Defocus Techniques for Camera Dynamic Range Expansion

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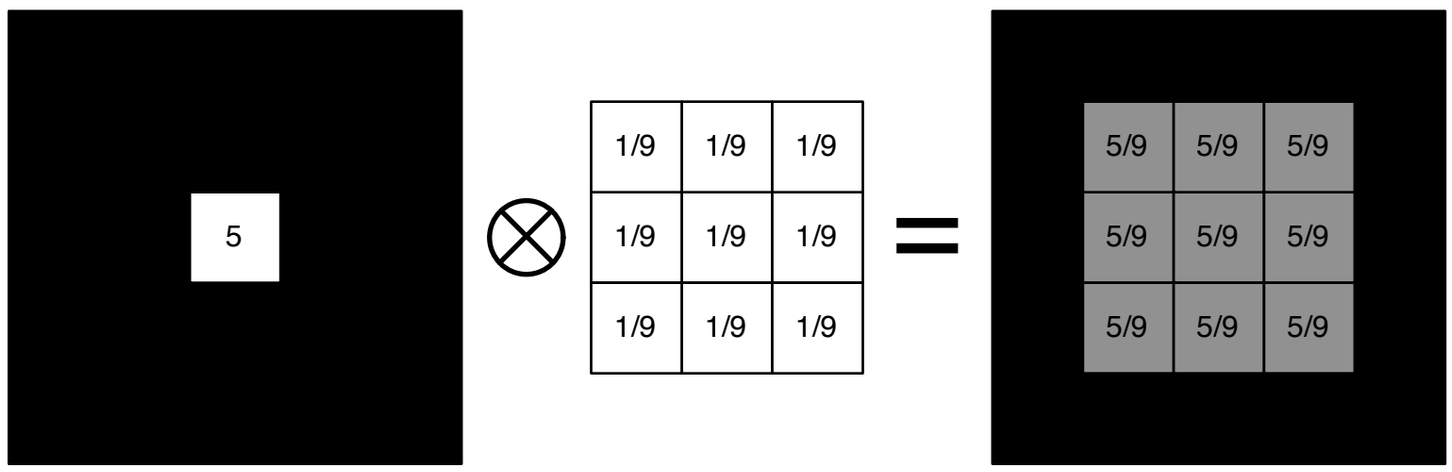
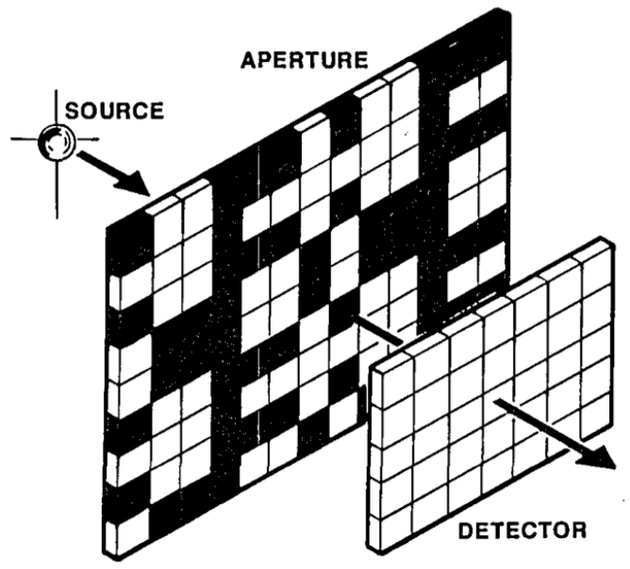
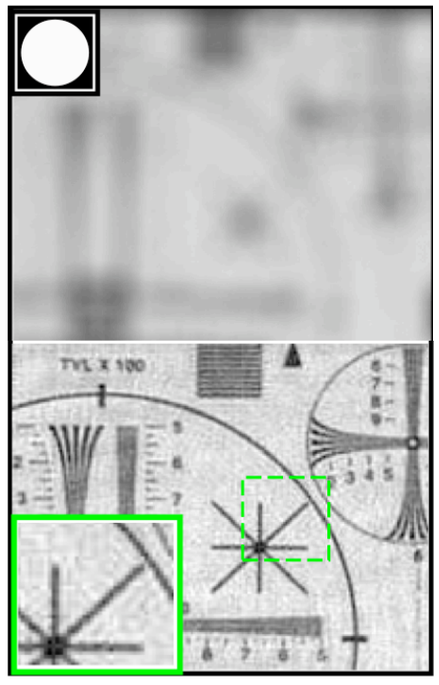
Defocus DR expansion

- Sensors limited in dynamic range
  Can be expanded, but tradeoffs exist
- Evaluate the opposite, reduce the dynamic range of the scene incident on the sensor by optical blurring, restore in software



Approach



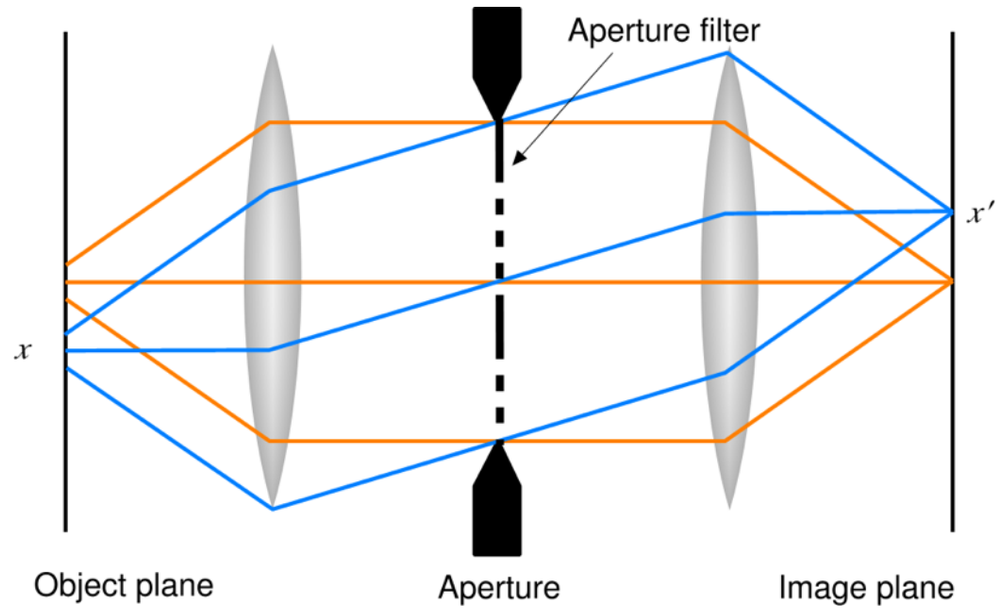


- Use 2 techniques to aid:
  coded aperture + deconvolution

- Aperture filter to improve deconvolution quality
  PSF preserves more information
  [Rashkar 2006][Levin 2007][Veeraraghavan 2007]

- Deconvolution to restore original image
  Recent advances using natural image statistics
  [Bando 2007][Levin 2007]

Physical setup

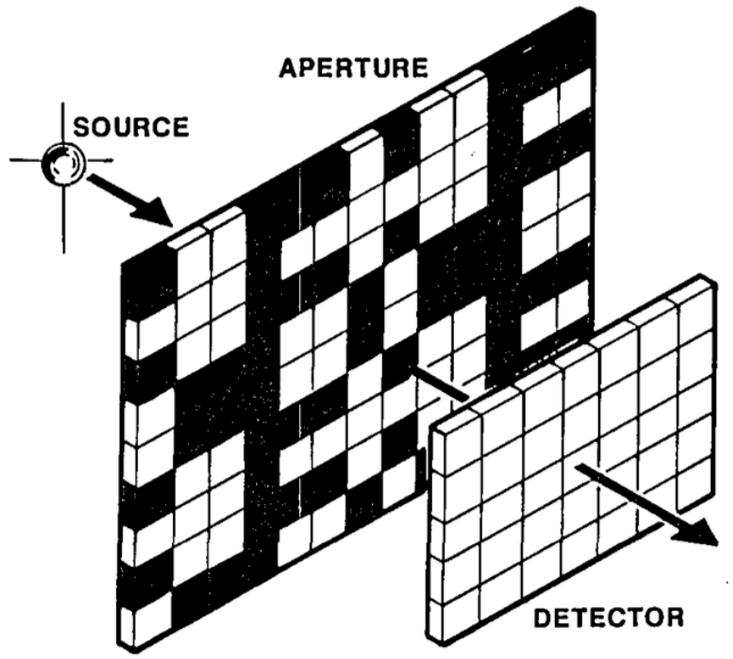


- Rays from scene pass through aperture plane and focused onto sensor

- Cone of rays from out-of-focus points intersects sensor, forming the shape of the aperture

