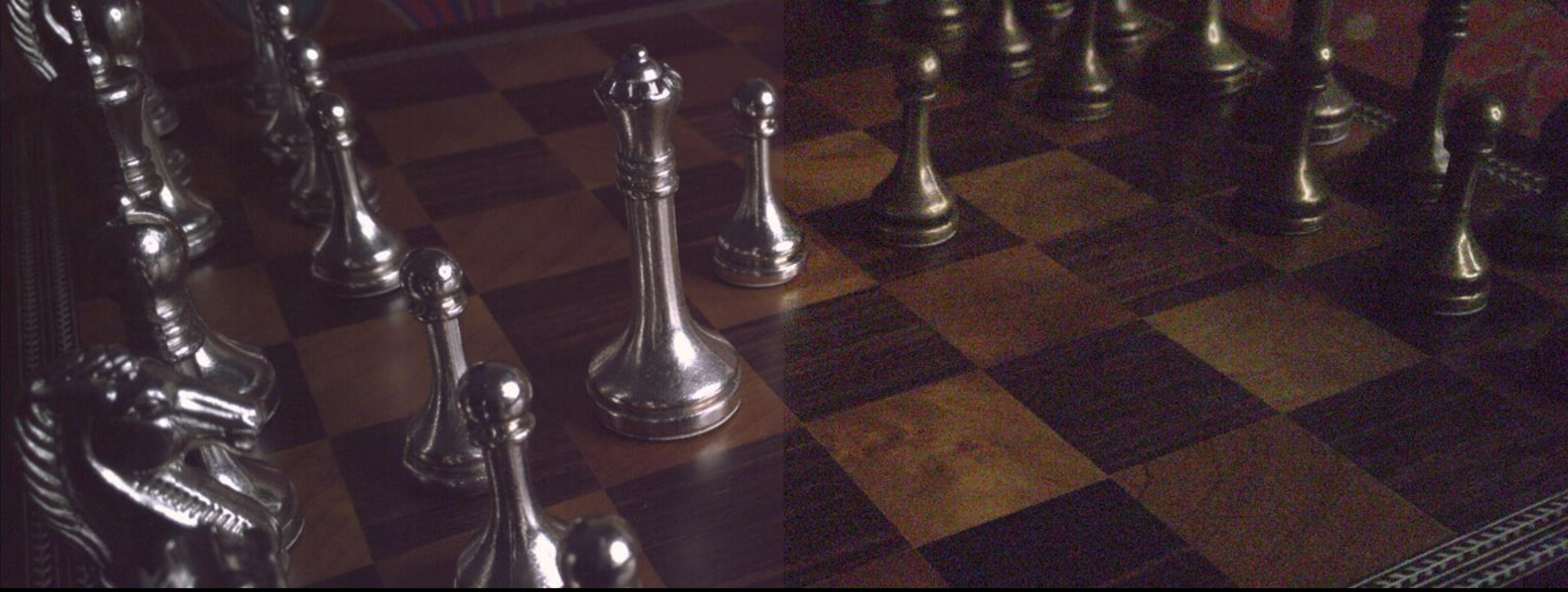

Feature-preserving Image Denoising with Multiresolution Filters

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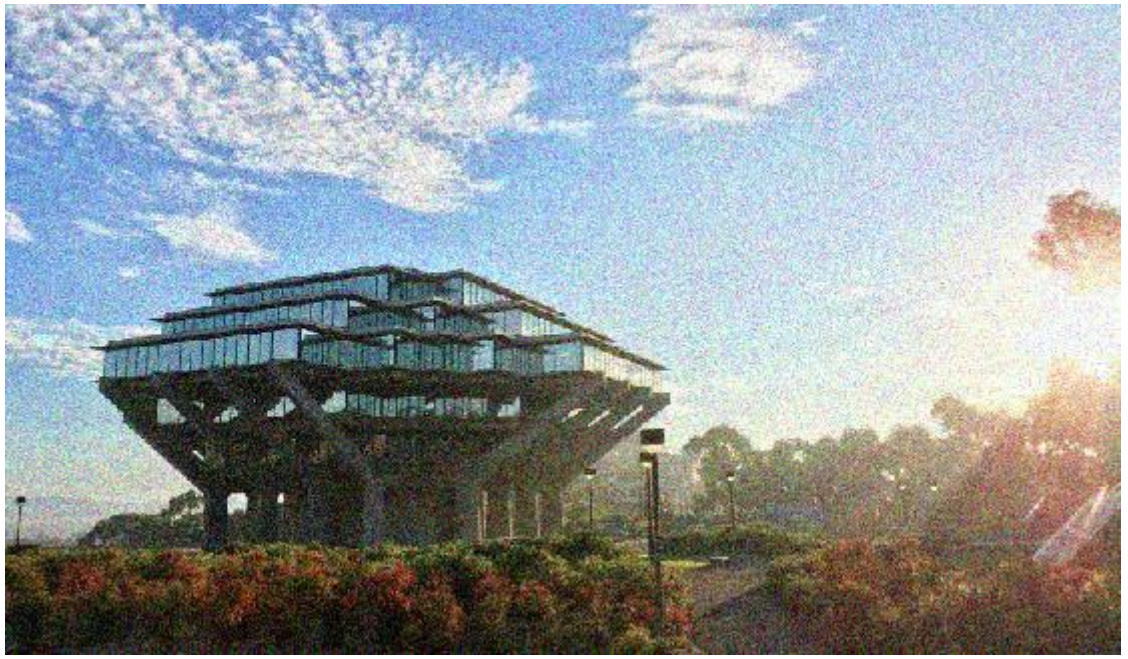
UCSD ECE 251C Project

Image Denoising

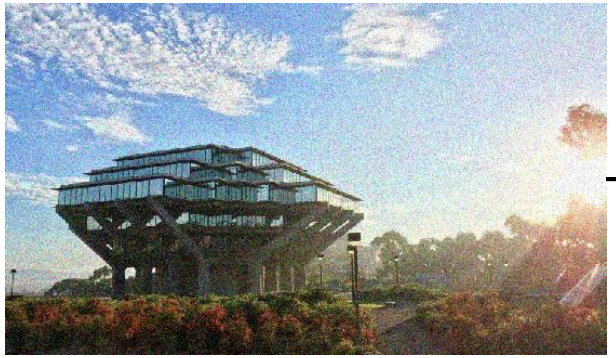
Original scene



Noisy image captured by a camera

- Noise can be produced by the **sensor** and **circuitry** of a digital camera
- Noise values are **less correlated**, can be smoothed away by **averaging**

