# Burst Denoising with Kernel Prediction Networks
# Supplemental Material

Ben Mildenhall[1,2*] Jonathan T. Barron[2] Jiawen Chen[2]
Dillon Sharlet[2] Ren Ng[1] Robert Carroll[2]
[1]UC Berkeley [2]Google Research

## 1. Derivation of noise model parameters

We can calculate the variance of our output signal as a function of the analog and digital gains we apply to the photoelectron count on the sensor as well as the read noise:

| | True signal | Variance |
|---|---|---|
| Initial photoe. count | $q$ | $q$ |
| Analog gain $g_a$ | $g_a q$ | $g_a^2 q$ |
| Readout w/ var. $r^2$ | $g_a q$ | $g_a^2 q + r^2$ |
| Digital gain $g_d$ | $g_d g_a q$ | $g_d^2 g_a^2 q + g_d^2 r^2$ |

Our measured output is thus $z = g_d g_a q$ with variance $(g_d g_a) z + (g_d r)^2$. In terms of the parameters used in the main text, this gives $\sigma_s = g_d g_a$ and $\sigma_r^2 = g_d^2 r^2$. Note that $r$ is fixed but $g_a$ and $g_d$ are controlled by the camera. See [4] for more details.

## 2. Baseline evaluation details

### 2.1. VBM4D

For our VBM4D [5] comparisons, we estimate a single noise level for each burst as

$$\sigma_{rms} = \sqrt{\sum_p \hat{\sigma}_p^2} \tag{1}$$

where $p$ varies over all pixels in the reference frame.

To generate Table 1 in the main text, we ran all methods on a synthetic test set in a linear color space with added shot and read noise. To evaluate VBM4D [5] fairly, we tried running it both on linear data as-is and on the data after additionally applying gamma correction. We found the final gamma-corrected PSNR to be better after running on the original linear data, likely because of the loss of information from clipping negative values when applying gamma correction before denoising. (We also found this to be the case when running single image BM3D [2] on the reference frame only.)

*Work done while interning at Google.

We additionally ran a parameter sweep over a multiplier for $\sigma_{rms}$, testing VBM4D with noise parameter $k\sigma_{rms}$ for $k \in [.5, 1, 2, 3]$, with $k = 1$ producing the best results.

To generate Table 2, we used a test set in a gamma corrected color space with added constant variance Gaussian noise. VBM4D is designed to work best in this setting, so we did not try any variations.

### 2.2. Nonlocal means

Nonlocal means [1] takes a single noise parameter. For the NLM comparisons, we run a parameter sweep over $k\sigma_{rms}$ with $k \in [.5, 1, 2, 3, 4]$. We find that $k = 2$ produces the best results.

### 2.3. HDR+

The merge technique in HDR+ takes a single free parameter $c$ (see equation 7 in [3]). We find that $c \approx 10^{2.5}$ works best on average for our linear data in $[0, 1]$.

## 3. Additional results

We include more synthetic and real comparisons below.

## References

[1] A. Buades, B. Coll, and J. M. Morel. A non-local algorithm for image denoising. *CVPR*, 2005. 1

[2] K. Dabov, A. Foi, V. Katkovnik, and K. Egiazarian. Image denoising by sparse 3-d transform-domain collaborative filtering. *IEEE Transactions on Image Processing*, 2007. 1

[3] S. W. Hasinoff, D. Sharlet, R. Geiss, A. Adams, J. T. Barron, F. Kainz, J. Chen, and M. Levoy. Burst photography for high dynamic range and low-light imaging on mobile cameras. *SIGGRAPH Asia*, 2016. 1

[4] G. Healey and R. Kondepudy. Radiometric CCD camera calibration and noise estimation. *TPAMI*, 1994. 1

[5] M. Maggioni, G. Boracchi, A. Foi, and K. Egiazarian. Video denoising, deblocking, and enhancement through separable 4-d nonlocal spatiotemporal transforms. *IEEE Transactions on Image Processing*, 2012. 1

