

Signal and Image Processing Seminar

***DESIGN AND QUALITY
ASSESSMENT OF FORWARD
AND INVERSE ERROR
DIFFUSION HALFTONING
ALGORITHMS***

Ph.D. Defense

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OUTLINE

- Introduction to halftoning
- Visual quality metrics for forward and inverse halftoning
 - ▶ Human visual system
 - ▶ Weighted noise metric (WSNR)
 - ▶ Modeling other distortions
- Halftoning by error diffusion
 - ▶ Linear gain model
 - ▶ Modified error diffusion
 - ▶ Noise metric
 - ▶ Tonality metric
- Inverse halftoning
 - ▶ Algorithm design and results
 - ▶ Modeling inverse halftoning
 - ▶ Quality metrics
- Rehalftoning and interpolation
- Contributions

INTRODUCTION: HALFTONING

- Was analog, now digital image processing
- Wordlength reduction for images
 - ▶ 8-bit to 1-bit for grayscale
 - ▶ 24-bit RGB to 8-bit for color displays
 - ▶ 24-bit RGB to CMY for color printers
- Applications
 - ▶ Printers
 - ▶ Digital copiers
 - ▶ Liquid crystal displays
 - ▶ Video cards
- Halftoning methods
 - ▶ Screening
 - ▶ Error diffusion
 - ▶ Direct binary search
 - ▶ Hybrids