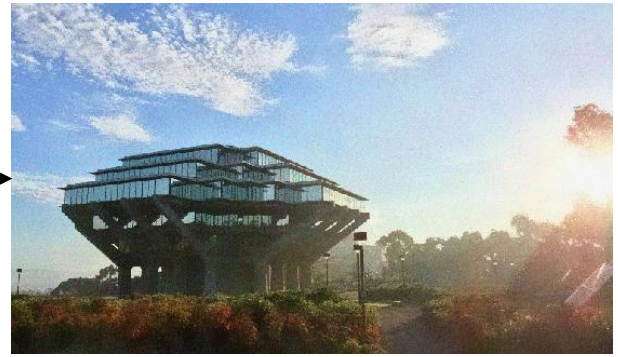
Problem with averaging



Noisy image

Averaging

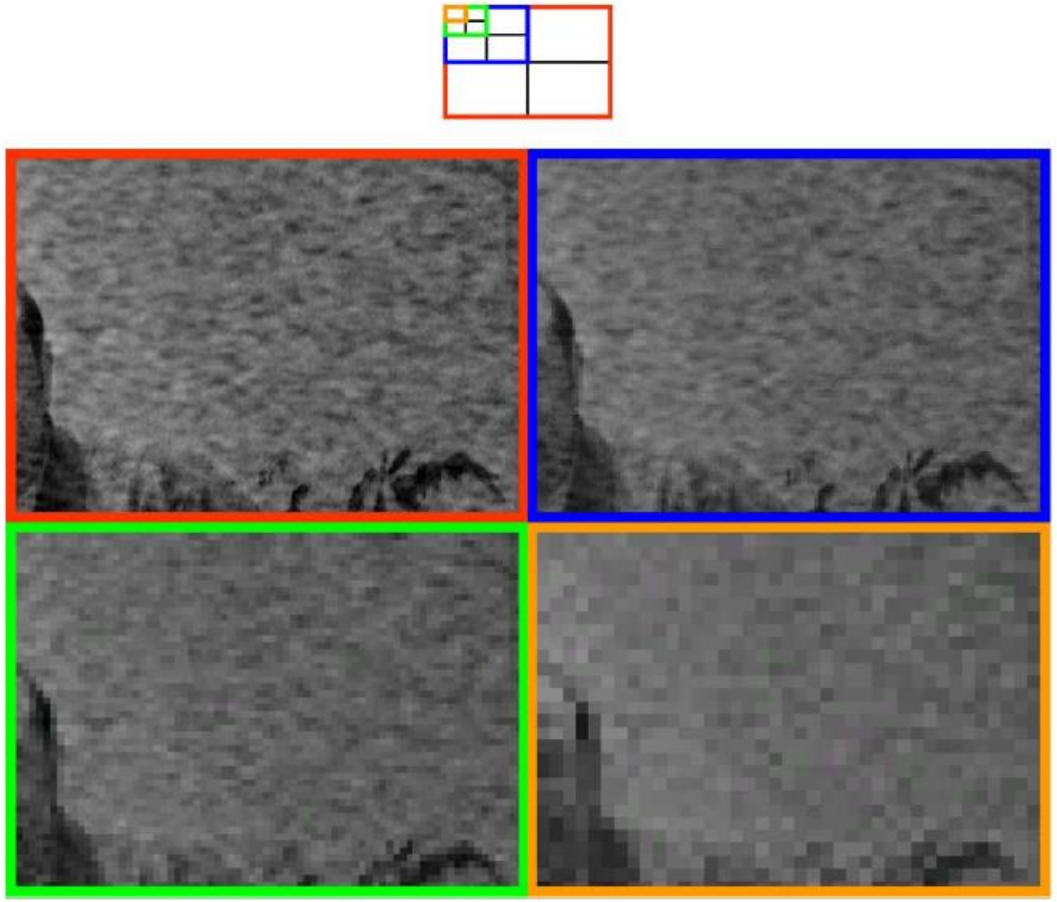
√ reduce noise
× edges / corners
× visual quality



Edge-preserving denoising

√ reduce noise
√ edges / corners
√ visual quality

Problem with single resolution filtering

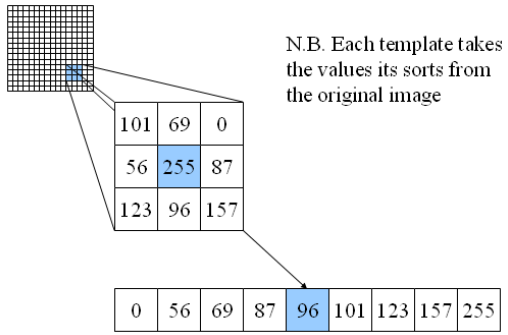


- A noisy image decomposed into its frequency sub-bands using ‘db8’ filters.
- The **coarse-grain noise** at the original level is difficult to eliminate
- The noise becomes **fine-grain** as the image is decomposed, and can be eliminated more easily

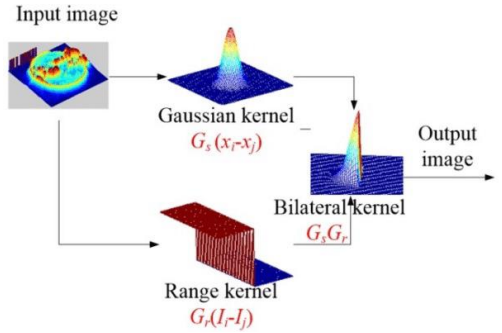
Previous Approach

Single resolution:

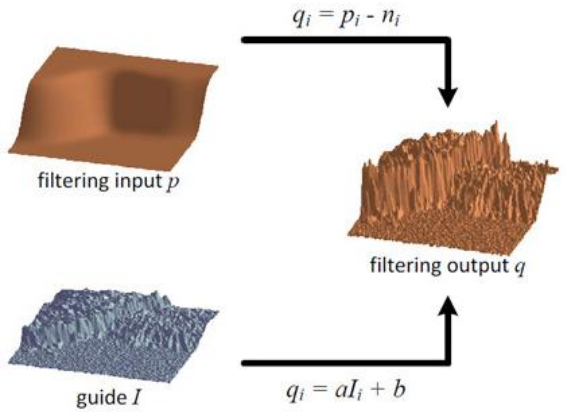
- Median filter[1]
- Bilateral filter[2]
- Guided filter[3] (new)



Median filter



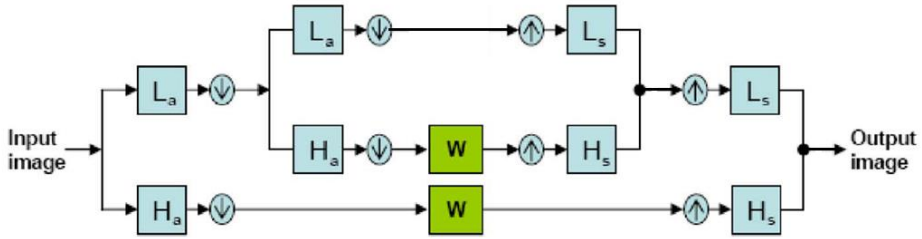
Bilateral filter



Guided filter

Multiresolution:

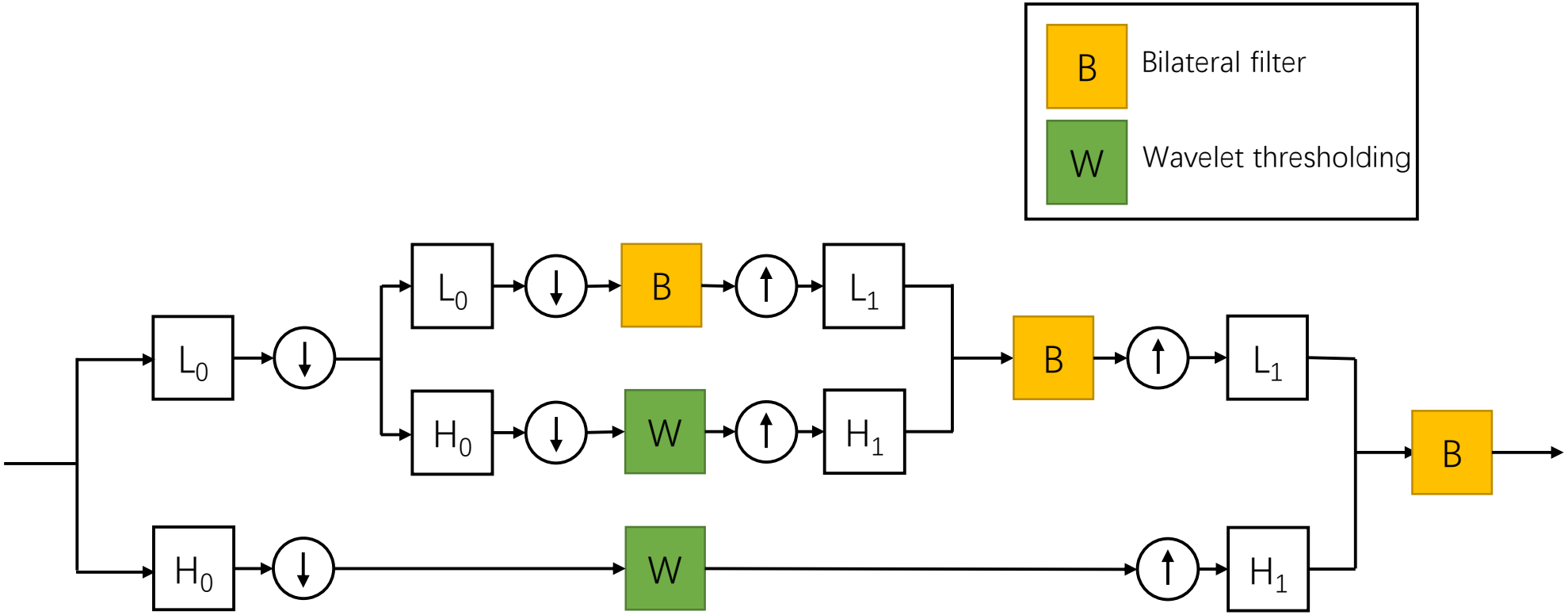
- Wavelet thresholding[4]



Wavelet thresholding

[1] Huang, Thomas, et al. "A fast two-dimensional median filtering algorithm" (PDF). IEEE Transactions on Acoustics, Speech, and Signal Processing. 1979
[2] Tomasi, Carlo, and Roberto Manduchi. "Bilateral filtering for gray and color images." in ICCV. 1998.
[3] He, Kaiming, et al. "Guided image filtering." in ECCV, 2010.
[4] Chang, S. et al. “Adaptive wavelet thresholding for image denoising and compression.”, IEEE Transactions on Image Processing. 2000

