Retinex by Two Bilateral Filters

Michael Elad
The CS Department
The Technion – Israel Institute of technology
Haifa 32000, Israel

Scale-Space 2005
The 5th international conference on scale-space
and PDE in computer vision
Hofgeismar, Germany
April 7-9th , 2005

Retinex?

Agenda

1. What is Retinex? The Basics
2. Retinex from a Variational Point of View
3. Bilateral Filter? Evolution of Denoising Methods
4. Bilateral Filter For Retinex
5. Examples and What Next?

Part 1

What is Retinex? The Basics

What is Retinex?

- The sensed image is $S = L \cdot R$,
  where: S – Scene intensity,
  L – illumination,
  R – reflectance.
- We can measure S, but not L or R.
- Getting R from S is an **ill-posed inverse problem**.
- The human visual system (HVS) sees R. How?
- Retinex is a similar **image enhancement algorithm**.

A Typical Retinex System

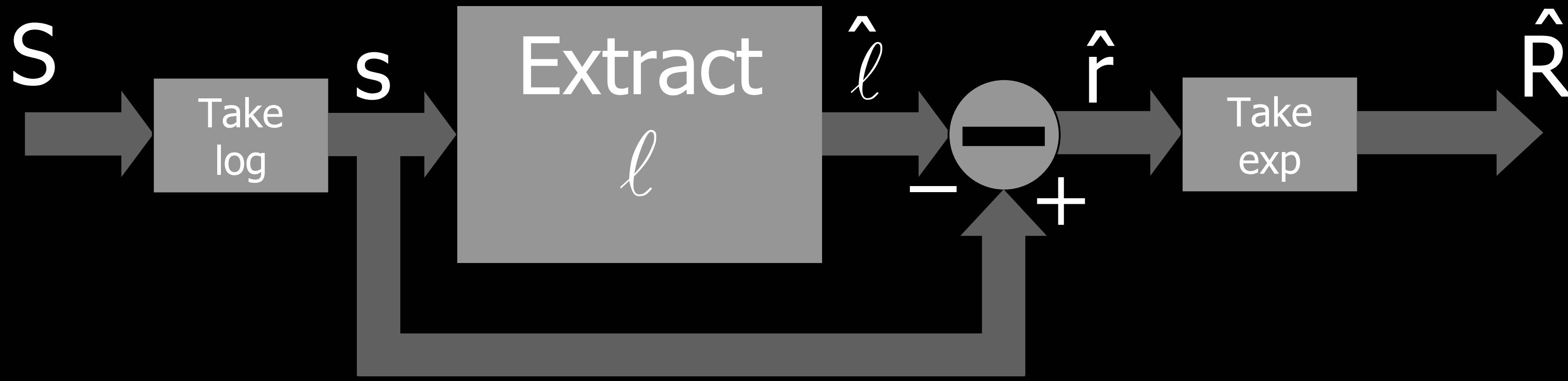
$$S = L \cdot R$$

$$s = \ell + r$$

