APPENDIX

This document provides additional material on CURL. In particular, we cover:

- Training details and hyperparameter settings (Section A)
- Transformed encoder-decoder (TED) architecture (Section B)
- Variations of the CURL block architecture (Section C)
- Additional qualitative visual examples (Section D)

A. Training Details and Hyperparameter Settings

In all experiments we use the Adam optimiser [28] with a batch size of 1, β_1=0.9, β_2=0.999, ϵ=10^{-8} and initial learning rate 10^{-4}. On the Samsung S7 dataset we train the models for 10,000 epochs and on the Adobe5K datasets we train for 1,000 epochs. In both cases we select the models that maximise the validation PSNR metric over those epochs. For data augmentation, random horizontal and vertical flips and rotations ($\pm 90°$) are used for the Adobe-DPE and Adobe-UPE datasets. In addition, for the high-resolution Samsung S7 and Adobe-UPE datasets, we train the models by cropping random patches of size 512×512 pixels from each image.

Based on a parameter study on the held-out validation datasets, we set the following hyperparameter values for the terms in the CURL loss function (Equation 2):

- **Adobe-DPE dataset:**
  - TED+CURL: ω_{rgb}=1, ω_{cosine}=1, ω_{lab}=1, ω_{hsv}=1, ω_{ssim}=10, ω_{reg}=10^{-6}, weight decay=10^{-9}
- **Adobe-UPE dataset:**
  - TED+CURL: ω_{rgb}=1, ω_{cosine}=1, ω_{lab}=1, ω_{hsv}=1, ω_{ssim}=1, ω_{reg}=10^{-6}, weight decay=10^{-10}
- **Samsung S7 dataset:**
  - TED+CURL: ω_{rgb}=1, ω_{cosine}=1, ω_{lab}=1, ω_{hsv}=1, ω_{ssim}=10^{-3}, ω_{reg}=10^{-6}

B. Transformed Encoder-Decoder (TED) Architecture

The RAW-to-RGB and RGB-to-RGB pixel-level block of TED is modelled as a U-Net, broadly following the specifications in [3]. For the RAW-to-RGB mapping we make modifications designed for ingesting RAW data formatted as a colour filter array (CFA). The RAW to RGB backbone for TED is shown in Figure 14 and the RGB-to-RGB backbone is shown in Figure 15. Additionally, in Figure 11 we show how precisely the U-Net architecture is amended with MSCA-skip connections.

In Table VIII we present the full ablation study on the TED MSCA-skip connection. For a parameter efficient model that produces images of high quality we find it is only necessary to place an MSCA-skip connection at level 1 of the U-Net (Figure 11).

C. Variations of the CURL Block Architecture

In this section we test minor variations of the CURL architecture. Specifically we examine the following:

TABLE VIII
ABLATION STUDY ON THE MSCA-SKIP CONNECTION OF TED. A SINGLE MSCA-SKIP CONNECTION AT THE TOP-MOST LEVEL OF THE TED BACKBONE SIGNIFICANTLY BOOSTS THE IMAGE QUALITY, EVEN OUTPERFORMING A U-NET WITH TWICE THE NUMBER OF PARAMETERS. ALL MODELS WERE TRAINED WITH L_1 LOSS IN RGB COLOUR SPACE, UNLESS OTHERWISE STATED.

Architecture	PSNR	SSIM	# Parameters
TED (MSCA, level 4)	25.09	0.757	2.7 M
TED (MSCA, level 3)	26.00	0.769	2.7M
TED (MSCA, level 2)	24.90	0.734	1.8M
TED (MSCA, level 1)	**26.56**	0.781	1.3M
TED (MSCA, all levels)	26.39	**0.793**	3.3M
U-Net	25.78	0.771	1.4 M
U-Net (large)	25.37	0.788	5.1 M
U-Net (L_1 Lab, MS-SSIM L)	25.75	0.771	1.3 M
U-Net (large) (L_1 Lab, MS-SSIM L)	25.90	0.783	5.1 M

TABLE IX
RESULTS ON THE MEDIUM-TO-MEDIUM EXPOSURE SAMSUNG DATASET FOR THE *multi-tasking* VERSION OF THE CURL BLOCK (FIGURE 13) COMPARED TO THE CURL BLOCK WITH THREE FEATURE EXTRACTION BLOCKS. THERE IS A SIGNIFICANT LOSS IN IMAGE QUALITY WITHOUT THE THREE FEATURE EXTRACTIONS BLOCKS.

Architecture	PSNR (test)↑	SSIM (test)↑
Multi-task CURL	25.96	0.767
CURL	**27.09**	**0.793**

- **Multiple feature extraction blocks:** In our suggested retouching block architecture there are three feature extraction block with no parameter sharing. In Table IX we explore a multi-task alternative with one feature extraction block (Figure 13) to determine whether having separate feature extraction blocks for each colour space is important. Our results suggest have three independent feature extraction blocks in the retouching layer is important for best image quality.
- **Visual examples:** We show in Figure 16 examples of the output from CURL with all colour spaces (CIELab, RGB, HSV) versus variants of the model with just one of the available colour spaces.
- **CURL: Number of knot points for the curves:** In Figure 12 we present an ablation study on how the number of knot points in the neural curve formulation effects the resulting image quality. This study is conducted on the held-out validation dataset of the medium exposure Samsung S7 dataset. We find that 16 knot points is optimal in terms of PSNR and SSIM, with quality falling for more and less knot points per curve.
- **Limitations of CURL:** The CURL block uses multiple conversions for the CIELab, RGB and HSV colour spaces. Each of these conversions may lead to a loss of image fidelity. We mitigate this issue by a long skip connection between the input and output of the retouching layer, which we found is important for model training and image quality.