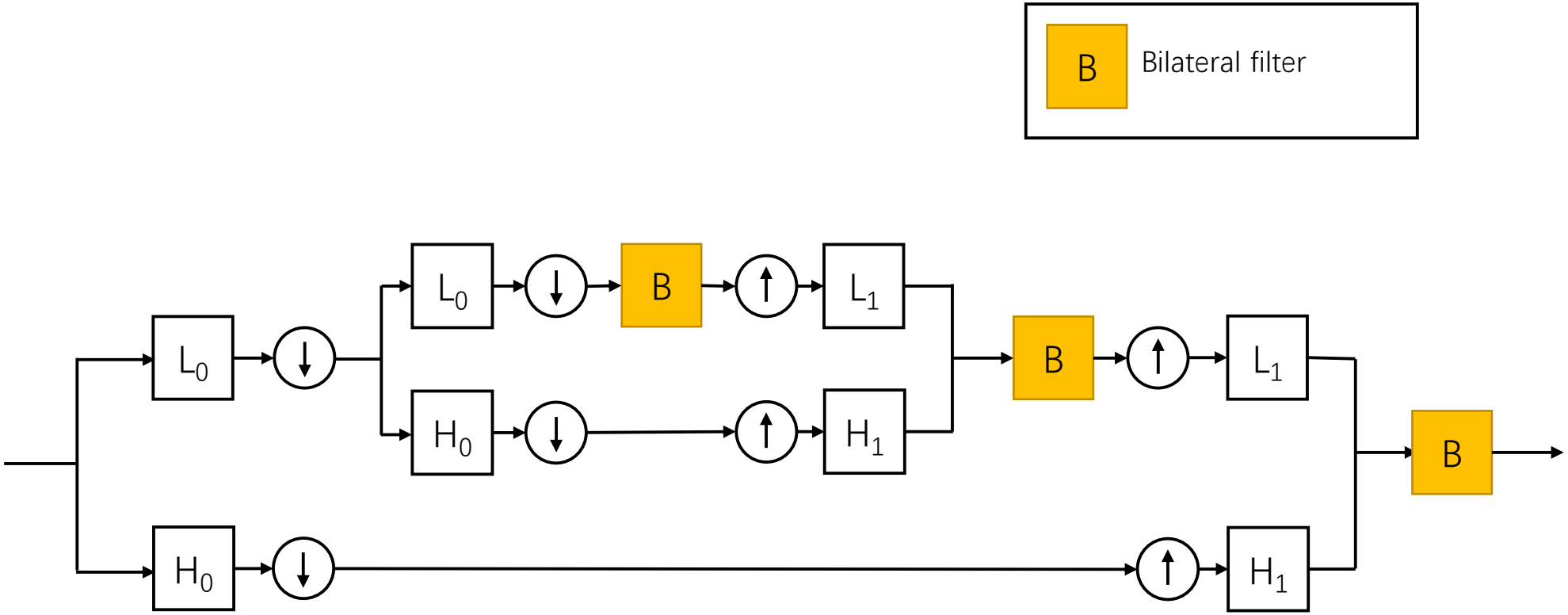
Multiresolution bilateral filter + thresholding



Structure of a 2-level multiresolution bilateral filter with wavelet thresholding [1]

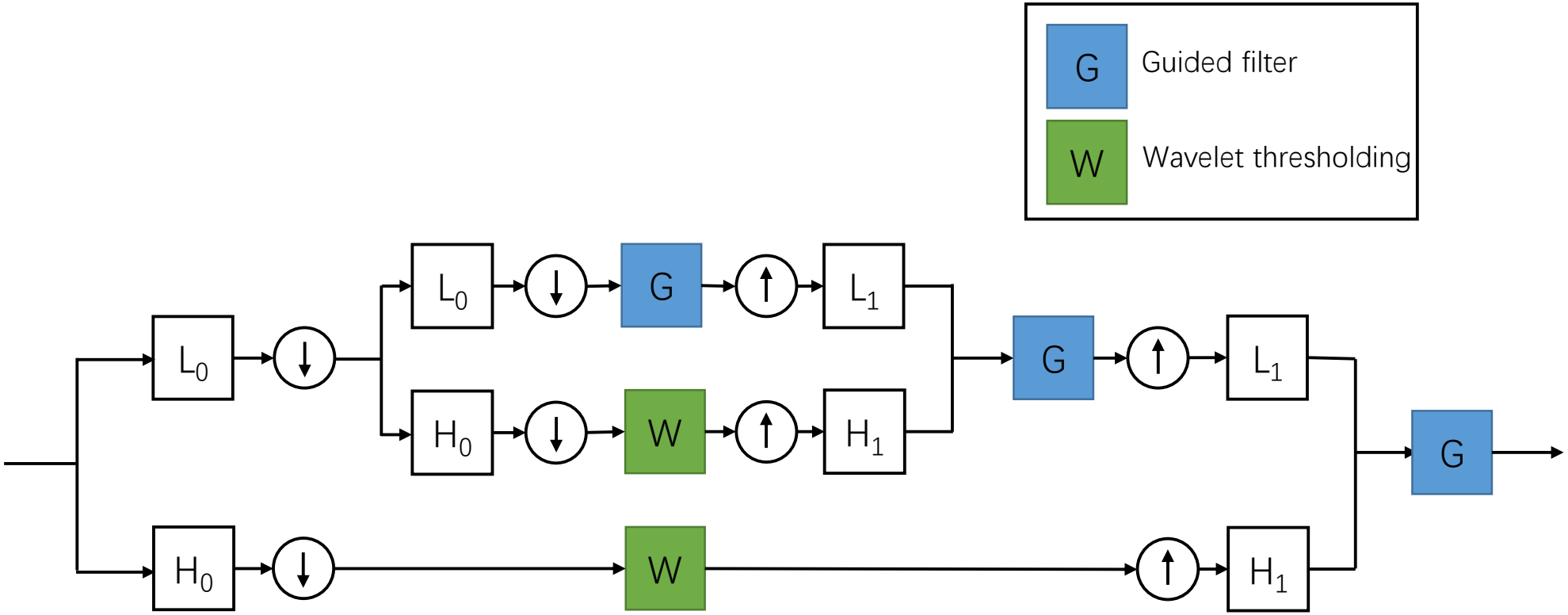
[1] Zhang, Ming, et al. "Multiresolution bilateral filtering for image denoising." *IEEE Transactions on image processing*, 2008

Multiresolution bilateral filter



Structure of a 2-level multiresolution bilateral filter without wavelet thresholding

Multiresolution guided filter + thresholding



Structure of a 2-level multiresolution guided filter with wavelet thresholding

Evaluation

Dataset: Smartphone image denoising dataset (SIDD)[1] – small version

Metrics for denoising performance:

- MSE: the lower the better

$$MSE = \frac{1}{m\,n}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[I(i,j) - K(i,j)]^2$$

- PSNR, SSIM: the higher the better

$$PSNR = 10 \cdot \log_{10}\left(\frac{MAX_I^2}{MSE}\right)$$

$$\text{SSIM}(x,y) = \frac{(2\mu_x\mu_y + c_1)(2\sigma_{xy} + c_2)}{(\mu_x^2 + \mu_y^2 + c_1)(\sigma_x^2 + \sigma_y^2 + c_2)}$$

[1] A. Abdelhamed, S. Lin, and M. S. Brown, "A High-Quality Denoising Dataset for Smartphone Cameras", IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2018

