rTMO/EO – Enhancement of SDR contents for HDR Rendering Applications

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ICC Expert Day

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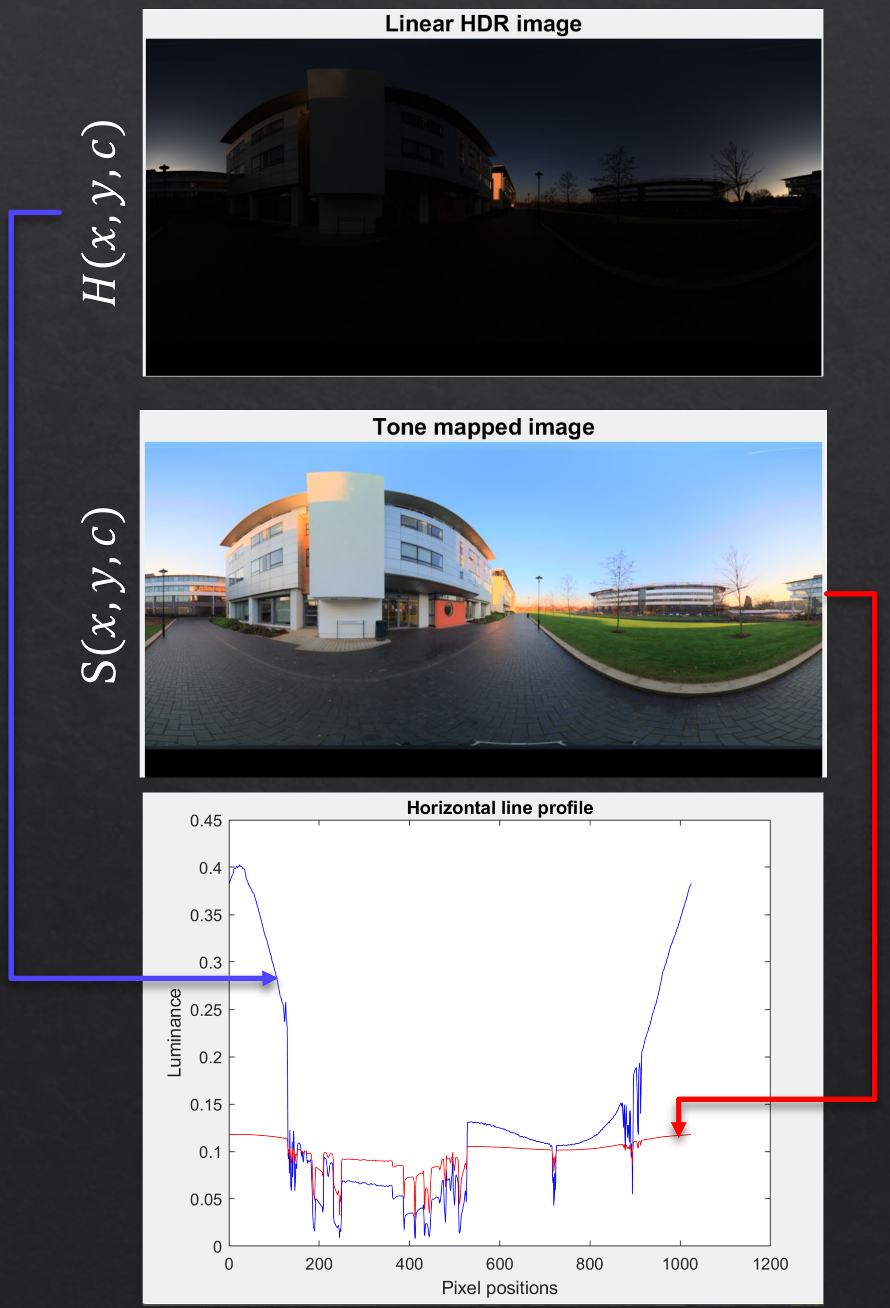
Contents



Introduction

- Tone Mapping Operators (TMO): defined as a general operator f over an HDR image H as
  - $f(H) = \mathbb{R}_{in} \xrightarrow{x \times y \times c} \mathbb{R}_{out}$ where, $\mathbb{R}_{out} \subset \mathbb{R}_{in}$
  - $S(x, y, c) = f(H)$
- Reverse Tone Mapping Operators (rTMOs) / Expansion Operators (EO)
  - $f(S) = \mathbb{R}_{in} \xrightarrow{x \times y \times c} \mathbb{R}_{out}$ where, $\mathbb{R}_{in} \subset \mathbb{R}_{out}$
  - $\mathrm{H}(x, y, c) = f(S)$

Introduction

rTMOs

- Ill-posed problem: details are lost in under- and over-exposed regions
- Mostly involves (as outlined by Banterle et al.) the following components.