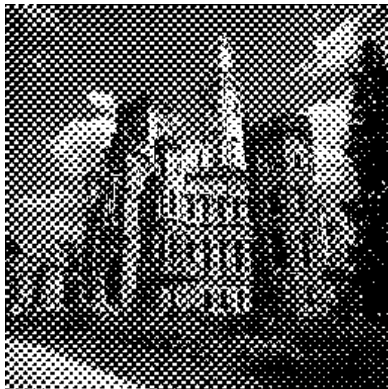
EXAMPLE HALFTONES



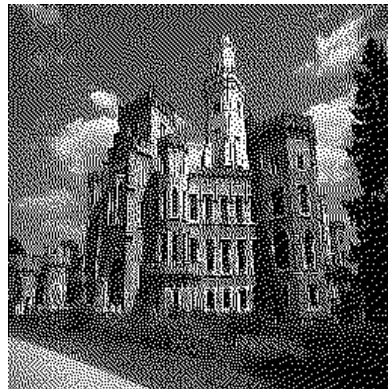
Original image



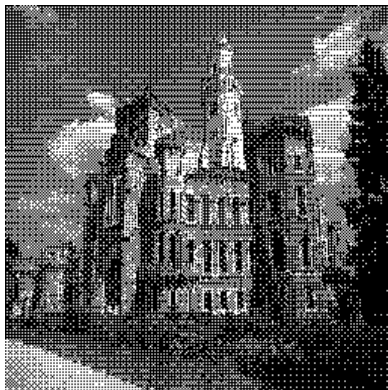
Direct binary search



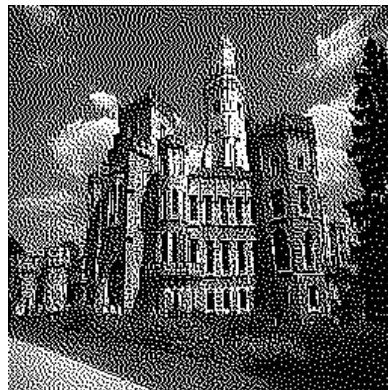
Clustered dot screen



Error diffusion I

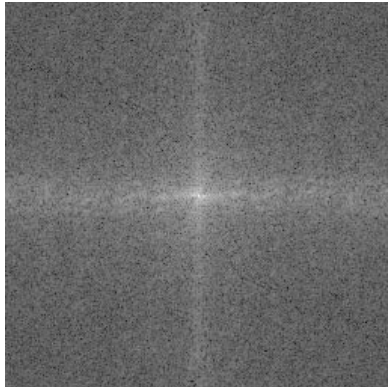


Dispersed dot screen

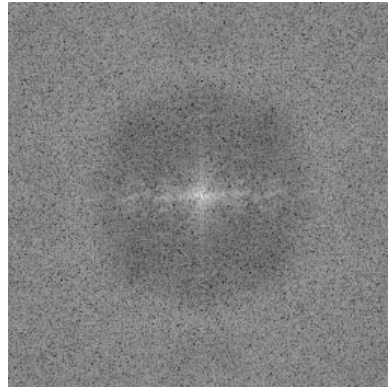


Error diffusion II

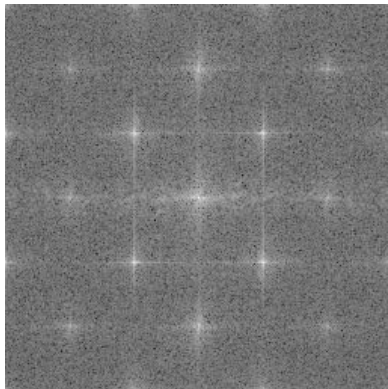
FOURIER TRANSFORMS



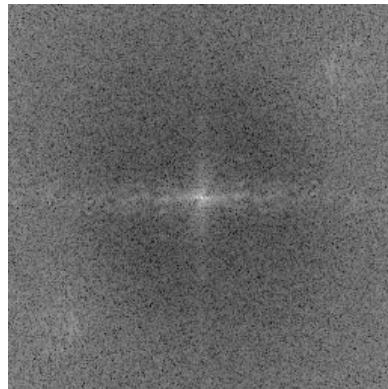
Original image



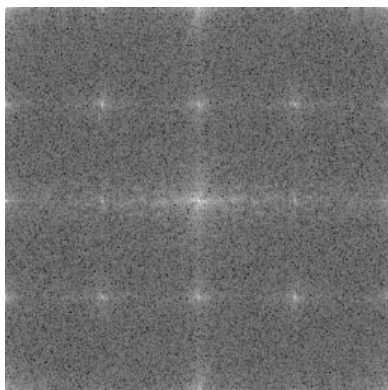
Direct binary search



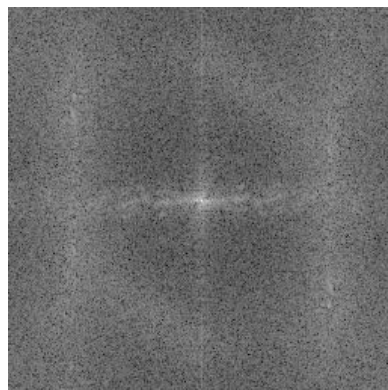
Clustered dot screen



Error diffusion I



Dispersed dot screen



Error diffusion II

PROBLEMS TO BE SOLVED

- Visual quality metrics for forward and inverse halftones
 - ▶ Quantify frequency distortion
 - ▶ Quantify artifacts
 - ▶ Quantify quantization noise
- Modeling error diffusion
 - ▶ Develop tractable model
 - ▶ Demonstrate accuracy of model
 - ▶ Use model to design applications
- Inverse halftoning
 - ▶ Develop efficient algorithm
 - ▶ Develop model for inverse halftoning

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HUMAN VISUAL SYSTEM (HVS)

- Non-linear, spatially varying
- Assuming linearity, spatial invariance explains [Cornsweet 1970]
 - ▶ Mach band effect
 - ▶ Apparent brightness *vs.* intensity



White noise
SNR = 10 dB

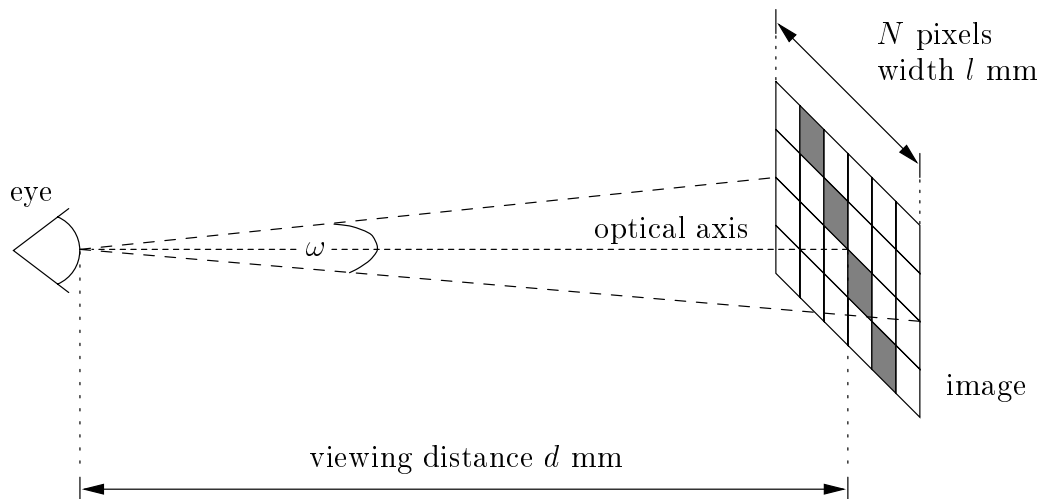


Blue (highpass) noise
SNR = 10 dB

- Weight by spatial frequency to quantify visual impact of noise

ANGULAR FREQUENCY

- Sensitivity depends on angular frequency subtended at eye
- Compute angular frequency from image size (pixels), printed image size (mm), viewing distance (mm)



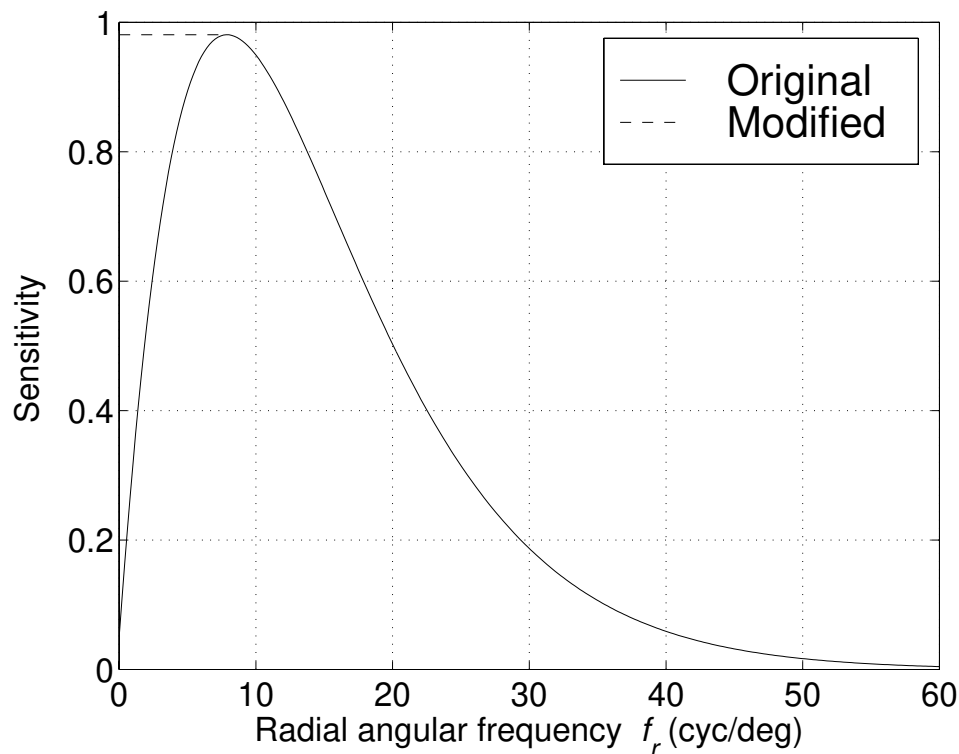
- At Nyquist frequency

$$f_a = \frac{N\pi d}{360l} \text{ cycles/degree}$$

CONTRAST SENSITIVITY (CSF)