Parameters Tuning

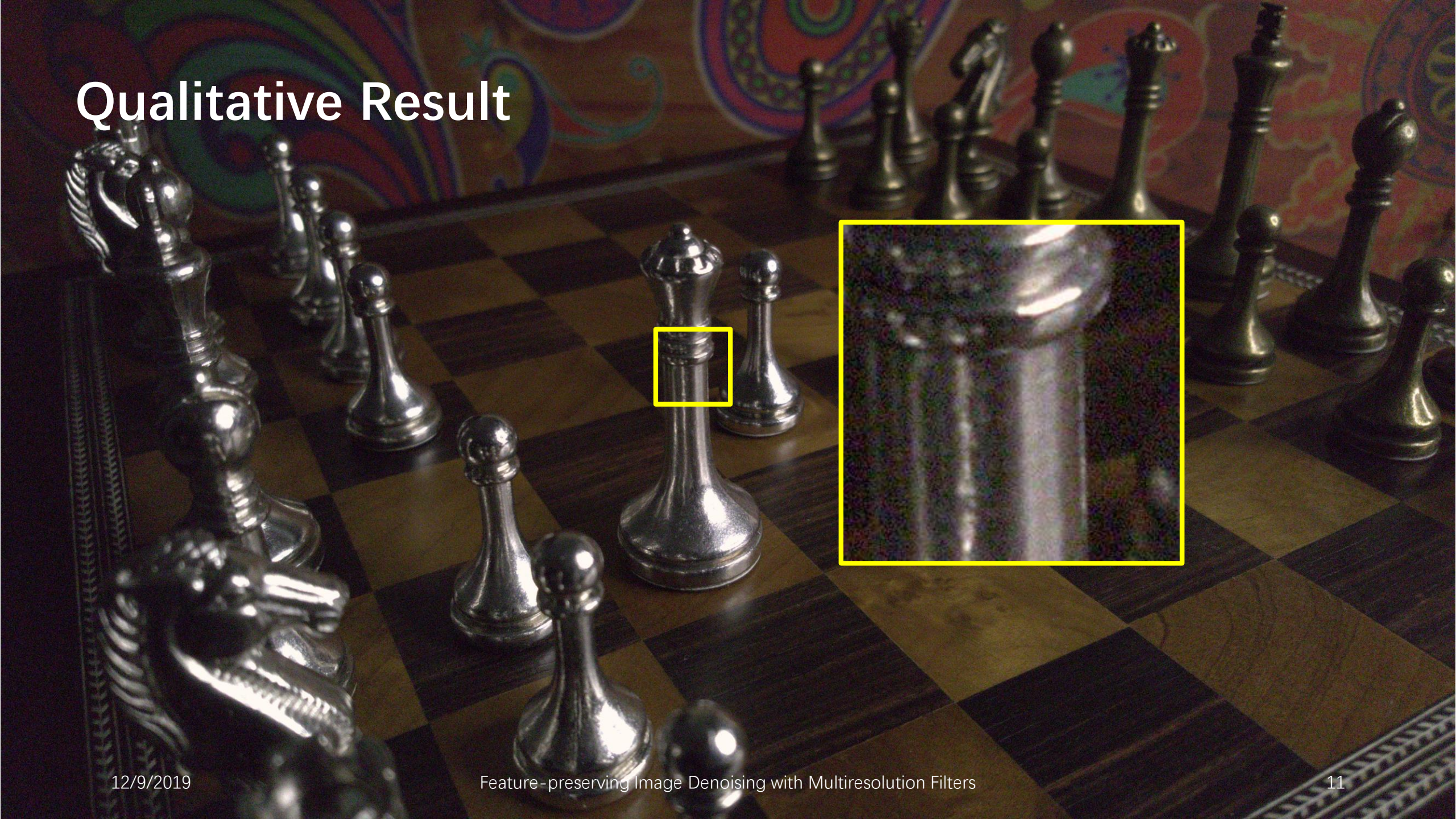
Filter coefficients:

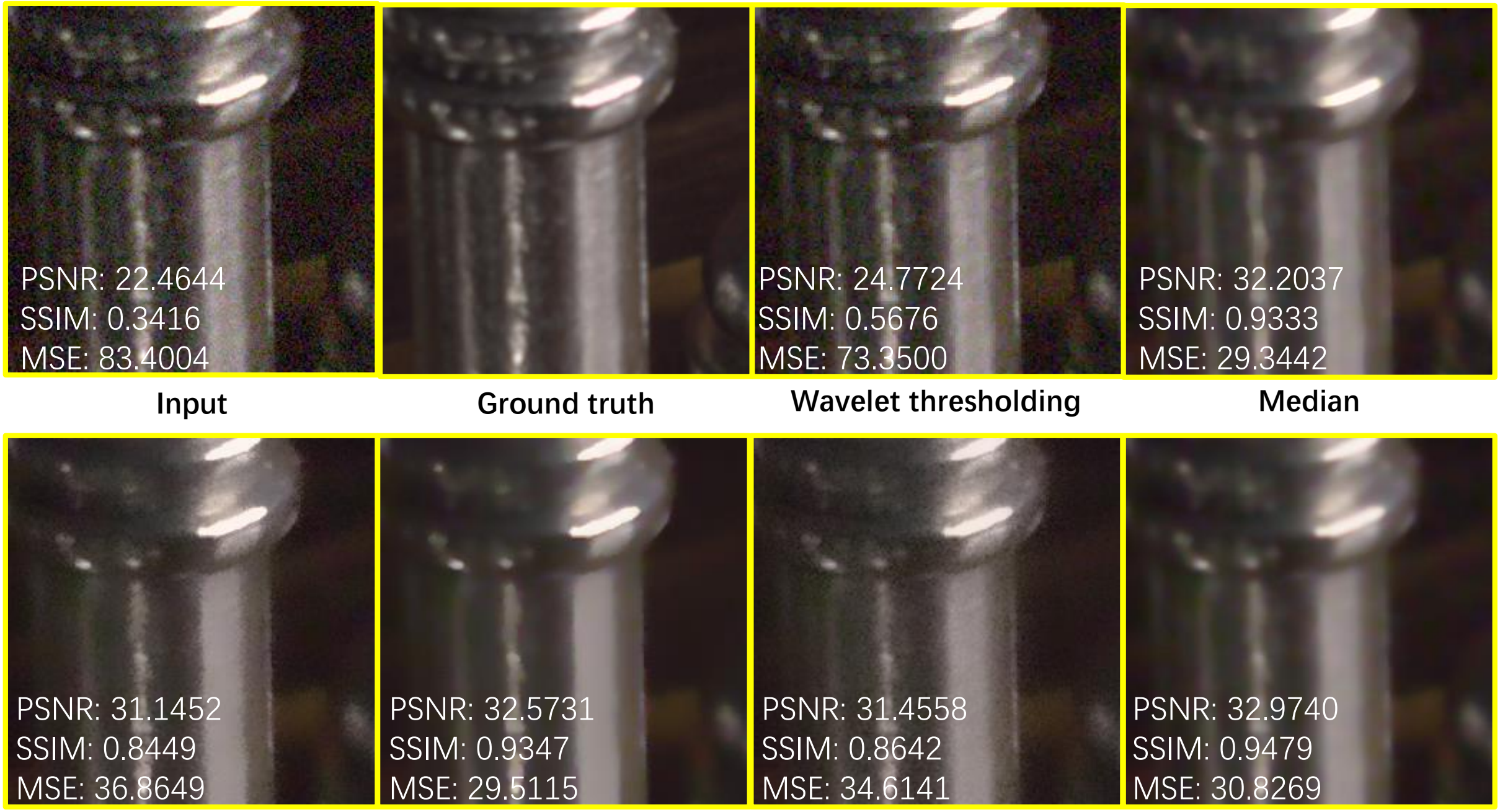
- Window size, SigmaSpace: found by grid search
- SigmaColor: estimated from image

Wavelet decomposition:

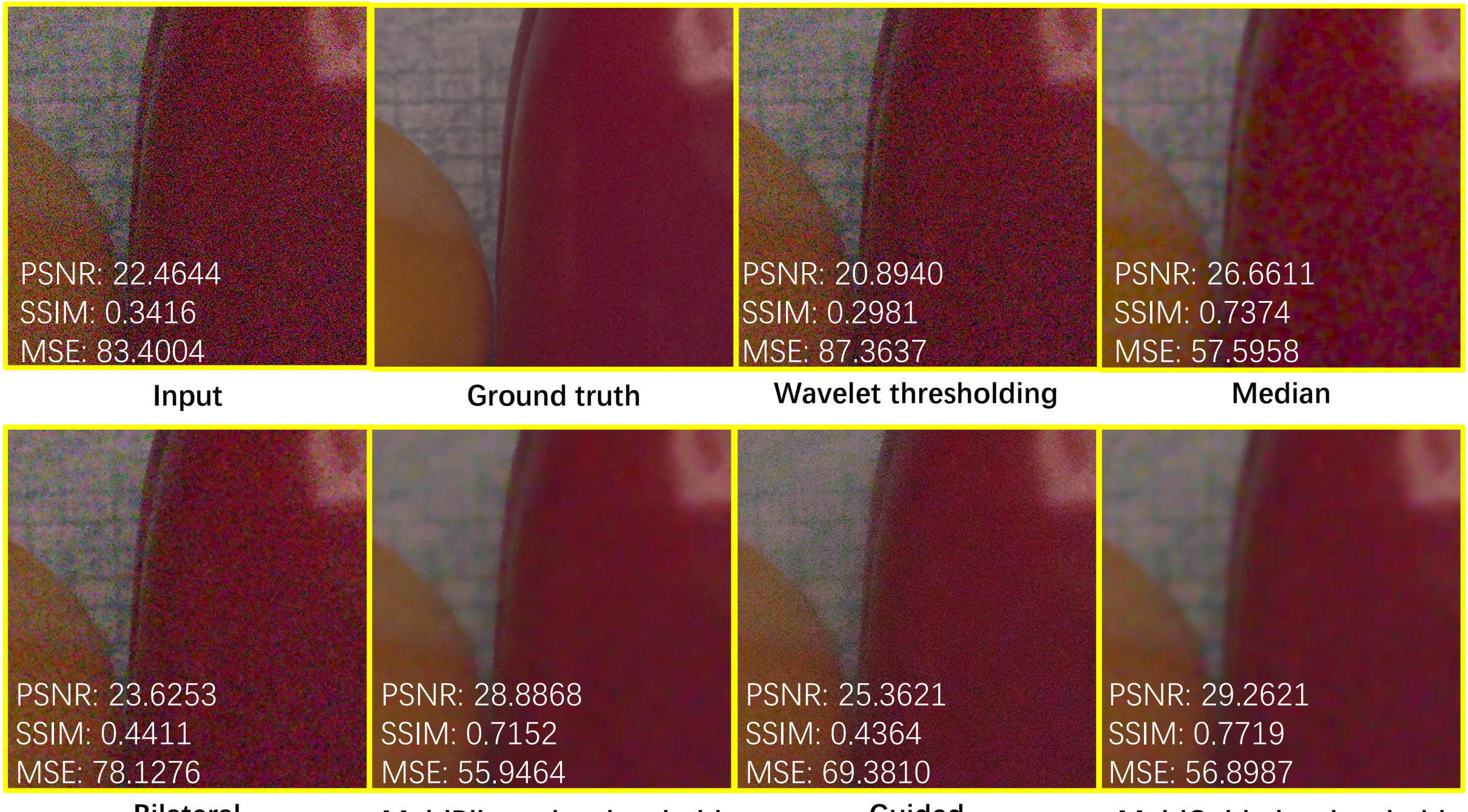
- Number of level, filter type, filter length