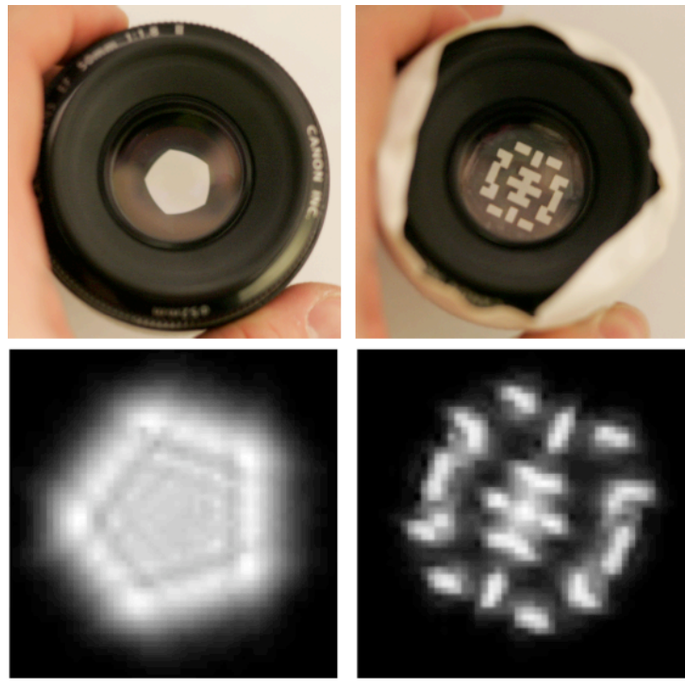
- A pattern in the aperture plane is projected onto the sensor for out-of-focus points

Coded Aperture

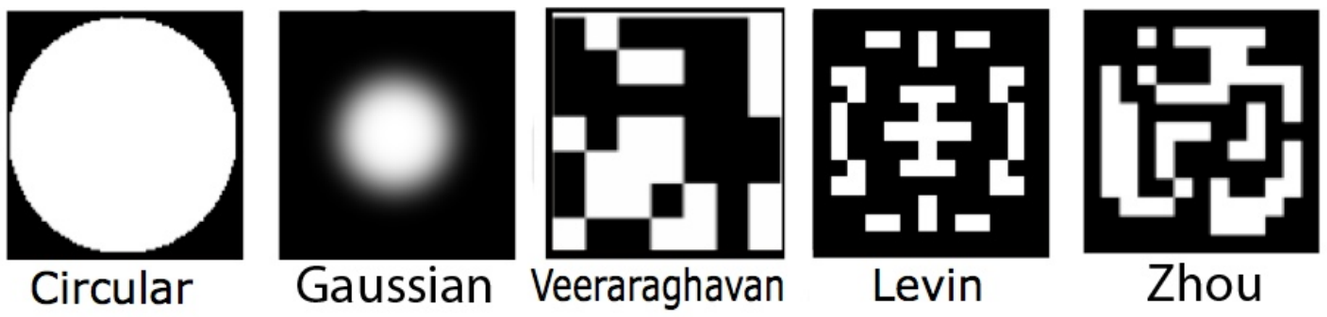


- Originally from x-ray astronomy
  [Fenimore 1978][Gottesman 1989]
- Structured arrays + decoding algorithm with resolution of pinhole, but better SNR
- Employed in visible light photography
  [Rashkar 2006][Levin 2007][Veeraraghavan 2007]
- Improve frequency properties of filter

Aperture filters



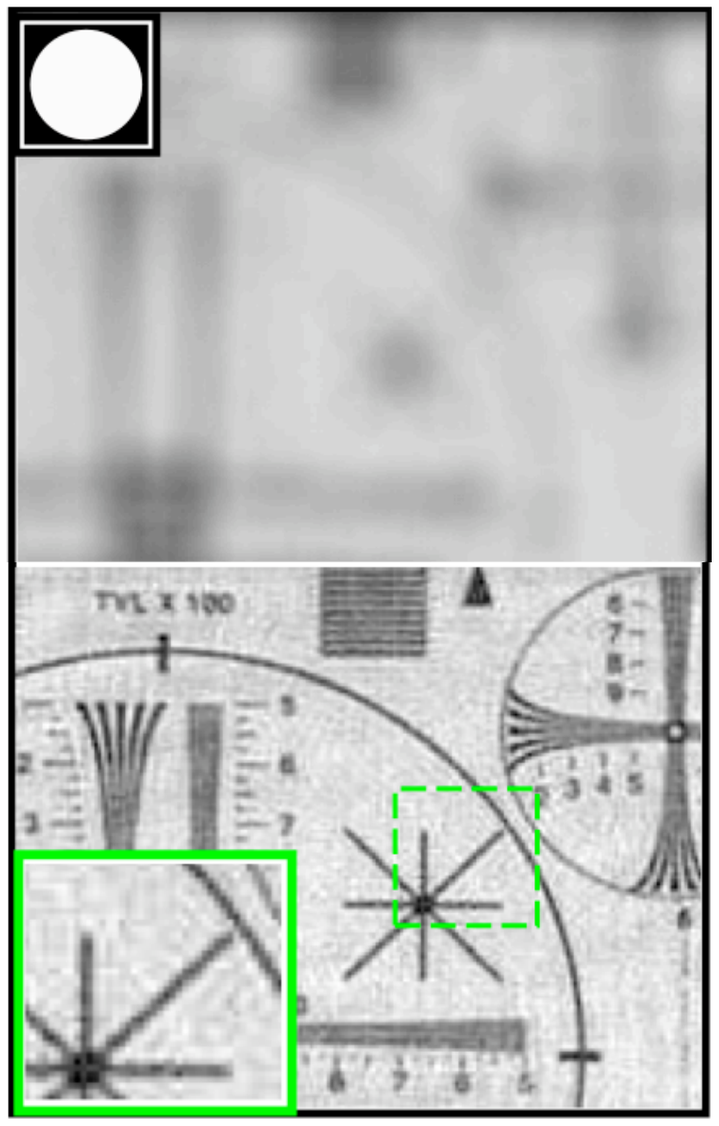
- What makes a good filter?
  - Frequency response
    - Position and spacing of zero frequencies
    - Diffraction / transmission



Deconvolution

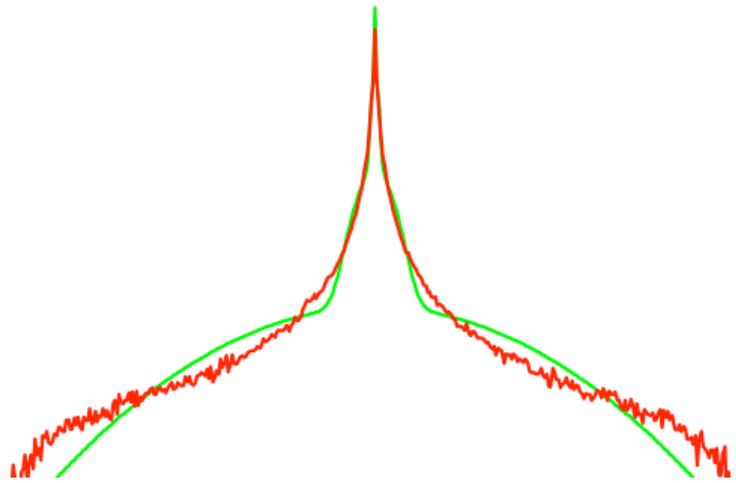
- Restore image distorted by PSF
  [Wiener 1964][Richardson 1972][Lucy 1974]

$$f = f_0 \otimes k + \eta$$



- Ill-posed, infinite solutions
- No exact solution due to noise
- Division in FFT, issues with small values in OTF of filter