where $s = \log S,$

$\ell = \log L,$

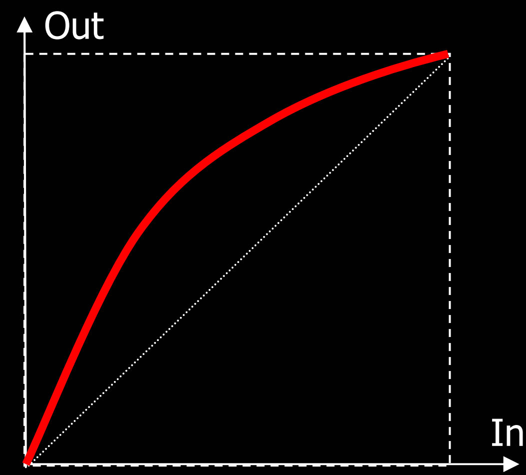
$r = \log R$

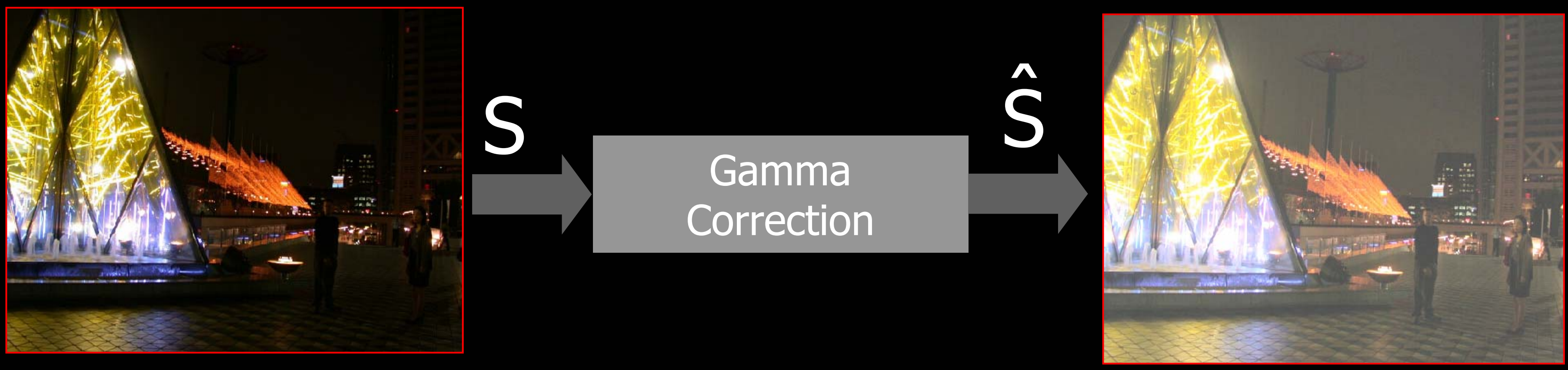


Example: Gamma Correction

Gamma correction is a simple Look-Up-Table operation of the form ($\gamma \approx 2.5$)

$$\hat{S} = 255 \cdot \left(\frac{S}{255}\right)^{1/\gamma} \Rightarrow \boxed{\hat{\ell} = \left(1-\frac{1}{\gamma}\right)(s-\log 255)}$$





Many Retinex Algorithms …

Various Retinex algorithms out there:

- Random walk smoothing [Land and MacCan 1971]
- Homomorphic filtering [Stockham 1972, Faugeras 1979]
- Poisson equation [Horn 1974, Blake 1985, Funt et. al. 1992]
- Multi-grid Poisson solver [Terzopoulos 1986]
- Bilateral filter for retinex [Durand & Dorsey, 2002]
- Sparse representations (Curvelet) [Starck et. al. 2003]
- Multi-scale heuristic envelope method [McCann 1999]
- Variational method [Kimmel et. al. 2003, Elad et. al. 2003]
- IIR envelope smoothing [Shaked 2004]