Qualitative Result




PSNR: 22.4644
SSIM: 0.3416
MSE: 83.4004
Input
Ground truth
PSNR: 24.7724
SSIM: 0.5676
MSE: 73.3500
Wavelet thresholding
PSNR: 32.2037
SSIM: 0.9333
MSE: 29.3442
Median
PSNR: 31.1452
SSIM: 0.8449
MSE: 36.8649
Bilateral
PSNR: 32.5731
SSIM: 0.9347
MSE: 29.5115
MultiBilateral + threshold
PSNR: 31.4558
SSIM: 0.8642
MSE: 34.6141
Guided
PSNR: 32.9740
SSIM: 0.9479
MSE: 30.8269
MultiGuided + threshold

Qualitative Result


PSNR: 22.4644
SSIM: 0.3416
MSE: 83.4004
Input
Ground truth
PSNR: 20.8940
SSIM: 0.2981
MSE: 87.3637
Wavelet thresholding
PSNR: 26.6611
SSIM: 0.7374
MSE: 57.5958
Median
PSNR: 23.6253
SSIM: 0.4411
MSE: 78.1276
Bilateral
PSNR: 28.8868
SSIM: 0.7152
MSE: 55.9464
MultiBilateral + threshold
PSNR: 25.3621
SSIM: 0.4364
MSE: 69.3810
Guided
PSNR: 29.2621
SSIM: 0.7719
MSE: 56.8987
MultiGuided + threshold

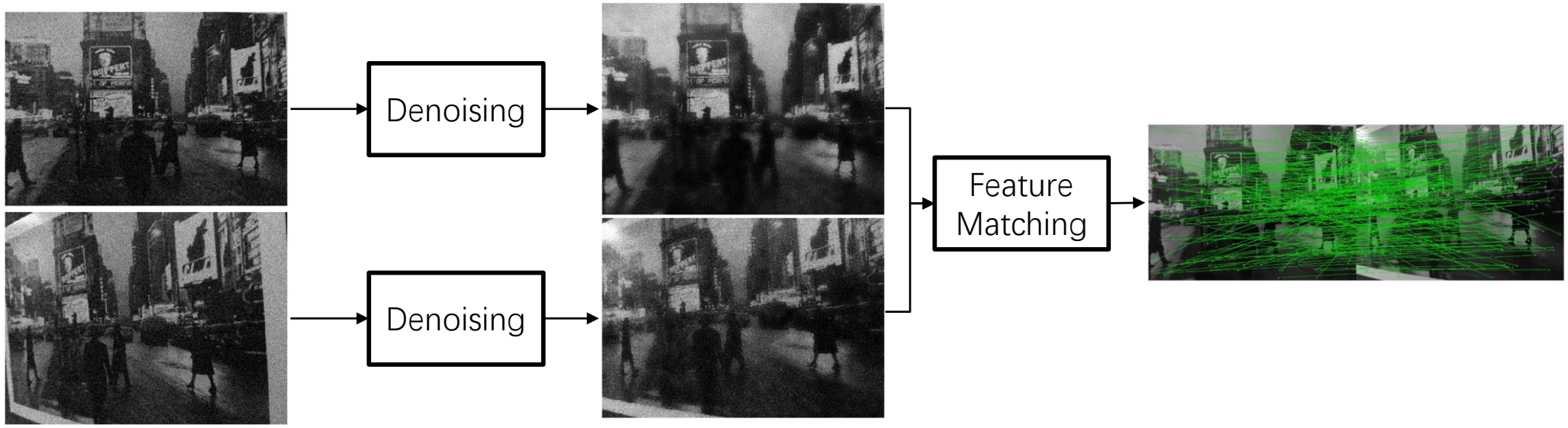
Quantitative Result

Table 1: Denoising result on SIDD small

Method	PSNR	SSIM	MSE
Noisy image	27.65	0.623	54.39
Wavelet thresholding (BayesShrink)	29.61	0.750	44.05
Median	32.32	0.845	25.24
Bilateral	33.22	0.841	28.86
Guided	31.75	0.870	32.80
MultiBilateral	34.45	0.843	23.77
MultiBilateral+threshold[1]	**35.46**	0.869	**21.64**
MultiGuided+threshold	34.86	**0.881**	22.57
DnCNN[2]	23.66	0.583	--
UNet_D[3]	**38.88**	**0.952**	--

[1] Zhang, Ming, et al. "Multiresolution bilateral filtering for image denoising." *IEEE Transactions on image processing*, 2008
[2] Zhang, Kai, et al. "Beyond a Gaussian Denoiser: Residual Learning of Deep CNN for Image Denoising", in CVPR, 2016
[3] Ronneberger, Olaf, et al. "U-Net: Convolutional Networks for Biomedical Image Segmentation", in CVPR 2015

Experiment - Feature matching



The feature matching after denoising pipeline

Feature-preserving denoising algorithm:

Feature matching algorithm is sensitive to noise

Feature matching also wouldn't work if denoising algorithm removes feature

Experiments - metrics for feature matching

Metric for homography estimation: inlier ratio 0~100% (↑ ↑ ↑)

- The mean distance of the four corners w.r.t. ground truth corners
- Set threshold: 1, 3, 5

Homography estimation of an image pair

Experiments - metrics for feature matching

Metrics for detector:

- Repeatability: 0~100% (↑ ↑ ↑)
- Mean localization error (MLE) (↓ ↓ ↓)

Keypoints detected in an image pair

Experiments - metrics for feature matching

Metrics for description:

- Nearest neighbor mean AP (NN mAP): 0~1 (↑ ↑ ↑)
- Matching score (mscore): 0~100% (↑ ↑ ↑)

Keypoints detected in an image pair

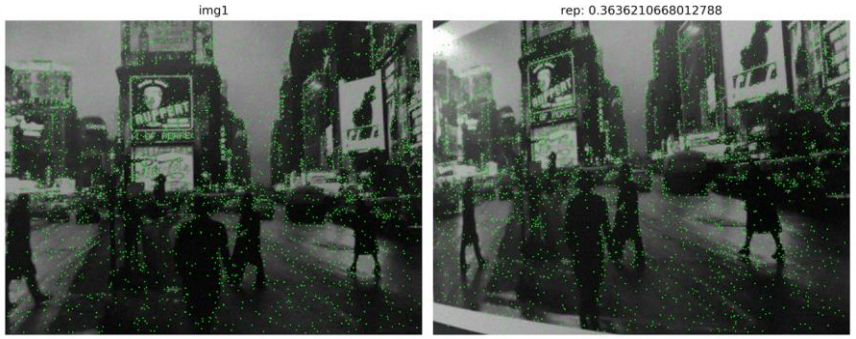
Experiments - metrics for feature matching

Metric for homography estimation: inlier ratio 0~100% (↑ ↑ ↑)

- The mean distance of the four corners w.r.t. ground truth corners
- Set threshold: 1, 3, 5

