Supplementary Material to "Patch Group based Bayesian Learning for Blind Image Denoising"

Jun Xu[1], Dongwei Ren[1,2], Lei Zhang[1]**, David Zhang[1]

[1]Dept. of Computing, The Hong Kong Polytechnic University, Hong Kong, China
[2]School of Computer Science and Technology, Harbin Institute of Technology, Harbin, China

In this supplementary material, we provide:

1. More denoising results on the 20 natural images corrupted by Gaussian noise;
2. More denoising results on the 20 natural images corrupted by mixed Gaussian and Random Value Impulse Noise (RVIN);
3. More denoising results on real noisy images;
4. Visual comparison with the PGPD algorithm.

1 More Results on Gaussian Noise Removal

In the main paper, we had given some examples of Gaussian noise removal on the 20 widely used images. We compared the proposed method with BM3D [1], WNNM [2], Two Phase [3], WESNR [4], Noise Clinic [5]. In Figures 1-8, we give more visual comparisons of those competing methods [1–5].

2 More Results on Mixed Gaussian and Random Vaule Impulse Noise Removal

In the main paper, we had given some examples of mixed Gaussian and random value impulse noise removal on the 20 widely used images. In this section, we give more visual comparisons of the proposed method with BM3D [1], WNNM [2], Two Phase [3], WESNR [4], Noise Clinic [5] in Figures 9-16.

3 More Results on Real Noise Removal

In this section, we give more visual comparisons of the proposed method with BM3D [1], WESNR [4], Noise Clinic [5], and the commercial software Neat Image [6] on real image denoising. The images 'Fibers' and 'Dog' are from the website of Noise Clinic on IPOL [7] while the images 'Library', 'Boat', and 'Cyclist' are from the website of Neat Image [6]. The image 'Library' was photographed on a cloudy day. The image 'Boat' is taken by Alexander Semenov at slow shutter speed (15 seconds) and moderate ISO rate of 1600. The image 'Cyclist' was shot under fast shutter speed, inadequate lighting and high ISO sensitivity. The results are listed in Figures 17-21.

** This work is supported by the HK RGC GRF grant (PolyU5313/12E).

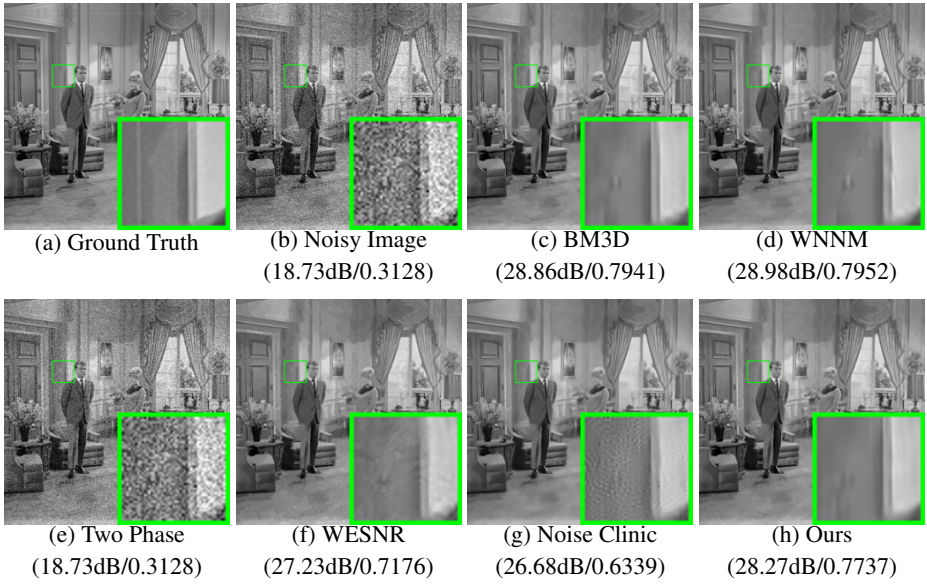


Fig. 1. Denoised images of *Couple* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 30$).

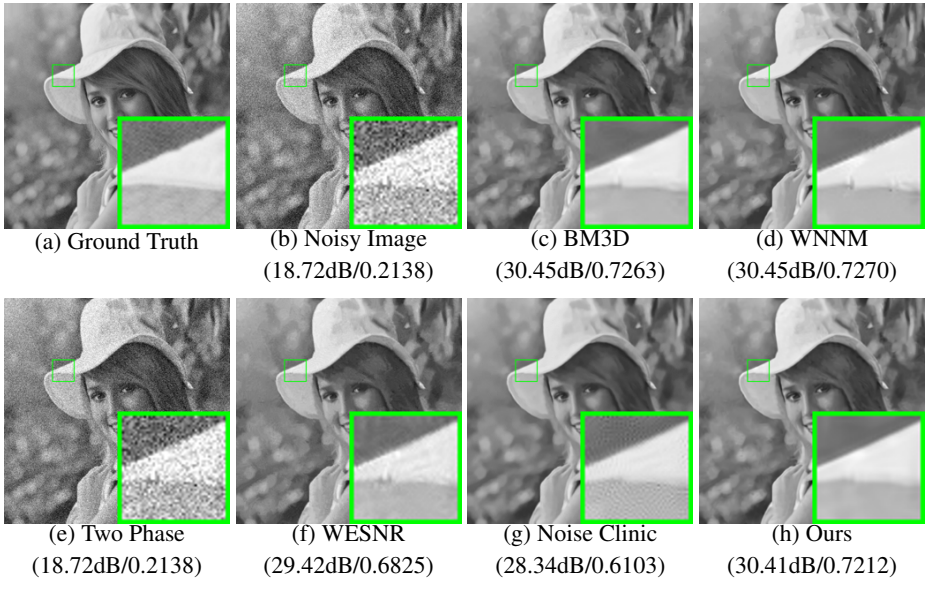


Fig. 2. Denoised images of *Elaine* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 30$).

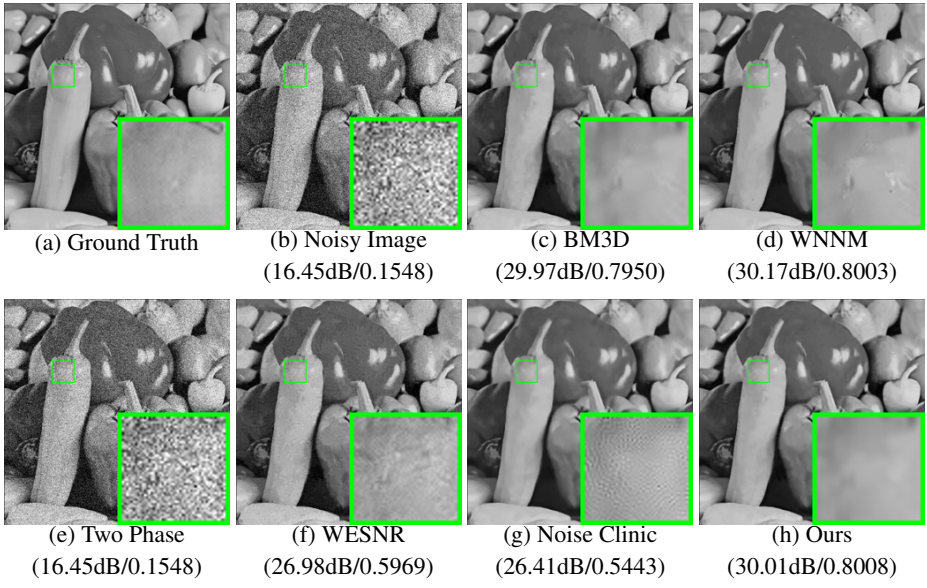


Fig. 3. Denoised images of *Peppers* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 40$).