A new Algorithm

Part 2

Retinex from a A Variational Point of View

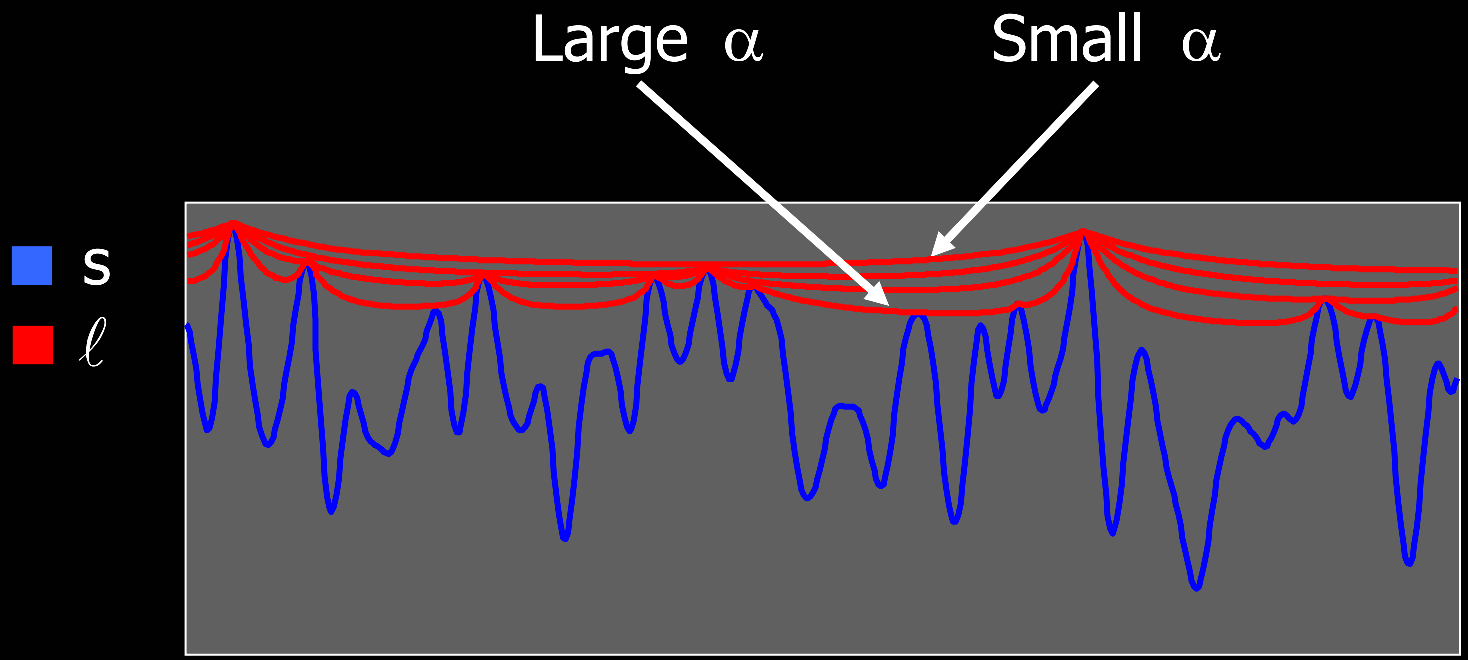
Things To Consider

- The illumination is supposed to be spatially (piecewise!?) smooth.
- Since the reflectance is passive, $0 \le R \le 1$, we require $S \le L$ and $s \le \ell$.
- Trivial solution (L=255) should be avoided - The illumination should be forced to be close to s.

$$\underset{\ell \ge s}{\text{Minimize}} \int_{\Omega} \left(\left| \nabla \ell \right|^2 + \alpha \left(\ell - s \right)^2 \right) d\Omega$$

Illumination as an Upper Envelope

$$\underset{\ell \geq s}{\text{Minimize}} \int_{\Omega} \left(\left| \nabla \ell \right|^2 + \alpha (\ell - s)^2 \right) d\Omega$$



The Overall Model

[Kimmel, Elad, Shaked, Keshet, & Sobel 2003]

$$\underset{\ell \geq s}{\text{Minimize}} \int_{\Omega} \left(|\nabla \ell|^2 + \alpha(\ell - s)^2 + \beta |\nabla(\ell - s)|^2 \right) d\Omega$$

The reflectance, s-ℓ should behave like a typical image

- This is a quadratic programming problem
- A multi-scale method numerical scheme was proposed

Shortcomings?

$$\underset{\underline{\ell}\geq\underline{s}}{\text{Minimize}}\ \overbrace{\left\|\mathbf{D}_x\underline{\ell}\right\|^2+\left\|\mathbf{D}_y\underline{\ell}\right\|^2}^{\text{Smooth illumination}}+\alpha\overbrace{\left\|\underline{\ell}-\underline{s}\right\|^2}^{\text{envelope}}+\beta\overbrace{\left(\left\|\mathbf{D}_x\left(\underline{s}-\underline{\ell}\right)\right\|^2+\left\|\mathbf{D}_y\left(\underline{s}-\underline{\ell}\right)\right\|^2\right)}^{\text{smooth reflectance}}$$

- ❑ Requires an iterative solver!
- ❑ Noise is magnified in dark areas. Forcing $\underline{s}=\underline{r}+\underline{\ell}$ works against noise suppression.
- ❑ Promotes hallows on the boundaries of the illumination.

Part 3

Bilateral Filter? Evolution of Denoising Methods

Evolution in Denoising (1D)

Task: Given a noisy signal $\underline{s}$, produce a denoised version of if, $\underline{z}$.

