suppl.2]		**19.21**	19.03	19.75	19.63	20.35	18.05	**19.54**
SADCT [Suppl.3]		19.01	19.03	**19.83**	19.50	20.29	**18.09**	19.45
NLM [Suppl.4]		18.50	18.43	19.29	19.18	19.73	17.89	18.99
FOVNLM [Suppl.5]		18.75	18.71	19.60	19.37	19.90	17.94	19.27
SAFIR [Suppl.6]		18.94	18.80	19.59	19.26	20.06	18.04	19.17
BLSGSM [Suppl.7]		18.67	18.80	19.33	19.33	19.94	17.90	19.21
KSVD [Suppl.8]		18.95	18.82	19.72	19.39	19.88	17.91	19.25
NLMPO [Suppl.9]		19.01	18.95	19.77	19.51	20.23	18.05	19.38
BM3D [Suppl.1]	1	20.44	**19.86**	**20.65**	**20.47**	**21.23**	**18.56**	20.50
SAPCA [Suppl.2]		**20.57**	19.86	20.65	20.43	21.21	18.53	**20.56**
SADCT [Suppl.3]		20.40	19.82	20.61	20.35	21.19	18.55	20.45
NLM [Suppl.4]		19.86	19.33	20.13	19.96	20.63	18.39	20.02
FOVNLM [Suppl.5]		20.18	19.54	20.43	20.20	20.80	18.48	20.34
SAFIR [Suppl.6]		20.42	19.65	20.44	20.20	20.88	18.51	20.28
BLSGSM [Suppl.7]		19.98	19.59	20.31	20.16	21.02	18.41	20.19
KSVD [Suppl.8]		20.34	19.67	20.50	20.22	20.86	18.42	20.25
NLMPO [Suppl.9]		20.36	19.70	20.50	20.26	21.05	18.50	20.40
BM3D [Suppl.1]	2	21.93	**20.69**	**21.46**	**21.40**	**22.32**	**19.14**	21.62
SAPCA [Suppl.2]		**22.18**	20.67	21.46	21.35	22.28	19.13	**21.69**
SADCT [Suppl.3]		21.89	20.57	21.39	21.25	22.21	19.10	21.53
NLM [Suppl.4]		21.22	20.12	20.95	20.78	21.57	18.95	21.13
FOVNLM [Suppl.5]		21.66	20.31	21.21	21.03	21.81	19.09	21.50
SAFIR [Suppl.6]		22.09	20.42	21.26	21.09	22.08	19.05	21.49
BLSGSM [Suppl.7]		21.16	20.38	21.13	21.04	22.05	19.03	21.25
KSVD [Suppl.8]		21.52	20.30	21.14	20.90	21.78	18.99	21.17
NLMPO [Suppl.9]		21.82	20.38	21.23	21.00	22.01	19.01	21.38
BM3D [Suppl.1]	4	24.04	**21.71**	22.53	**22.52**	**23.29**	19.65	22.75
SAPCA [Suppl.2]		24.25	21.69	**22.59**	22.50	23.23	**19.68**	**22.82**
SADCT [Suppl.3]		23.91	21.61	22.38	22.36	23.20	19.62	22.67
NLM [Suppl.4]		23.18	21.04	21.85	21.79	22.51	19.45	22.30
FOVNLM [Suppl.5]		23.74	21.28	22.20	22.08	22.71	19.60	22.65
SAFIR [Suppl.6]		**24.25**	21.48	22.32	22.30	23.10	19.51	22.71
BLSGSM [Suppl.7]		22.91	21.41	22.17	22.13	23.00	19.64	22.32
KSVD [Suppl.8]		23.51	21.22	22.10	21.92	22.61	19.46	22.32
NLMPO [Suppl.9]		24.14	21.40	22.39	22.21	23.00	19.46	22.55

Therefore, our denoising algorithm, given an input unknown noisy Poisson image, proceeds as follows in order to decide the values for the four parameters. First, it computes the input image's 5% quantiles. Next, it compares them against the look-up table: specifically, it computes the likelihoods that the quantiles of the input image belong to the quantile distributions measured in the training for each peak. Finally, each of the four parameters is computed as the weighted average of the parameters in the look-up table, using the above likelihoods as weights over all training peaks.