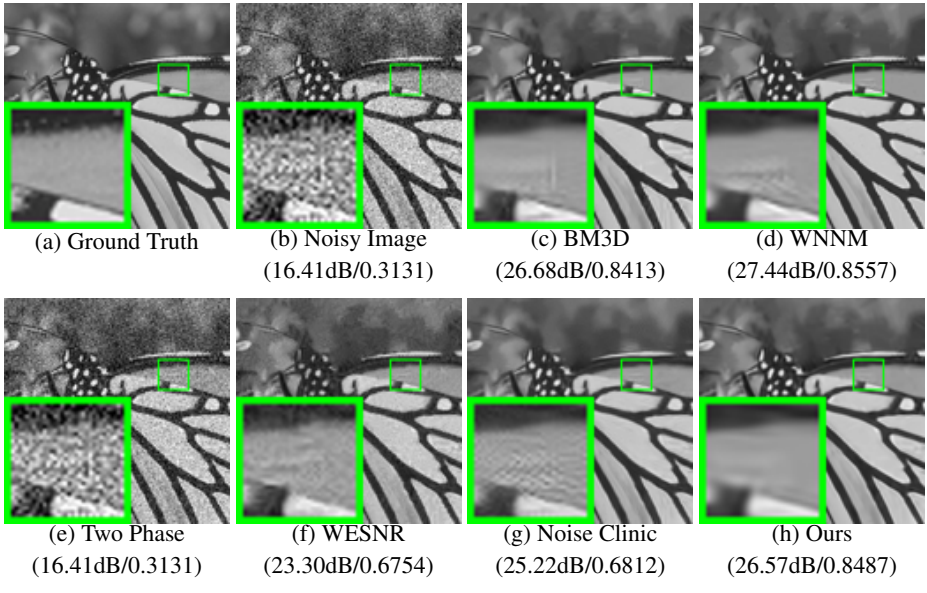
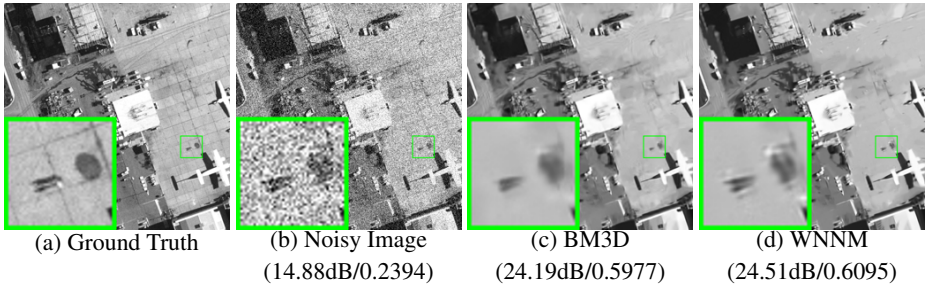


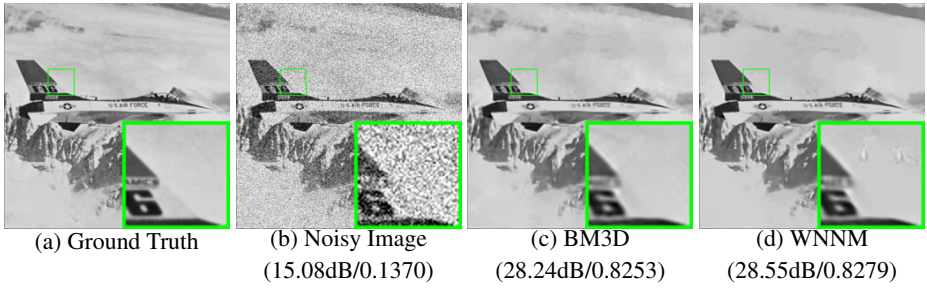
Fig. 4. Denoised images of *Monarch* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 40$).



(a) Ground Truth (b) Noisy Image (14.88dB/0.2394) (c) BM3D (24.19dB/0.5977) (d) WNNM (24.51dB/0.6095)

(e) Two Phase (14.88dB/0.2394) (f) WESNR (17.89dB/0.4126) (g) Noise Clinic (22.31dB/0.4867) (h) Ours (24.12dB/0.5910)

Fig. 5. Denoised images of *Airfield* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 50$).



(a) Ground Truth (b) Noisy Image (15.08dB/0.1370) (c) BM3D (28.24dB/0.8253) (d) WNNM (28.55dB/0.8279)

(e) Two Phase (15.08dB/0.1370) (f) WESNR (23.14dB/0.4278) (g) Noise Clinic (25.02dB/0.5122) (h) Ours (28.18dB/0.8295)

Fig. 6. Denoised images of *Airplane* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 50$).

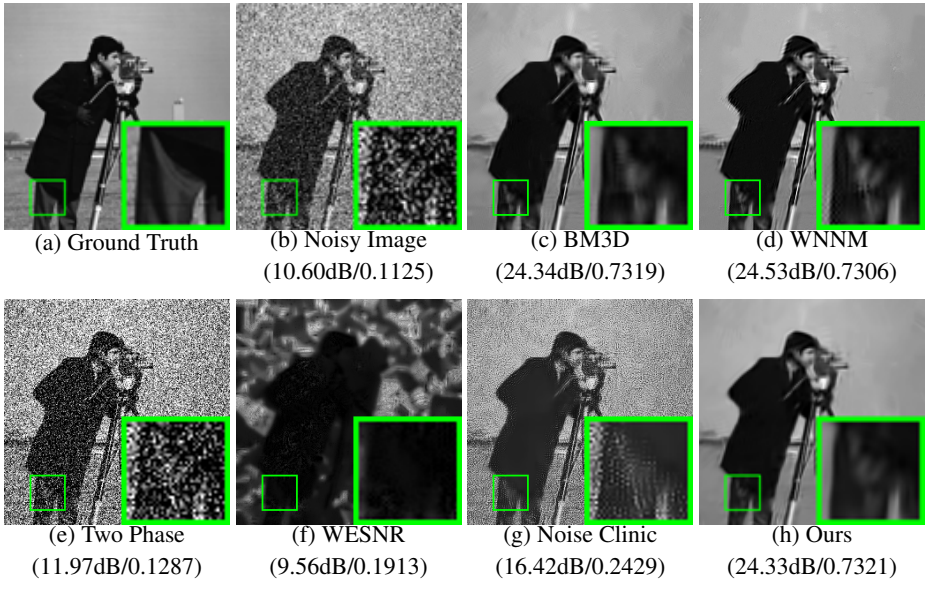


Fig. 7. Denoised images of *Cameraman* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 75$).