First Stage

$$\underset{\underline{z}}{\text{Minimize}}\ \alpha\left\|\underline{z}-\underline{s}\right\|^2+\left\|\mathbf{D}\underline{z}\right\|^2$$

Or written differently with a shift-operator **C**:

$$\underset{\underline{z}}{\text{Minimize}}\ \alpha\left\|\underline{z}-\underline{s}\right\|^2+\left\|(\mathbf{I}-\mathbf{C})\underline{z}\right\|^2$$

Going “Weighted” & “Robust”

Second Stage

Over-smoothing – introduce weights in order to preserve edges

$$\underset{\underline{z}}{\text{Minimize}}\ \alpha\left\|\underline{z}-\underline{s}\right\|^2+\left[(\mathbf{I}-\mathbf{C})\underline{z}\right]^T\mathbf{W}\left[(\mathbf{I}-\mathbf{C})\underline{z}\right]$$

Third Stage

Better yet – use signal dependent weights (robust statistics)

$$\underset{\underline{z}}{\text{Minimize}}\ \alpha\left\|\underline{z}-\underline{s}\right\|^2+\left[(\mathbf{I}-\mathbf{C})\underline{z}\right]^T\mathbf{W}(\underline{z})\left[(\mathbf{I}-\mathbf{C})\underline{z}\right]$$

The Bilateral Filter

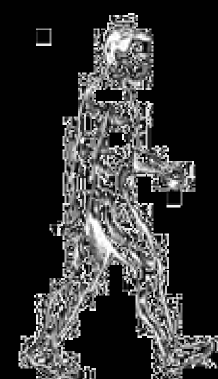
Fourth Stage

Too many iterations – use wide-support smoothness term

The bilateral filter is a weighted average smoothing, with weights inversely proportional to the (total!) distance between the center pixel and the neighbor [Tomasi and Manduchi, 1998]

$$\underset{\underline{z}}{\text{Minimize}} \quad \alpha\left\|\underline{z}-\underline{s}\right\|^2 + \mathbf{B}\left\{\underline{z}\right\}$$

The first Jacobi iteration that minimizes the above function leads to the bilateral filter [Elad, 2002]



Fifth Stage

Part 4

Bilateral Filter For Retinex

Retinex - Restatement

Avoid trivial solution by forcing the illumination to be close to s

Piecewise smooth illumination

Piecewise smooth reflectance

$$\underset{\underline{\ell}\geq\underline{s},\underline{r}}{\text{Minimize}}\left(\lambda_{\ell}\left\|\underline{\ell}-\underline{s}\right\|^{2}+B\{\underline{\ell}\}\right)+\alpha\left(\lambda_{r}\left\|\underline{r}-(\underline{s}-\underline{\ell})\right\|^{2}+B\{\underline{r}\}\right)$$

Envelope illumination due to passive reflectance

- Give an estimate of $\underline{\ell}$, if there is no noise, then $\underline{r}=\underline{s}-\underline{\ell}$.
- If there is an additive noise, it is $\underline{r}-\underline{s}+\underline{\ell}$, and its norm is the proper likelihood term to use.

The New Formulation

$$\underset{\ell \geq s, r}{\text{Minimize}} \left(\lambda_\ell \left\| \underline{\ell} - \underline{s} \right\|^2 + B\{\underline{\ell}\} \right) + \alpha \left(\lambda_r \left\| \underline{r} - (\underline{s} - \underline{\ell}) \right\|^2 + B\{\underline{r}\} \right)$$

With this new formulation:

- Non-iterative solver can be deployed,
- Both the illumination and the reflectance are forced to be piece-wise smooth, thus preventing hallows,
- Noise is treated appropriately,
- Clear relation to Durand & Dorsey's method is built.

Numerical (Sub-Optimal) Solution

$$\underset{\ell \geq s, r}{\text{Minimize}} \left(\lambda_{\ell} \left\| \underline{\ell} - \underline{s} \right\|^2 + B\{\underline{\ell}\} \right) + \alpha \left(\lambda_r \left\| \underline{r} - (\underline{s} - \underline{\ell}) \right\|^2 + B\{\underline{r}\} \right)$$

Part 1: Find $\underline{\ell}$ by assuming $\underline{r}=0$

$$\underset{\ell \geq s}{\text{Minimize}} \left((\lambda_{\ell} + \alpha\lambda_r) \left\| \underline{\ell} - \underline{s} \right\|^2 + B\{\underline{\ell}\} \right)$$