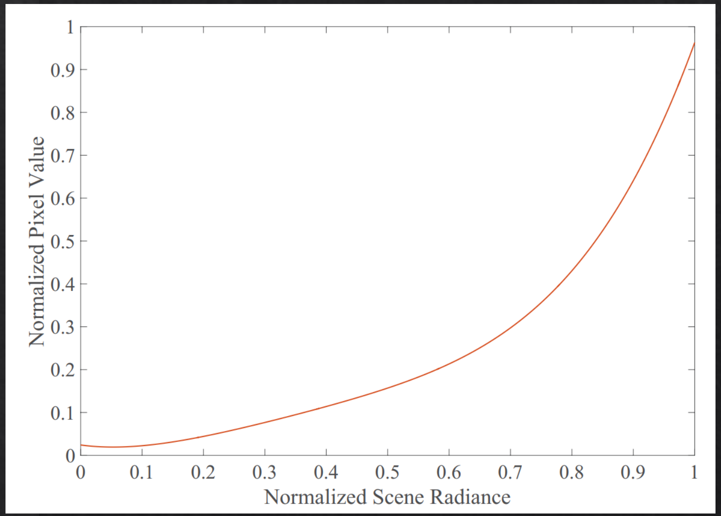
Linearization

Expansion of Pixel values

Artifact reduction & Color correction

Detail reconstruction

$S(x, y, c)$



$H(x, y, c)$

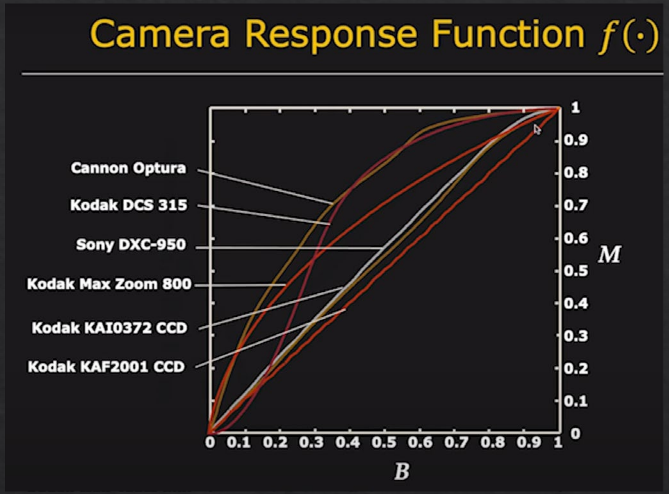
State of the Art - rTMOs

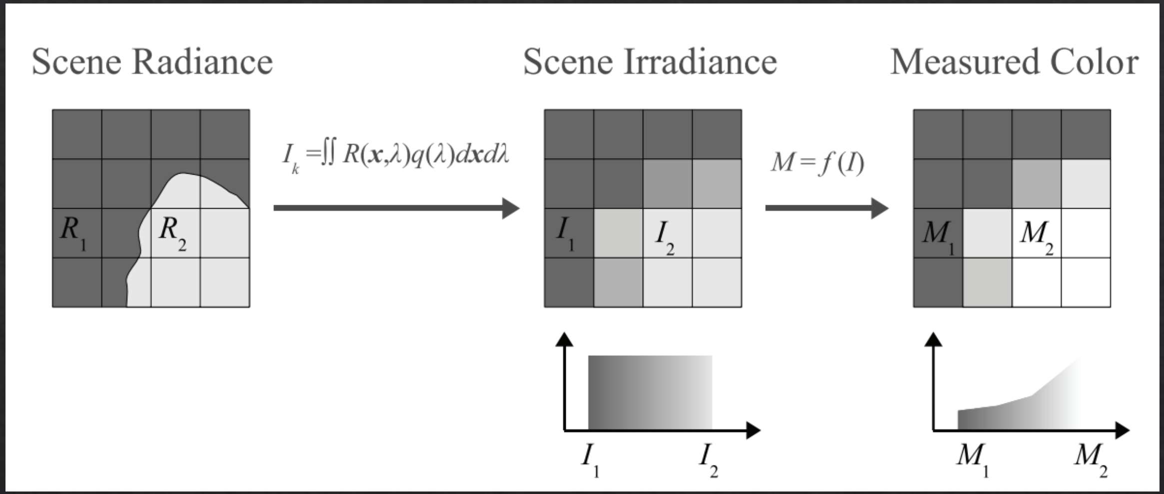
Linearization

- RAW files sometimes are not linear
- Standard sRGB or sensor gamma γ

$$S_{Lin} = S^{1/\gamma}$$

- If radiometric calibration is not possible:
  - Real time estimation of CRF → CRF $g(.)$ which increases linearity or histogram uniformity across edges of uniform image regions





Banterle et al., Advanced High Dynamic Range Imaging

$$argmin_g E(g,\Omega) = \left\{ g \mid E(g,\Omega) = \min_{g'} f\,(g',\Omega) \right\}$$

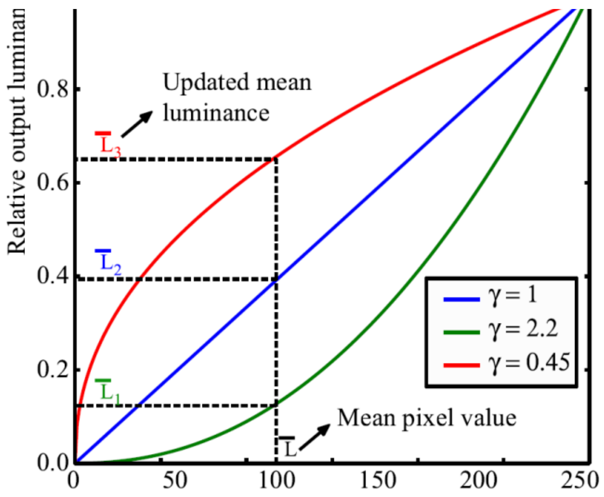
$$E(g,\Omega) = \sum_{H\in\Omega} w_H N(g(H))$$

State of the Art - rTMOs

Expansion of Pixel values

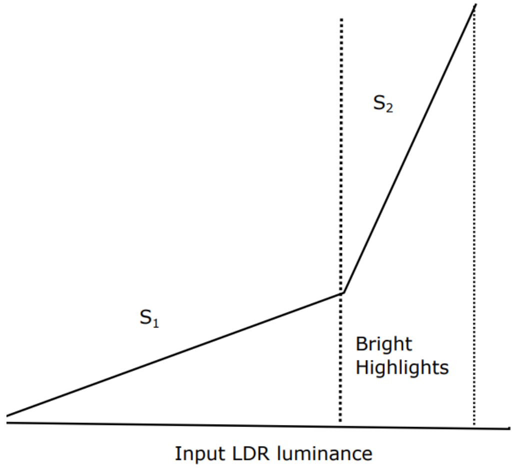
- **Global approaches**
- Classification and map based
- Perceptual based methods

Akyuz et al.



$$L_H(x) = a\left(\frac{L_S(x) - L_{S_{min}}}{L_{S_{max}} - L_{S_{min}}}\right)^{\gamma}$$

$$k = \left(\frac{L_S(x) - \tau}{1 - \tau}\right)^{\alpha}$$



Meylan et al.

$$L_H = \begin{cases} (1-k)L_S(x) + kL_{H_{max}}L_S(x) & \text{if } L_S(x) \geq \tau \\ L_S(x) & \text{otherwise} \end{cases}$$