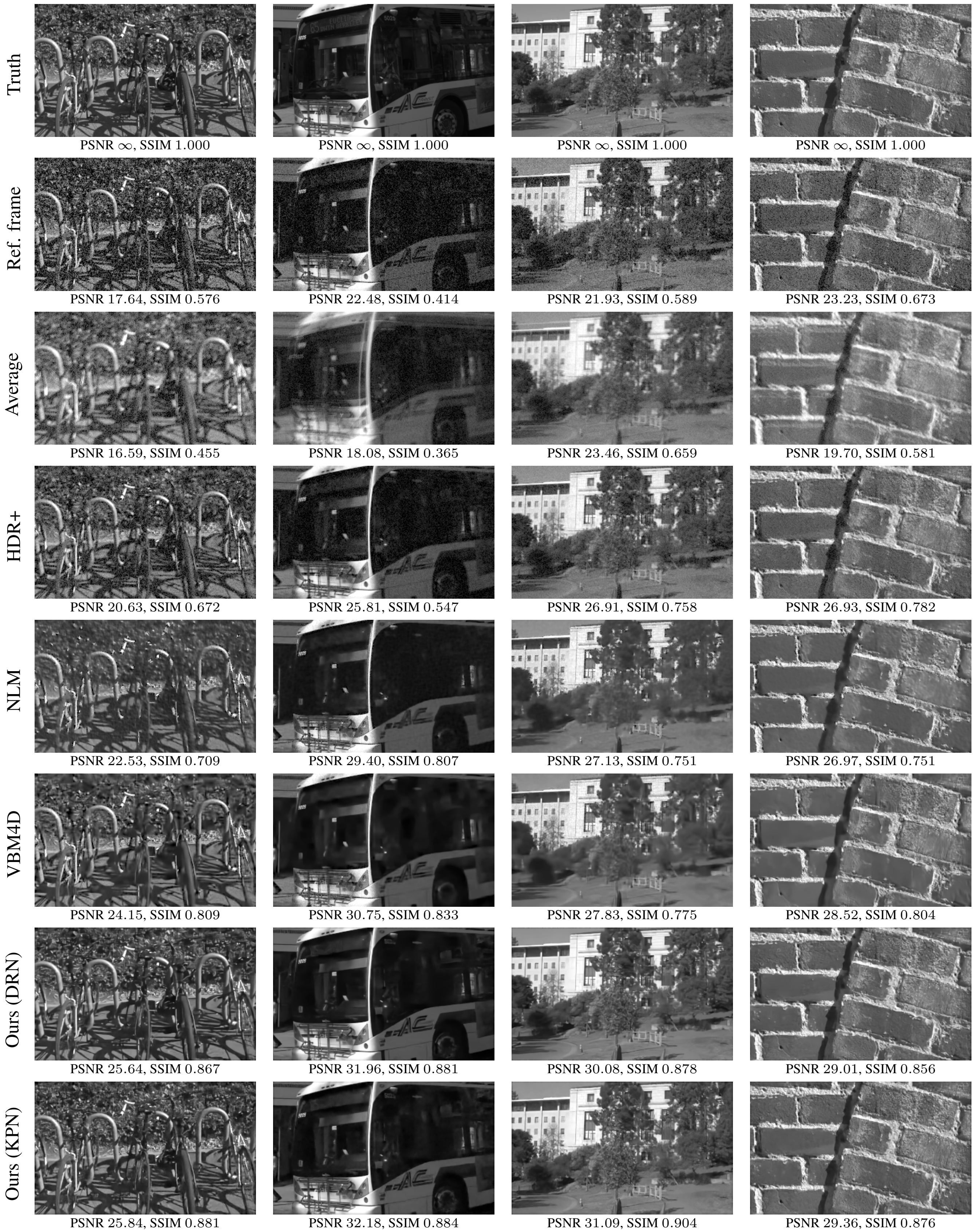


Figure 1: Example results from our synthetic test set at gain $\propto 2$ (Table 1 column 2 in main text).