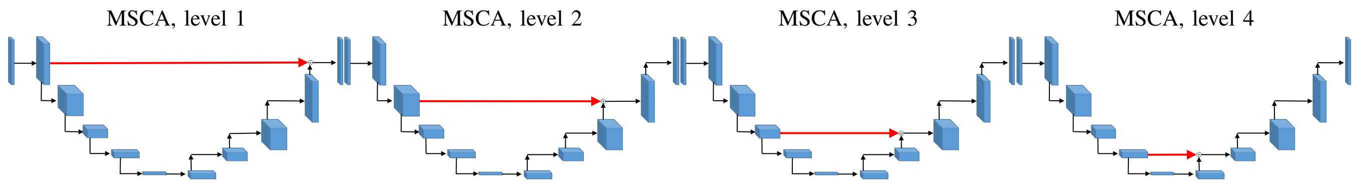

Fig. 11. Variants of the **TED** backbone with MSCA skip connections at various levels. For our "all-levels" model variant we add MSCA skip connections at all levels of the TED.

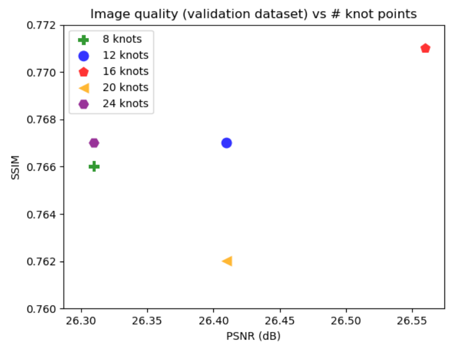

Fig. 12. Effect of the number of knot points in a neural curve on the image quality (PSNR/SSIM). Maximum quality reached at 16 knot points. Results measured on the Samsung held-out *validation* dataset.

D. Additional Qualitative Visual Examples

We provide additional examples of output images from TED+CURL and the baseline models on the Samsung and Adobe datasets in Figures 17-18. The following visual examples are provided:

- Figure 16: Comparing a CURL block with just RGB, versus a a CURL block with all three colour spaces (CIELab, RGB, HSV).
- Figure 17: Examples images produced by DeepISP [8] and TED+CURL on the Samsung S7 Medium Exposure dataset.
- Figure 18: Examples images produced by DeepISP [8] and TED+CURL on the Samsung S7 Short Exposure dataset.
- Figure 19: Examples images produced by U-Net (large) [13] and TED+CURL on the Samsung S7 Medium Exposure dataset.
- Figure 20: Examples images produced by U-Net (large) [13] and TED+CURL on the Samsung S7 Short Exposure dataset.
- Figures 21-22: Examples images produced by Deep-UPE [1] and TED+CURL on the Adobe-UPE dataset.
- Figures 23-24: Examples images produced by DPE [3] and TED+CURL on the Adobe-DPE dataset.

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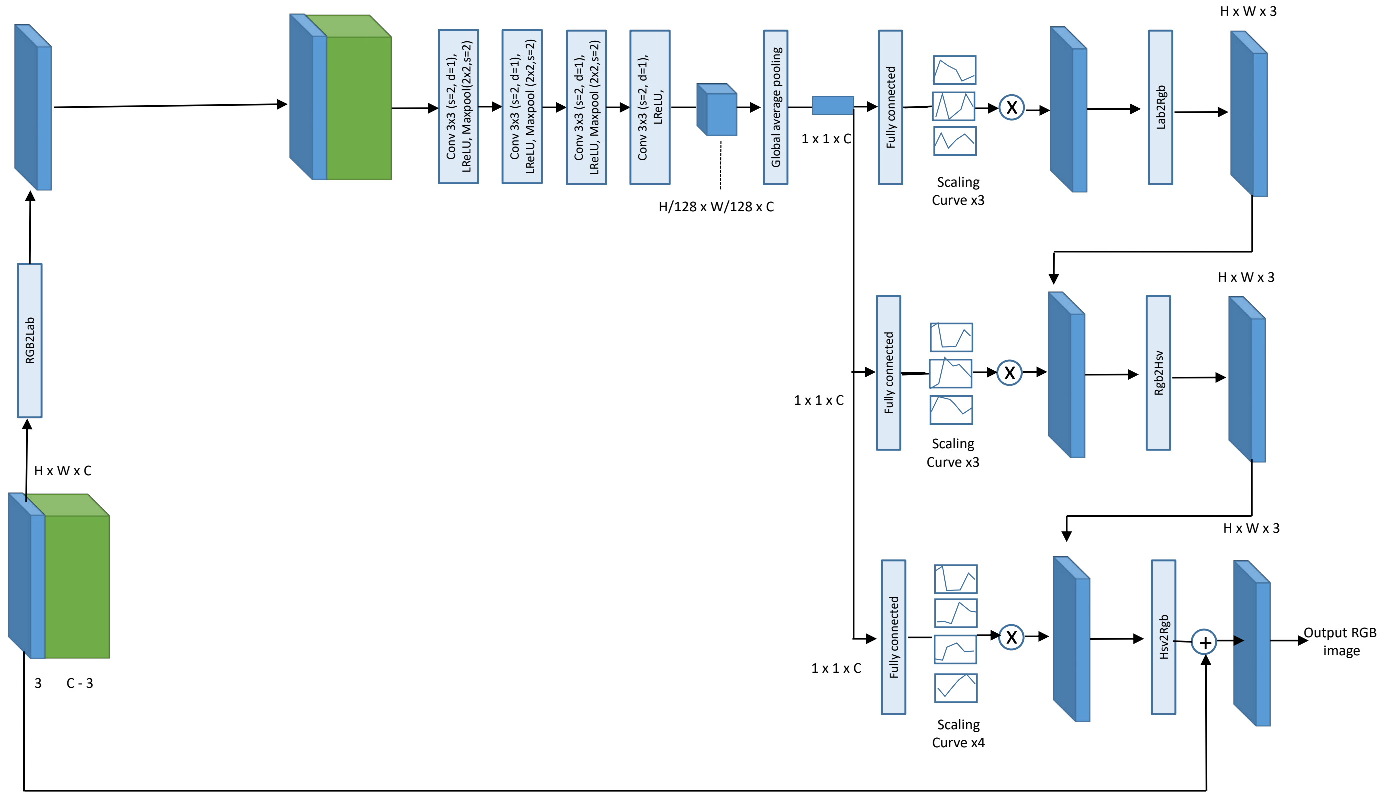

Fig. 13. **Multi-task (shared parameter)** version of the CURL block. One feature extractor is used by all three parameter prediction full-connected layers.