State of the Art - rTMOs

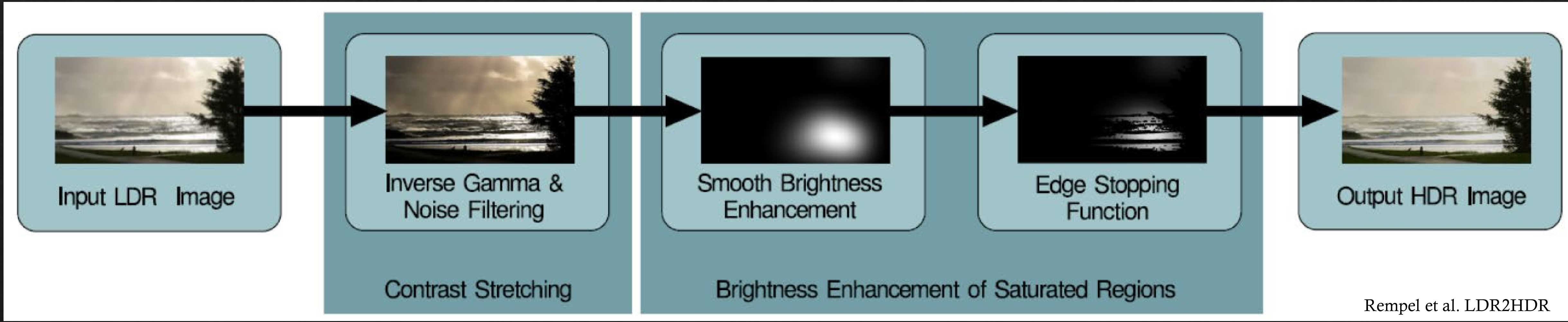
Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

Bilateral filter → $S_{Lin} = S^{1/\gamma}$

$$L_{Htemp}(x) = L_S(x)\left(L_{H_{max}} - L_{H_{min}}\right) + L_{H_{max}}$$

- Saturated region map detected $\tau = 0.92$
- Map is filtered with Gaussian filter
- Flood fill contrast enhancement algorithm used to enhance contrast around edges
- $L_H(x) = L_{Htemp}(x) * \text{Map}$



Rempel et al. LDR2HDR

State of the Art - rTMOs

Expansion of Pixel values

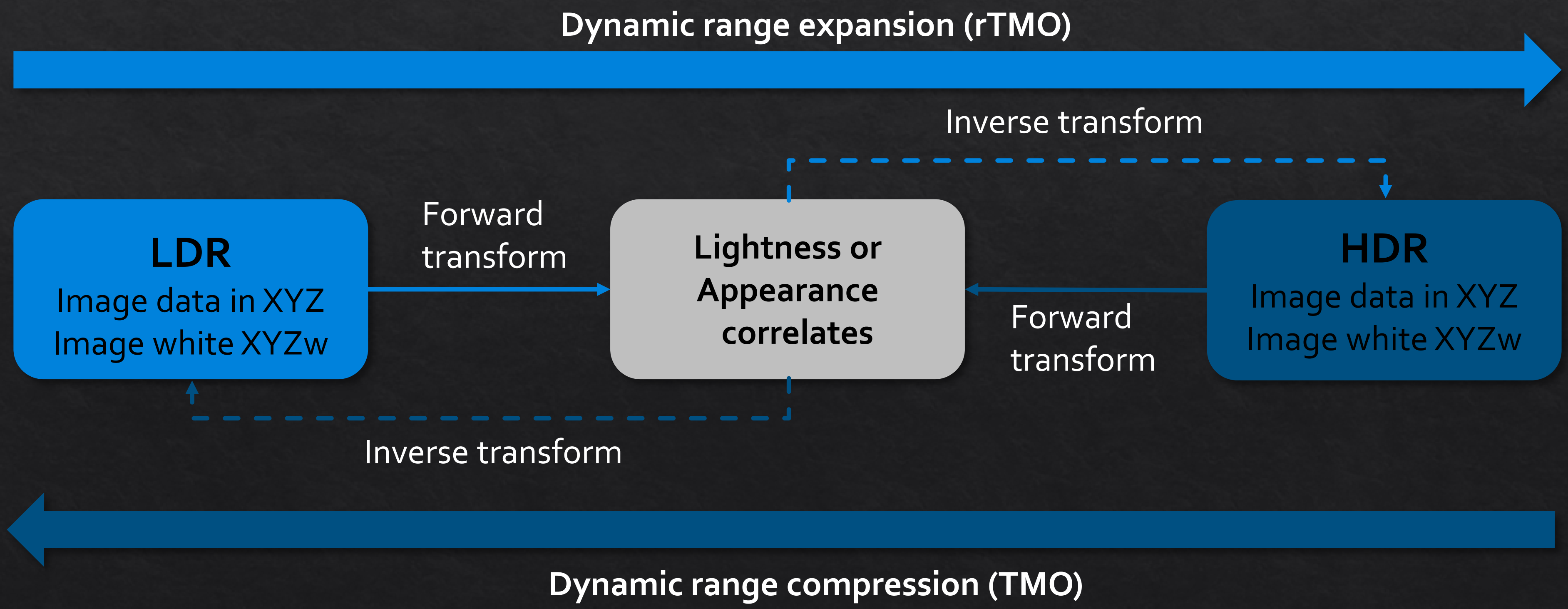
- Global approaches
- Classification and map based
- **Perceptual based methods**

$$f_{pl}(Y,Y_n) = \begin{cases} 1.226\left(\frac{Y}{Y_n}\right)^{0.266} - 0.226 & \text{if } Y_n \leq 100\ cd/m2 \\ 1.127\left(\frac{Y}{Y_n}\right)^{0.230} - 0.127 & \text{if } Y_n > 100\ cd/m2 \end{cases}$$

$$f_{mm}(Y,Y_n) = \begin{cases} \dfrac{1.448\left(\frac{Y}{Y_n}\right)^{0.582}}{0.813\left(\frac{Y}{Y_n}\right)^{0.582} + 0.635} & if\ Y_n \leq 100\ cd/m^2 \\ \dfrac{1.680\left(\frac{Y}{Y_n}\right)^{0.293}}{0.096\left(\frac{Y}{Y_n}\right)^{0.293} + 1.584} & if\ Y_n > 100\ cd/m^2 \end{cases}$$

PCS → CIE Lab color space – with replaced luminance function.