Metrics for detector:

- Repeatability: 0~100% (↑ ↑ ↑)
- Mean localization error (MLE) (↓ ↓ ↓)



Metrics for description:

- Nearest neighbor mean AP (NN mAP): 0~1 (↑ ↑ ↑)
- Matching score (mscore): 0~100% (↑ ↑ ↑)

Experiments - setting

- **Dataset:** HPatches
- **Parameters:**

No filter	N/A
Median filter	window_size = 5 (visually good)
Bilateral filter	window_size = 11 SigmaColor = sigma*2 [1] SimgaSpace = 1.8
Multiresolution bilateral filter	Bilateral. Wavelet layers: 4
Multiresolution bilateral filter with wavelet thresholding	BayesShrink

- **Noise:** sigma = 0, 5, 10, 15, 20, 25

[1] Zhang, Ming, et al. "Multiresolution bilateral filtering for image denoising." *IEEE Transactions on image processing*, 2018

Feature matching – fixed noise level, different filters

- **Filters:** no filter, median, bilateral, multiresolution bilateral
- **Sigma:** 10

	Homography estimation			Detector metric		Descriptor metrics	
Different filters	1	3	5	Repeatability	MLE	NN mAP	Matching scores
None	0.137	0.176	0.196	0.314	1.75	0.417	0.138
Median	0.0784	0.118	0.137	0.403	1.83	0.359	0.101
Bilateral	0.137	0.157	0.196	0.36	1.8	0.415	0.124
Multi-resolution Bilateral	0.157	**0.255**	**0.275**	0.284	**1.74**	0.448	0.173
Multi-resolution Bilateral threshold	**0.176**	0.235	0.255	**0.307**	**1.74**	**0.449**	**0.178**

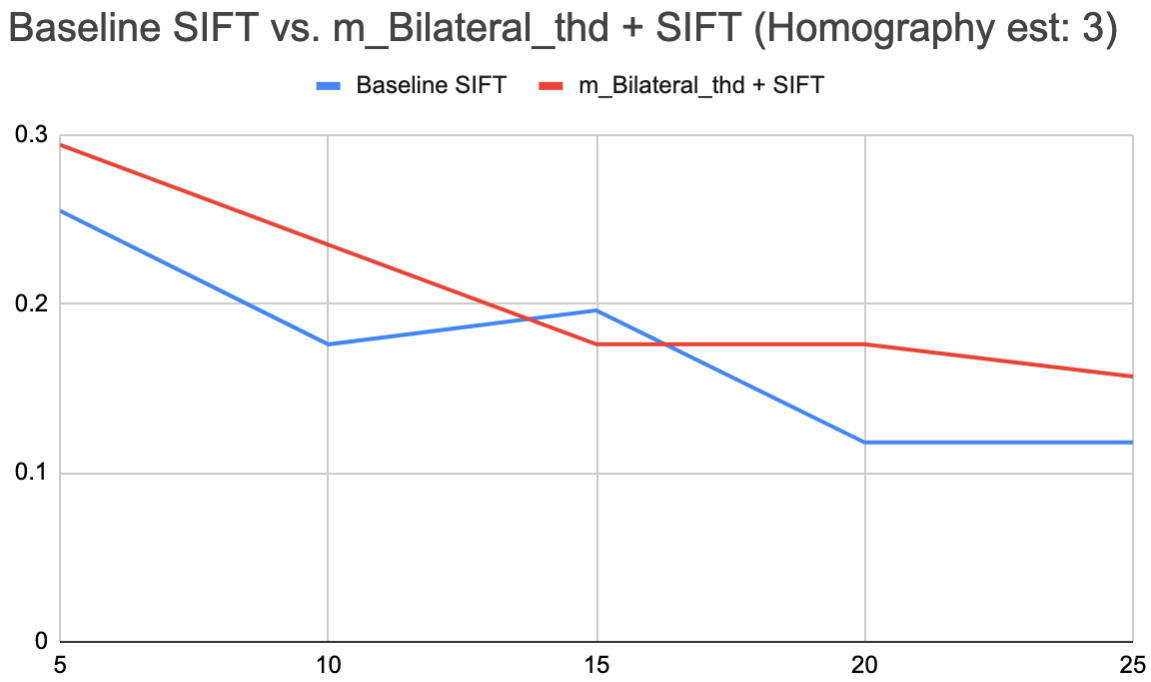
Feature matching – one filter, different noise level

- **Filter:** multi-resolution bilateral with threshold (m_bilateral_thd)
- **Sigma:** 5, 10, 15, 20, 25

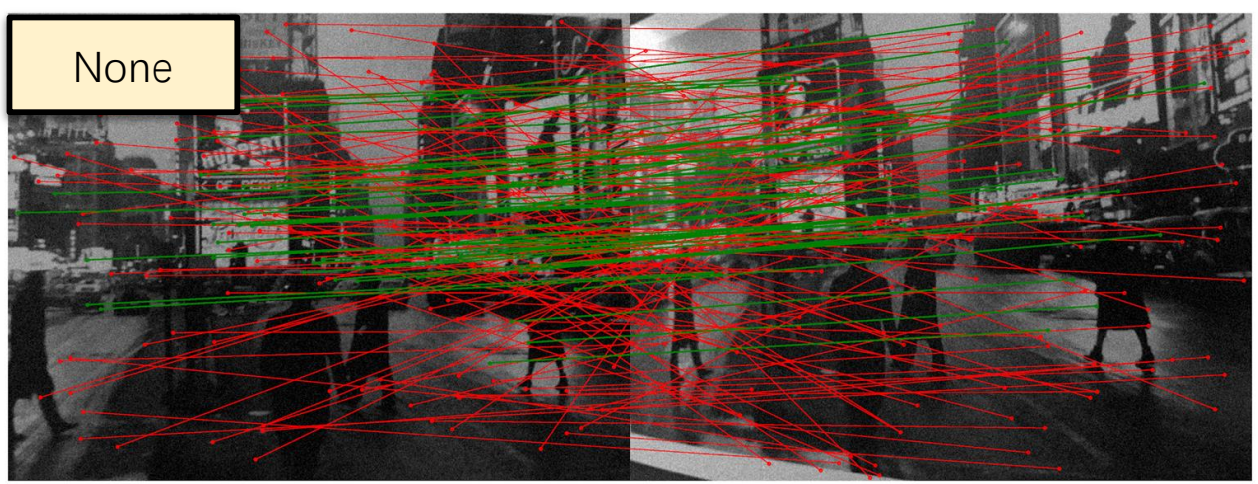
		Homography estimation			Detector metric		Descriptor metrics	
Filters	Sigma	1	3	5	Repeatability	MLE	NN mAP	Matching scores
	5	**0.235**	**0.255**	**0.275**	**0.35**	**1.71**	**0.514**	**0.185**
	10	0.137	0.176	0.196	0.314	1.75	0.417	0.138
	15	0.118	0.196	0.216	0.287	1.78	0.38	0.11
	20	0.0784	0.118	0.137	0.261	1.8	0.324	0.0844
Baseline SIFT	25	0.0784	0.118	0.157	0.242	1.82	0.263	0.0616
	5	**0.255**	**0.294**	**0.294**	**0.351**	**1.7**	**0.519**	**0.206**
	10	0.176	0.235	0.255	0.307	1.74	0.449	0.178
	15	0.157	0.176	0.196	0.266	1.77	0.394	0.155
	20	0.157	0.176	0.196	0.233	1.8	0.355	0.137
m_Bilateral_thd + SIFT	25	0.137	0.157	0.157	0.206	1.79	0.312	0.125

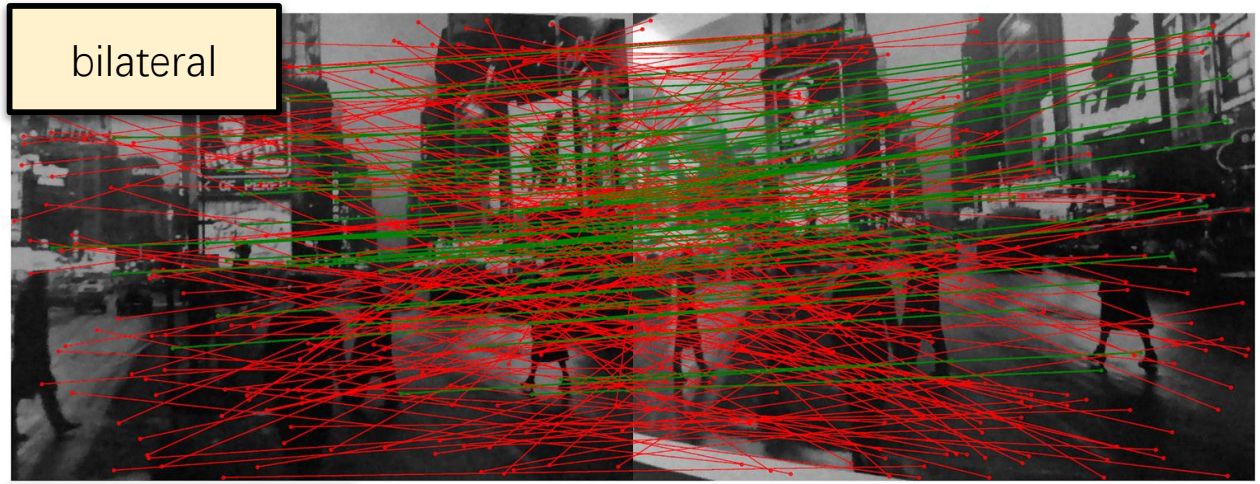
Feature matching – best filter, different noise level