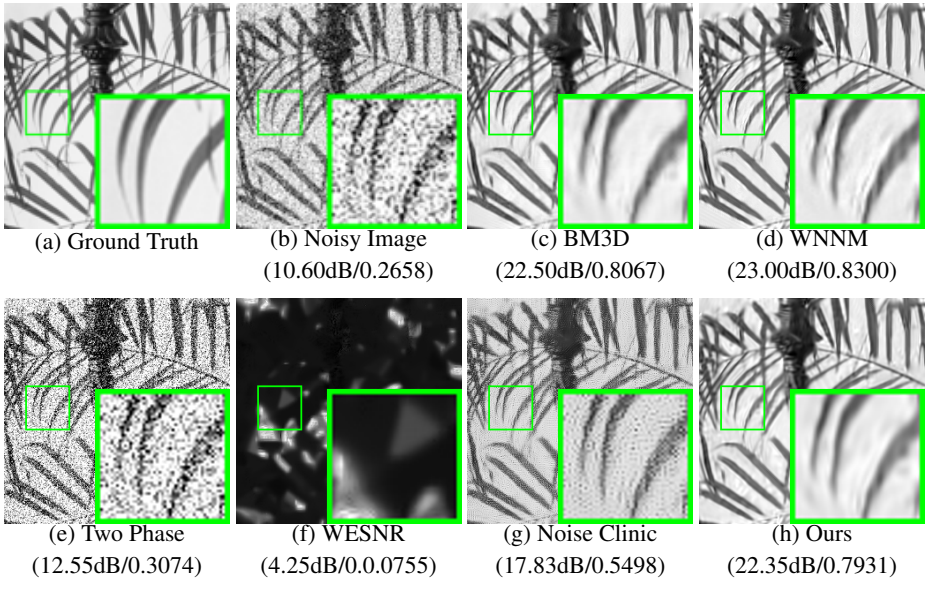
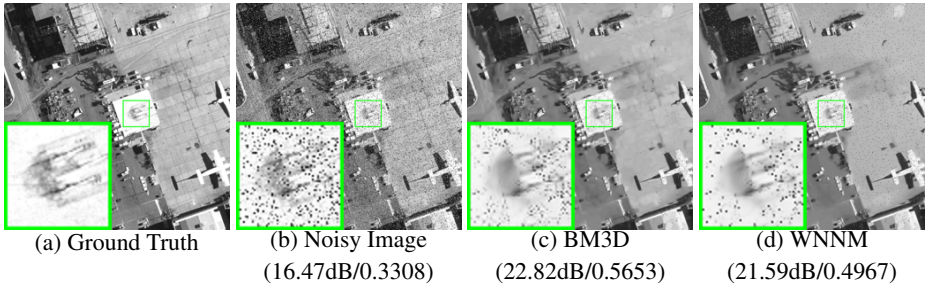


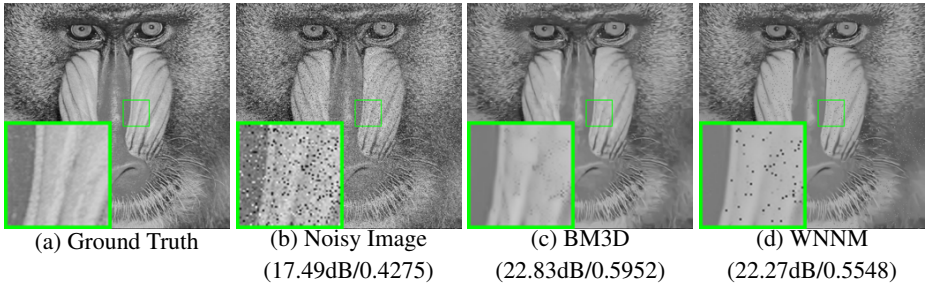
Fig. 8. Denoised images of *Leaves* and PSNR/SSIM results by different methods (the standard deviation of Gaussian noise is $\sigma = 75$).



(a) Ground Truth (b) Noisy Image (16.47dB/0.3308) (c) BM3D (22.82dB/0.5653) (d) WNNM (21.59dB/0.4967)

(e) Two Phase (25.41dB/0.7173) (f) WESNR (23.85dB/0.6919) (g) Noise Clinic (18.18dB/0.3604) (h) Ours (24.49dB/0.6177)

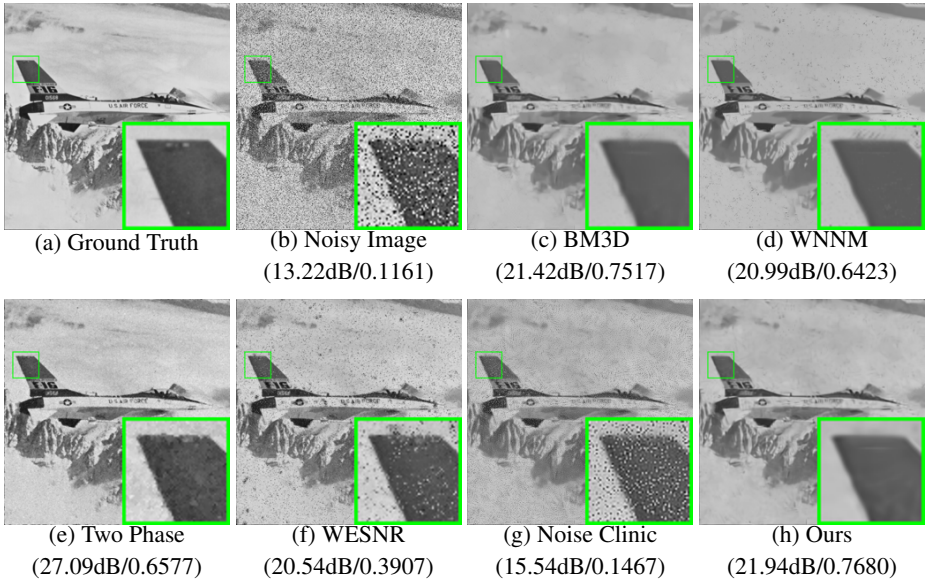
Fig. 9. Denoised images of *Airfield* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.15).



(a) Ground Truth (b) Noisy Image (17.49dB/0.4275) (c) BM3D (22.83dB/0.5952) (d) WNNM (22.27dB/0.5548)

(e) Two Phase (22.94dB/0.6717) (f) WESNR (24.49dB/0.7261) (g) Noise Clinic (19.52dB/0.4463) (h) Ours (23.01dB/0.5963)

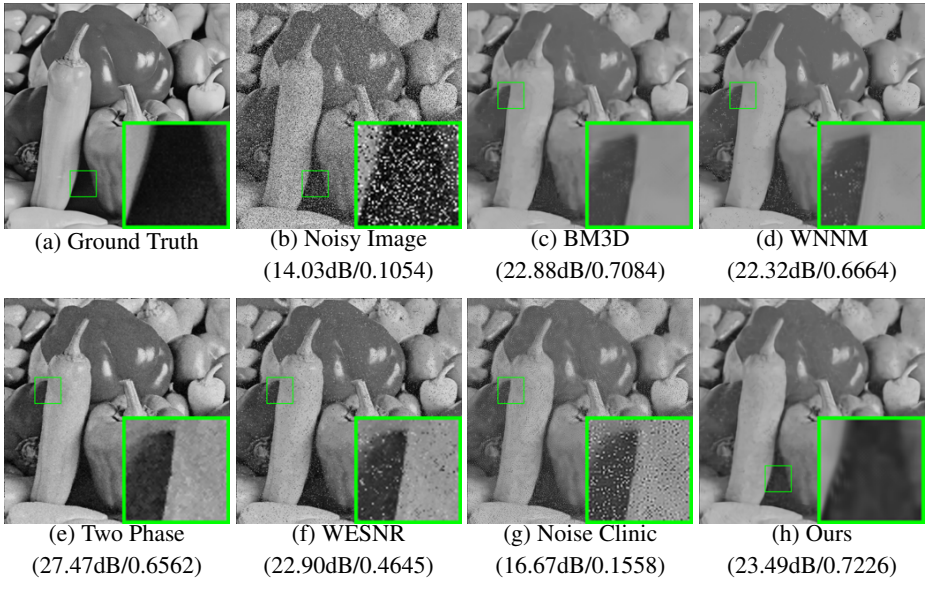
Fig. 10. Denoised images of *Baboon* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.15).