Mekides Assefa et al. Perceptual lightness modeling for high-dynamic-range imaging

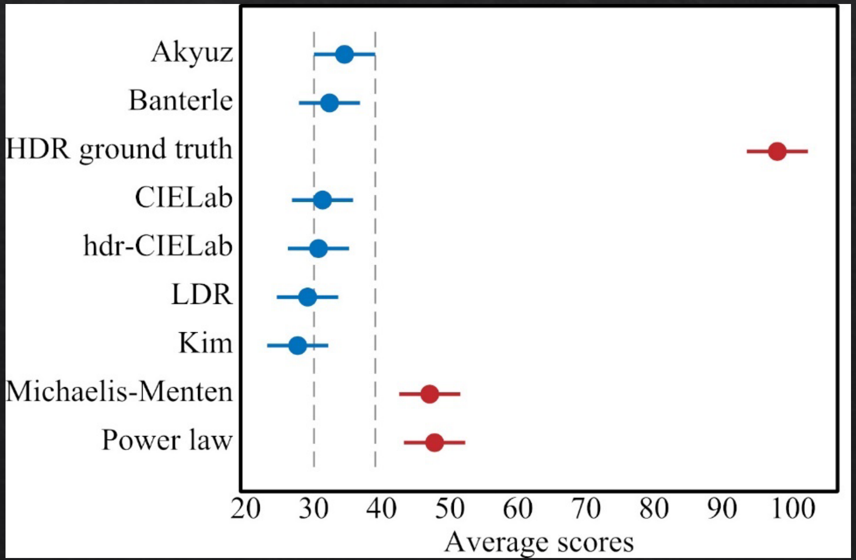


State of the Art - rTMOs

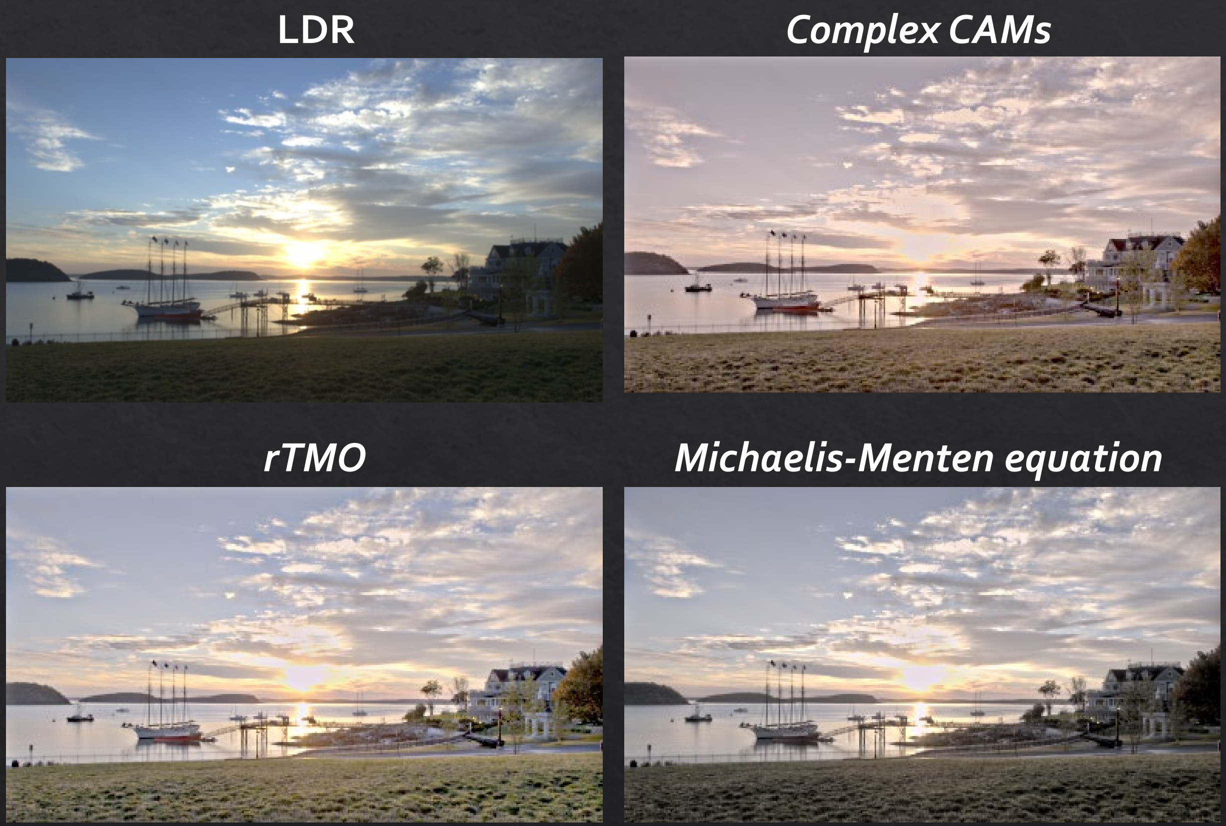
Expansion of Pixel values

- Global approaches
- Classification and map based
- Perceptual based methods

ANOVA multiple comparison: subjective evaluation results



Mekides Assefa et al. Perceptual lightness modeling for high-dynamic-range imaging



Tone mapped results: iCAM06

Perceptual Quality:

- Pleasantness
- Color appearance fidelity

State of the Art - rTMOs

Artifact reduction & Color correction

- Quantization artifacts
  - 8-bit per channel creates banding artifacts for expanded luminance ranges on HDR screens
  - With ground truth – **Dithering, and companding**
  - With no ground truth – **Decontouring** (Such as adaptive filtering and predictive cancellation)
- Color correction
  - Correction of color desaturation

$$C_H = r\frac{S}{H}C_S\,,\quad r = \frac{f(C_S,H)}{f(C_S,S)}\,,\quad f(C,I) = \frac{C}{\sqrt{C^2+I^2}}$$

Tania Pouli et al. Color Correction for Tone Reproduction

State of the Art - rTMOs

Detail reconstruction

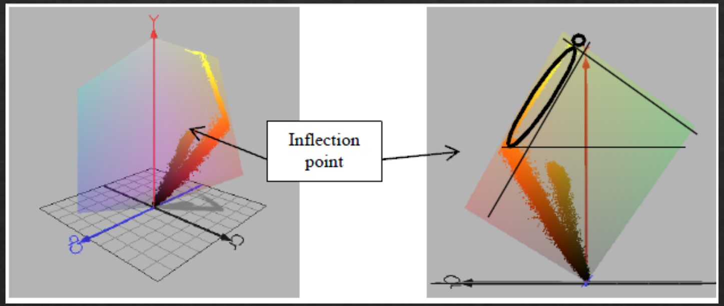
Majority of currently available image and video content have exposure problems.