- Minimum contrast to distinguish sine grating from uniform field
- Model [Mannos & Sakrison 1974]
- Modification [Mitsa & Varkur 1993]

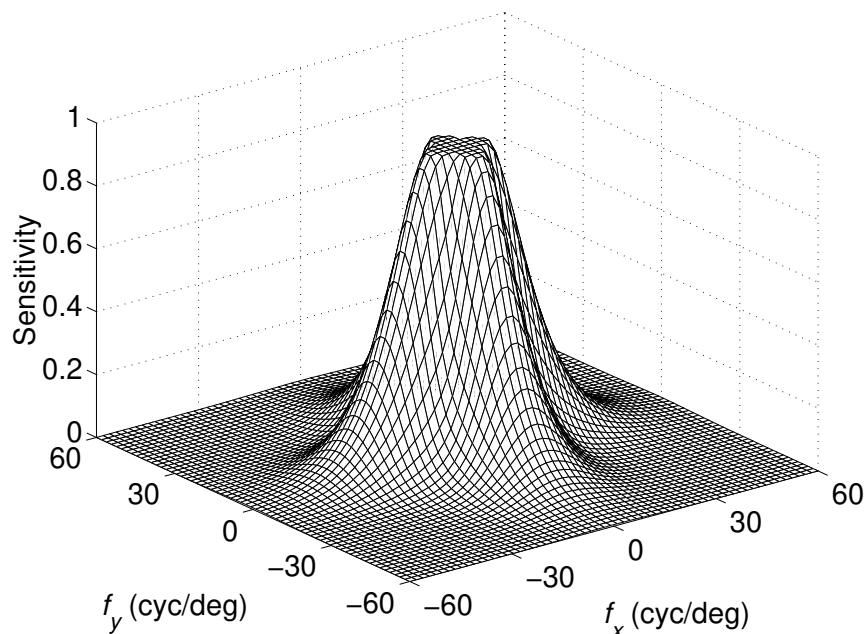
$$CSF = 2.6 (0.02 + 0.1 f_a) e^{-(0.1 f_a)^{1.1}}$$



- Orientation-independent

WEIGHTED SNR METRIC

- Include orientation (angular dependence) in CSF
[Sullivan, Miller & Pios 1993]

