

Decomposable Nonlocal Tensor Dictionary Learning for Multispectral Image Denoising: Supplementary Material

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Abstract

This supplementary material lists the detailed PQI comparison for the experiments on the Columbia MSI dataset.

We have used two types of noises commonly existed in real MSIs. One is the additive white Gaussian noise (AWGN), which comes from many natural sources, such as the spontaneous thermal generation of electrons. And the other is the Poisson noise (also known as shot noise) which is originated from the mechanism of quantized photons and uniform exposure. We parameterized AWGN by its standard deviation σ , and Poisson noise by the variance $\mathcal{H}/2^\kappa$ where \mathcal{H} is the noise-free signal. We designed two series of experiments. In the first series, we perturbed each of the 32 Columbia MSIs with mixture of Gaussian noises with deviations varying from $\sigma = 0.1$ to $\sigma = 0.3$ at step 0.05 and Poisson noise with fixed $\kappa = 5$. In the second series, we embedded each of the 32 Columbia MSIs with mixture of Poisson noise with variances varying from 2 to 6 and Gaussian noise with fixed $\sigma = 0.1$. The results are summarized in Tables 1 and 2, respectively.

From these two tables, it can be easily observed that the proposed method outperforms all other competing methods in all noise cases with respect to all of the five PQI measures, only except that $\sigma \leq 0.2$ in first experiments and $\kappa = 2, 5, 6$ for the second experiments, our method performs unsubstantially less than BM4D with respect to only two PQI measures (PSNR and ERGAS). And in average, our method performs best with respect to all PQIs.