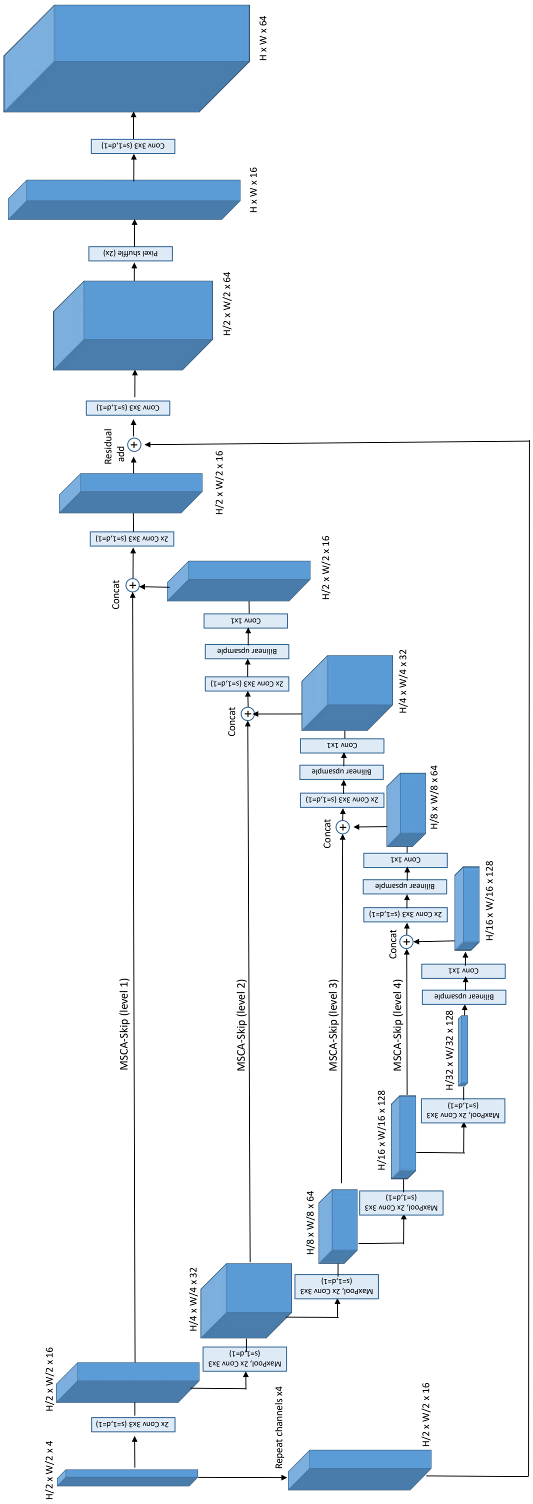

Fig. 14. **RAW-to-RGB TED Architecture**. The block is broadly modelled as a U-Net. The RAW image data is input on the left and the RGB image is output on the right. The skip connections denote our novel multi-scale contextual fusion blocks (MCF-skip).