Bilateral filter on $\underline{s}$ in an envelope mode

Both can be speeded up dramatically [Durand & Dorsey 2002]

Part 2: Given $\underline{\ell}$, find $\underline{r}$ by

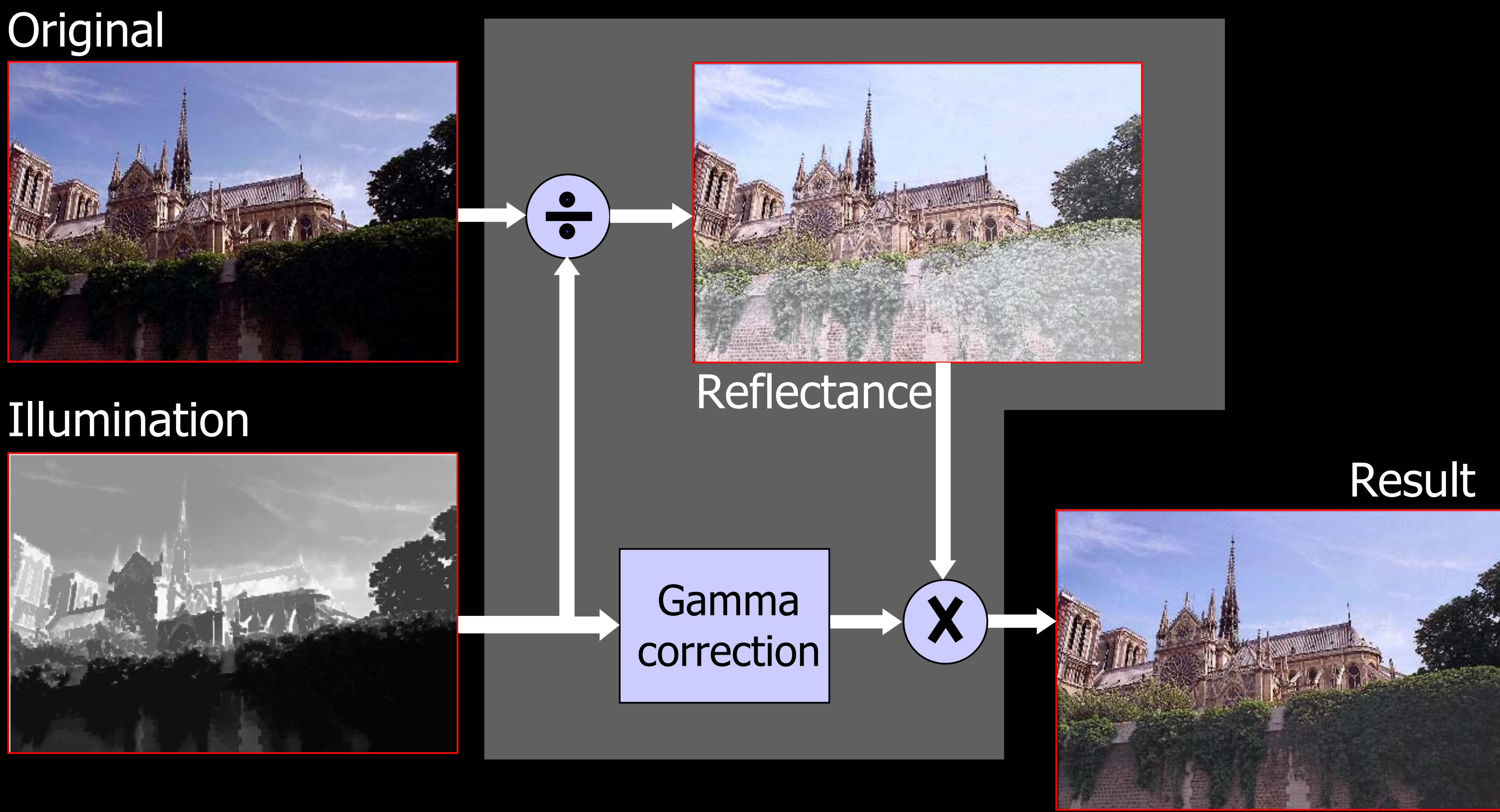
$$\underset{r}{\text{Minimize}} \left(\lambda_r \left\| \underline{r} - (\underline{s} - \underline{\ell}) \right\|^2 + B\{\underline{r}\} \right)$$

Bilateral filter on $\underline{s}$-$\underline{\ell}$ in a regular mode

Part 5

Examples
and
What Next?