	PSNR	SSIM	FSIM	ERGAS	SAM
$\sigma = 0.1$					
<i>Noisy image</i>	19.82 \pm 0.11	0.131 \pm 0.056	0.640 \pm 0.098	585.0 \pm 161.6	0.970 \pm 0.233
BwK-SVD	29.23 \pm 1.25	0.555 \pm 0.028	0.881 \pm 0.026	192.8 \pm 37.0	0.519 \pm 0.164
BwBM3D	36.86 \pm 2.81	0.910 \pm 0.035	0.950 \pm 0.010	82.4 \pm 24.9	0.238 \pm 0.102
IntK-SVD	31.41 \pm 1.25	0.675 \pm 0.022	0.922 \pm 0.020	153.7 \pm 28.1	0.499 \pm 0.170
ANLM3D	35.94 \pm 1.68	0.865 \pm 0.016	0.937 \pm 0.021	89.9 \pm 16.4	0.346 \pm 0.144
BM4D	39.60 \pm 2.29	0.944 \pm 0.016	0.966 \pm 0.011	59.5 \pm 13.1	0.218 \pm 0.104
LRTA	36.92 \pm 2.79	0.907 \pm 0.042	0.955 \pm 0.011	81.8 \pm 25.2	0.195 \pm 0.077
PARAFAC	30.45 \pm 2.93	0.824 \pm 0.090	0.900 \pm 0.038	172.8 \pm 57.9	0.310 \pm 0.110
<i>Ours</i>	39.31 \pm 2.54	0.953 \pm 0.018	0.975 \pm 0.006	61.4 \pm 14.8	0.133 \pm 0.047
$\sigma = 0.15$					
<i>Noisy image</i>	16.40 \pm 0.05	0.071 \pm 0.039	0.525 \pm 0.112	869.9 \pm 244.6	1.080 \pm 0.212
BwK-SVD	27.08 \pm 1.19	0.435 \pm 0.026	0.832 \pm 0.032	246.9 \pm 46.9	0.579 \pm 0.166
BwBM3D	34.70 \pm 2.69	0.866 \pm 0.044	0.928 \pm 0.013	105.3 \pm 30.7	0.299 \pm 0.121
IntK-SVD	29.29 \pm 1.30	0.569 \pm 0.022	0.887 \pm 0.023	195.9 \pm 35.1	0.552 \pm 0.172
ANLM3D	33.29 \pm 1.42	0.772 \pm 0.021	0.896 \pm 0.030	121.7 \pm 22.2	0.425 \pm 0.160
BM4D	37.46 \pm 2.20	0.914 \pm 0.023	0.952 \pm 0.012	76.3 \pm 16.4	0.278 \pm 0.123
LRTA	34.99 \pm 2.74	0.875 \pm 0.056	0.938 \pm 0.014	102.0 \pm 30.8	0.219 \pm 0.080
PARAFAC	28.84 \pm 2.90	0.782 \pm 0.099	0.878 \pm 0.047	207.1 \pm 62.3	0.355 \pm 0.109
<i>Ours</i>	37.23 \pm 2.51	0.932 \pm 0.026	0.962 \pm 0.008	77.7 \pm 18.4	0.161 \pm 0.062
$\sigma = 0.2$					
<i>Noisy image</i>	13.93 \pm 0.03	0.045 \pm 0.028	0.446 \pm 0.116	1156.1 \pm 327.2	1.154 \pm 0.192
BwK-SVD	25.43 \pm 1.15	0.346 \pm 0.028	0.787 \pm 0.038	298.6 \pm 56.9	0.624 \pm 0.163
BwBM3D	33.10 \pm 2.57	0.825 \pm 0.050	0.908 \pm 0.016	126.0 \pm 35.1	0.348 \pm 0.132
IntK-SVD	27.71 \pm 1.33	0.480 \pm 0.026	0.856 \pm 0.025	235.1 \pm 41.5	0.590 \pm 0.170
ANLM3D	33.84 \pm 2.81	0.876 \pm 0.048	0.931 \pm 0.017	118.8 \pm 30.1	0.317 \pm 0.126
BM4D	35.89 \pm 2.14	0.884 \pm 0.028	0.938 \pm 0.013	91.4 \pm 19.4	0.323 \pm 0.134
LRTA	33.57 \pm 2.74	0.847 \pm 0.067	0.923 \pm 0.018	120.1 \pm 36.2	0.237 \pm 0.083
PARAFAC	27.37 \pm 2.88	0.739 \pm 0.102	0.860 \pm 0.057	245.2 \pm 65.0	0.401 \pm 0.119
<i>Ours</i>	35.85 \pm 2.56	0.913 \pm 0.032	0.951 \pm 0.009	91.0 \pm 21.6	0.184 \pm 0.071
$\sigma = 0.25$					
<i>Noisy image</i>	12.01 \pm 0.02	0.031 \pm 0.021	0.389 \pm 0.116	1443.1 \pm 409.7	1.209 \pm 0.175
BwK-SVD	24.09 \pm 1.05	0.281 \pm 0.026	0.747 \pm 0.045	349.1 \pm 71.2	0.660 \pm 0.162
BwBM3D	31.83 \pm 2.46	0.787 \pm 0.054	0.889 \pm 0.018	145.2 \pm 38.4	0.390 \pm 0.141
IntK-SVD	26.46 \pm 1.29	0.408 \pm 0.024	0.827 \pm 0.028	272.4 \pm 51.3	0.621 \pm 0.170
ANLM3D	32.89 \pm 2.69	0.848 \pm 0.049	0.916 \pm 0.017	131.5 \pm 32.6	0.352 \pm 0.137
BM4D	34.67 \pm 2.10	0.856 \pm 0.032	0.924 \pm 0.014	105.1 \pm 21.9	0.361 \pm 0.144
LRTA	32.45 \pm 2.71	0.822 \pm 0.075	0.910 \pm 0.021	136.6 \pm 41.1	0.253 \pm 0.084
PARAFAC	26.22 \pm 2.84	0.705 \pm 0.105	0.843 \pm 0.061	282.8 \pm 81.7	0.428 \pm 0.129
<i>Ours</i>	34.85 \pm 2.58	0.895 \pm 0.036	0.941 \pm 0.009	102.2 \pm 25.2	0.206 \pm 0.083
$\sigma = 0.3$					
<i>Noisy image</i>	10.44 \pm 0.01	0.022 \pm 0.016	0.345 \pm 0.113	1730.2 \pm 492.0	1.251 \pm 0.159
BwK-SVD	23.01 \pm 0.98	0.235 \pm 0.025	0.712 \pm 0.050	395.3 \pm 79.9	0.689 \pm 0.158
BwBM3D	30.79 \pm 2.37	0.751 \pm 0.055	0.872 \pm 0.019	163.2 \pm 41.1	0.424 \pm 0.145
IntK-SVD	25.47 \pm 1.27	0.354 \pm 0.023	0.801 \pm 0.030	305.5 \pm 56.2	0.645 \pm 0.168
ANLM3D	32.09 \pm 2.59	0.820 \pm 0.048	0.902 \pm 0.017	143.4 \pm 34.5	0.383 \pm 0.146
BM4D	33.66 \pm 2.07	0.829 \pm 0.036	0.911 \pm 0.015	117.8 \pm 24.0	0.391 \pm 0.148
LRTA	31.56 \pm 2.72	0.801 \pm 0.082	0.898 \pm 0.024	151.5 \pm 45.7	0.265 \pm 0.086
PARAFAC	25.43 \pm 3.12	0.684 \pm 0.106	0.829 \pm 0.065	308.7 \pm 84.6	0.444 \pm 0.118
<i>Ours</i>	34.01 \pm 2.60	0.876 \pm 0.041	0.931 \pm 0.010	112.5 \pm 28.0	0.225 \pm 0.088