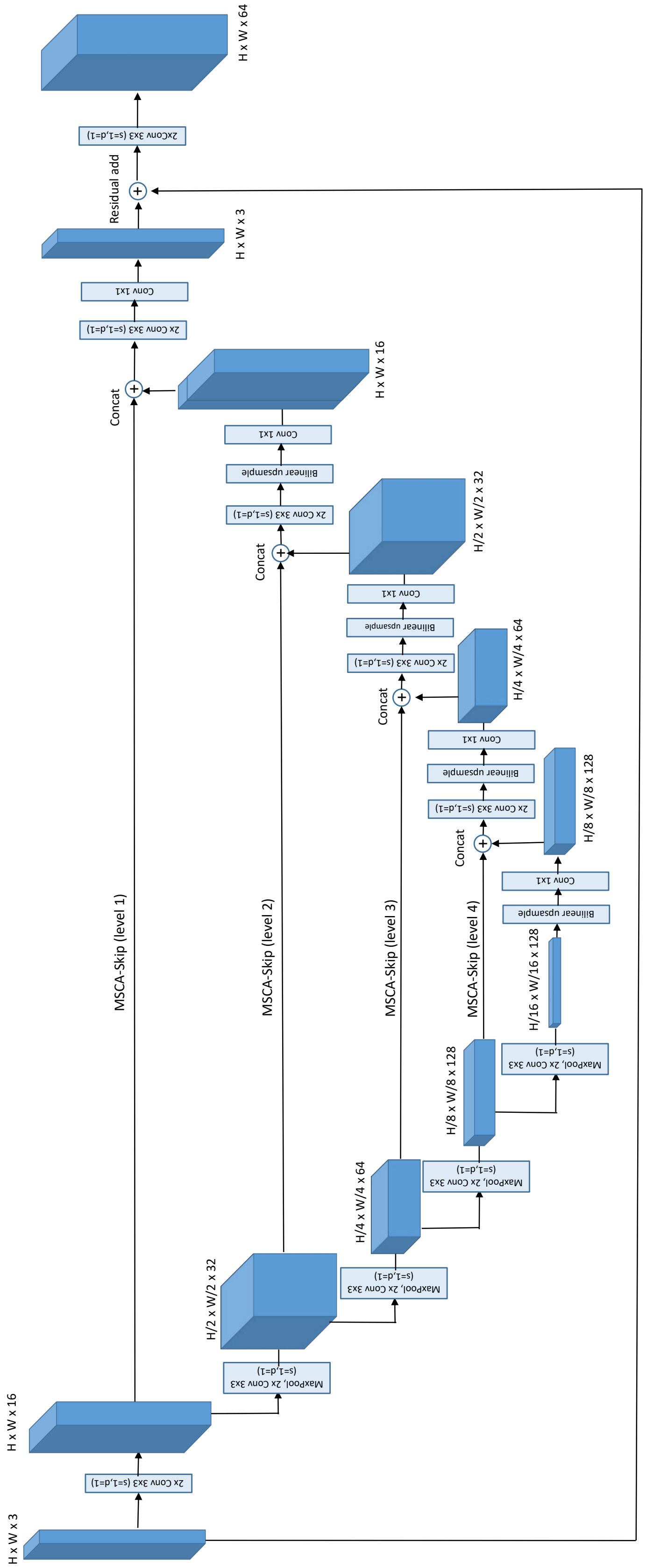

Fig. 15. **RGB-to-RGB TED Architecture**. The block is broadly modelled as a U-Net. The RGB image data is input on the left and the RGB image is output on the right. The skip connections denote our novel multi-scale contextual fusion blocks (MCF-skip).

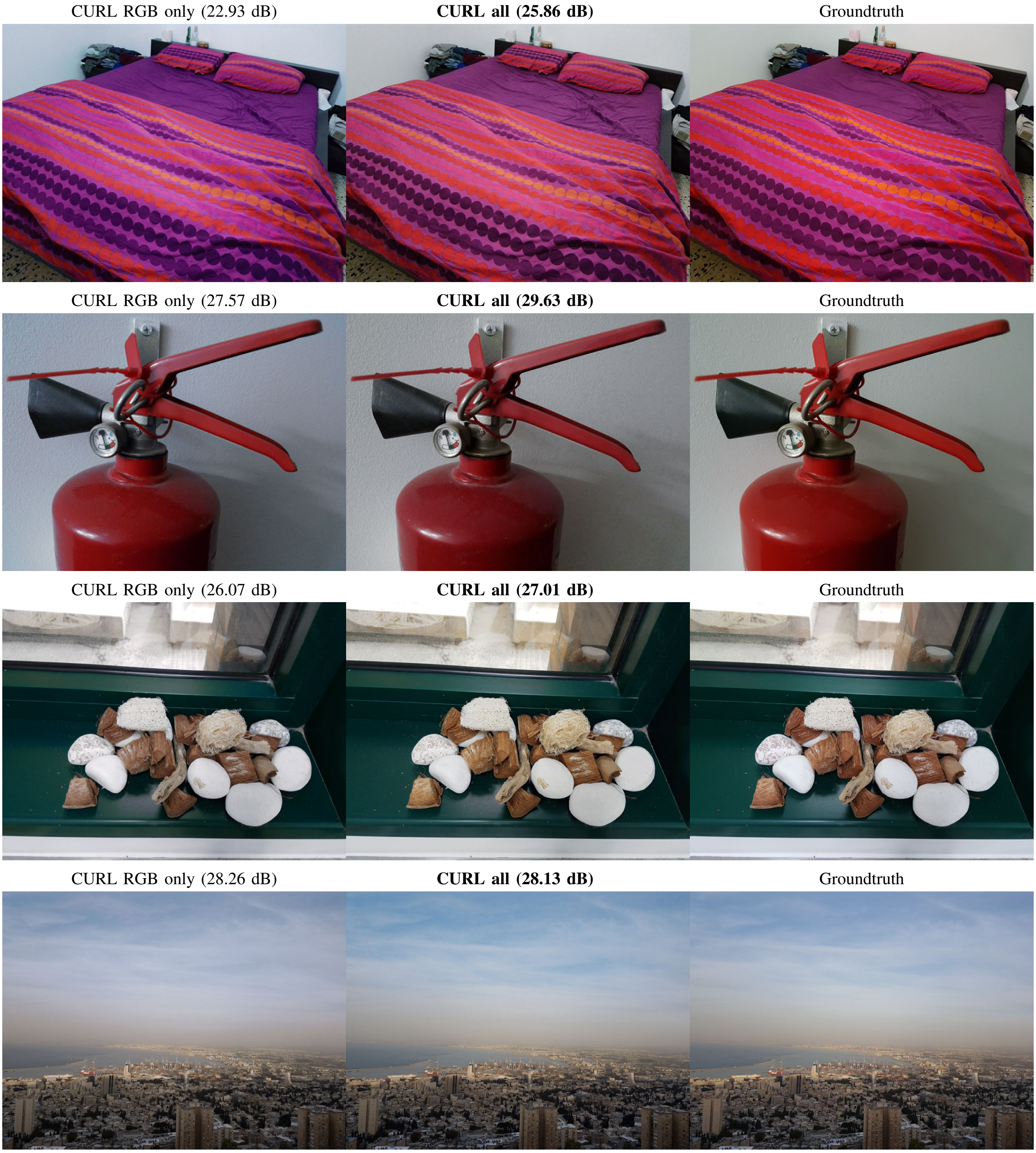

Fig. 16. Comparing a CURL block with just RGB, versus a CURL block with all three colour spaces (CIELab, RGB, HSV). Examples images from the the **Samsung S7 Medium Exposure** dataset.