Deconvolution



- Current state-of-the-art methods rely on natural image statistics

- Real-world images share several properties:
  Heavy-tail distribution of gradients

- Prior term in deconvolution algorithms
  [Bando 2007][Levin 2007]

- Favors interpretations of the image with all the gradient intensity at a few pixels

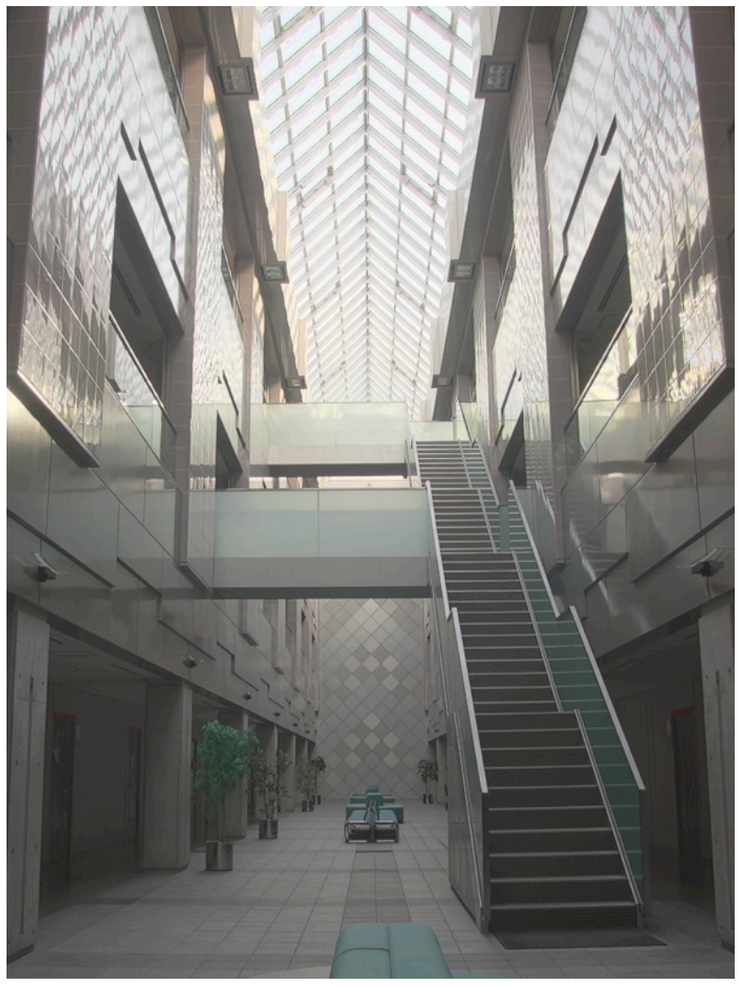
Evaluation

- Goal : determine whether any combo of filter / deconvolution yields meaningful reduction in DR with acceptable final image quality

- Measure DR reduction both in terms of image local contrast and filter

- Measure image quality as difference between deconvolved and original images

Source material



Atrium Morning

Radius	**Atrium Morning**			**Atrium Night**		
	min	max	**reduction**	min	max	**reduction**
Original	0.00	11.0		0.00	12.0	
1	0.00	10.8	**0.200**	0.452	12.0	**0.452**
2	0.00	10.6	**0.424**	0.622	12.0	**0.622**
3	0.00	10.3	**0.716**	1.163	11.8	**1.34**
4	0.02	10.0	**1.00**	1.436	11.4	**1.99**
5	0.08	9.94	**1.14**	1.589	11.4	**2.23**
6	0.15	9.92	**1.24**	1.731	11.2	**2.51**
8	0.31	9.83	**1.48**	1.890	10.8	**3.13**
9	0.40	9.79	**1.61**	1.950	10.5	**3.41**
11	0.66	9.71	**1.94**	2.08	10.3	**3.74**
13	0.86	9.67	**2.19**	2.18	10.1	**4.13**
16	1.04	9.59	**2.45**	2.26	9.61	**4.65**

Atrium Night

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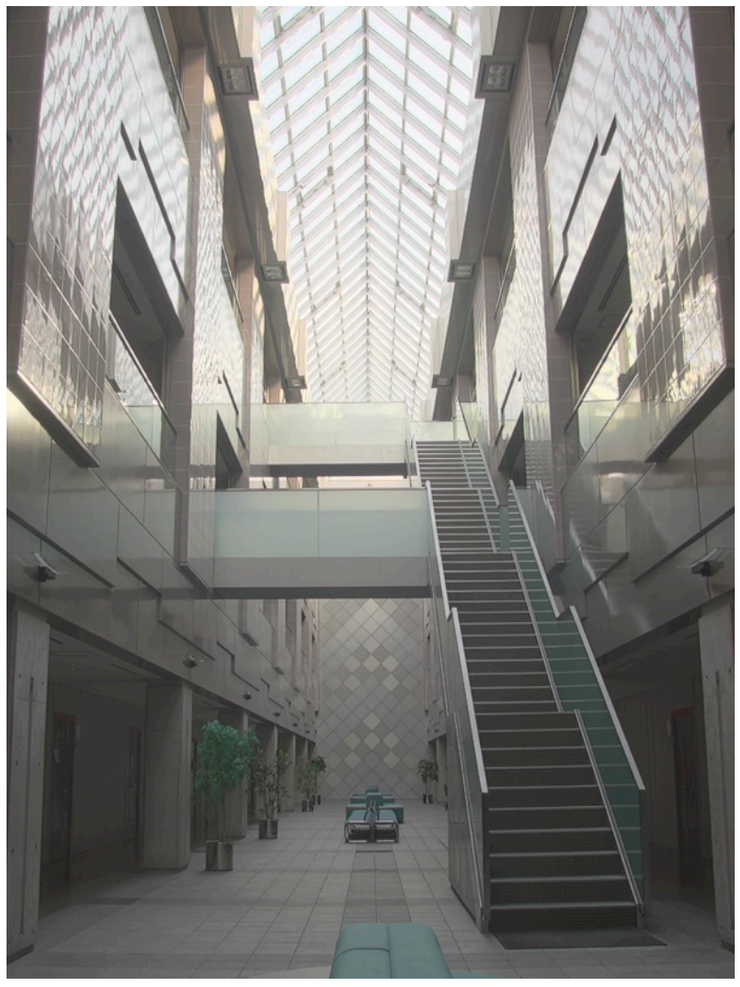