- *Detail recovery*
- *Artistic intent*
- *Appearance and quality*
- *Enhancing computer vision and imaging applications*

State of the Art - rTMOs

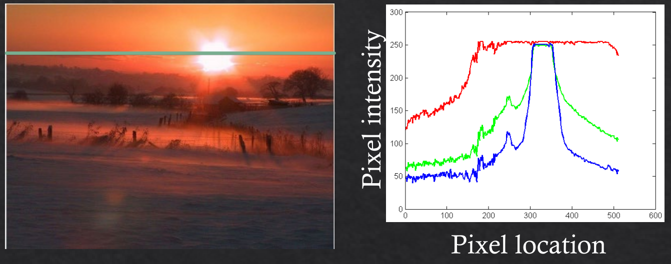
Detail reconstruction

Color clipping correction



J. Fu, et al., "Correcting saturated pixels in images"

RGB channel correlation and RGB channel saturation at different spatial position

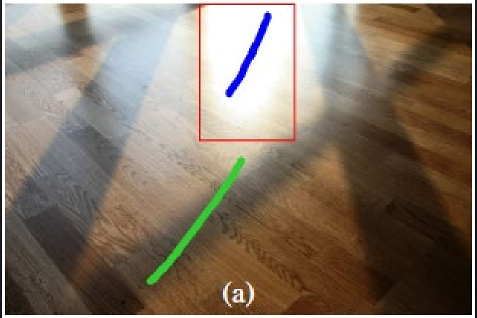


Clipped video

Processed video

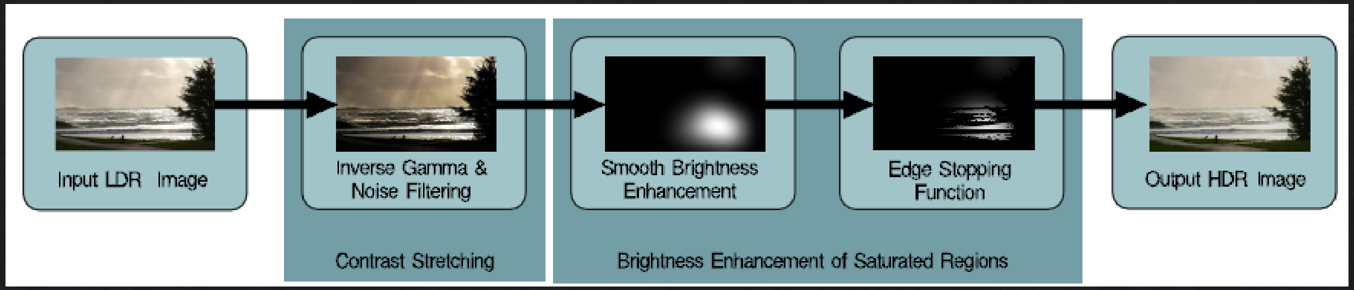
Abebe, M. A et al. "Color Clipping and Over-exposure Correction"