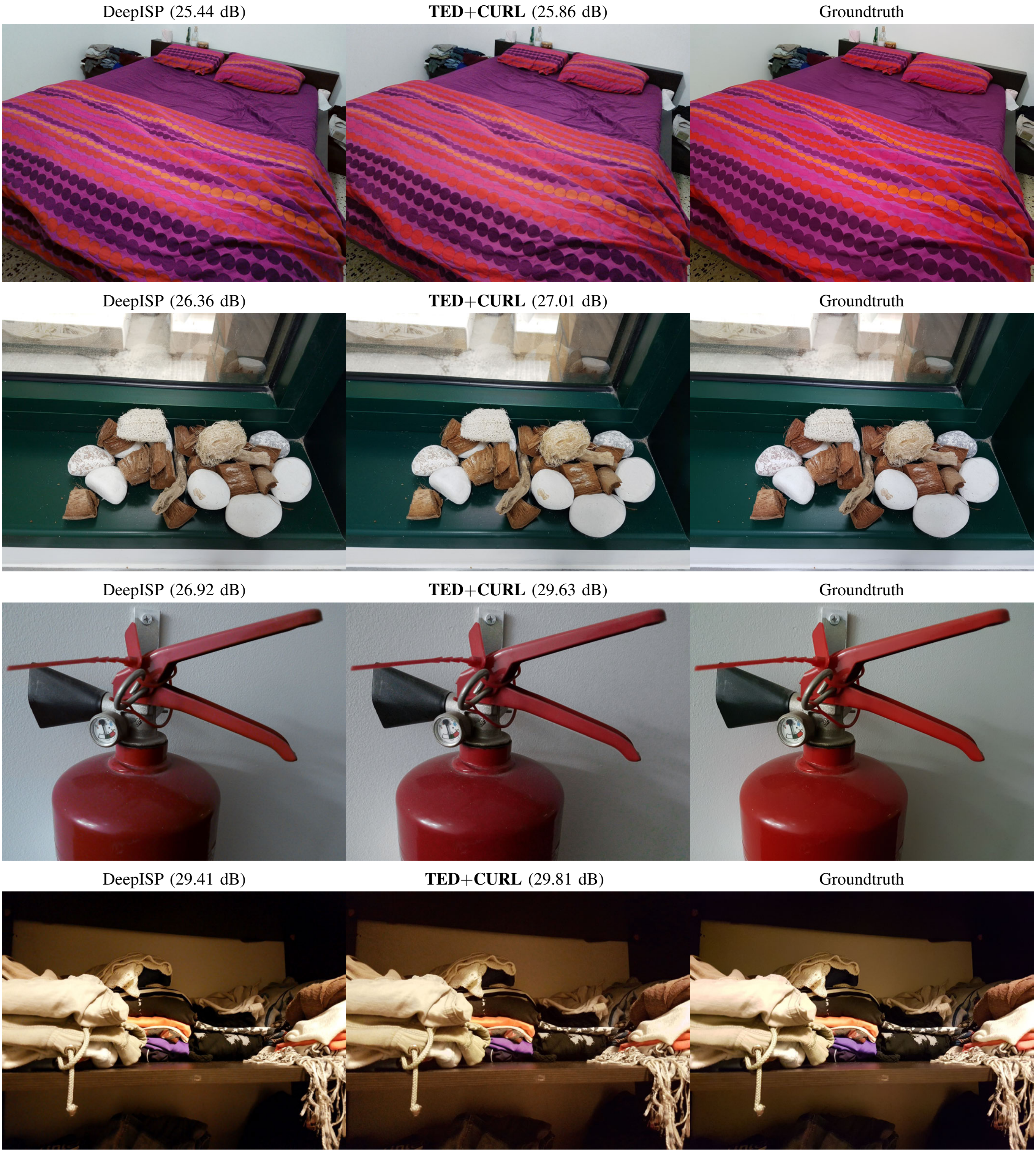

Fig. 17. Examples images produced by **DeepISP** [8] and **TED+CURL** on the Samsung S7 **Medium Exposure** dataset.