Table 1. Average performance comparison of 8 competing methods with respect to 5 PQIs for our first series of experiments. Each result is obtained by averaging through the 32 scenes.

	PSNR	SSIM	FSIM	ERGAS	SAM
$\kappa = 6$					
Noisy image	19.33 \pm 0.37	0.118 \pm 0.050	0.625 \pm 0.097	612.4 \pm 154.4	0.987 \pm 0.225
BwK-SVD	28.65 \pm 1.36	0.531 \pm 0.031	0.872 \pm 0.027	204.9 \pm 35.8	0.525 \pm 0.160
BwBM3D	36.25 \pm 2.86	0.904 \pm 0.038	0.946 \pm 0.011	88.2 \pm 26.8	0.238 \pm 0.098
IntK-SVD	30.86 \pm 1.38	0.655 \pm 0.025	0.916 \pm 0.020	162.7 \pm 27.1	0.503 \pm 0.167
ANLM3D	35.31 \pm 1.75	0.851 \pm 0.017	0.930 \pm 0.022	96.2 \pm 16.7	0.351 \pm 0.141
BM4D	39.02 \pm 2.34	0.939 \pm 0.018	0.964 \pm 0.011	63.3 \pm 13.7	0.221 \pm 0.101
LRTA	36.44 \pm 2.82	0.904 \pm 0.043	0.953 \pm 0.011	86.3 \pm 26.3	0.192 \pm 0.076
PARAFAC	29.42 \pm 2.96	0.805 \pm 0.094	0.889 \pm 0.041	195.3 \pm 62.8	0.329 \pm 0.111
Ours	38.74 \pm 2.59	0.950 \pm 0.020	0.973 \pm 0.006	65.3 \pm 15.5	0.135 \pm 0.047
$\kappa = 5$					
Noisy image	18.76 \pm 0.64	0.106 \pm 0.044	0.608 \pm 0.096	647.5 \pm 146.1	1.007 \pm 0.215
BwK-SVD	28.18 \pm 1.55	0.516 \pm 0.037	0.863 \pm 0.028	215.3 \pm 34.0	0.525 \pm 0.153
BwBM3D	35.49 \pm 2.84	0.892 \pm 0.041	0.941 \pm 0.011	96.1 \pm 28.8	0.241 \pm 0.093
IntK-SVD	30.59 \pm 1.63	0.656 \pm 0.034	0.913 \pm 0.019	166.7 \pm 24.4	0.496 \pm 0.159
ANLM3D	34.14 \pm 1.66	0.811 \pm 0.019	0.915 \pm 0.025	109.6 \pm 18.1	0.373 \pm 0.142
BM4D	38.24 \pm 2.32	0.929 \pm 0.020	0.961 \pm 0.011	69.1 \pm 14.7	0.230 \pm 0.100
LRTA	35.74 \pm 2.99	0.896 \pm 0.053	0.947 \pm 0.013	94.1 \pm 30.6	0.194 \pm 0.073
PARAFAC	29.09 \pm 3.12	0.804 \pm 0.097	0.884 \pm 0.045	202.0 \pm 63.6	0.321 \pm 0.103
Ours	38.12 \pm 2.64	0.946 \pm 0.022	0.970 \pm 0.006	69.9 \pm 16.6	0.137 \pm 0.047
$\kappa = 4$					
Noisy image	17.80 \pm 1.00	0.089 \pm 0.036	0.582 \pm 0.094	714.5 \pm 132.7	1.042 \pm 0.199
BwK-SVD	27.74 \pm 1.79	0.517 \pm 0.043	0.853 \pm 0.028	225.6 \pm 32.5	0.514 \pm 0.142
BwBM3D	33.98 \pm 2.61	0.850 \pm 0.045	0.929 \pm 0.013	113.7 \pm 31.6	0.263 \pm 0.092
IntK-SVD	30.59 \pm 1.97	0.686 \pm 0.046	0.914 \pm 0.018	166.1 \pm 22.9	0.469 \pm 0.147