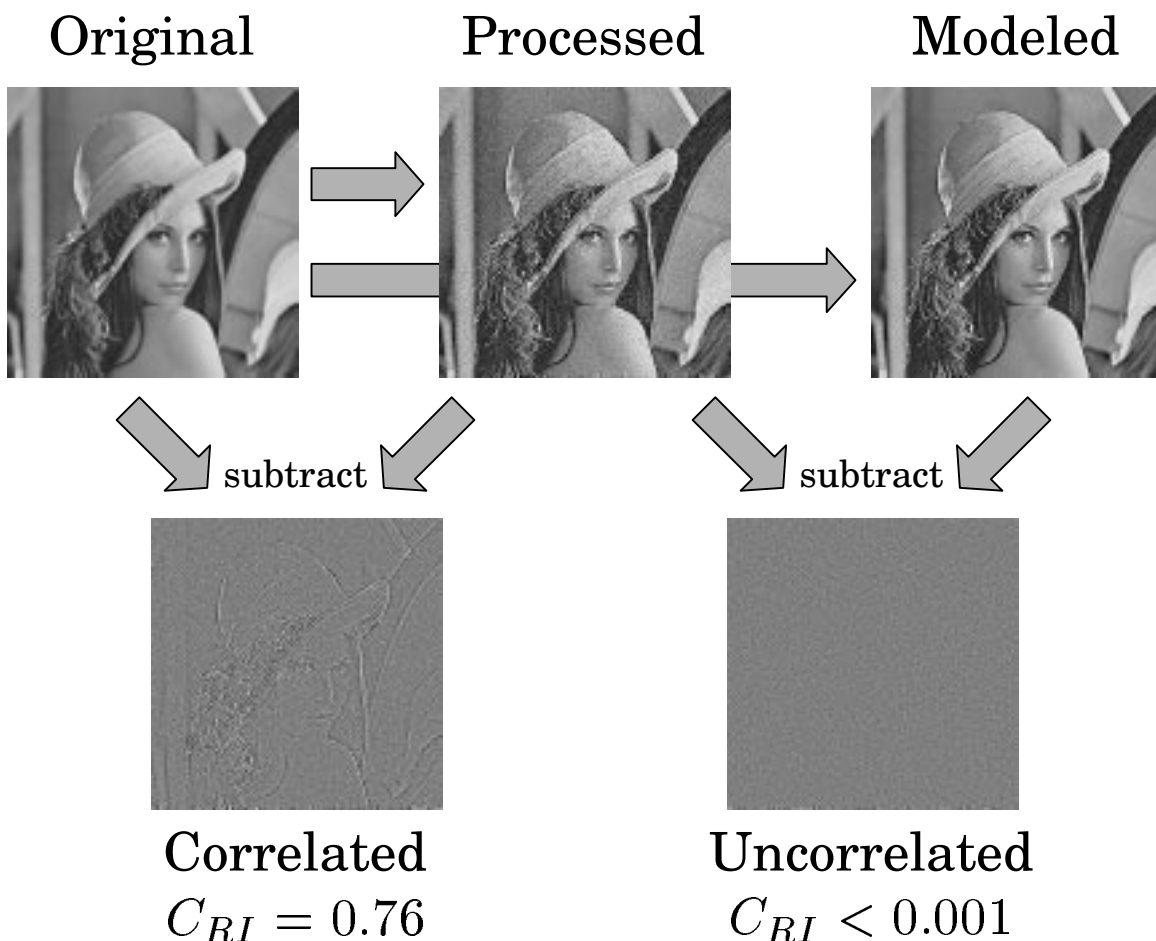


- Compute weighted signal-to-noise ratio between original image x and processed image y

$$\text{WSNR} = 10 \log_{10} \left(\frac{\sum |\text{CSF} \times X(u, v)|^2}{\sum |\text{CSF} \times (X(u, v) - Y(u, v))|^2} \right)$$

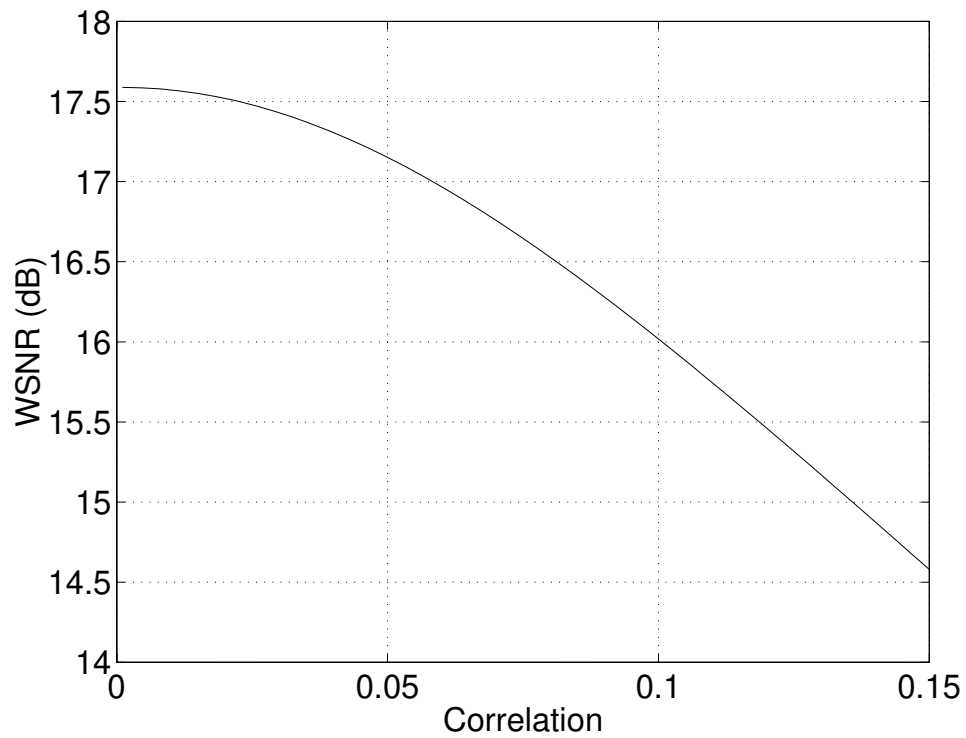
MODELING DISTORTION

- WSNR is a *noise* metric
 - ▶ Difference (residual) between original and processed images must be noise
 - ▶ Model, compensate for other distortions
 - ▶ Measure correlation of residual and original; for accuracy, $C_{RI} < 0.020$



WSNR vs. CORRELATION

- WSNR increasingly inaccurate as correlation increases

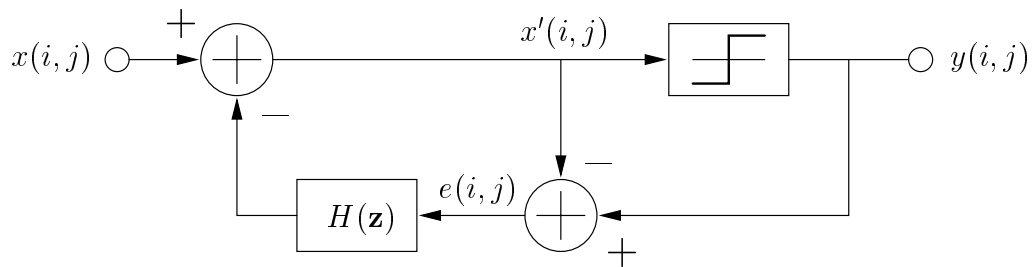


OUTLINE

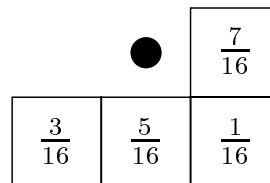
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- **Halftoning by error diffusion**
 - ▶ Linear gain model
 - ▶ Modified error diffusion
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ERROR DIFFUSION

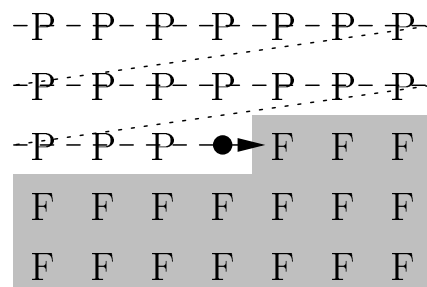
- 2-D delta-sigma modulator
- Noise shaping feedback coder



- Error filter



- Raster scan order



P = Past
F = Future

- Serpentine scan also used

ERROR DIFFUSION (contd.)