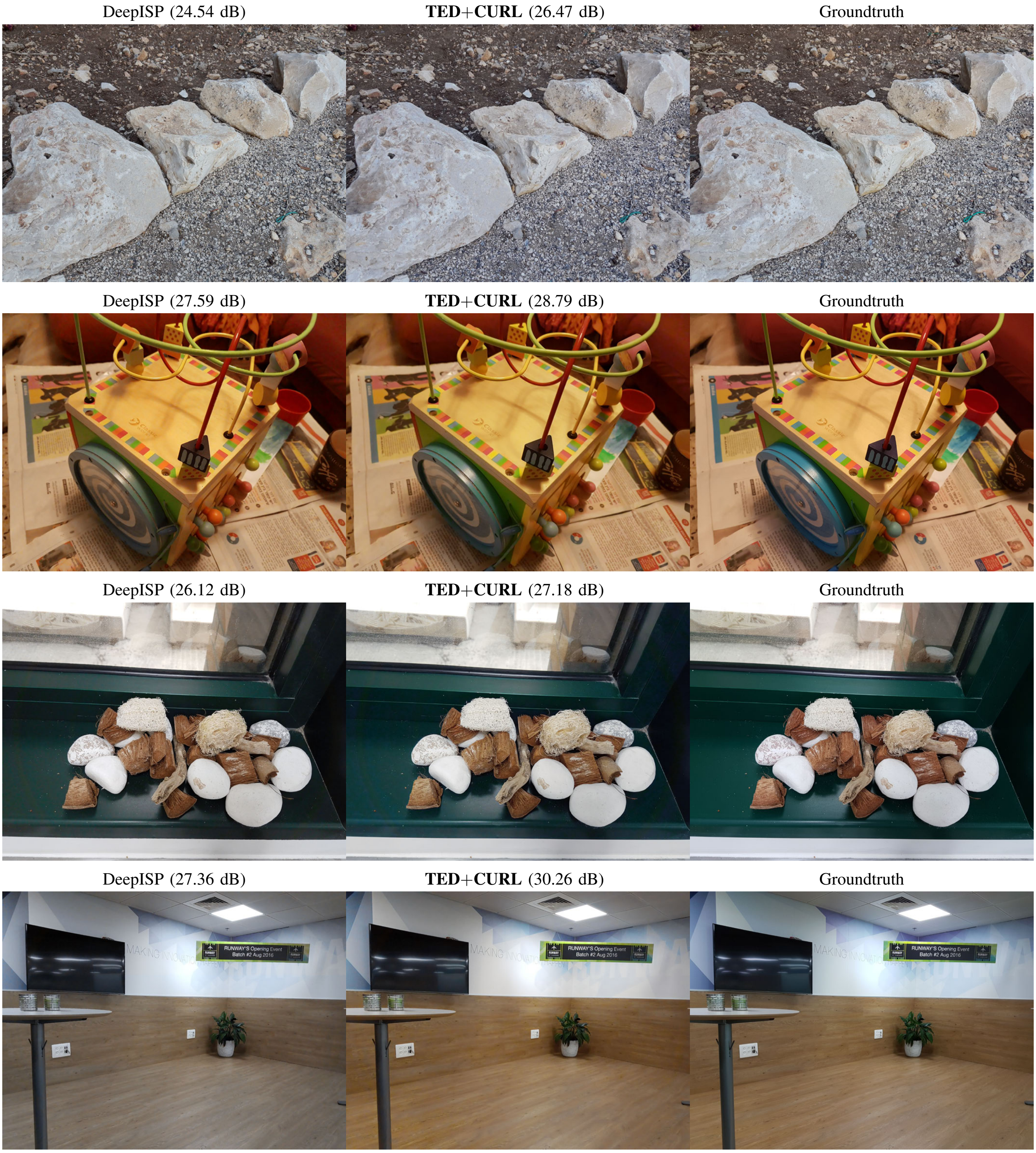

Fig. 18. Examples images produced by **DeepISP** [8] and **TED+CURL** on the Samsung S7 **Short Exposure** dataset.

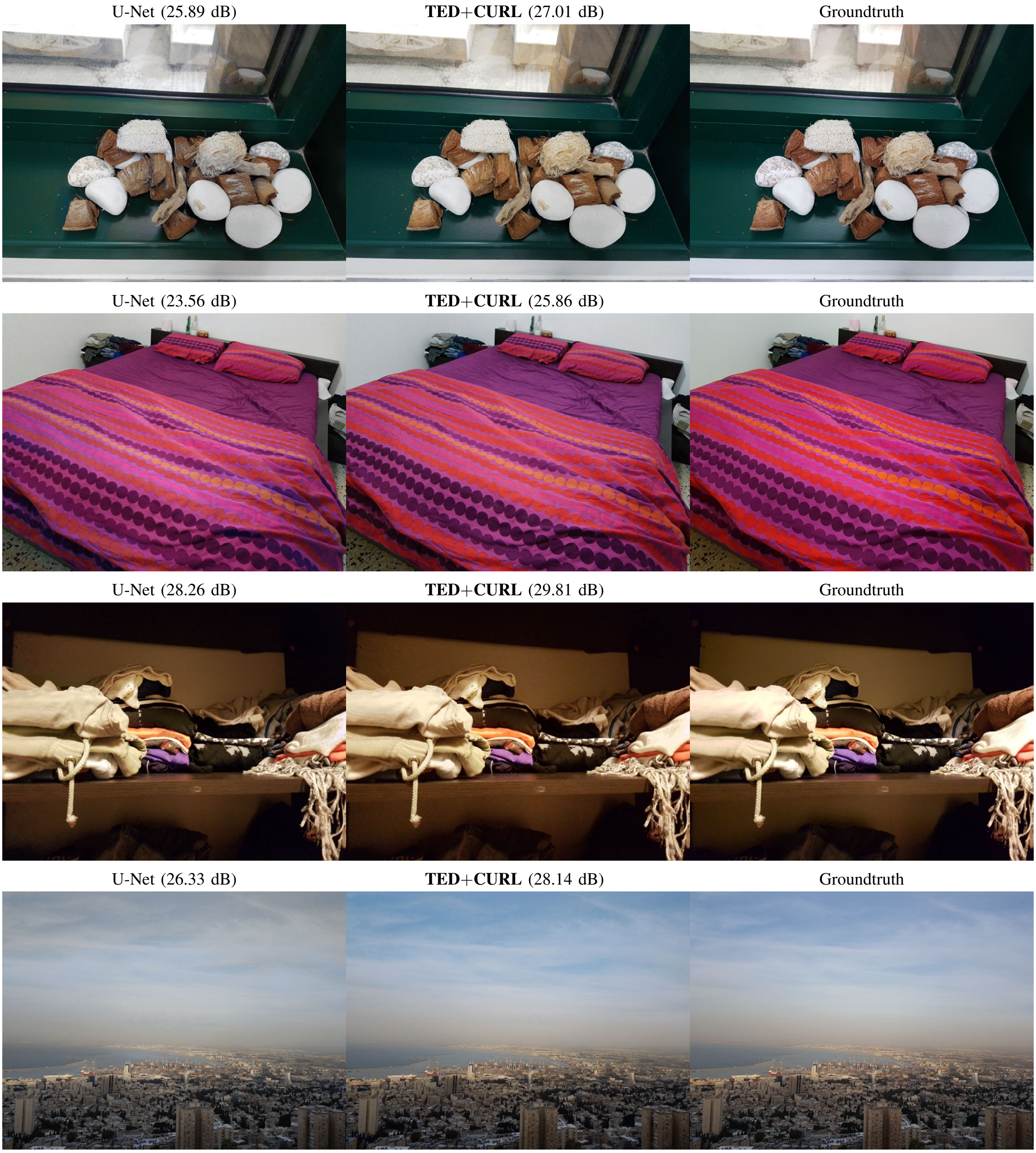

Fig. 19. Examples images produced by **U-Net (large)** and **TED+CURL** on the Samsung S7 **Medium Exposure** dataset.

Fig. 20. Examples images produced by **U-Net (large)** and **TED+CURL** on the Samsung S7 **Short Exposure** dataset.