Returning Some Illumination



Example 1 – General

Original

Result (γ=3)

Illumination

Reflectance

Special thanks to Eyal Gordon for his help in simulating the retinex algorithm(s) on stills and videos

Example 2 – Noise Reduction

Original

Result (γ=3)

Result with noise reduction

Example 3 – Hallows?

Conclusion

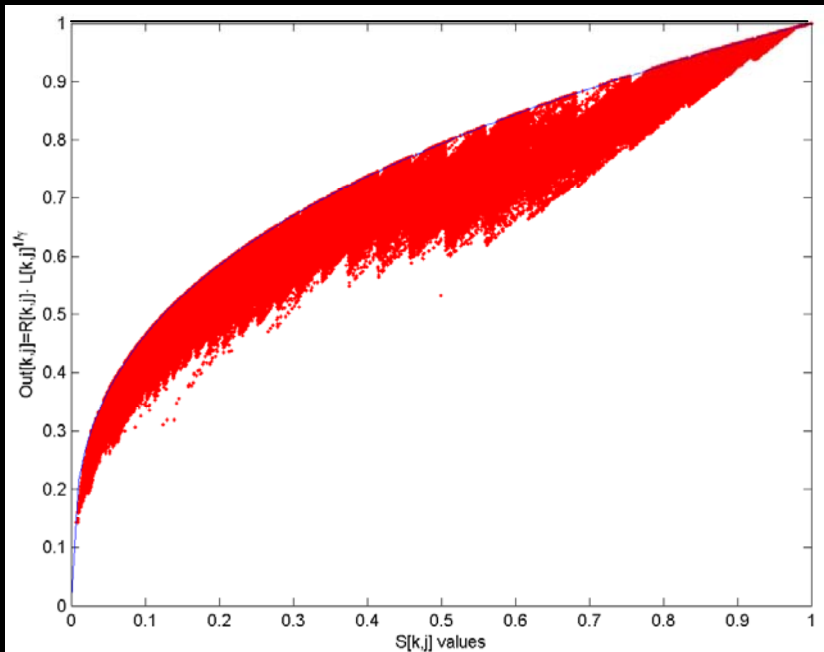
- Retinex by two bilateral filters – based on [Kimmel et.al. 2003] and [Durand et. al. 2002].
- It overcomes hallows, the need for iterations, and handles noise well.
- Bilateral retinex – excellent choice for video retinex – Future work.

THANK YOU !

תודה רבה !

Other slides

Example 3 – Gamma Correction?



Computing the effective gamma per pixel and showing as a graph

The same gamma values per location – Retinex could be interpreted as an spatially adaptive gamma correction

What About Video?

- When this work started, we planned to develop a retinex algorithm for video sequences.
- Things to consider for video:
  - Causality?
  - Inter-frame versus Intra-frame modes
  - Motion estimation and compensation
  - Run time and speedups
- Bilateral Retinex seems like a very good match for video purposes: no need to estimate motion.
- Our experiments gave successful retinex results with the simple intra-frame mode of work.
- So, what could be the benefit in inter-frame mode for video?

Example2: Homomorphic Filtering

Homomorphic filtering assumes that the low frequencies in S correspond to the illumination, whereas high frequencies to the reflectance

[Stockham 1972, Faugeras 1979]

```
A=imread('0541 01 source.jpg');
imagesc(A); colormap(gray(256)); axis image; axis off;
A=rgb2ycbcr(A);
S=double(A(:,:,1)); s=log(S+1);
Iest=conv2(s,ones(31,31)/31^2,'same');
sest=s-Iest;
Sest=exp(sest);
A(:,:,1)=uint8(max(min(80*Sest,255),0));
A=ycbcr2rgb(A);
imagesc(A); colormap(gray(256)); axis image; axis off;
```

$S \rightarrow$ Homomorphic Filter $\rightarrow \hat{S}$