- **Quantizer**

$$y(i, j) = \begin{cases} 0, & x'(i, j) < 0.5 \\ 1, & x'(i, j) \geq 0.5 \end{cases}$$

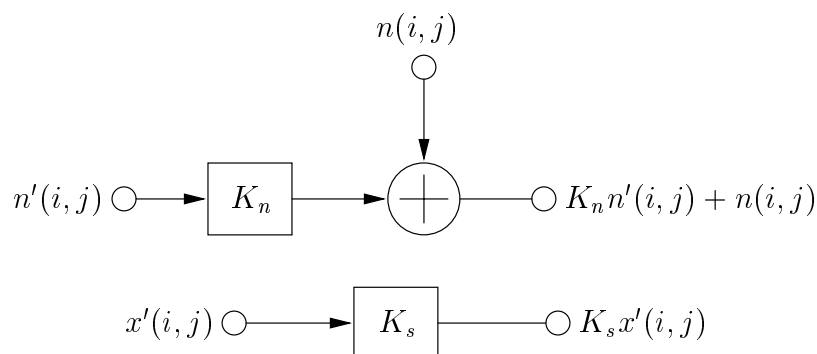
- **Governing equations**

$$\begin{aligned} e(i, j) &= y(i, j) - x'(i, j) \\ x'(i, j) &= x(i, j) - h(i, j) * e(i, j) \end{aligned}$$

- **Non-linearity difficult to analyze**

- **Linearize quantizer**

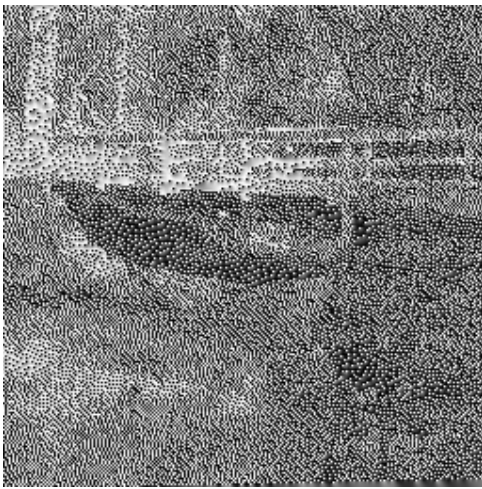
[Kite, Evans, Bovik & Sculley 1997]



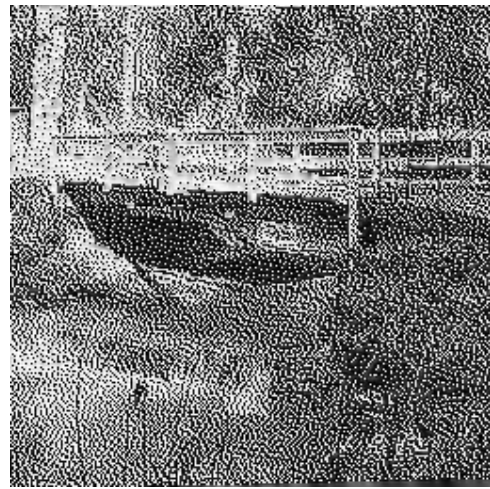
- **Separate signal and noise paths**
[Ardalan & Paulos 1987]

LINEAR GAIN MODEL

- Quantization error correlated with input [Knox 1992]



Floyd-Steinberg



Jarvis, Judice & Ninke

- Least squares fit of quantizer input to output defines signal gain

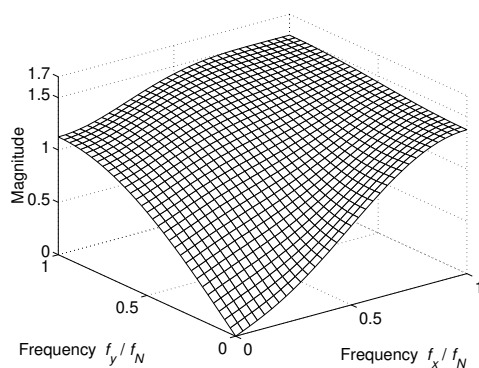
$$K_s = \frac{E[|x'(i, j)|]}{2E[x'(i, j)^2]}$$

- Signal gain: $K_s \approx \text{constant}$
- Noise gain: $K_n = 1$

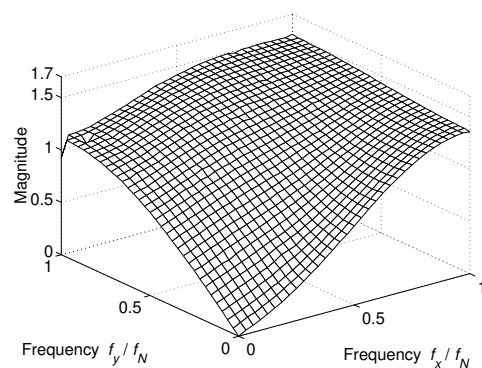
GAIN MODEL PREDICTIONS

■ Noise transfer function (NTF)