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2.45 EV

Atrium Night

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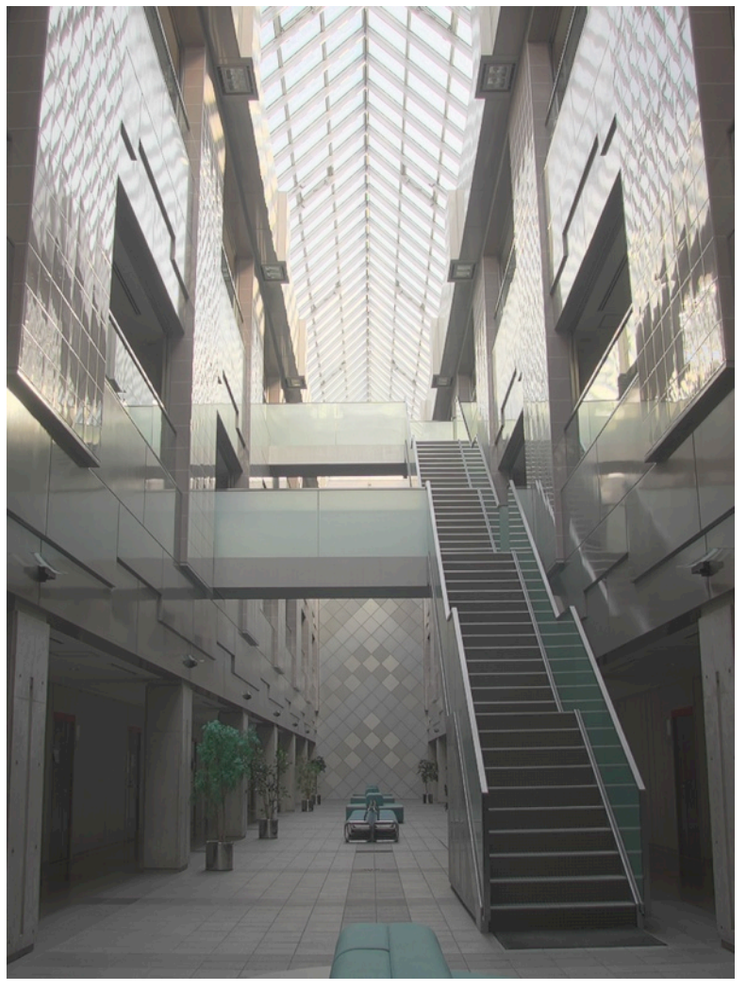

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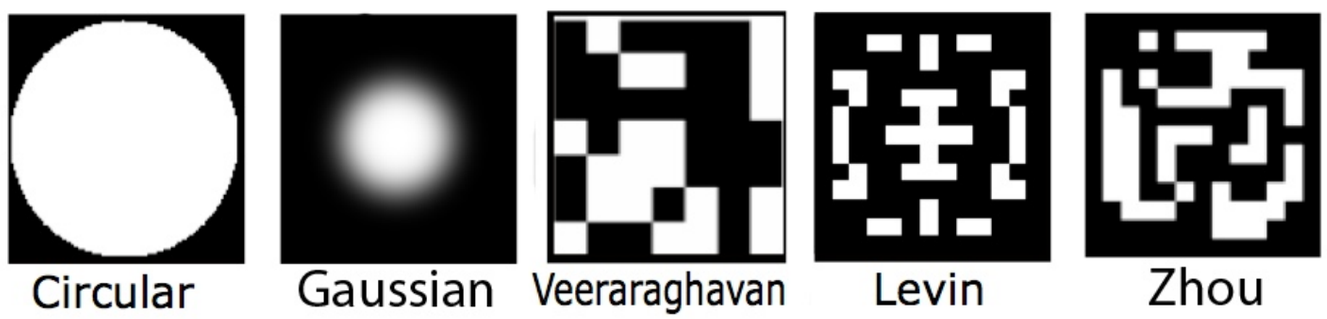
2.45 EV 4.56 EV

Atrium Night

Tests

- Filters evaluated:
  - Normal aperture
  - Gaussian
  - Veeraraghavan
  - Levin
  - Zhou
- Deconvolution evaluated:
  - Wiener filtering
  - Richardson-Lucy
  - Bando
  - Levin



Evaluation (cont)

- Success criteria:
  - Reduction of at least 2 stops
    to justify the computational cost of deconv
  - Quality of at least PSNR 35