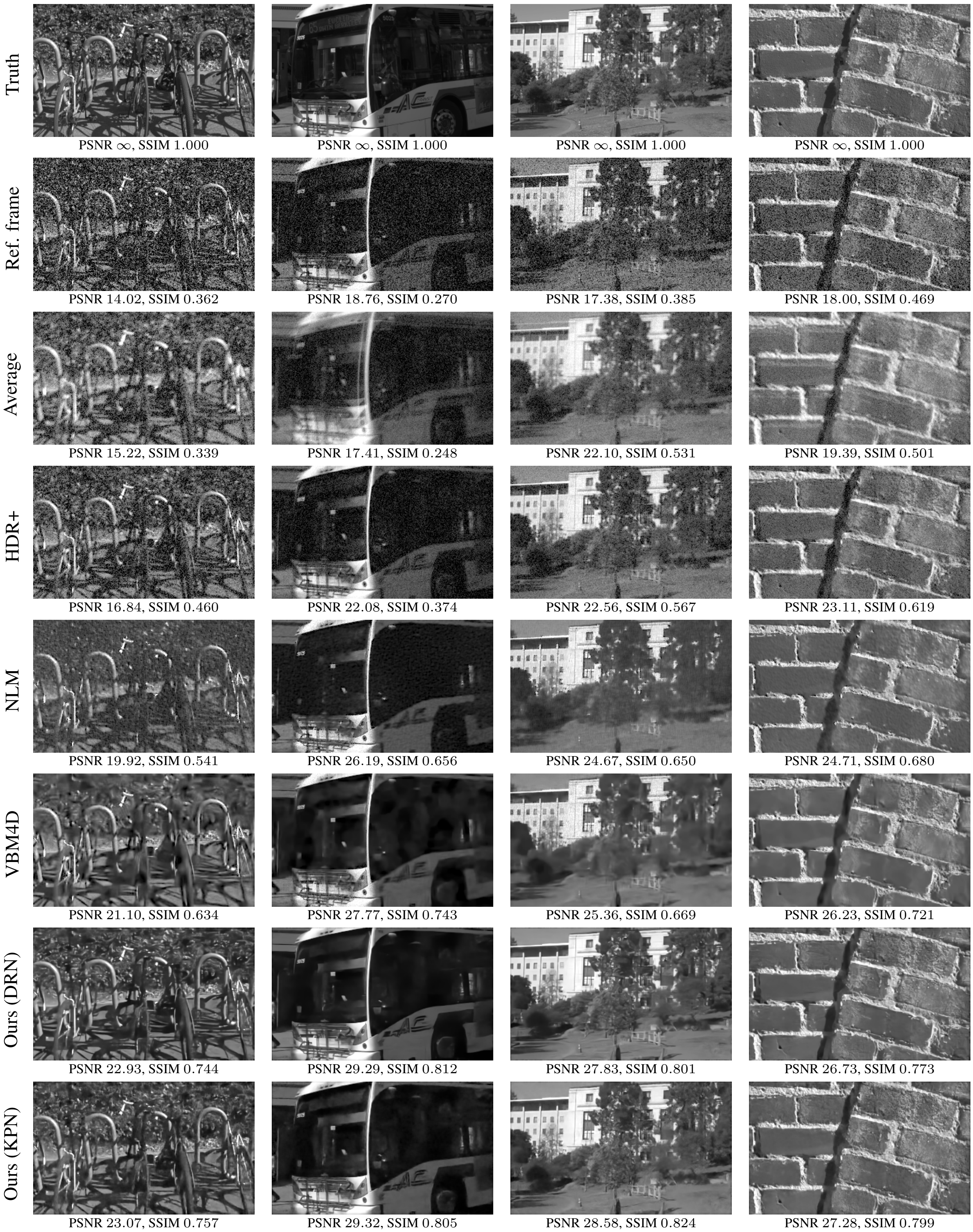


Figure 2: Example results from our synthetic test set at gain $\propto 4$ (Table 1 column 3 in main text).