Over-exposure correction



L. Wang, et al., "High dynamic range image hallucination"

Bright Region Enhancement



A. G. Rempel, et al. "Ldr2Hdr: on-the-fly reverse tone mapping of legacy video and photographs "

State of the Art - rTMOs

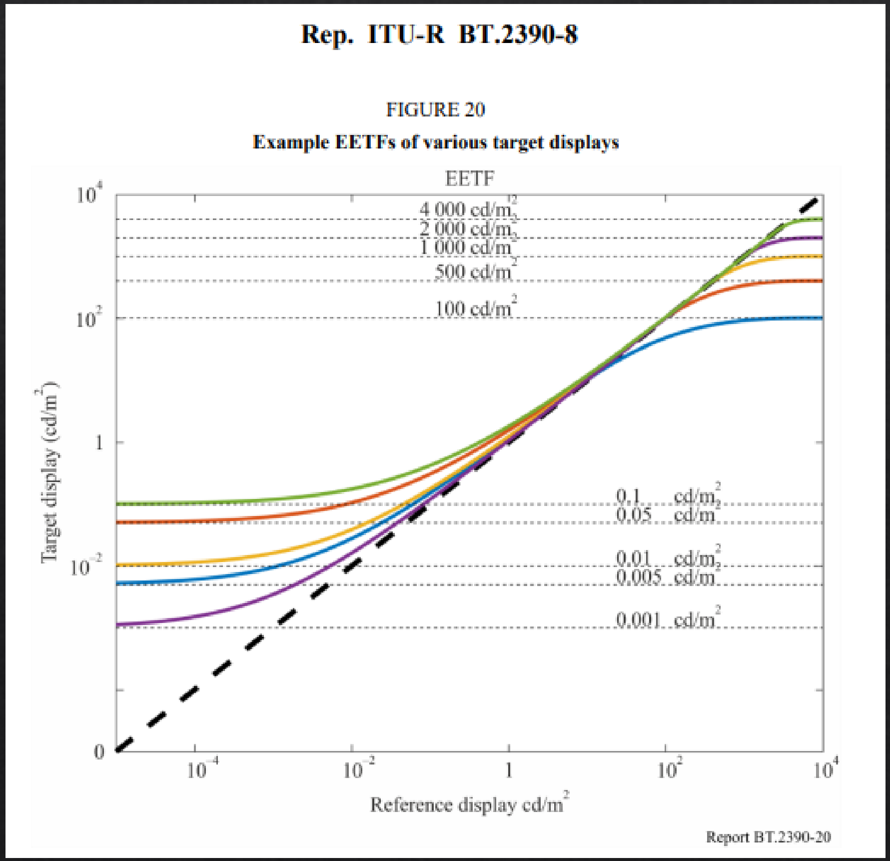
Detail reconstruction

Works well for color clipping and specular highlights

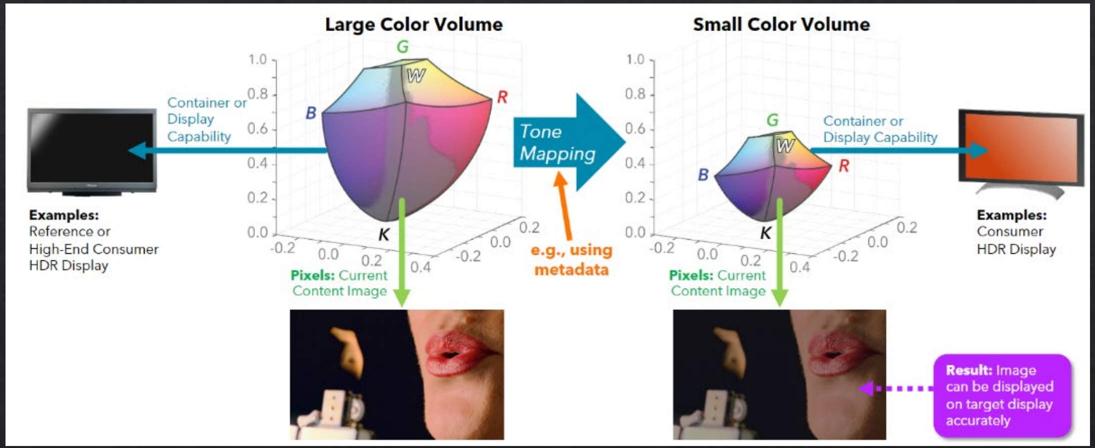
Fails in the presence of severely over-exposed regions

Current trends - rTMOs

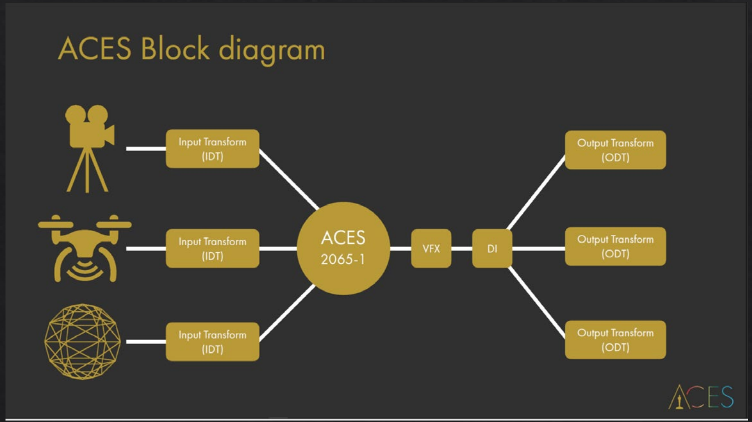
- **HDR standards**
  - Various ITU standards on PQ and HLG encoding and interoperability



- **Volumetric mapping**
- **Color management solutions**



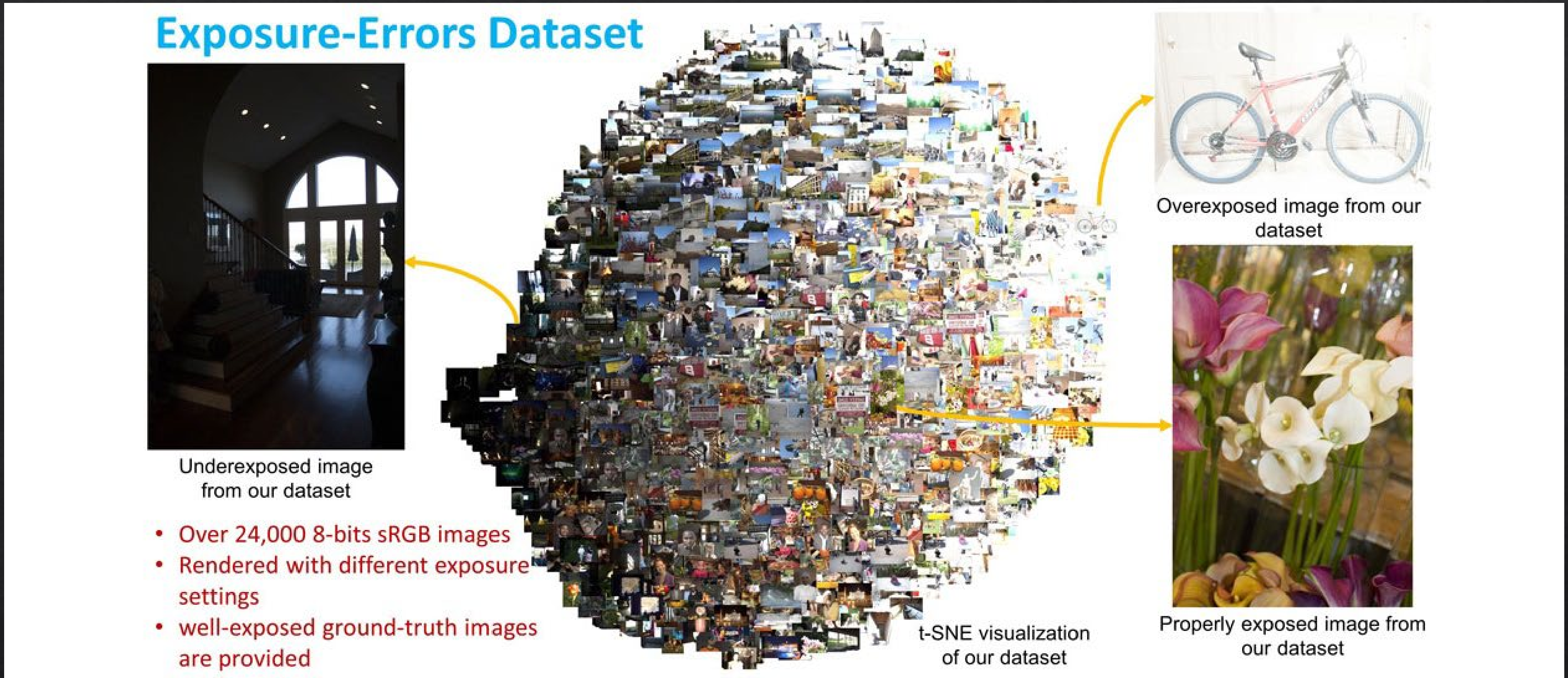
https://www.w3.org/Graphics/Color/Workshop/slides/talk/kunkel



Current trends - rTMOs

Deep Learning Methods

MIT-Adobe FiveK dataset



Taken from Mahmoud Afifi et al. Learning Multi-Scale Photo Exposure Correction

More data set and DL methods are available for under-exposed/low light image enhancement application.