Images

Weiner

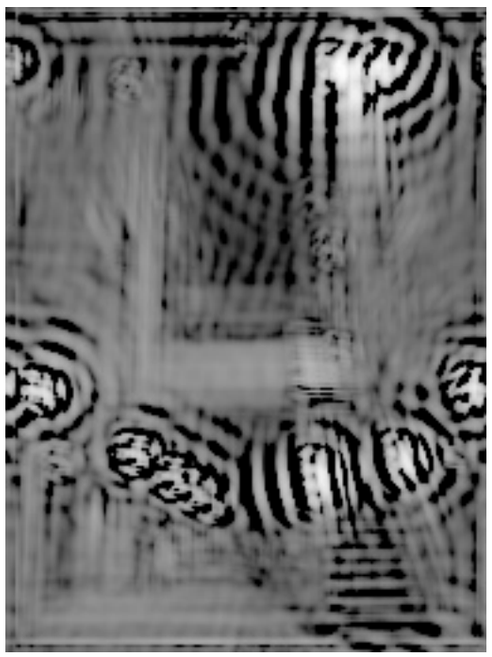
Richardson-Lucy

Bando

Levin

filter=Zhou, noise = 0, radius = 1

Images



Weiner

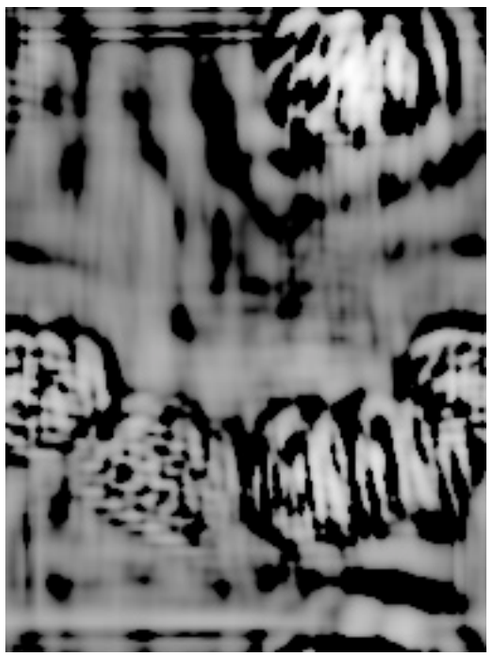
Richardson-Lucy

Bando

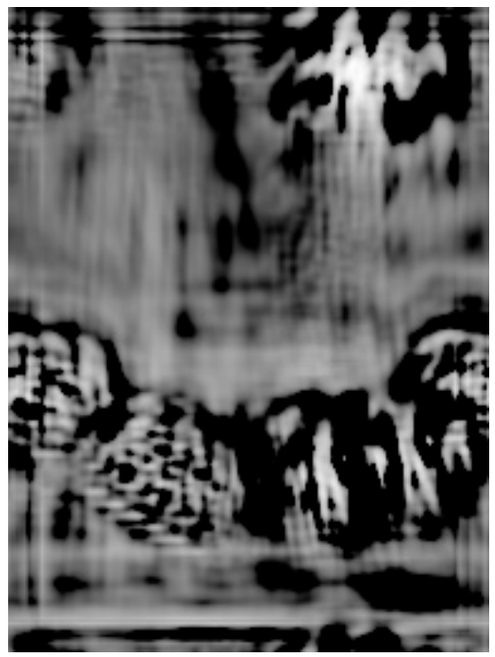
Levin

filter=Zhou, noise = 0, radius = 5