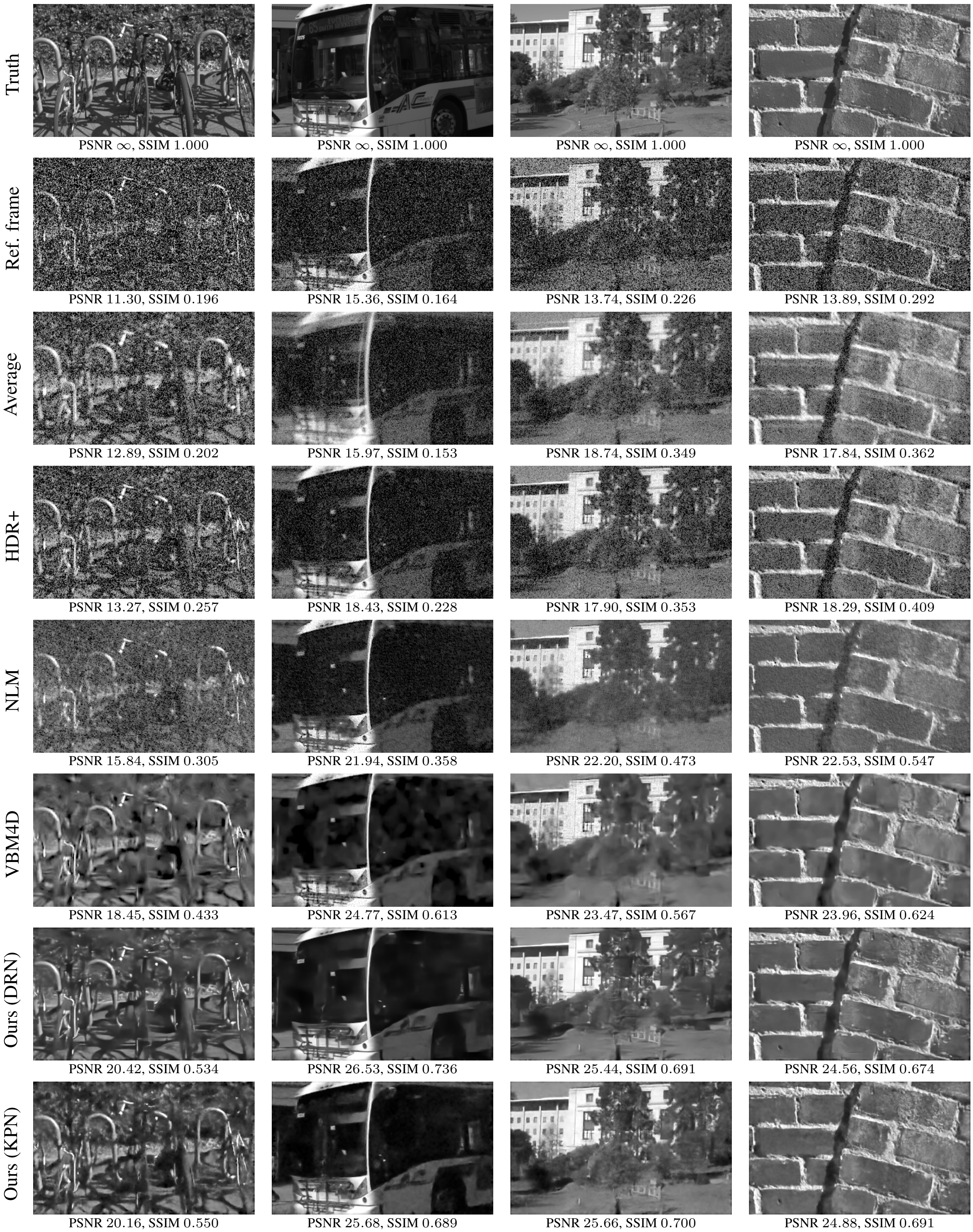


Figure 3: Example results from our synthetic test set at gain $\propto 8$ (Table 1 column 4 in main text).