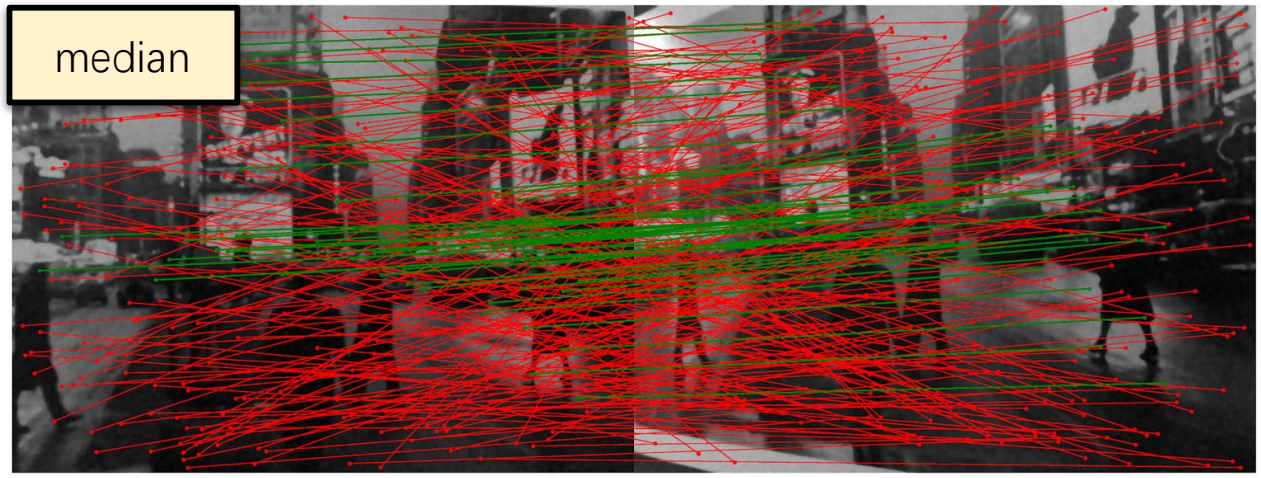
- **Filter:** multi-resolution bilateral with threshold (m_bilateral_thd)
- **Sigma:** 5, 10, 15, 20, 25
- **Homography estimation:** 3

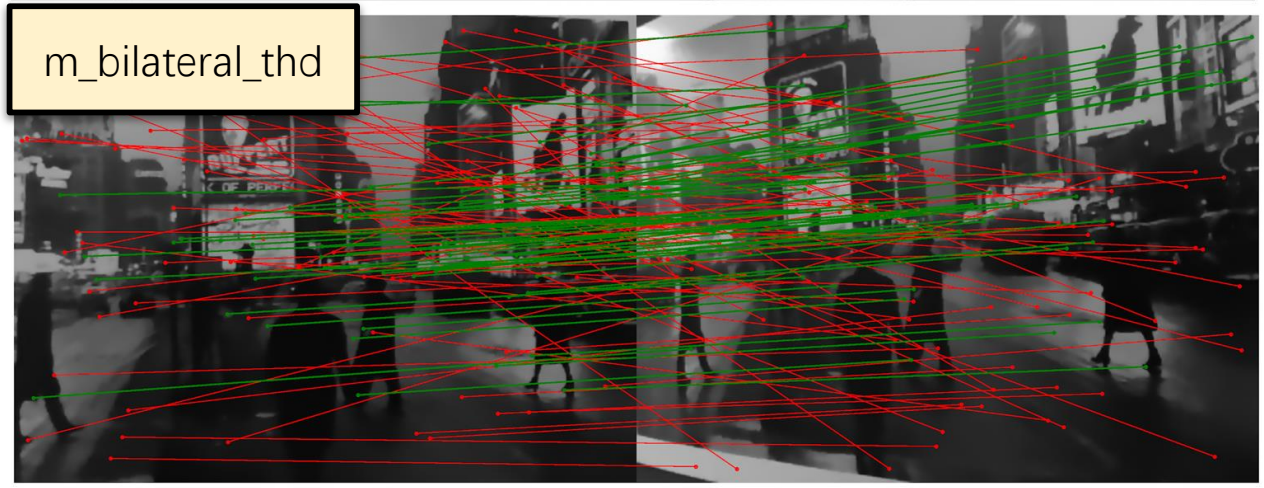


Qualitative results (different filters, noise level: 10)