ANLM3D	31.68 \pm 1.34	0.699 \pm 0.028	0.879 \pm 0.035	145.0 \pm 24.6	0.433 \pm 0.149
BM4D	36.76 \pm 2.14	0.901 \pm 0.026	0.954 \pm 0.011	81.7 \pm 16.8	0.258 \pm 0.105
LRTA	34.64 \pm 3.13	0.881 \pm 0.064	0.938 \pm 0.017	107.1 \pm 35.8	0.201 \pm 0.074
PARAFAC	30.42 \pm 3.58	0.829 \pm 0.093	0.899 \pm 0.041	176.7 \pm 67.0	0.292 \pm 0.100
Ours	37.24 \pm 2.81	0.939 \pm 0.027	0.965 \pm 0.006	77.6 \pm 19.6	0.142 \pm 0.053
$\kappa = 3$					
Noisy image	16.57 \pm 1.36	0.072 \pm 0.028	0.549 \pm 0.093	814.3 \pm 117.0	1.087 \pm 0.180
BwK-SVD	27.60 \pm 2.20	0.552 \pm 0.066	0.843 \pm 0.031	228.3 \pm 29.8	0.495 \pm 0.133
BwBM3D	33.19 \pm 2.83	0.852 \pm 0.050	0.918 \pm 0.016	124.1 \pm 34.8	0.270 \pm 0.095
IntK-SVD	29.57 \pm 2.18	0.674 \pm 0.058	0.896 \pm 0.021	186.2 \pm 27.8	0.472 \pm 0.142
ANLM3D	29.26 \pm 1.30	0.575 \pm 0.038	0.841 \pm 0.043	190.7 \pm 30.3	0.496 \pm 0.150
BM4D	35.95 \pm 2.40	0.900 \pm 0.028	0.945 \pm 0.011	89.6 \pm 18.3	0.269 \pm 0.108
LRTA	33.78 \pm 3.28	0.855 \pm 0.072	0.927 \pm 0.020	117.8 \pm 40.3	0.236 \pm 0.092
PARAFAC	31.80 \pm 3.19	0.813 \pm 0.070	0.911 \pm 0.032	148.3 \pm 57.8	0.319 \pm 0.124
Ours	36.25 \pm 2.88	0.929 \pm 0.031	0.960 \pm 0.006	87.1 \pm 22.6	0.149 \pm 0.053
$\kappa = 2$					
Noisy image	14.77 \pm 1.73	0.053 \pm 0.019	0.503 \pm 0.090	993.0 \pm 96.8	1.153 \pm 0.153
BwK-SVD	26.88 \pm 2.33	0.524 \pm 0.075	0.814 \pm 0.038	247.9 \pm 32.5	0.512 \pm 0.134
BwBM3D	31.80 \pm 2.86	0.822 \pm 0.057	0.896 \pm 0.020	145.3 \pm 39.9	0.323 \pm 0.115
IntK-SVD	28.14 \pm 2.55	0.637 \pm 0.076	0.868 \pm 0.029	219.8 \pm 41.1	0.489 \pm 0.140
ANLM3D	27.27 \pm 1.60	0.496 \pm 0.047	0.803 \pm 0.052	237.3 \pm 27.9	0.543 \pm 0.143
BM4D	34.67 \pm 2.58	0.883 \pm 0.034	0.930 \pm 0.013	104.6 \pm 21.9	0.317 \pm 0.125
LRTA	25.96 \pm 3.79	0.522 \pm 0.142	0.817 \pm 0.050	298.4 \pm 114.9	0.533 \pm 0.187
PARAFAC	30.62 \pm 2.79	0.761 \pm 0.066	0.897 \pm 0.029	167.1 \pm 53.4	0.354 \pm 0.126
Ours	34.34 \pm 2.85	0.885 \pm 0.043	0.948 \pm 0.008	107.7 \pm 28.2	0.187 \pm 0.062

Table 2. Average performance comparison of 8 competing methods with respect to 5 PQIs for our second series of experiments. Each result is obtained by averaging through the 32 scenes.