Current trends - rTMOs

Deep Learning Methods

Slightly tone mapped HDR - LDR data set: created from RIT Photographic Survey database and data set.

- 402 paired images and 804 unpaired images

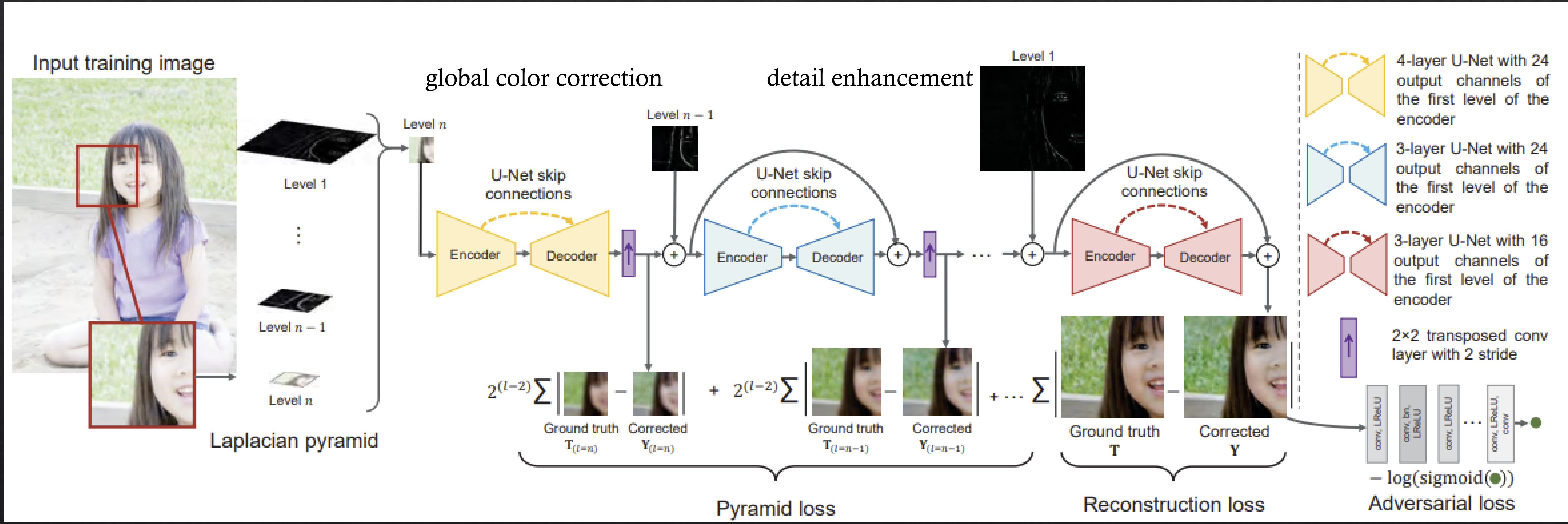
(a) Reference HDR (b) Input LDR (c) Slightly tone mapped HDR

Mekides Assefa et al., Content Fidelity of Deep Learning Methods for Clipping and Over-exposure Correction

Current trends - rTMOs

Deep Learning Methods

Mahmoud Afifi et al., Learning Multi-Scale Photo Exposure Correction

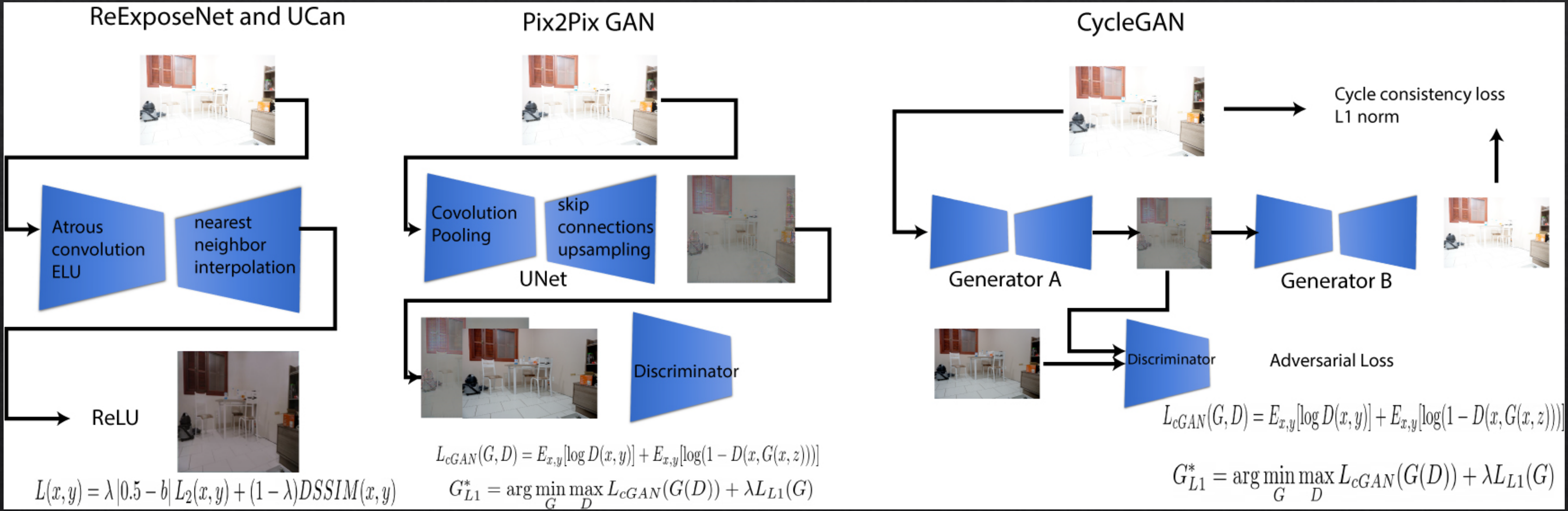


Loss function $L_{final} = \sum_{l=1}^{n} 2^{l-2} L_{1norm_l}(T_l, Y_l) + L_{1norm_l}(T, Y) - log(D(T, Y))$

Current trends - rTMOs

Deep Learning Methods

GAN based image-to-image translation models were adapted for exposure correction application.