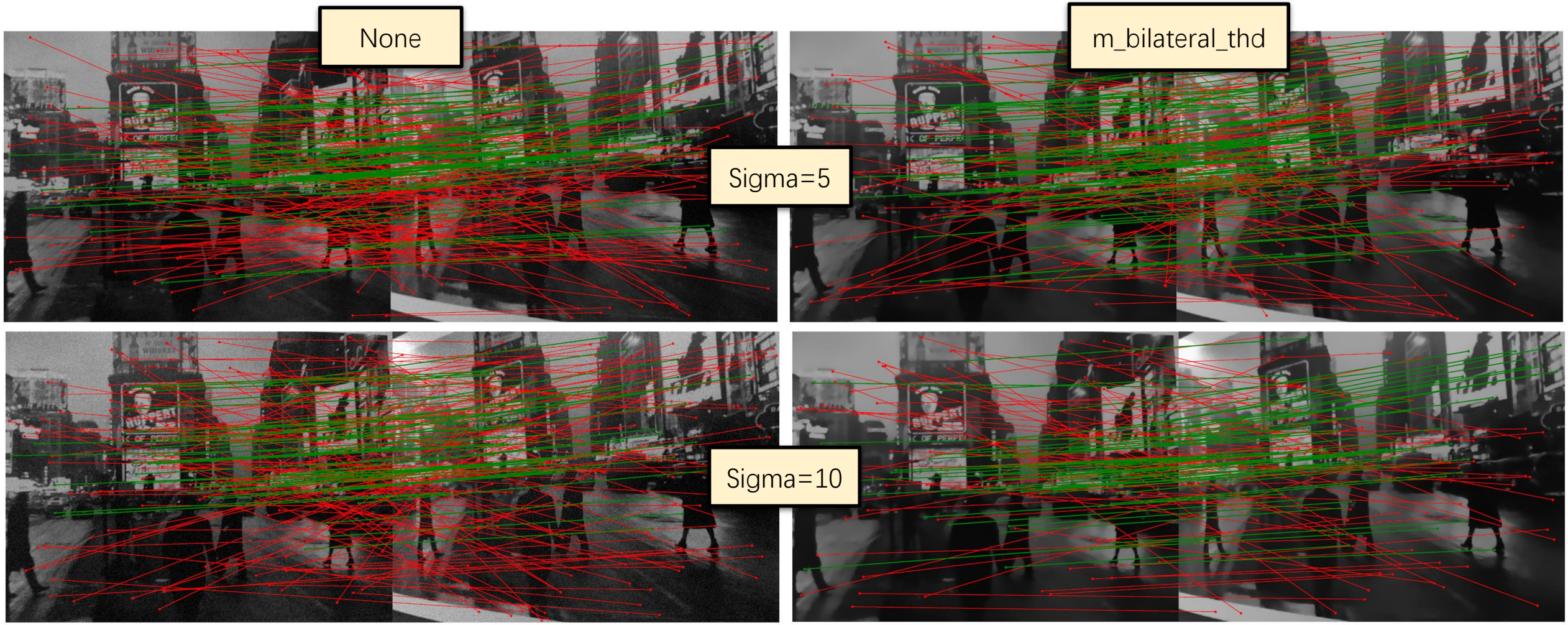




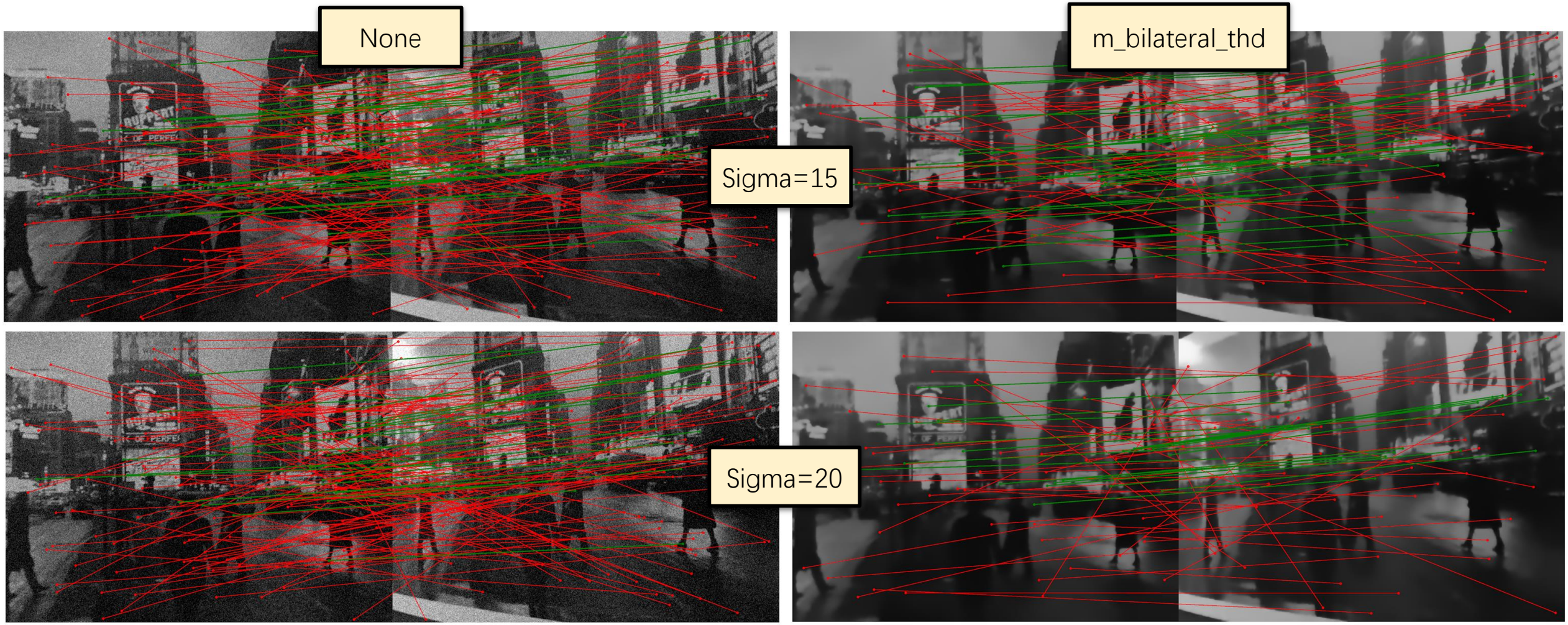




Qualitative results (one filter, different noise levels)



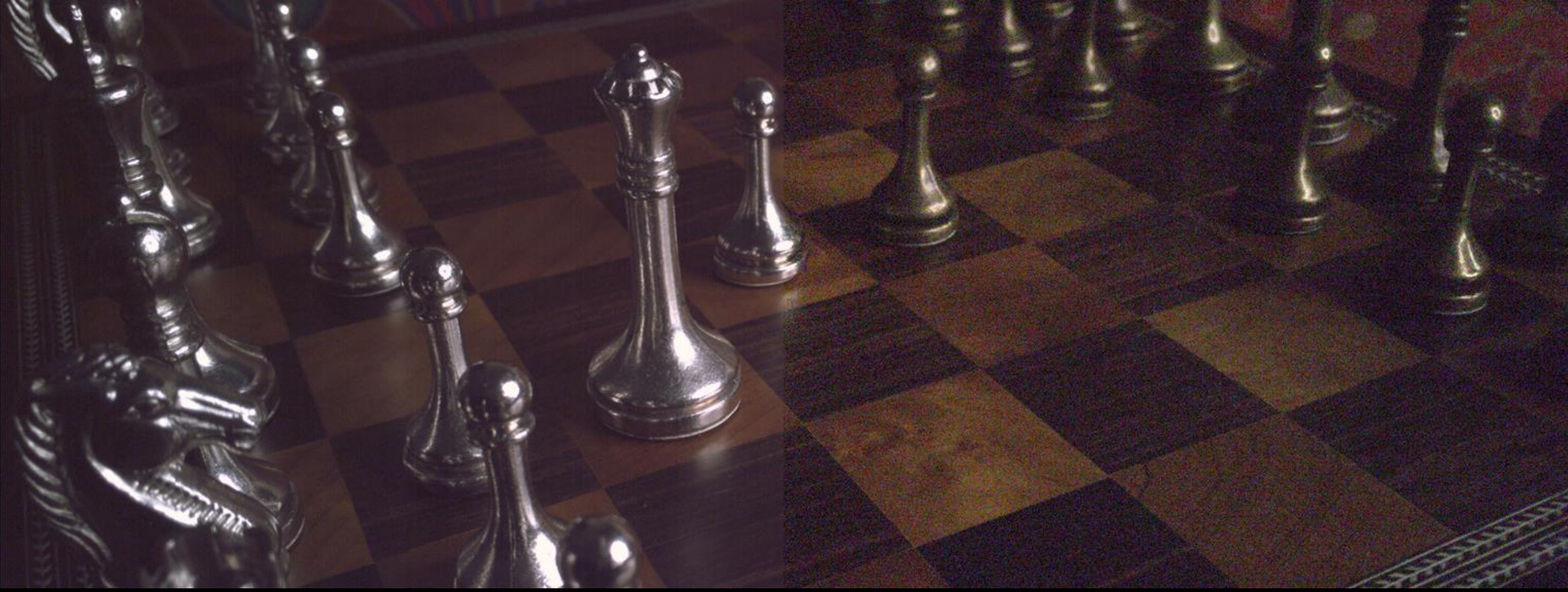
Qualitative results (one filter, different noise levels)



Summary

Conclusion

- Compared median filter, bilateral filter, guided filter and wavelet thresholding
- Implemented multiresolution bilateral filter
- Proposed multiresolution guided filter
- Evaluated the feature-preserving performance by feature matching experiment
- Multiresolution bilateral filter improves the performance



Thank you!

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UCSD ECE 251C Project

References

- [1] Thomas Huang, et al. "A fast two-dimensional median filtering algorithm" (PDF). IEEE Transactions on Acoustics, Speech, and Signal Processing. 1979
- [2] Tomasi, Carlo, and Roberto Manduchi. "Bilateral filtering for gray and color images." *ICCV*. Vol. 98. No. 1. 1998.
- [3] He, Kaiming, Jian Sun, and Xiaoou Tang. "Guided image filtering." *European conference on computer vision*. Springer, Berlin, Heidelberg, 2010.
- [4] Chang, S. Grace, Bin Yu, and Martin Vetterli. "Adaptive wavelet thresholding for image denoising and compression." Image Processing, IEEE Transactions on 9.9 (2000): 1532-1546..
- [5] Zhang, Ming, and Bahadir K. Gunturk. "Multiresolution bilateral filtering for image denoising." *IEEE Transactions on image processing* 17.12 (2008): 2324-2333.
- [6] Zhang, Kai, et al. "Beyond a Gaussian denoiser: Residual learning of deep CNN for image denoising." *IEEE Transactions on Image Processing* 26.7 (2017): 3142-3155.
- [7] Ronneberger, Olaf, Philipp Fischer, and Thomas Brox. "U-net: Convolutional networks for biomedical image segmentation." *International Conference on Medical image computing and computer-assisted intervention*. Springer, Cham, 2015.
- [8] A. Abdelhamed, S. Lin, and M. S. Brown, "A High-Quality Denoising Dataset for Smartphone Cameras", IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2018
- [9] V. Balntas, K. Lenc, A. Vedaldi, and K. Mikolajczyk, "HPatches: A benchmark and evaluation of handcrafted and learned local descriptors," *arXiv:1704.05939 [cs]*, Apr. 2017.
- [10] D. DeTone, T. Malisiewicz, and A. Rabinovich, "SuperPoint: Self-Supervised Interest Point Detection and Description," *arXiv:1712.07629 [cs]*, Dec. 2017.
- [11] Aurich, Volker, and Jörg Weule. "Non-linear gaussian filters performing edge preserving diffusion." *Mustererkennung 1995*. Springer, Berlin, Heidelberg, 1995. 538-545.