(a) Ground Truth (b) Noisy Image (13.22dB/0.1161) (c) BM3D (21.42dB/0.7517) (d) WNNM (20.99dB/0.6423)

(e) Two Phase (27.09dB/0.6577) (f) WESNR (20.54dB/0.3907) (g) Noise Clinic (15.54dB/0.1467) (h) Ours (21.94dB/0.7680)

Fig. 11. Denoised images of *Airplane* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.3).



(a) Ground Truth (b) Noisy Image (14.03dB/0.1054) (c) BM3D (22.88dB/0.7084) (d) WNNM (22.32dB/0.6664)

(e) Two Phase (27.47dB/0.6562) (f) WESNR (22.90dB/0.4645) (g) Noise Clinic (16.67dB/0.1558) (h) Ours (23.49dB/0.7226)

Fig. 12. Denoised images of *Peppers* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.3).

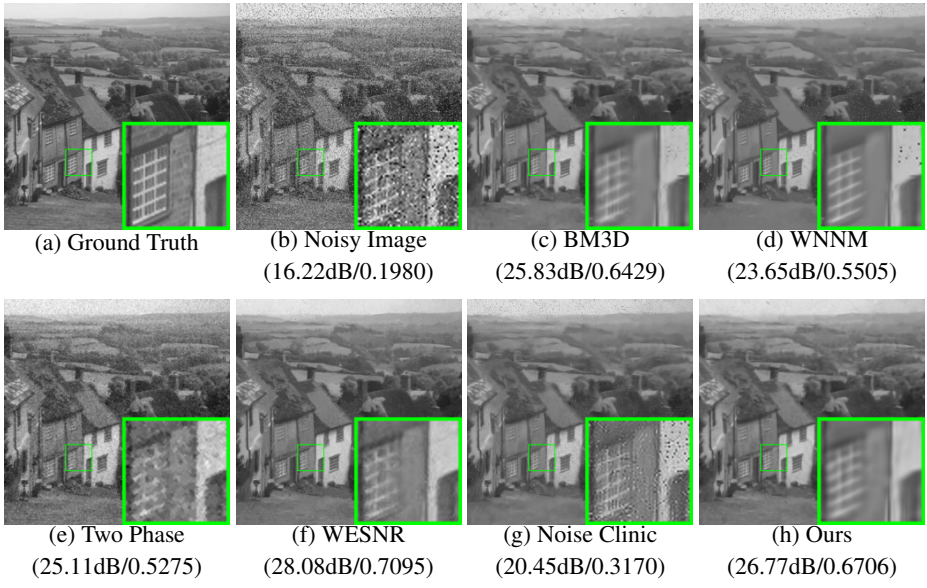


Fig. 13. Denoised images of *Hill* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.15).

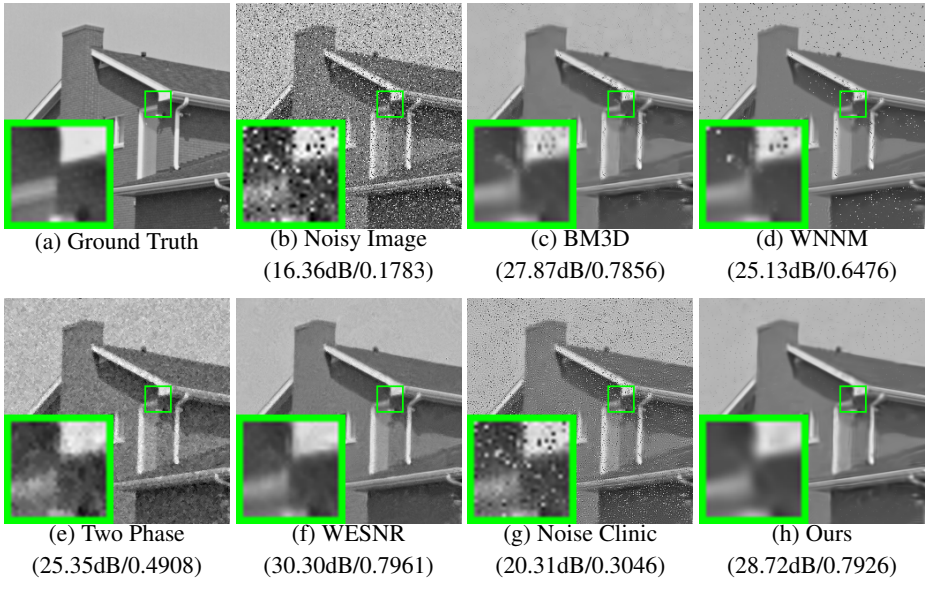


Fig. 14. Denoised images of *House* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.15).

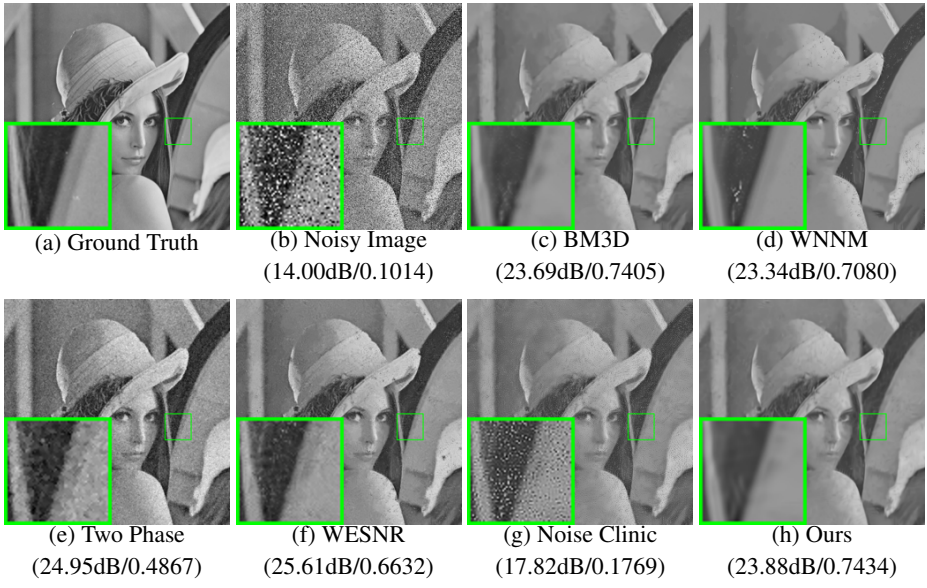


Fig. 15. Denoised images of *Lena* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.3).