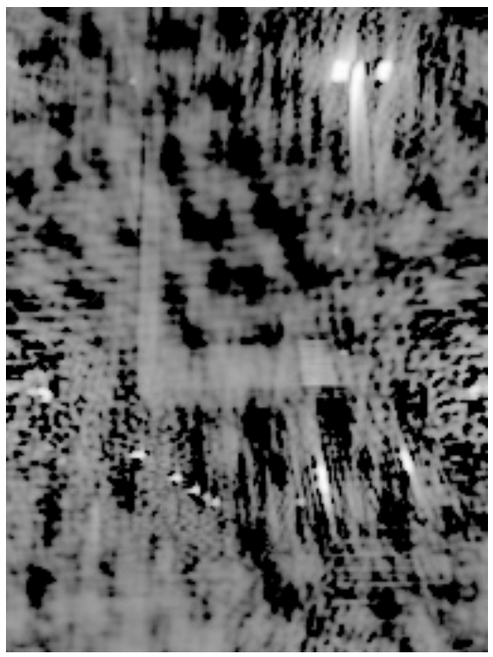
Images



Weiner



Richardson-Lucy

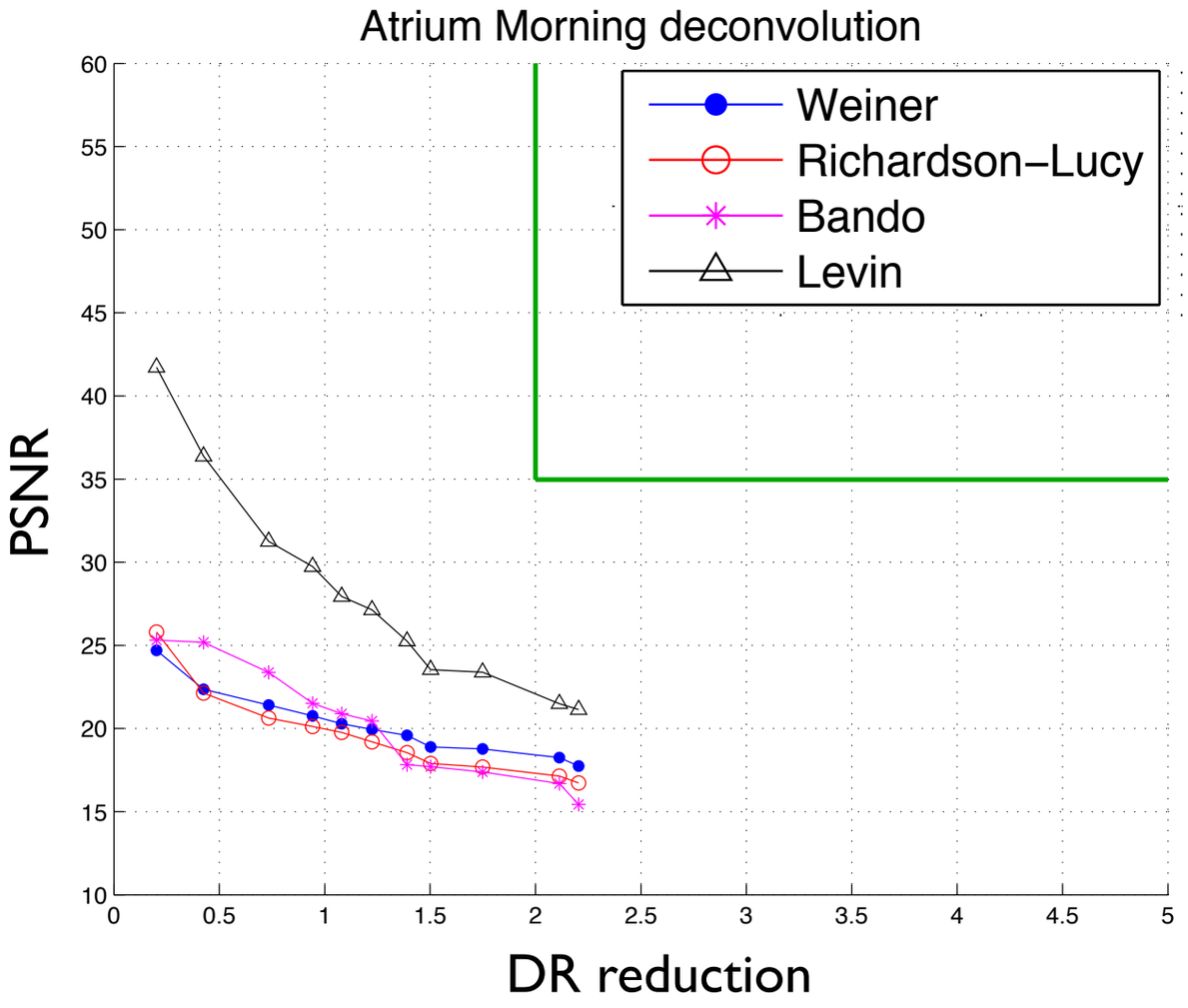


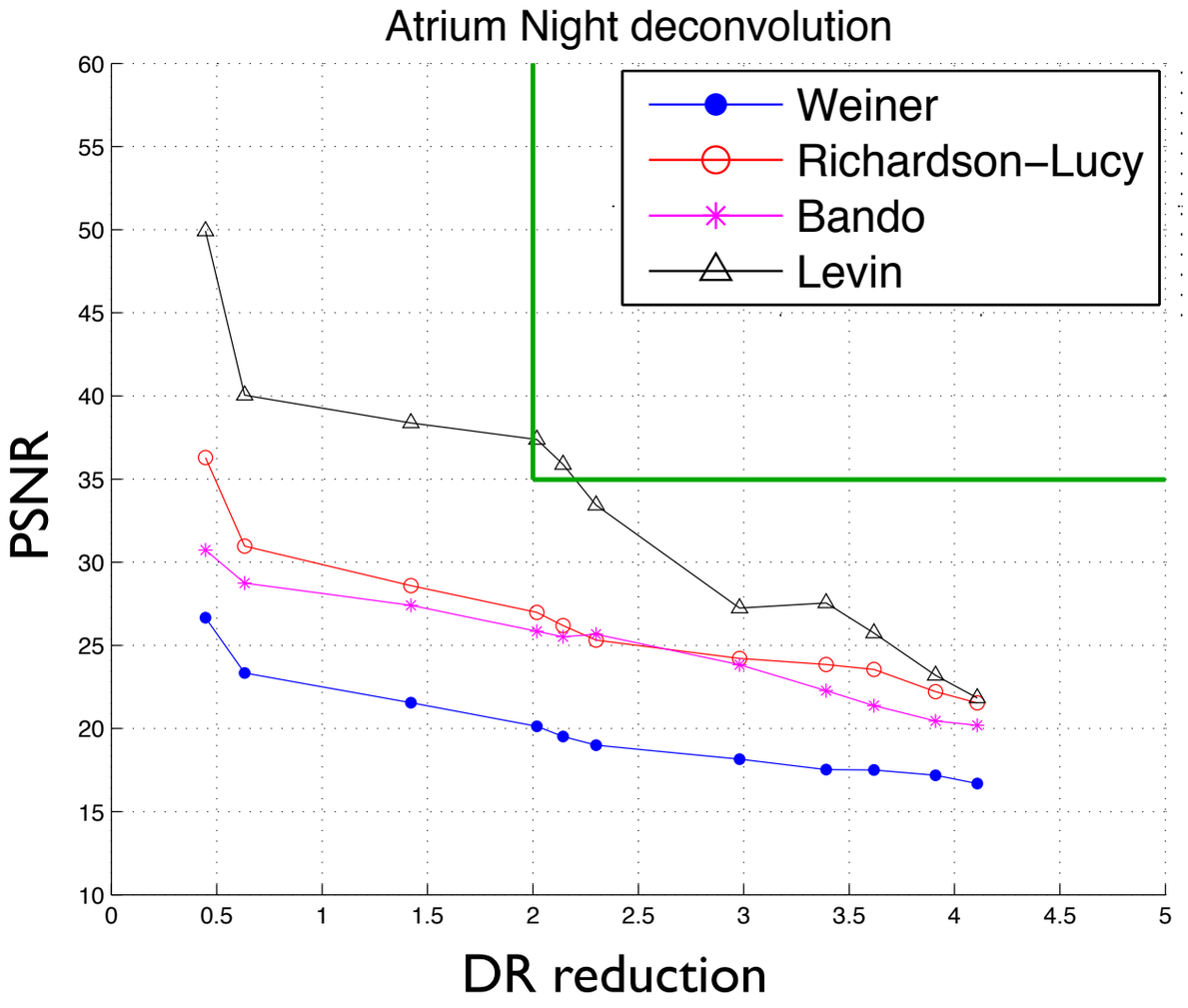
Bando

Levin

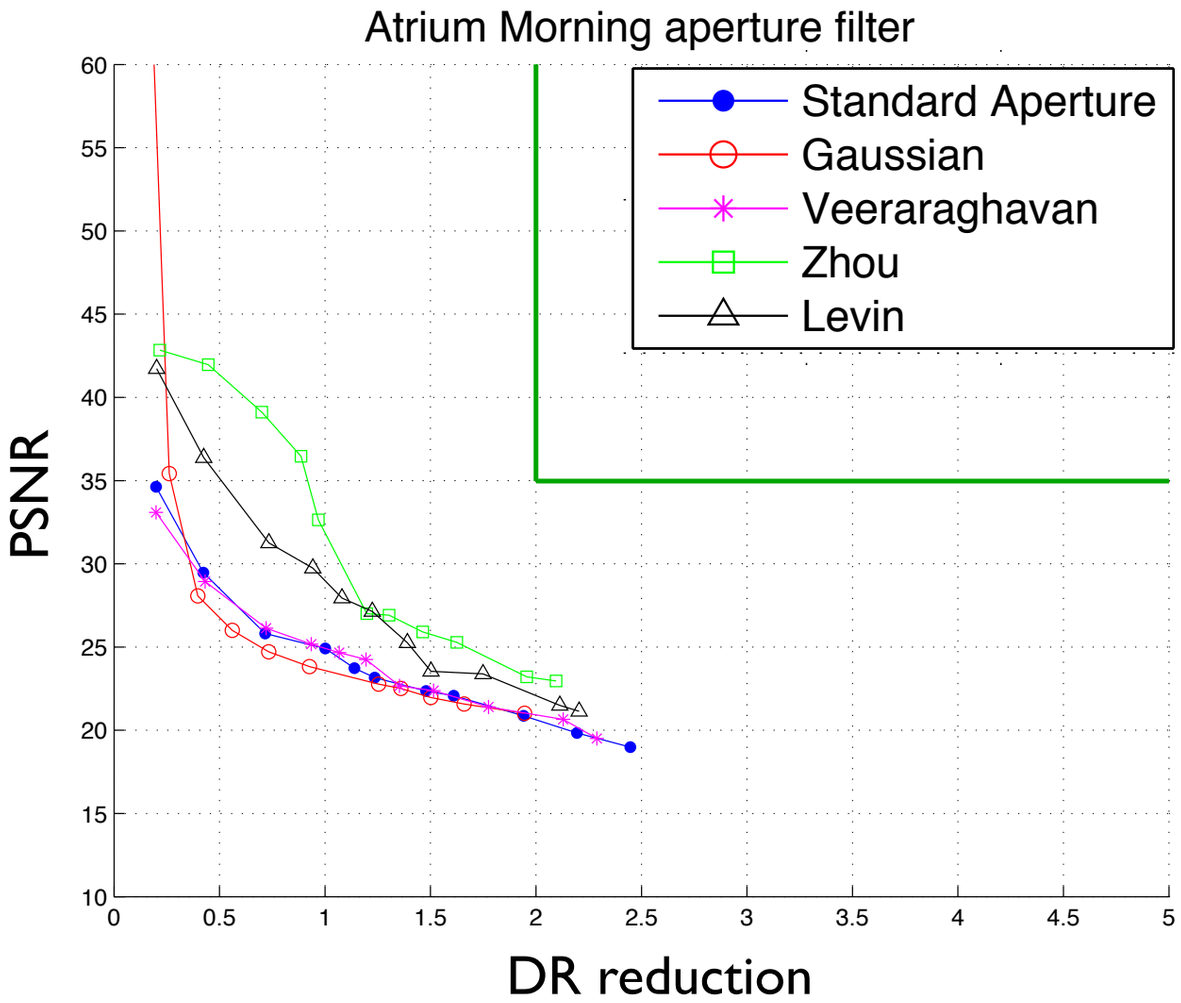
filter=Zhou, noise = 0, radius = 16