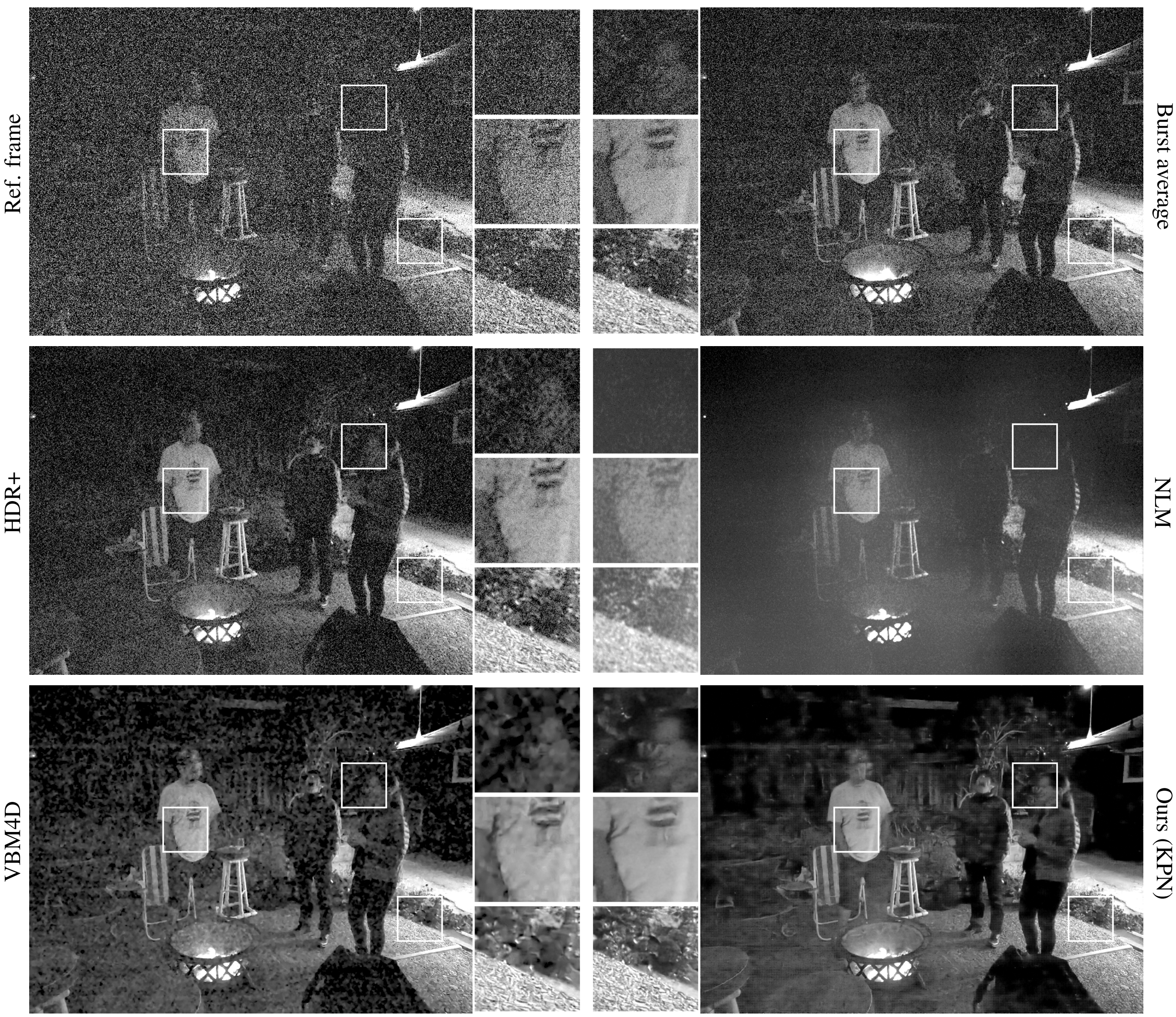


Figure 4: Real cellphone burst with extremely high noise level.