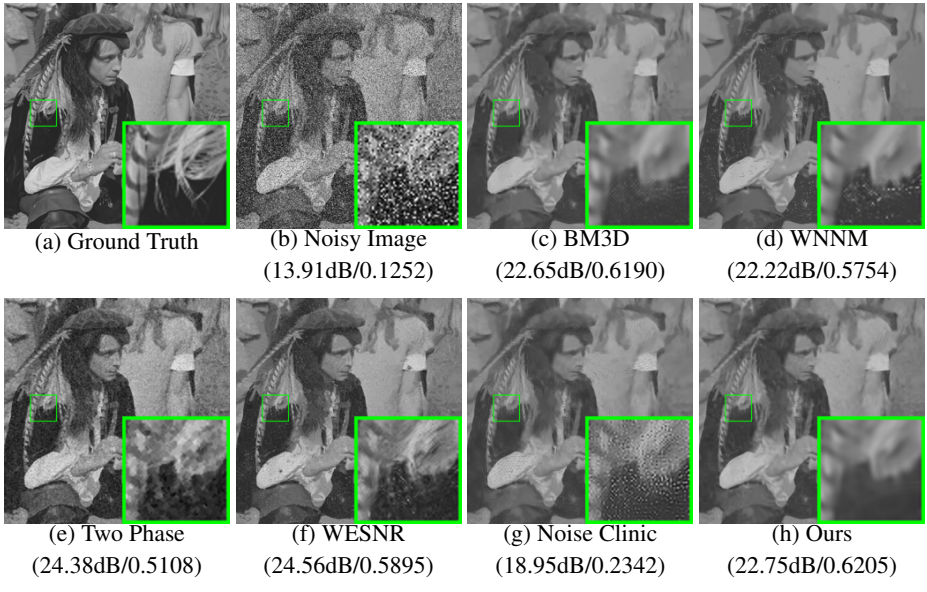
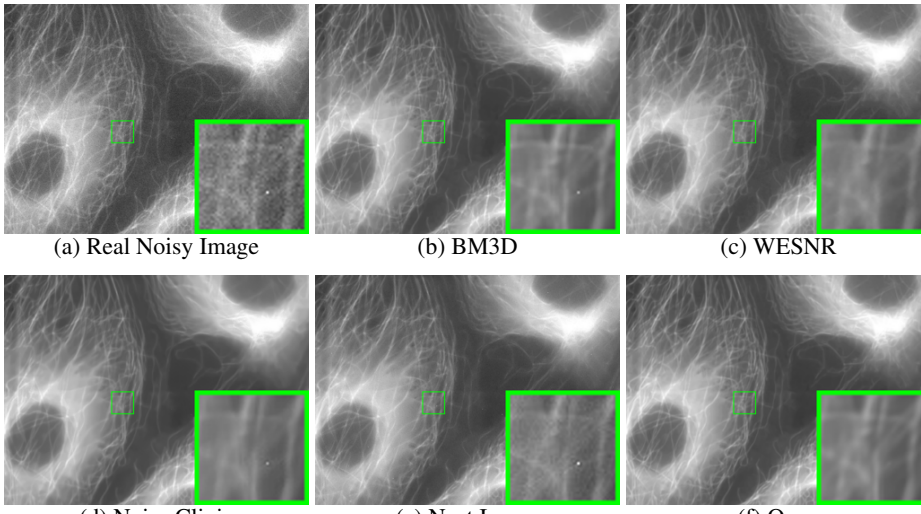


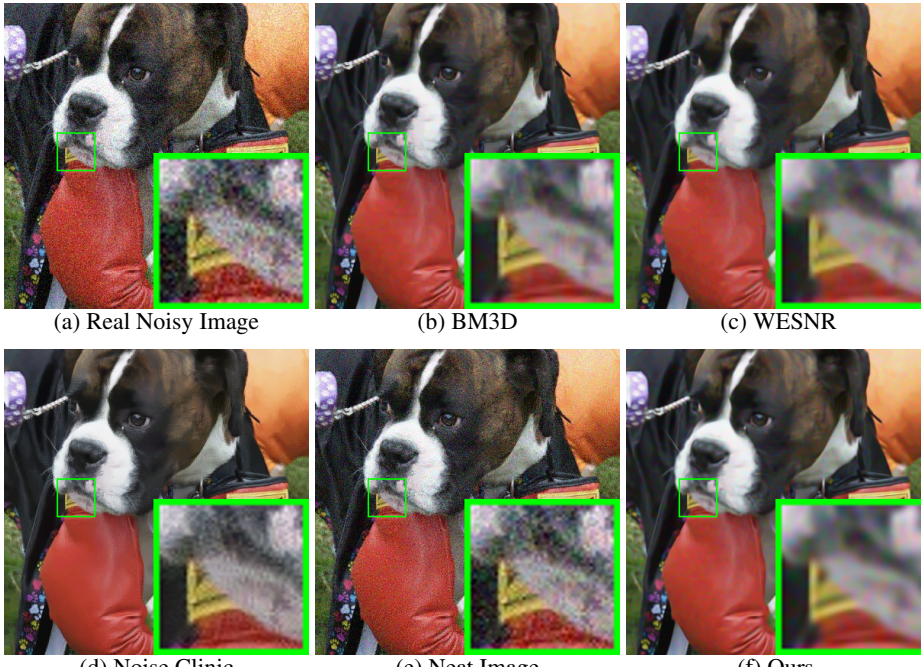
Fig. 16. Denoised images of *Man* by different methods (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.3).



(a) Real Noisy Image (b) BM3D (c) WESNR

(d) Noise Clinic (e) Neat Image (f) Ours

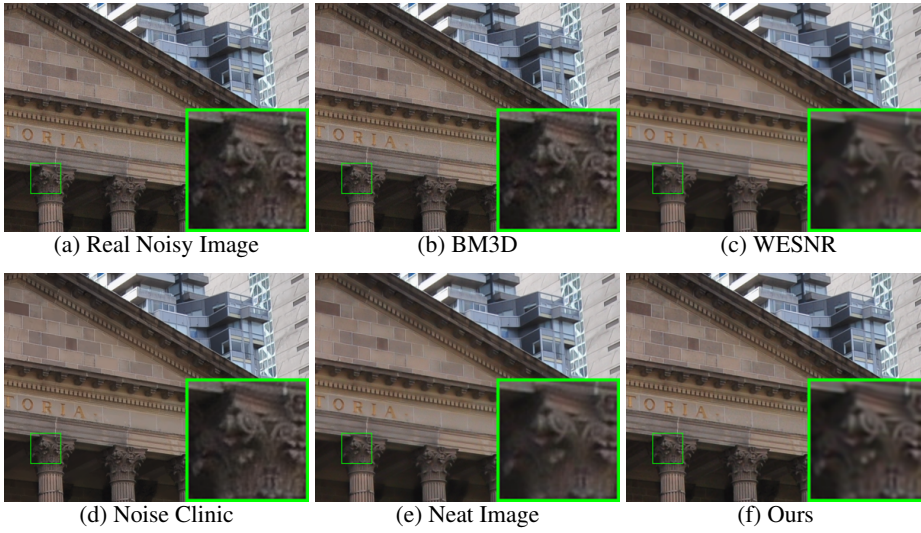
Fig. 17. Denoised images of the medical image "Fibers" by different methods. The images are better to be zoomed in on screen.