$$\text{NTF} = 1 - H(\mathbf{z})$$



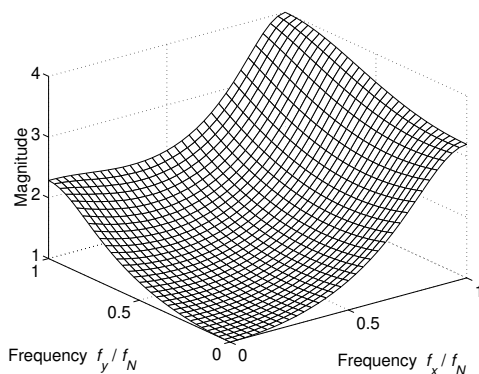
Predicted



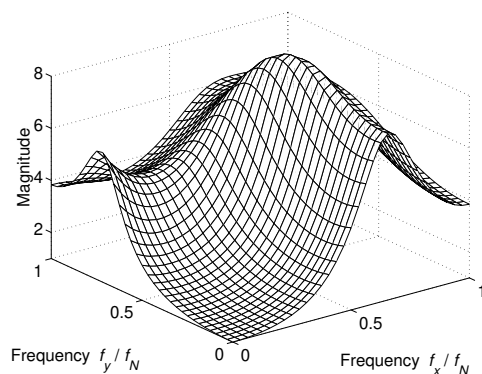
Measured

■ Signal transfer function (STF)

$$\text{STF} = \frac{K_s}{1 + (K_s - 1)H(\mathbf{z})}$$



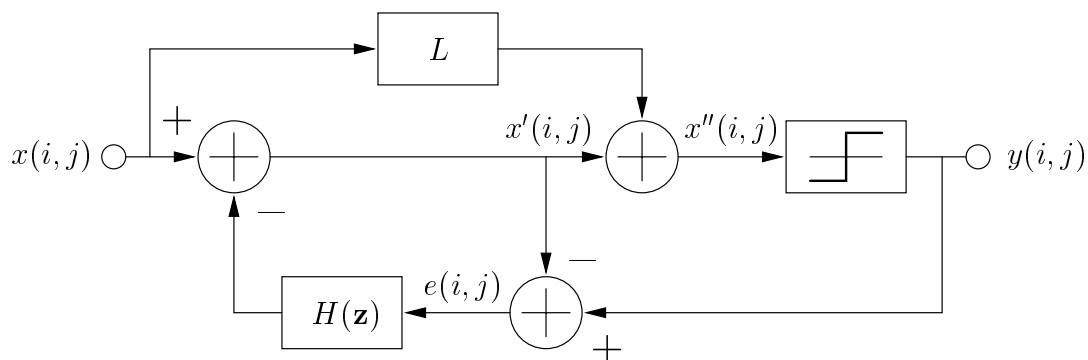
Floyd-Steinberg



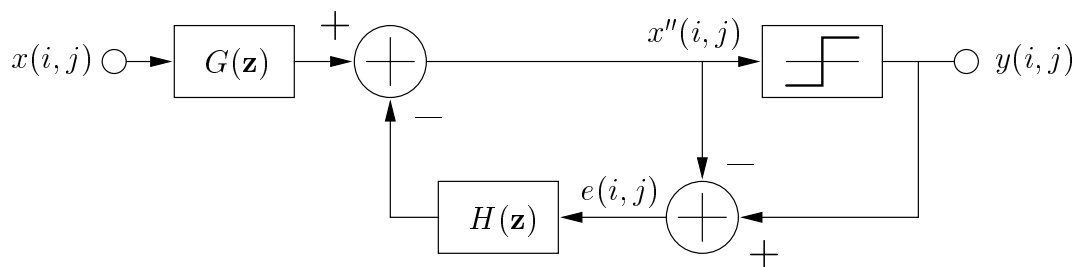
Jarvis *et al.*

MODIFIED ERROR DIFFUSION

- Efficient method of adjusting sharpness [Eschbach & Knox 1991]



- Equivalent circuit: pre-filter



$$G(\mathbf{z}) = 1 + L(1 - H(\mathbf{z}))$$

UNSHARPENED HALFTONES

- If $L = \frac{1 - K_s}{K_s}$ then STF = 1 (flat)