Figure 5: Real cellphone burst with large scene motion.

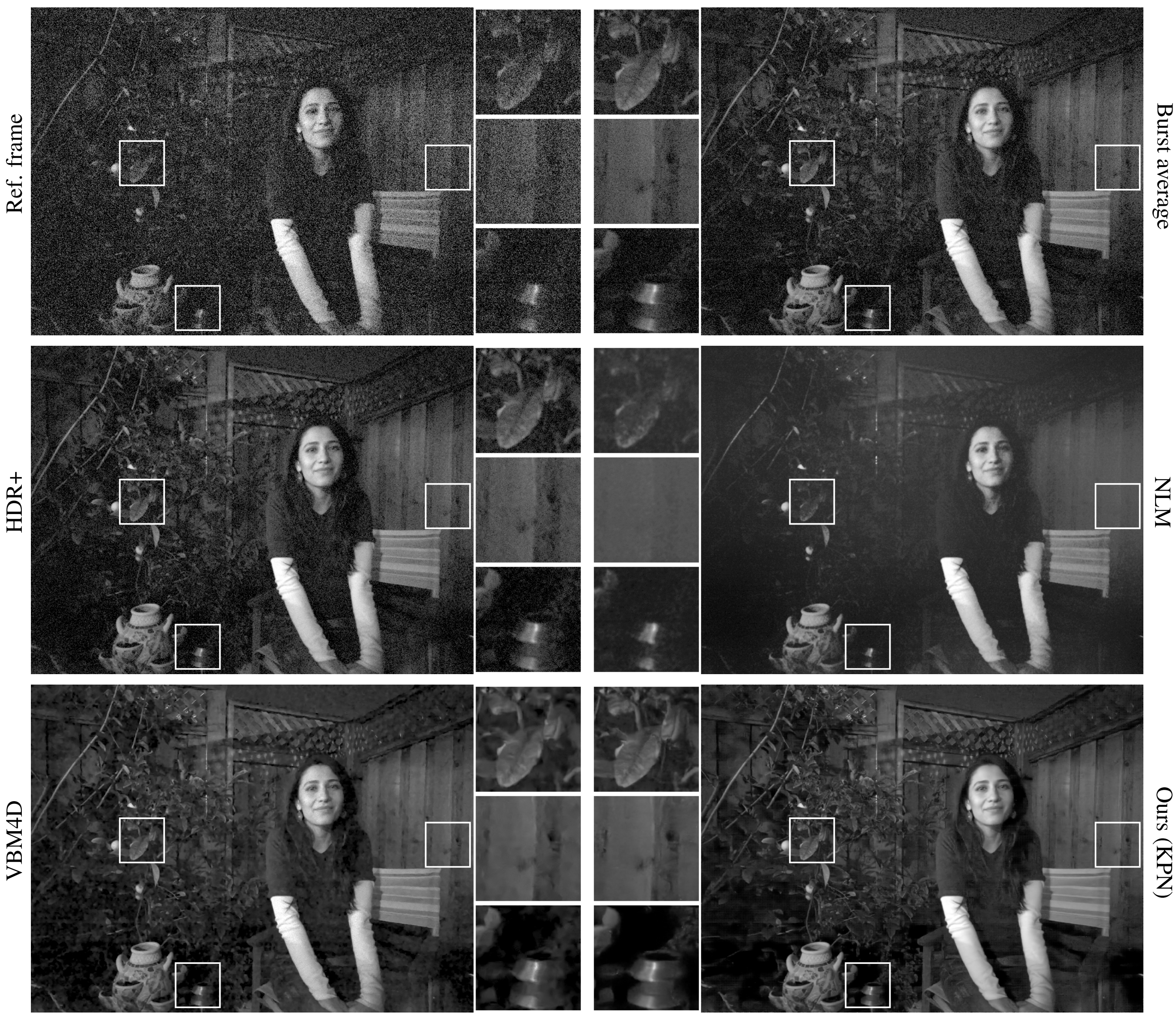


Figure 6: Real cellphone burst.