(a) Real Noisy Image (b) BM3D (c) WESNR

(d) Noise Clinic (e) Neat Image (f) Ours

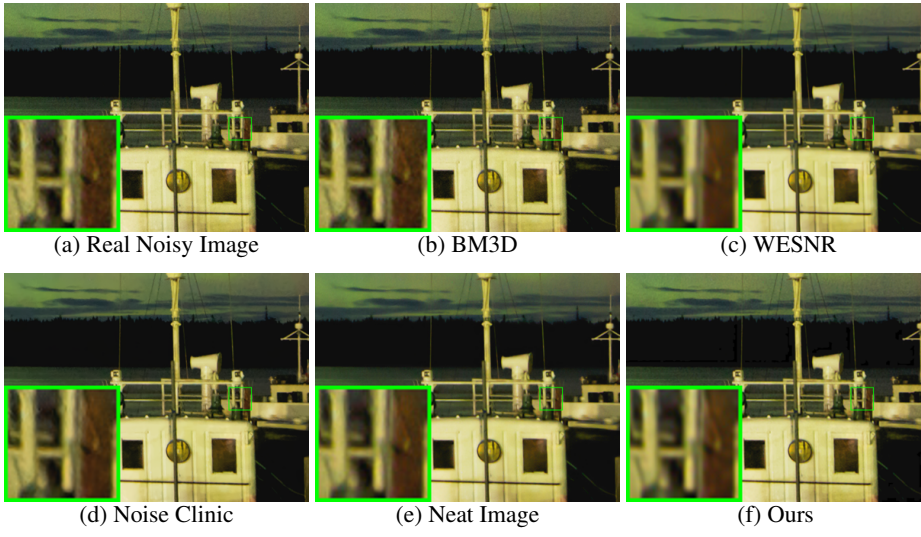
Fig. 18. Denoised images of the old image "Dog" by different methods. The images are better to be zoomed in on screen.



(a) Real Noisy Image (b) BM3D (c) WESNR

(d) Noise Clinic (e) Neat Image (f) Ours

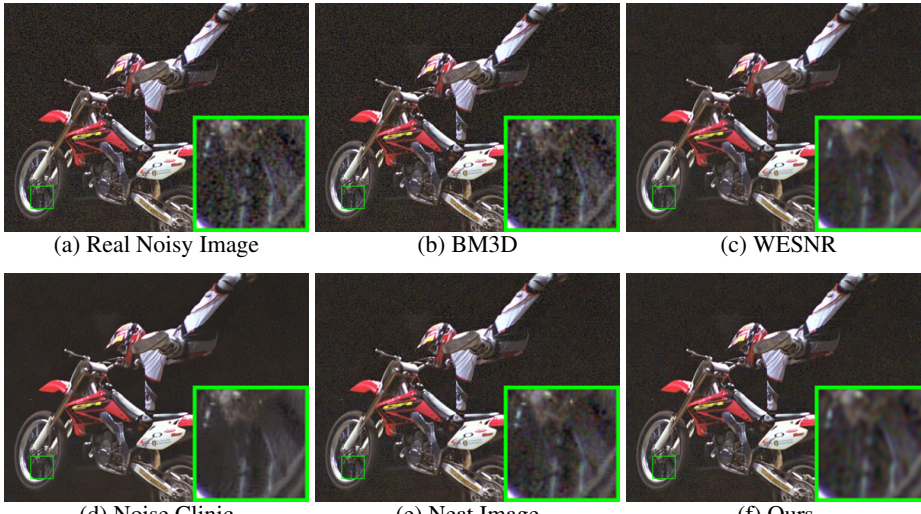
Fig. 19. Denoised images of the old image ”Library” by different methods. The images are better to be zoomed in on screen.



(a) Real Noisy Image (b) BM3D (c) WESNR

(d) Noise Clinic (e) Neat Image (f) Ours

Fig. 20. Denoised images of the old image ”Boat” by different methods. The images are better to be zoomed in on screen.



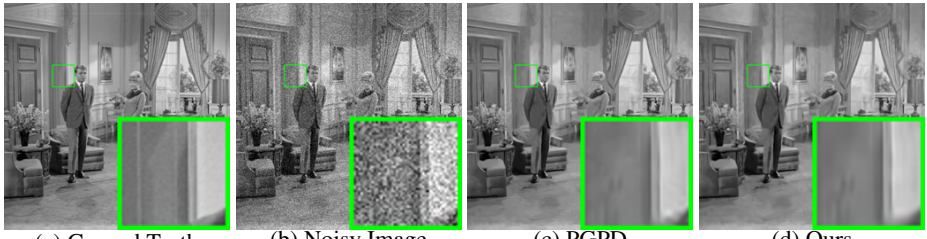
(a) Real Noisy Image (b) BM3D (c) WESNR

(d) Noise Clinic (e) Neat Image (f) Ours

Fig. 21. Denoised images of the old image ”Cyclist” by different methods. The images are better to be zoomed in on screen.

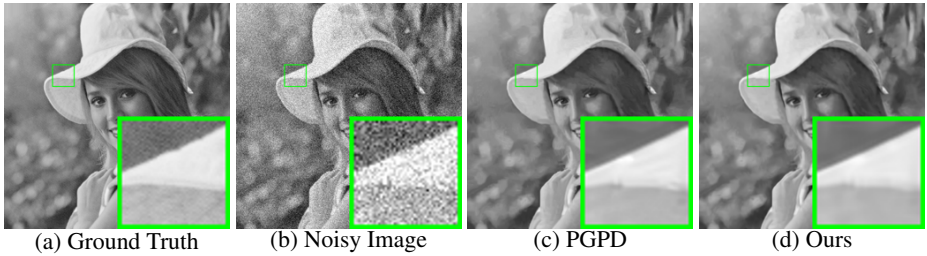
4 Visual comparison with the PGPD algorithm

In the main paper, we had given the PSNR/SSIM results of PGPD, but we didn't compare the visual quality of PGPD with the proposed method due to space limitation. In this section, we will offset the loss by comparing the results on denoising Gaussian noise (Figures 22-29), mixed Gaussian and RVIN noise (Figures 30-35) on the 20 widely used images, and on denoising real noisy images (Figures 36-41).



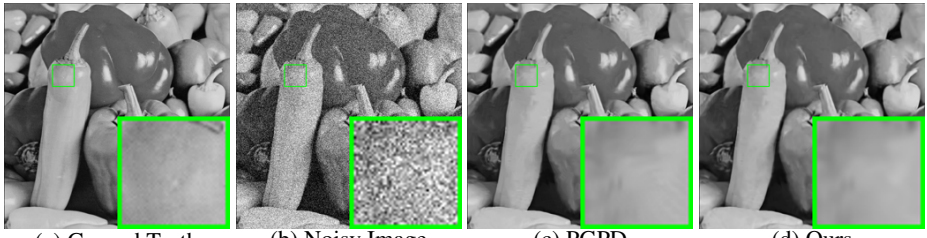
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (28.84dB/0.7897) (d) Ours (28.27dB/0.7737)

Fig. 22. Denoised images of *Couple* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 30$).



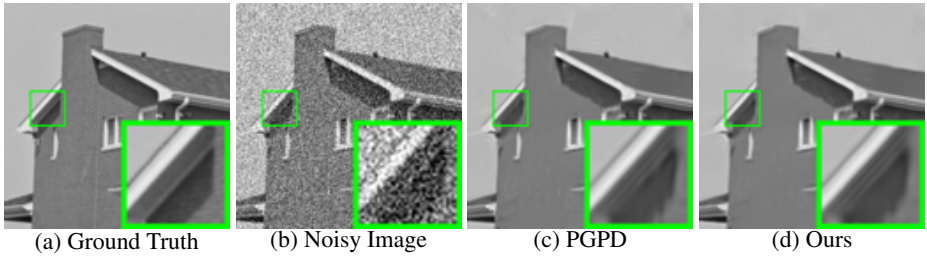
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (30.37dB/0.7217) (d) Ours (30.41dB/0.7212)

Fig. 23. Denoised images of *Elaine* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 30$).