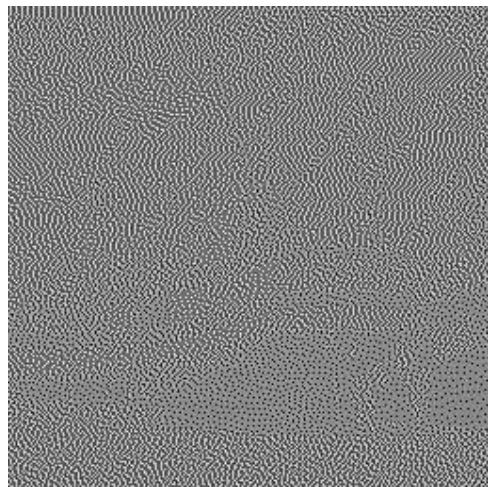
Original image



Jarvis halftone



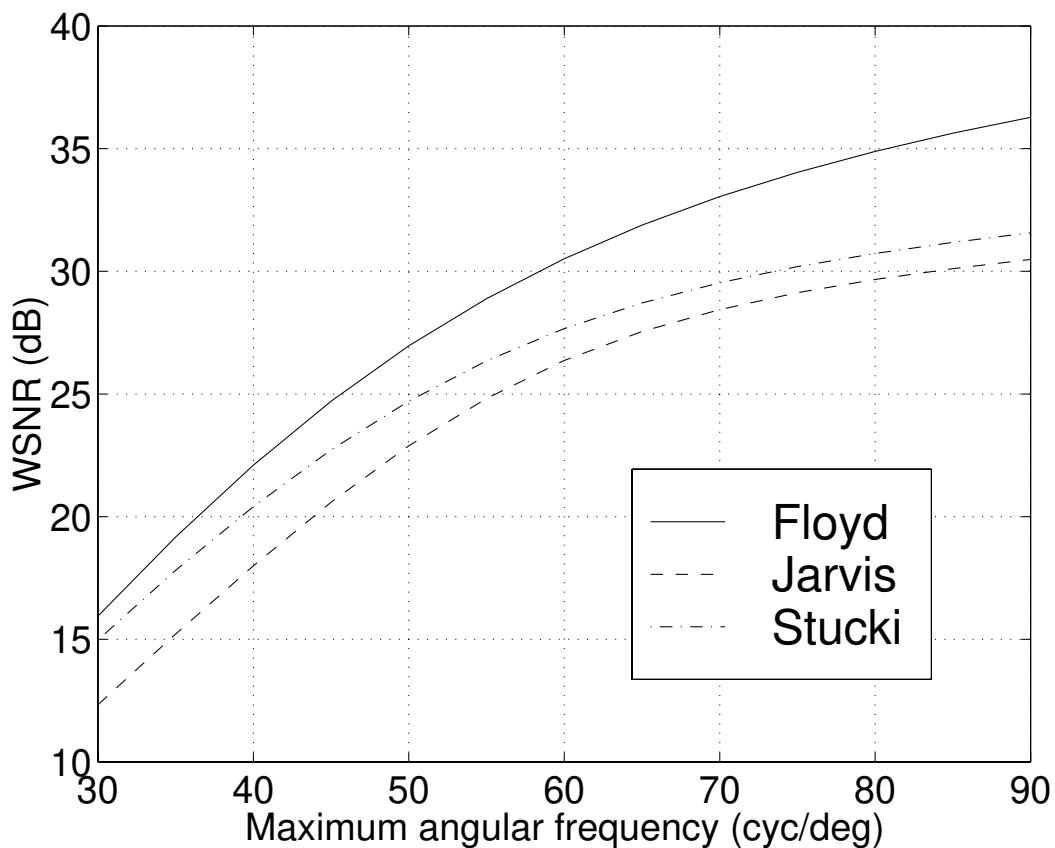
Unsharpened halftone



Residual

OBJECTIVE NOISE METRIC

- To find WSNR
 - ▶ Compute signal gain K_s , or use average
 - ▶ Generate unsharpened halftone using modified error diffusion
 - ▶ Compute WSNR of unsharpened halftone relative to original image



OBJECTIVE TONALITY METRIC

- Limit cycles cause visual ‘worm’ artifacts [Fan & Eschbach 1994]
- Larger filters and serpentine scan result in lower tonality
- Define tonality metric
 - ▶ Measure total distortion of sine grating

$$T = \left[\frac{1}{Y(e^{j\omega_f})Y^*(e^{j\omega_f})} \sum_{\omega \in \{\omega_d\}} Y(e^{j\omega})Y^*(e^{j\omega}) \right]^{\frac{1}{2}}$$

- ▶ Average T over grating frequencies
- Agrees with visual results
 - ▶ Correct ordering of error filters
 - ▶ Serpentine scan less tonal

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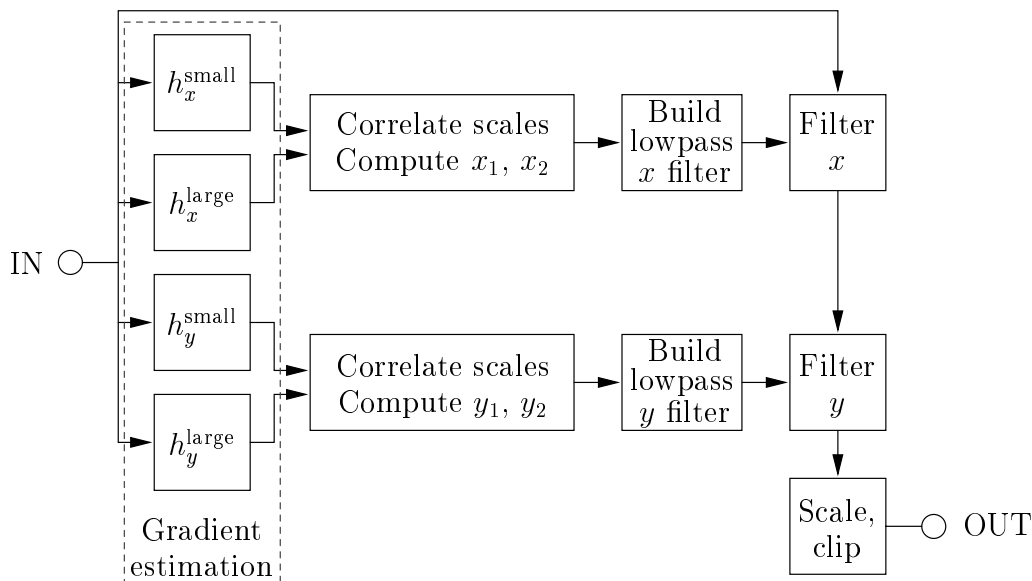
INVERSE HALFTONING

- Attempt to recover grayscale images from halftones
- Applications
 - ▶ Digital copiers
 - ▶ Scanner software
- Many approaches:
 - ▶ Bayesian estimation
[Schweizer & Stevenson 1993]
 - ▶ Vector quantization
[Ting & Riskin 1994]
 - ▶ Projection onto convex sets
[Hein & Zakhor 1995]
 - ▶ Lowpass smoothing and nonlinear filtering [Wong 1995]
 - ▶ Wavelet denoising
[Xiong, Orchard & Ramchandran 1997]
- Most are iterative and slow
- Best results from wavelet scheme

PROPOSED METHOD

- Apply anisotropic diffusion
[Kite, Damera-Venkata, Evans & Bovik 1998]
 - ▶ Estimate image gradients
 - ▶ Compute diffusion coefficient
 - ▶ Smooth within areas, preserve edges
- Unique environment
 - ▶ Highpass noise, SNR \approx 3 dB
 - ▶ Tonal
- Solution
 - ▶ Specialized gradient estimator
 - ▶ Correlate estimate across scales
[Mallat & Zhong 1992]
 - ▶ Separable—smooth parallel to edges
- Local operations
 - ▶ Low memory requirement
 - ▶ Low computational cost

PROPOSED METHOD (contd.)