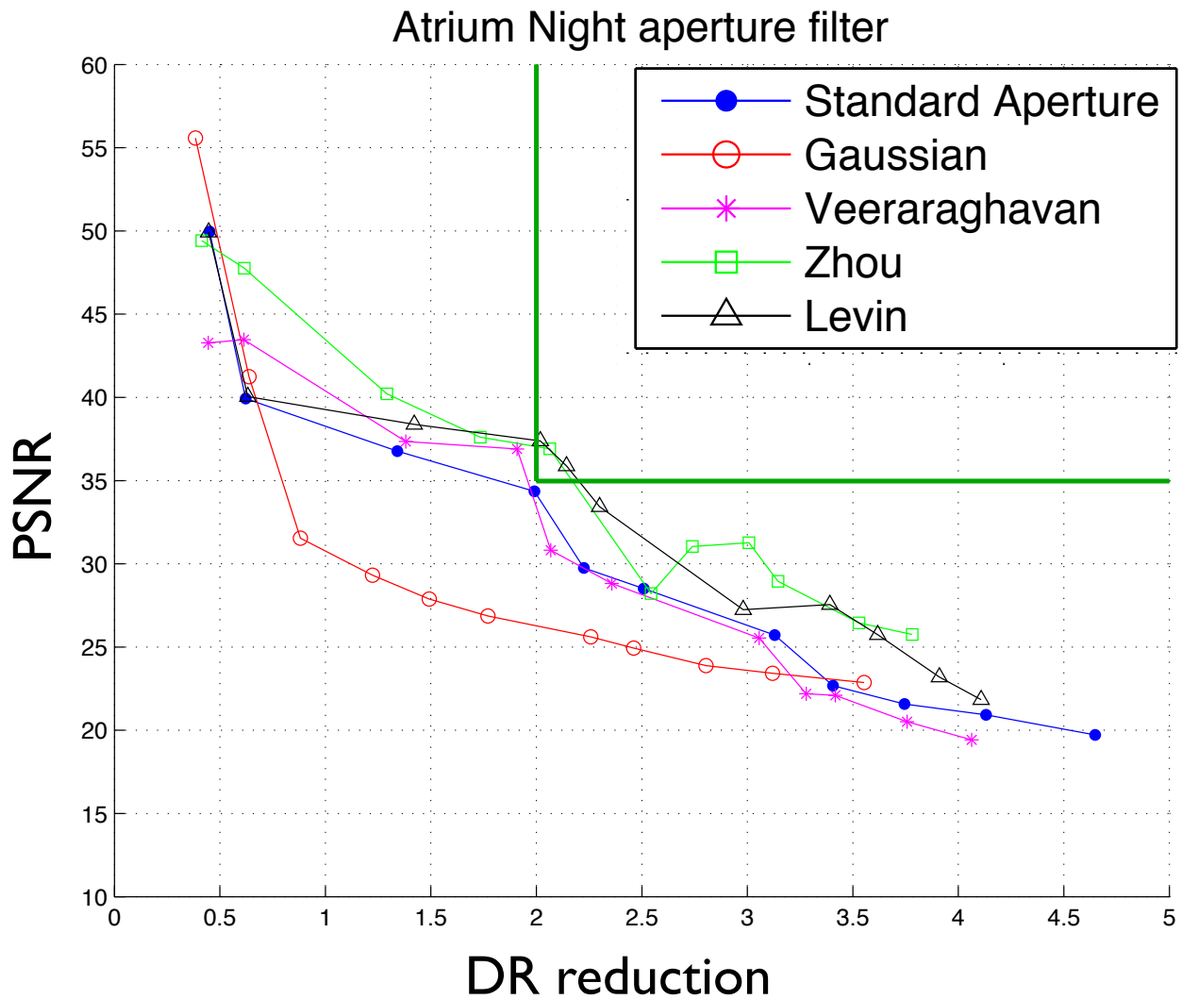
Deconv: no noise



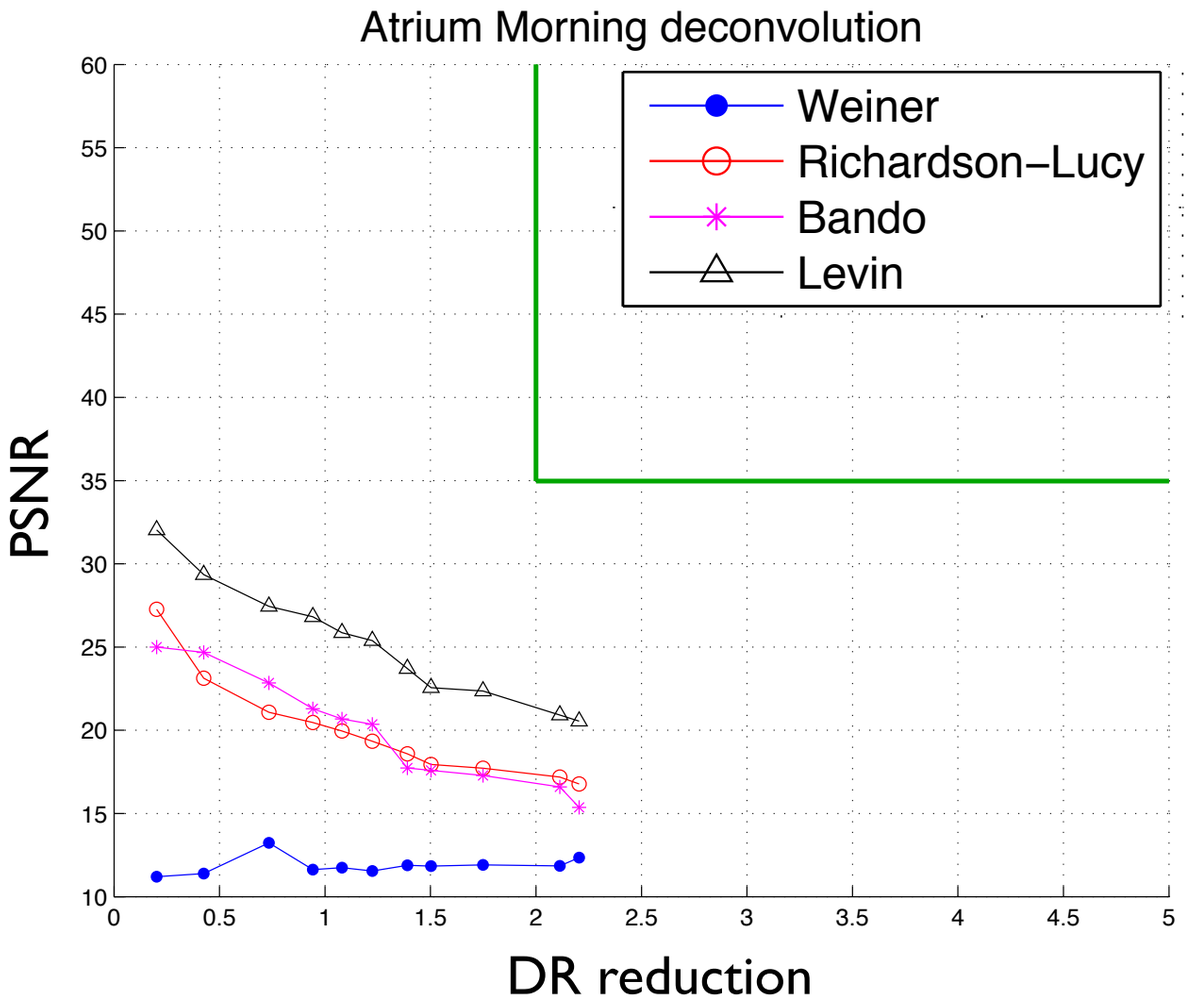


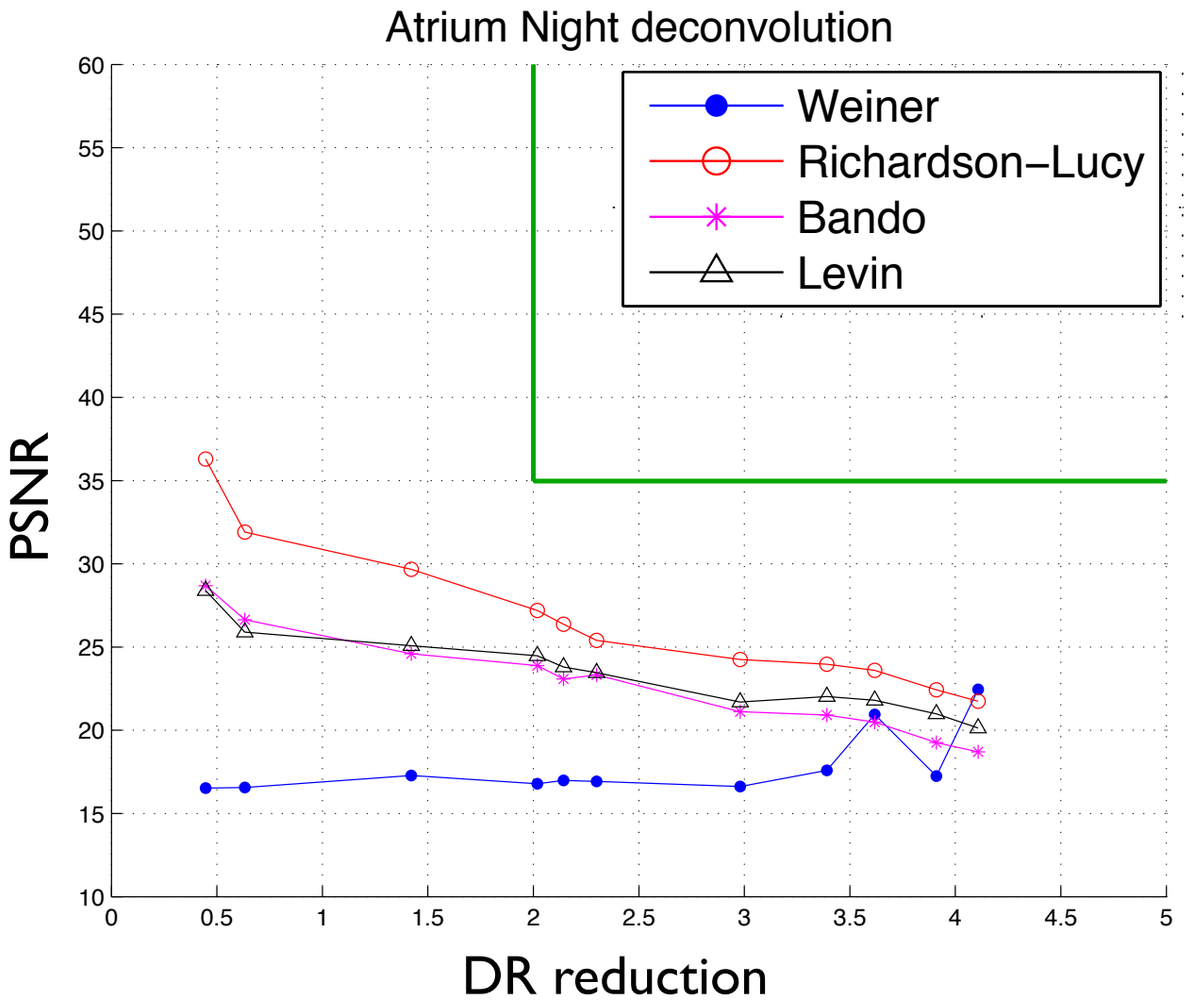
Aperture: no noise



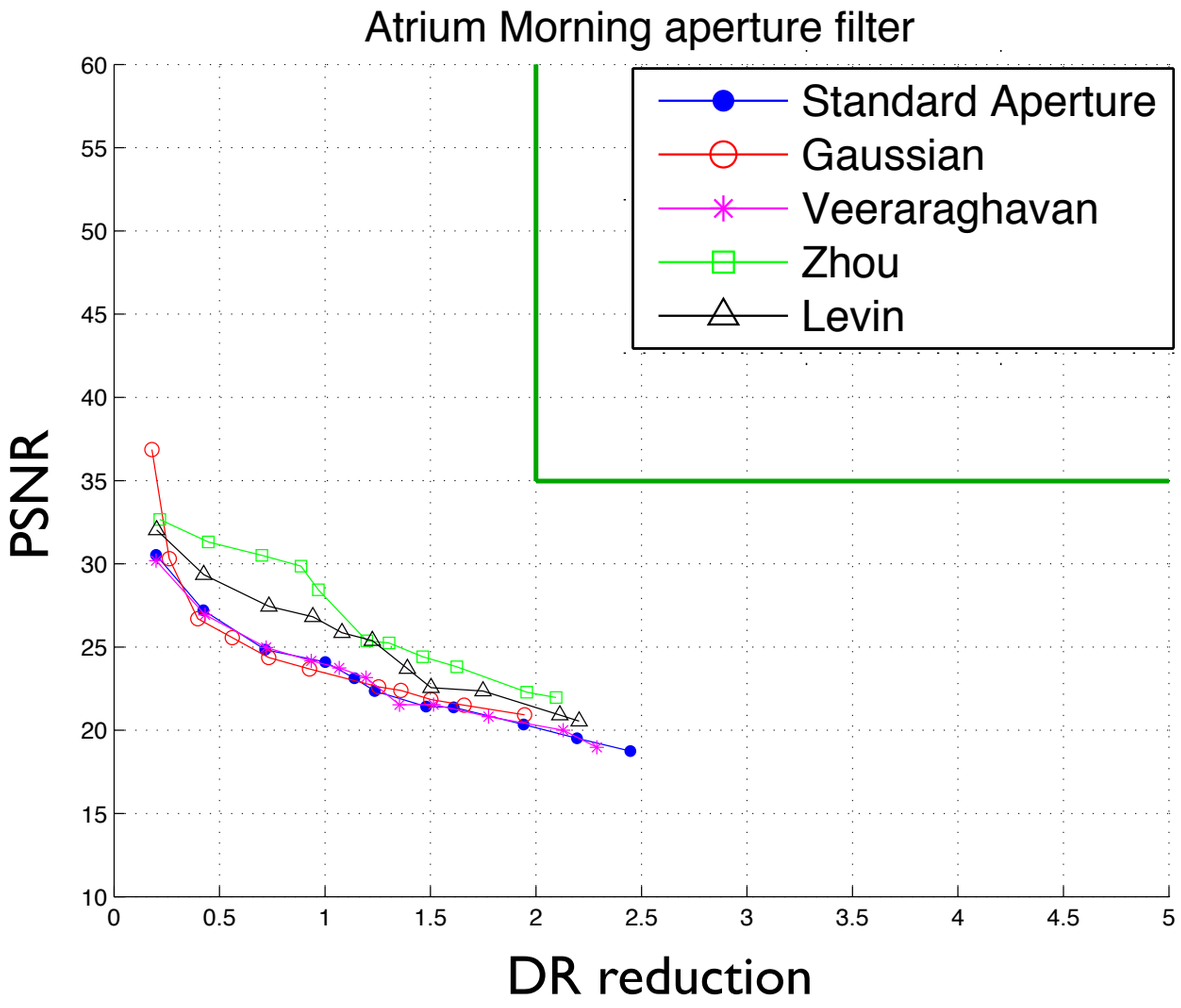


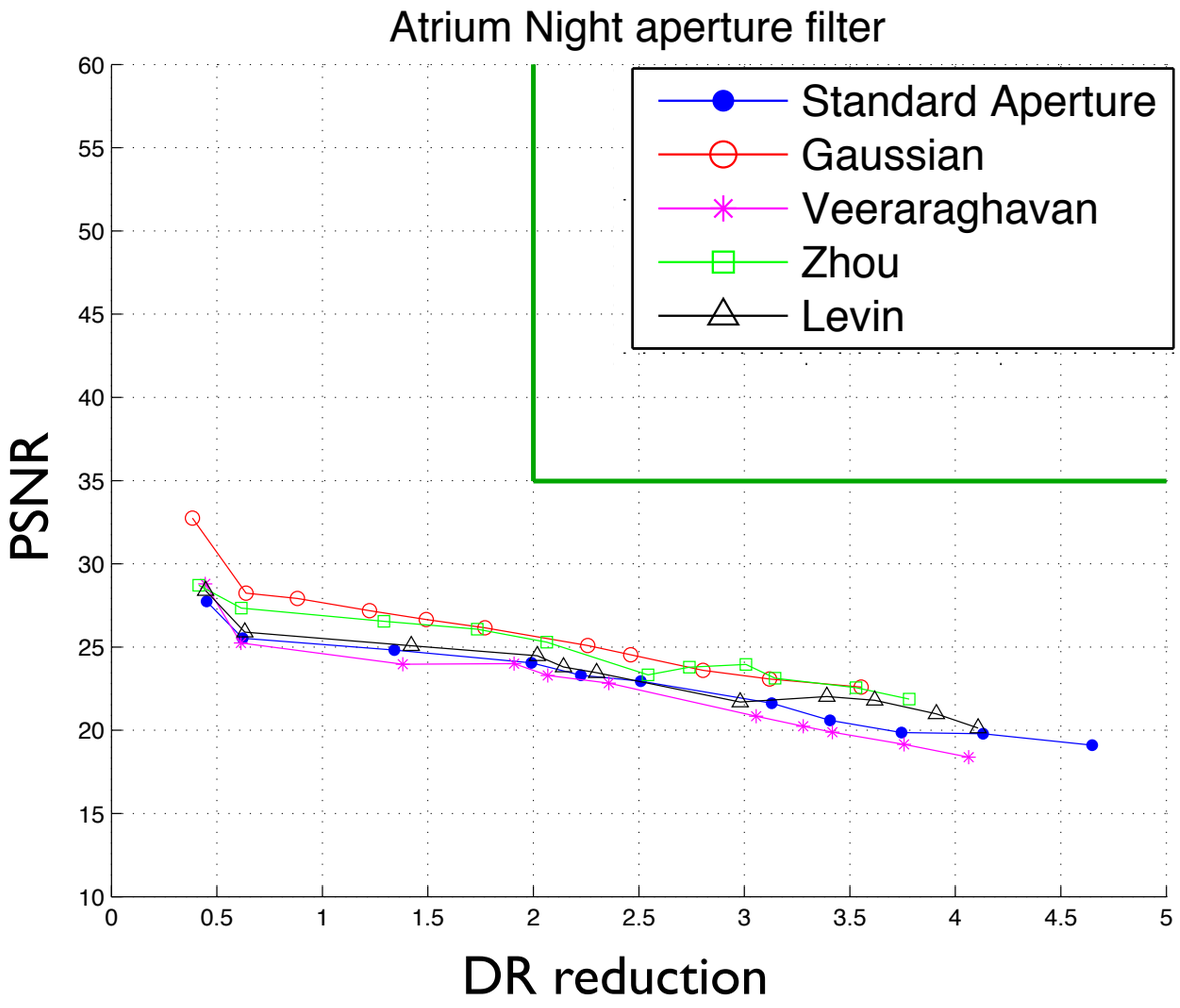
Deconv: noise





Aperture: noise





Conclusions

- Levin deconv the best, obtaining results with coded filters at *very* low noise levels
- No combination of filter and deconvolution consistently produced acceptable results
- Efficiency of the approach is scene dependent
  Most efficient for small, isolated bright regions