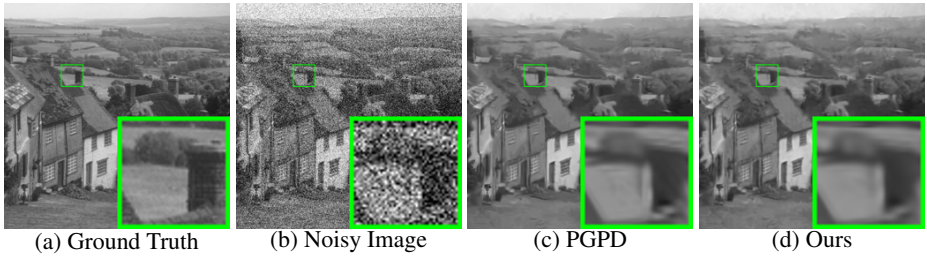
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (30.18dB/0.8008) (d) Ours (30.01dB/0.8008)

Fig. 24. Denoised images of *Peppers* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 40$).



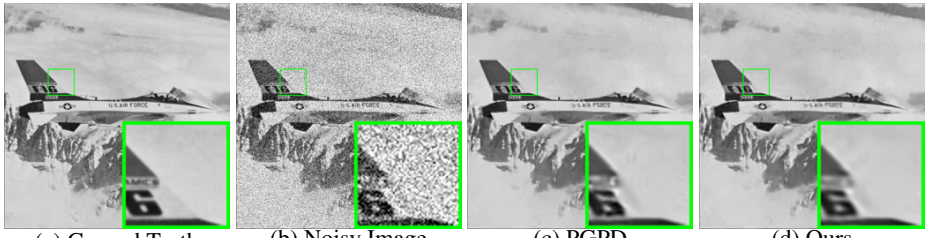
(a) Ground Truth (b) Noisy Image (16.30dB/0.1701) (c) PGPD (31.02dB/0.8302) (d) Ours (30.90dB/0.8328)

Fig. 25. Denoised images of *House* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 40$).



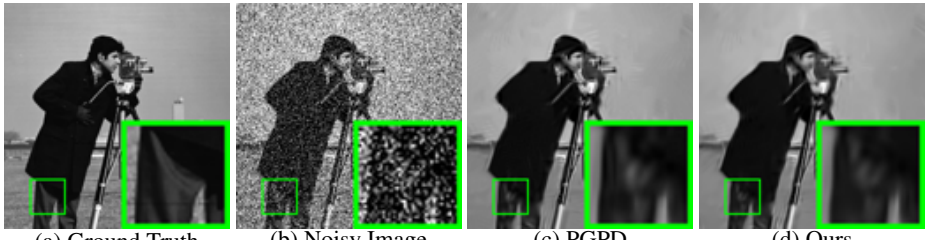
(a) Ground Truth (b) Noisy Image (14.68dB/0.1357) (c) PGPD (27.22dB/0.6702) (d) Ours (27.02dB/0.6618)

Fig. 26. Denoised images of *Hill* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 50$).



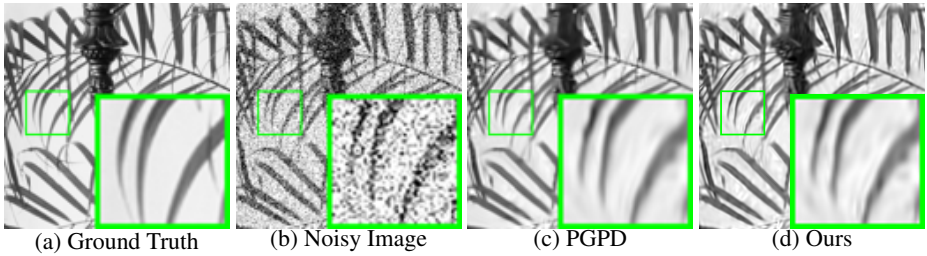
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (28.38dB/0.8251) (d) Ours (28.18dB/0.8295)

Fig. 27. Denoised images of *Airplane* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 50$).



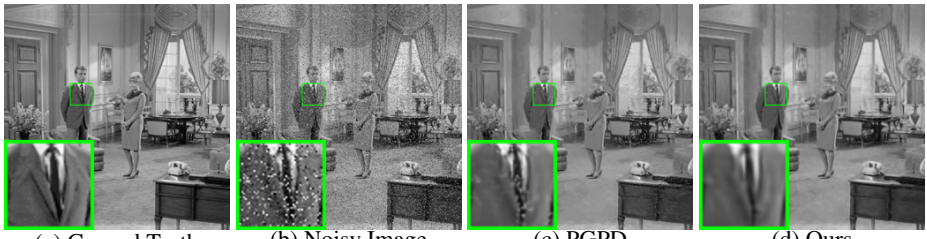
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (24.64dB/0.7300) (d) Ours (24.33dB/0.7321)

Fig. 28. Denoised images of *Cameraman* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 75$).



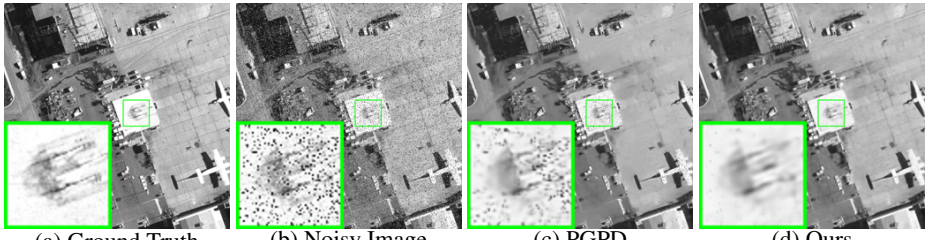
(a) Ground Truth (b) Noisy Image (18.73dB/0.3128) (c) PGPD (22.61dB/0.8121) (d) Ours (22.35dB/0.7931)

Fig. 29. Denoised images of *Leaves* and PSNR/SSIM results by PGPD and the proposed method (the standard deviation of Gaussian noise is $\sigma = 75$).



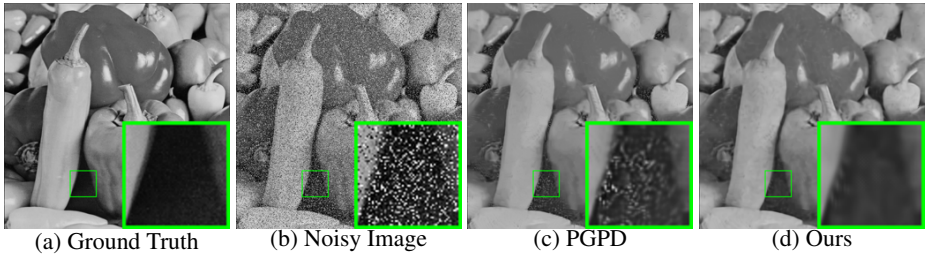
(a) Ground Truth (b) Noisy Image (17.35dB/0.2852) (c) PGPD (25.75dB/0.7208) (d) Ours (27.26dB/0.7438)

Fig. 30. Denoised images of *Couple* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.15).



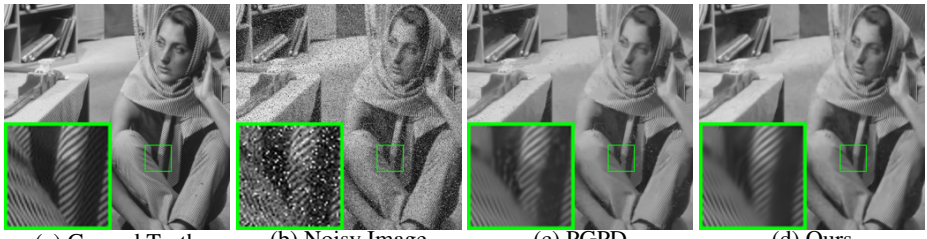
(a) Ground Truth (b) Noisy Image (16.47dB/0.3308) (c) PGPD (23.16dB/0.5856) (d) Ours (24.49dB/0.6177)

Fig. 31. Denoised images of *Airfield* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.15).