Mekides Assefa et al., Content Fidelity of Deep Learning Methods for Clipping and Over-exposure Correction

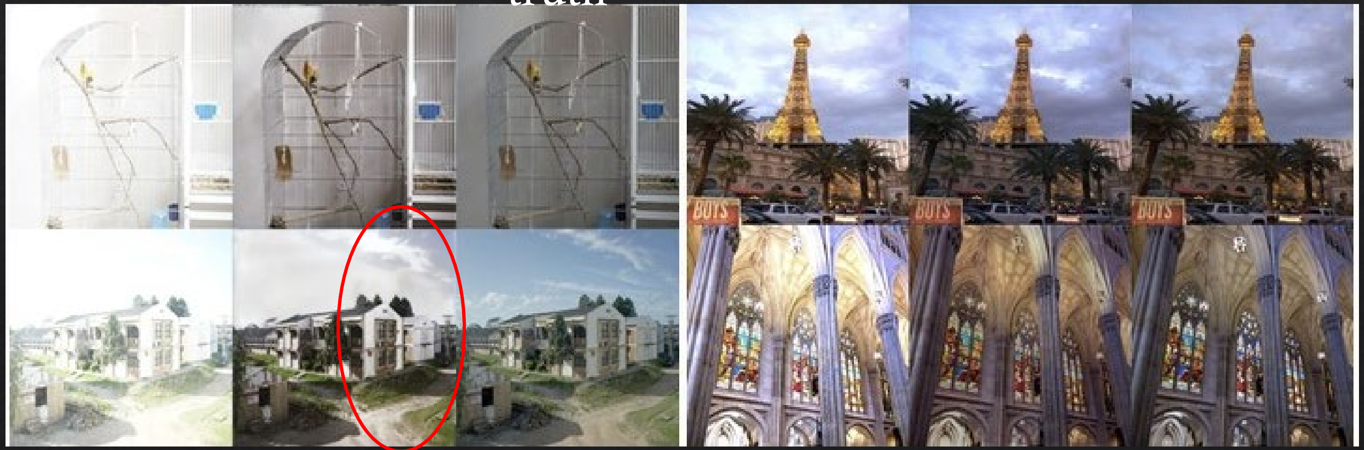
Current trends - rTMOs

Deep Learning Methods

Input Corrected Ground truth

Mahmoud Afifi et al., Learning Multi-Scale Photo Exposure Correction

Input Corrected Ground truth Input Corrected Ground truth



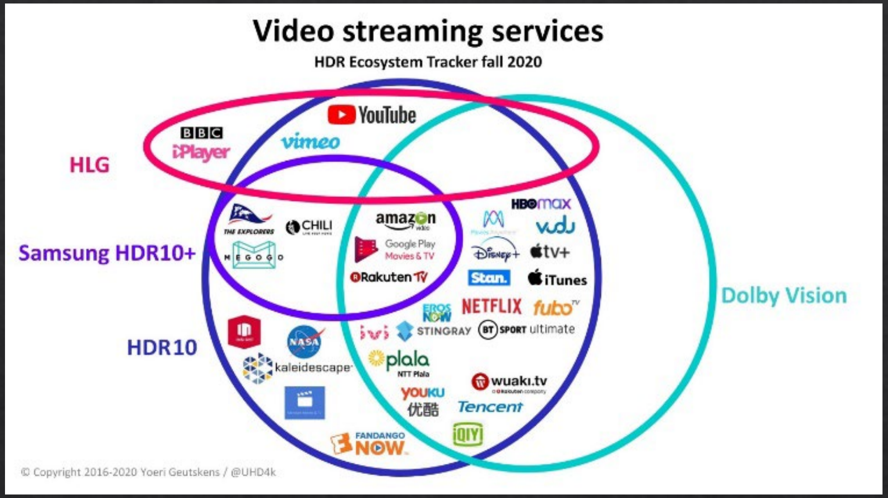
Steffens et al., Deep Learning Based Exposure Correction

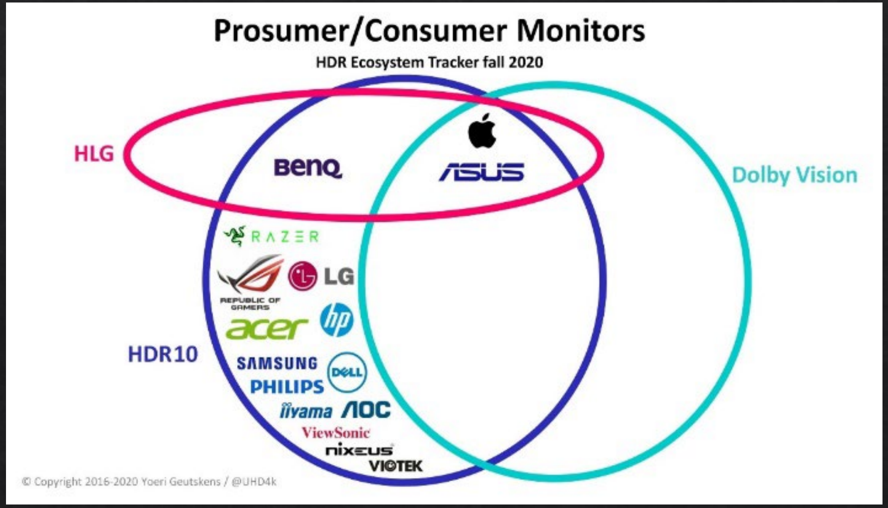
Results and Color fidelity issues

- Color and content fidelity issues.
- Semantically incoherent corrections.
- Poor generalization.
- Problems get worse for severely over-exposed contents.

Limitations and Future Research Directions

- **Color fidelity**
  - **Perceptually uniform** color spaces
  - Quality intent: pleasantess, reproduction quality
- **Interoperablity**
  - Display screens calibration:
    - displays with multiple HDR stanard modes are available
    - **Radiometric calibration**
  - Videos: **dynamically changing** scenes
  - **HDR + wide color gamut** devices: **volumetric mapping**
- **Content recovery**
  - Better data set
  - Semantically coherent and cross-class attention models
  - Image/video quality aware loss functions





HDR ecosystem tracker:
https://www.flatpanelshd.com/focus.php?subaction=showfull&id=1559638820

Thank you for your attention. Thank you for your attention. Thank you for

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