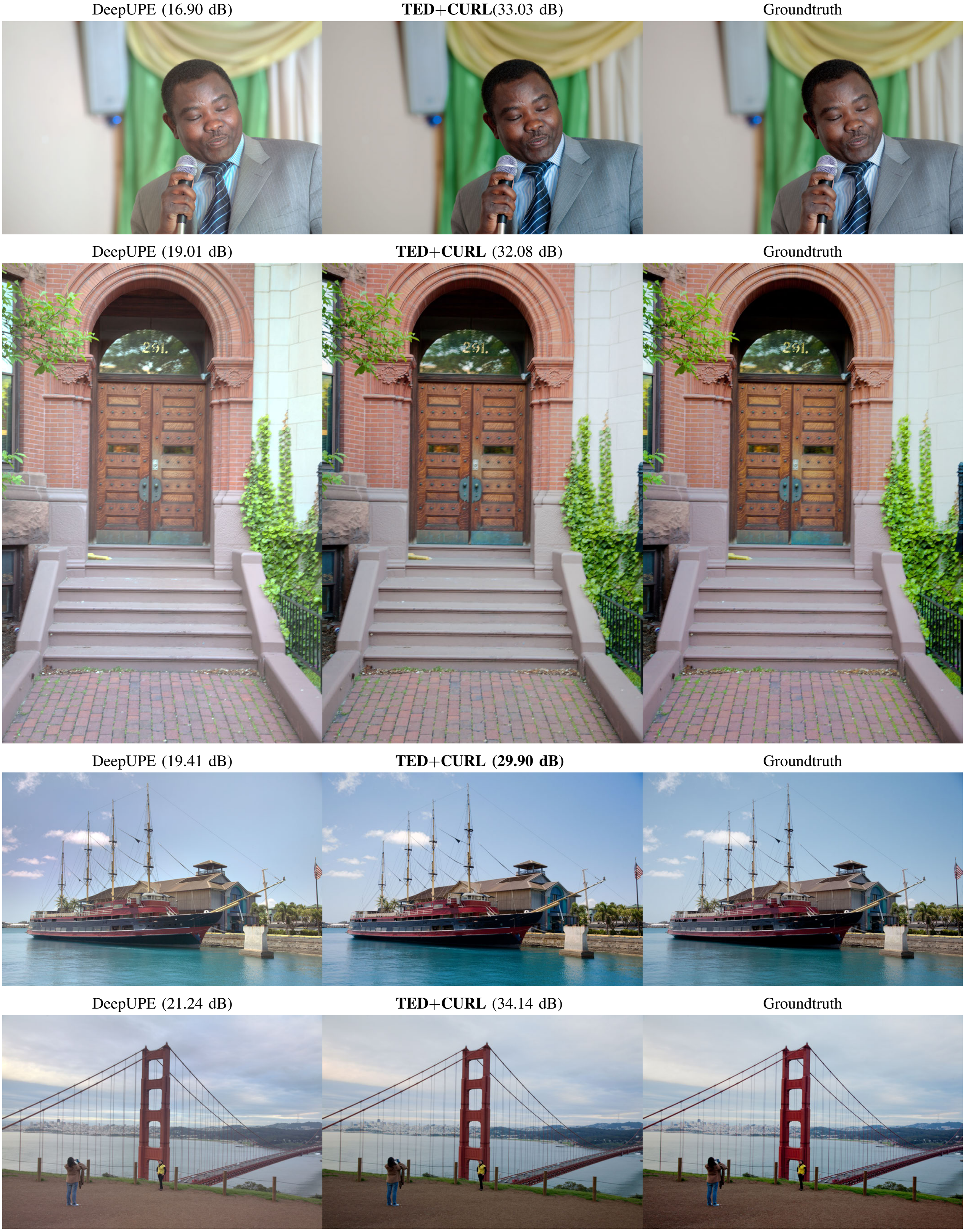

Fig. 21. Examples images produced by **DeepUPE** [1] and **TED+CURL** on the **Adobe-UPE** dataset.

Fig. 22. Examples images produced by **DeepUPE** [1] and **TED+CURL** on the **Adobe-UPE** dataset.