We emphasize that using the look-up table or computing the quantiles is computationally inexpensive and particularly it is insignificant when compared to other parts of the denoising process.

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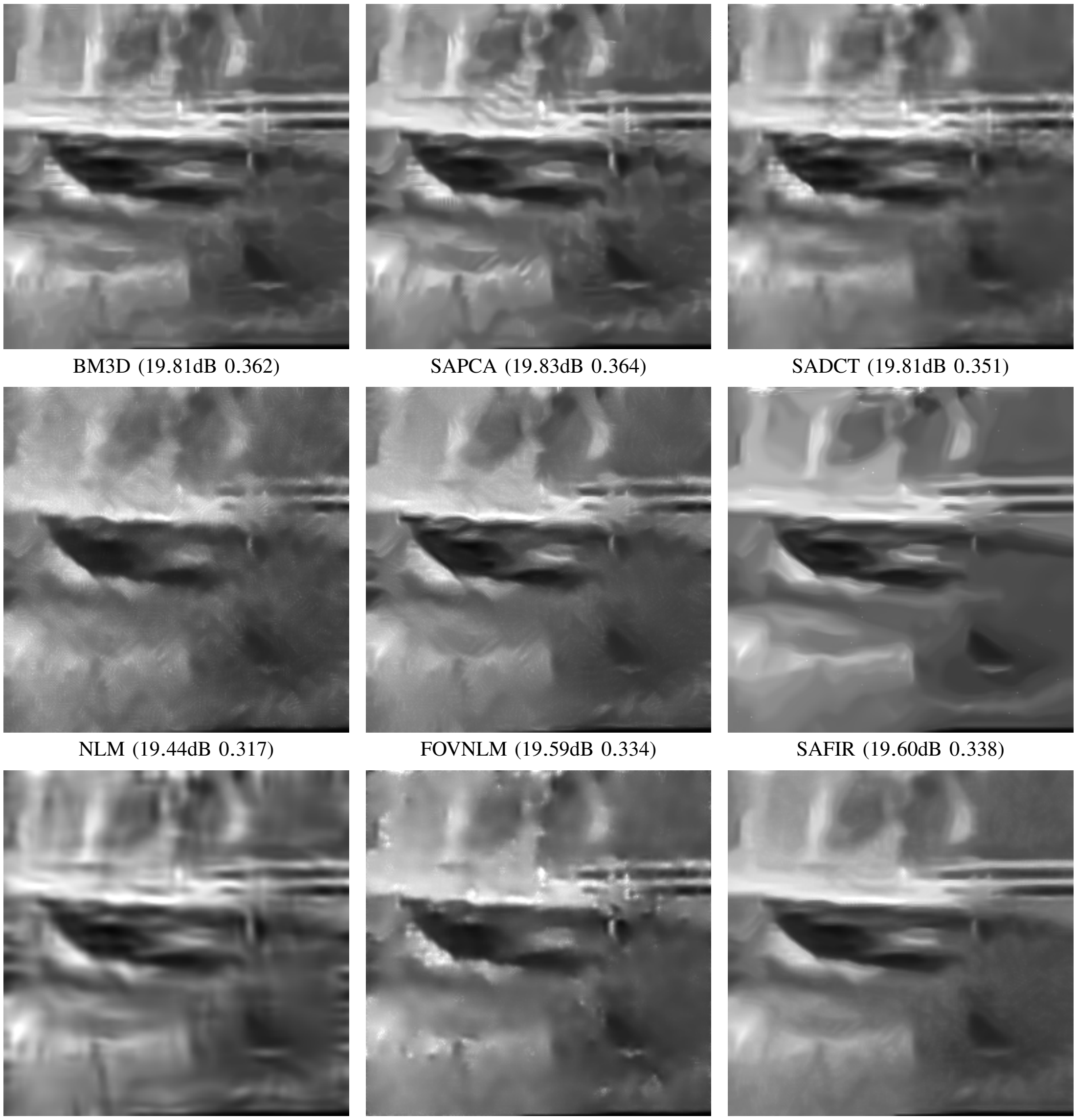

BLSGSM (19.57dB 0.347) KSVD (19.72dB 0.341) NLMPO (19.66dB 0.339)

Figure Suppl.III.1. Denoising of *Bridge* at peak 1. PSNR and SSIM of $\hat{y}$ are given in brackets.

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