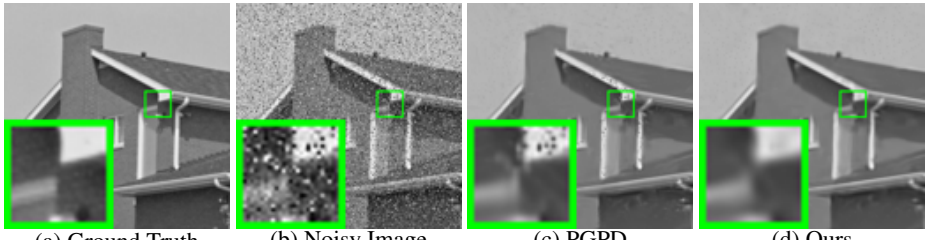
(a) Ground Truth (b) Noisy Image (14.03dB/0.1054) (c) PGPD (22.76dB/0.7005) (d) Ours (23.49dB/0.7226)

Fig. 32. Denoised images of *Peppers* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 10$ and ratio 0.30).



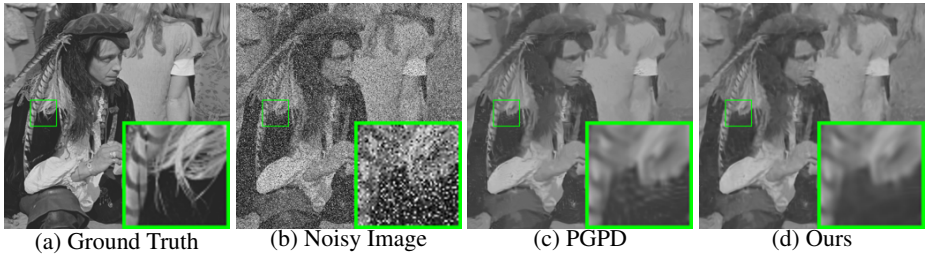
(a) Ground Truth (b) Noisy Image (16.09dB/0.2644) (c) PGPD (25.61dB/0.7633) (d) Ours (26.58dB/0.7853)

Fig. 33. Denoised images of *Barbara* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.15).



(a) Ground Truth (b) Noisy Image (16.36dB/0.1783) (c) PGPD (27.79dB/0.7923) (d) Ours (28.72dB/0.7926)

Fig. 34. Denoised images of *House* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.15).

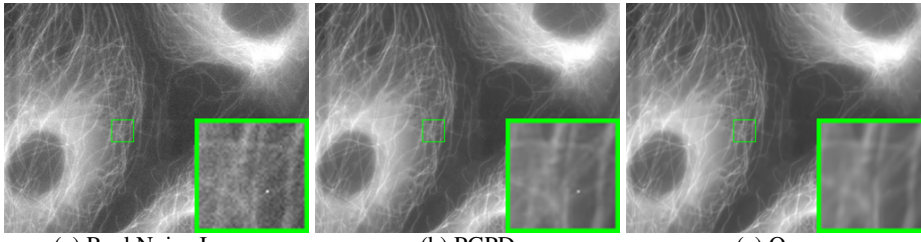


(a) Ground Truth (b) Noisy Image (13.91dB/0.1252) (c) PGPD (22.63dB/0.6175) (d) Ours (22.75dB/0.6205)

Fig. 35. Denoised images of *Man* and PSNR/SSIM results by PGPD and the proposed method (the mixed Gaussian and RVIN noise is with $\sigma = 20$ and ratio 0.30).

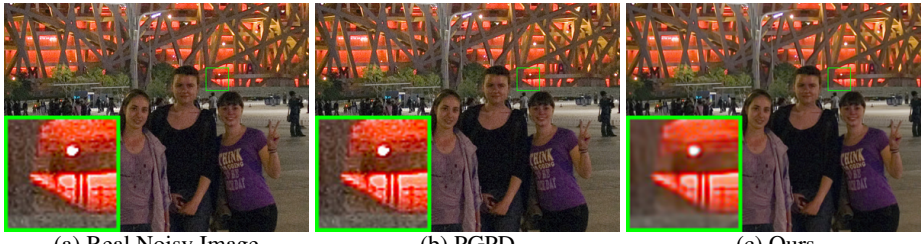
(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 36. Denoised images of the old image "SolvayConf1927" by PGPD and the proposed method. The images are better to be zoomed in on screen.



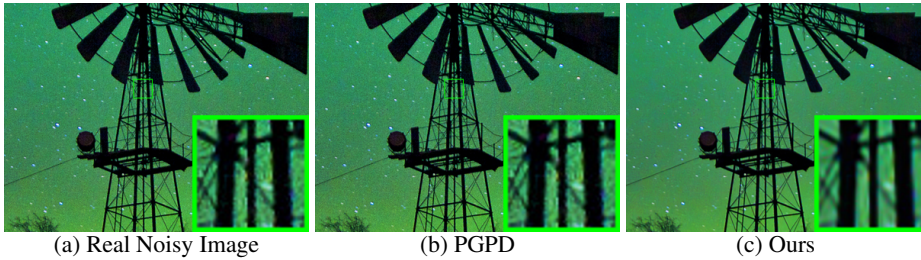
(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 37. Denoised images of the old image "Fibers" by PGPD and the proposed method. The images are better to be zoomed in on screen.



(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 38. Denoised images of the old image "Niaochaogirls" by PGPD and the proposed method. The images are better to be zoomed in on screen.



(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 39. Denoised images of the old image "Windmill" by PGPD and the proposed method. The images are better to be zoomed in on screen.

(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 40. Denoised images of the old image "Cyclist" by PGPD and the proposed method. The images are better to be zoomed in on screen.

(a) Real Noisy Image (b) PGPD (c) Ours

Fig. 41. Denoised images of the old image "Library" by PGPD and the proposed method. The images are better to be zoomed in on screen.

References

1. Dabov, K., Foi, A., Katkovnik, V., Egiazarian, K.: Image denoising by sparse 3-D transform-domain collaborative filtering. Image Processing, IEEE Transactions on **16**(8) (2007) 2080–2095
2. Gu, S., Zhang, L., Zuo, W., Feng, X.: Weighted nuclear norm minimization with application to image denoising. CVPR (2014) 2862–2869
3. Cai, J.F., Chan, R.H., Nikolova, M.: Fast two-phase image deblurring under impulse noise. Journal of Mathematical Imaging and Vision **36**(1) (2010) 46–53
4. Jiang, J., Zhang, L., Yang, J.: Mixed noise removal by weighted encoding with sparse nonlocal regularization. Image Processing, IEEE Transactions on **23**(6) (2014) 2651–2662
5. Lebrun, M., Colom, M., Morel, J.M.: Multiscale image blind denoising. Image Processing, IEEE Transactions on **24**(10) (2015) 3149–3161
6. ABSoft, N.: Neat image. `https://ni.neatvideo.com/home`
7. Lebrun, M., Colom, M., Morel, J.M.: The noise clinic: a blind image denoising algorithm. `http://www.ipol.im/pub/art/2015/125/` Accessed 01 28, 2015.