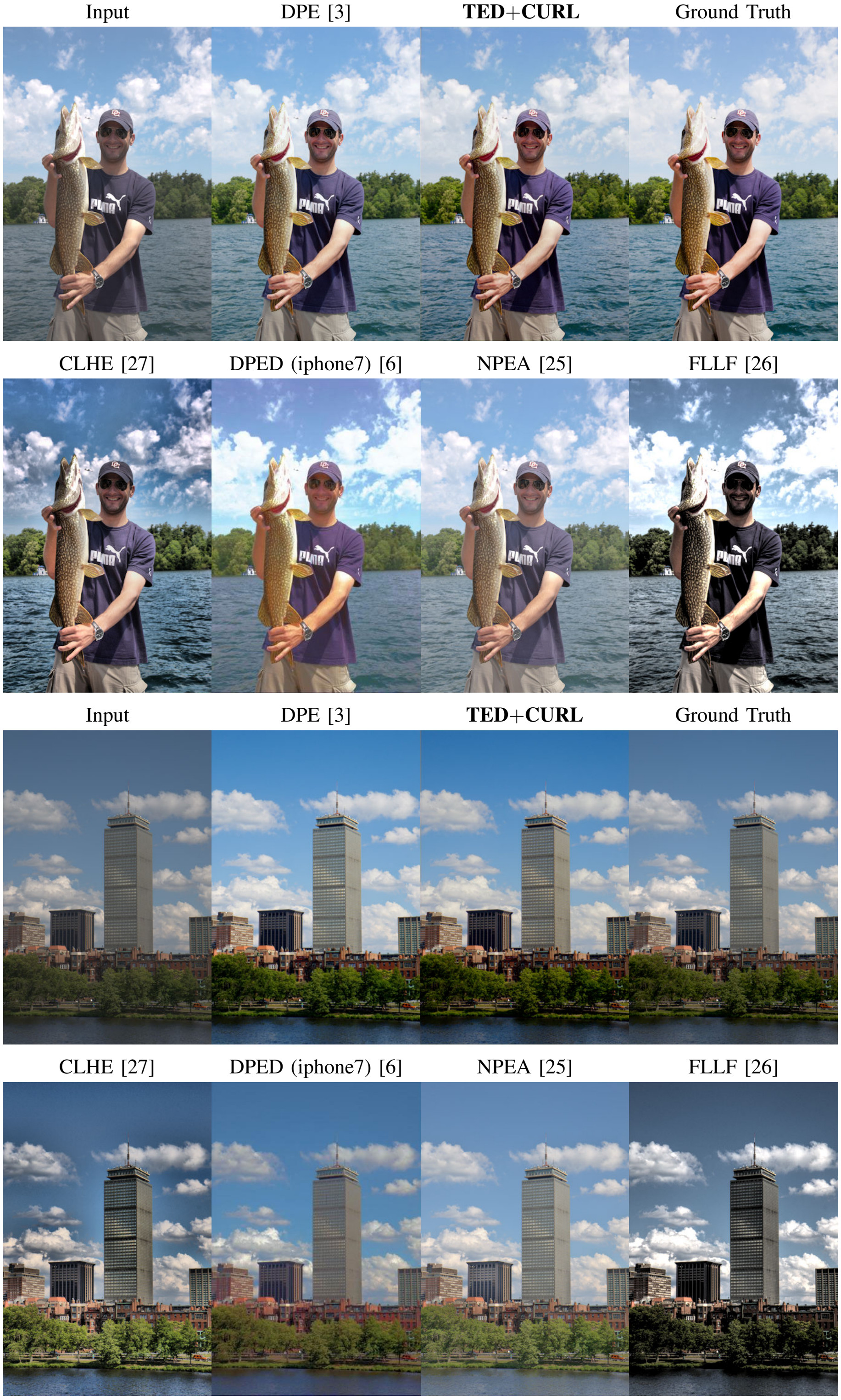

Fig. 23. Examples images produced by **DPE** [3], **CLHE** [27], **DPED (iphone7)** [6], **NPEA** [25], **FLLF** [26] and **TED+CURL** on the **Adobe-DPE** dataset.

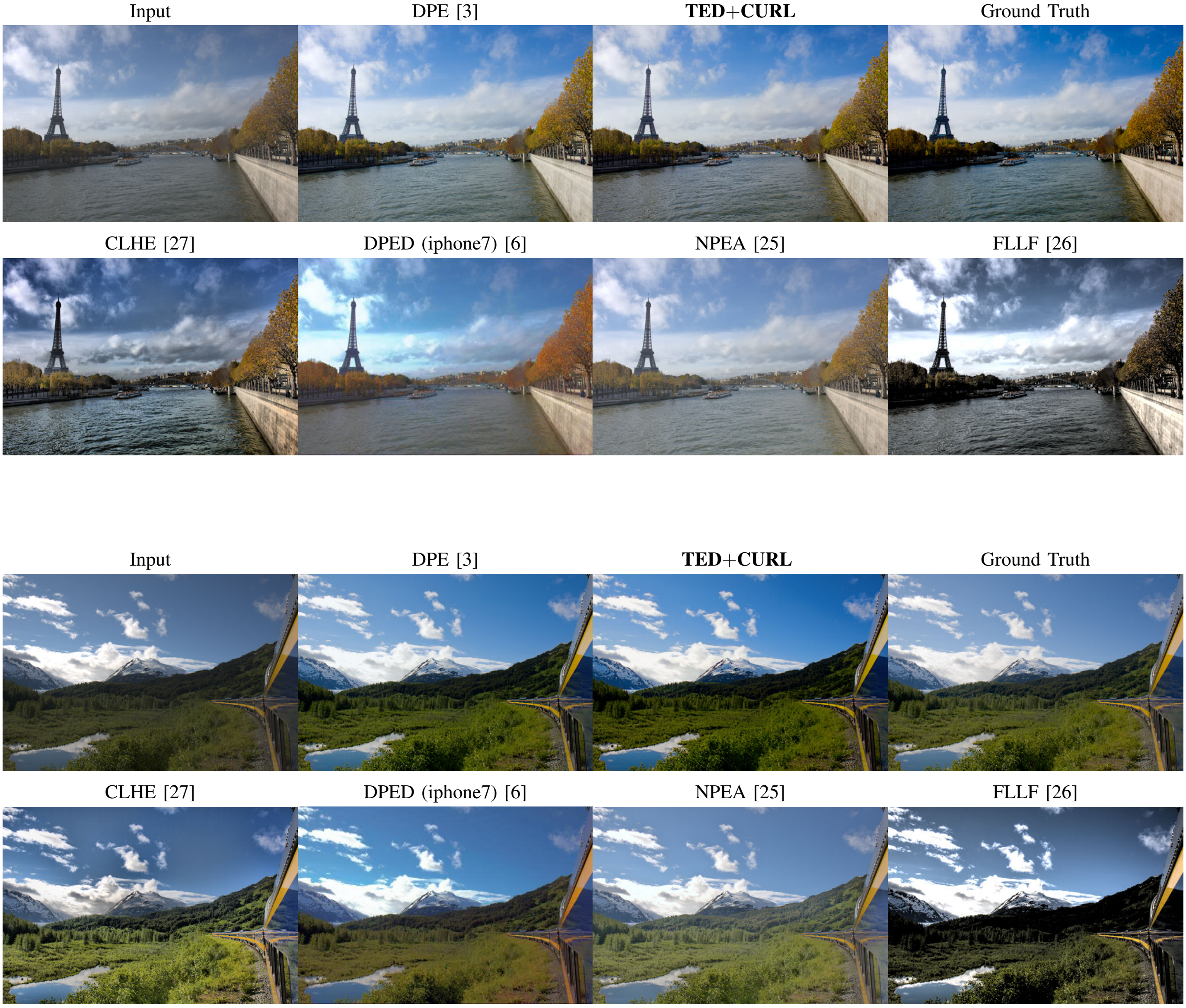

Fig. 24. Examples images produced by **DPE** [3], **CLHE** [27], **DPED (iphone7)** [6], **NPEA** [25], **FLLF** [26] and **TED+CURL** on the **Adobe-DPE** dataset.