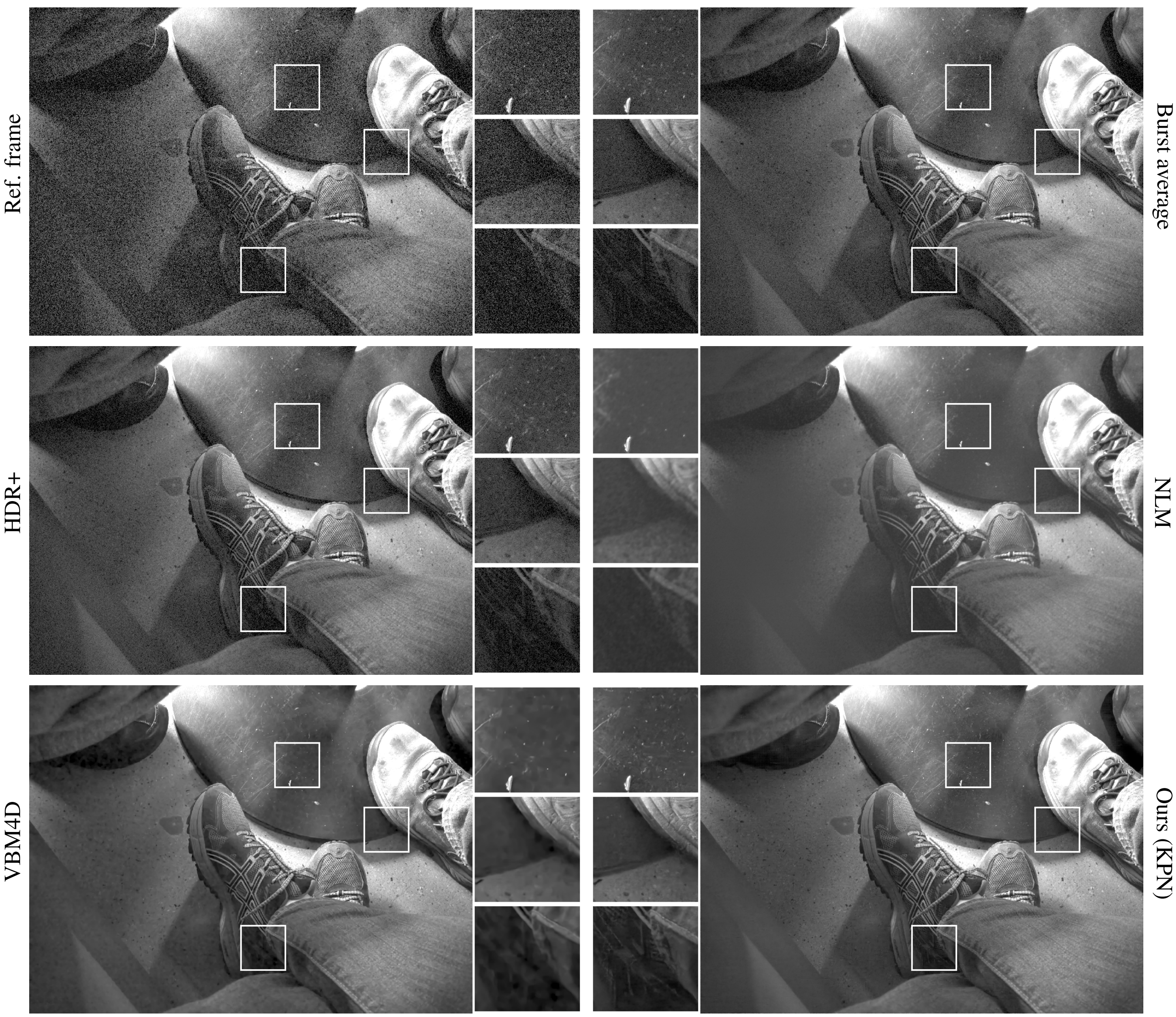


Figure 7: Real cellphone burst.