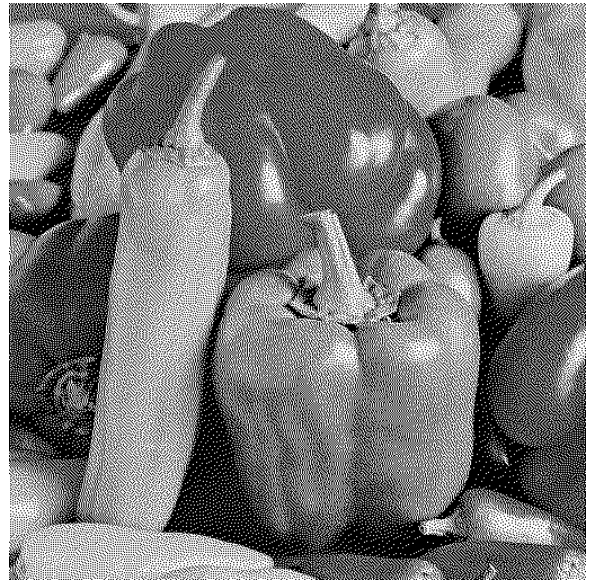


- Estimate gradients at two scales
 - ▶ 7×7 , 5×5 FIR filters
 - ▶ Integer additions only
- Correlate gradients across scales
 - ▶ 5 dB improvement in gradient SNR
- Construct parametric smoother
 - ▶ 7×7 separable FIR filter
 - ▶ Family optimized for halftones
 - ▶ Quantized integer coefficients

INVERSE HALFTONE RESULTS



Original image



Halftone



Proposed method



Wavelet method

INVERSE HALFTONING MODEL

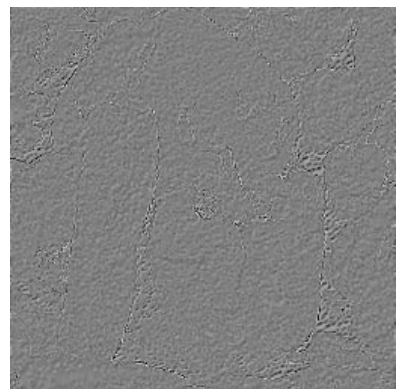
- Forward/inverse halftoning system blurs image and adds noise
- Model inverse halftoning
 - ▶ Compute unsharpened halftone
 - ▶ Inverse halftone; save filter parameters at each pixel
 - ▶ Filter original image using saved filters
- Typical correlation
 - ▶ Inverse halftone: $C_{RI} = 0.32$
 - ▶ Model inverse halftone: $C_{RI} = 0.01$



Inverse halftone



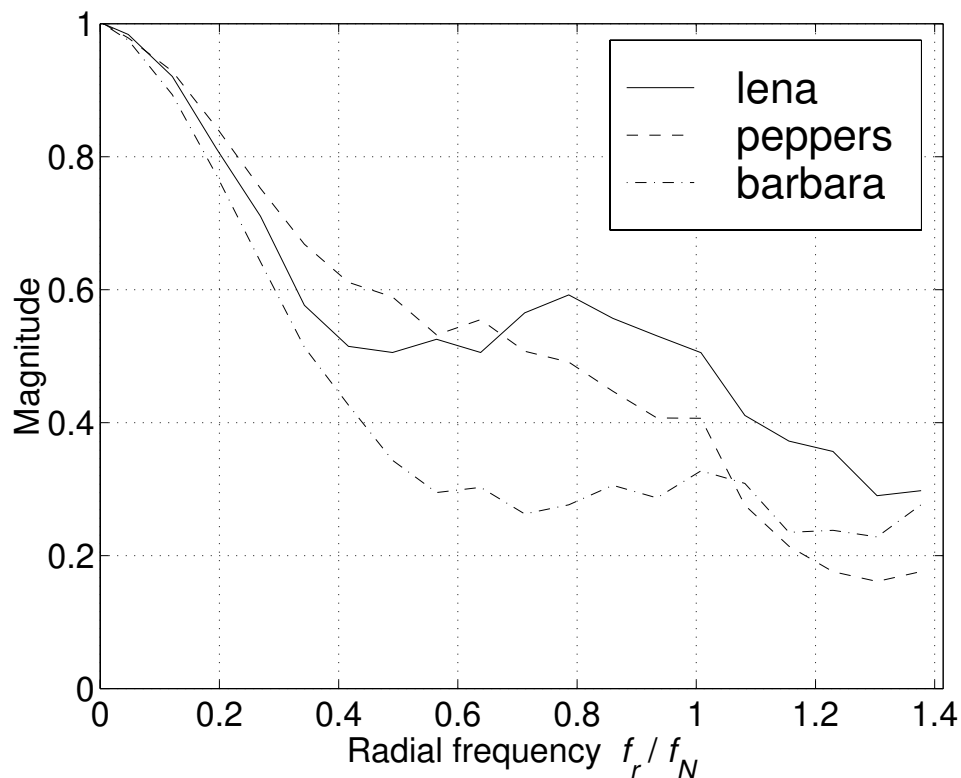
Modeled



Residual ($\times 4$)

INVERSE HALFTONE QUALITY

- Compute WSNR
- Compute effective transfer function
 - ▶ Divide FFT of model inverse halftone by FFT of original image
 - ▶ Radially average over annuli

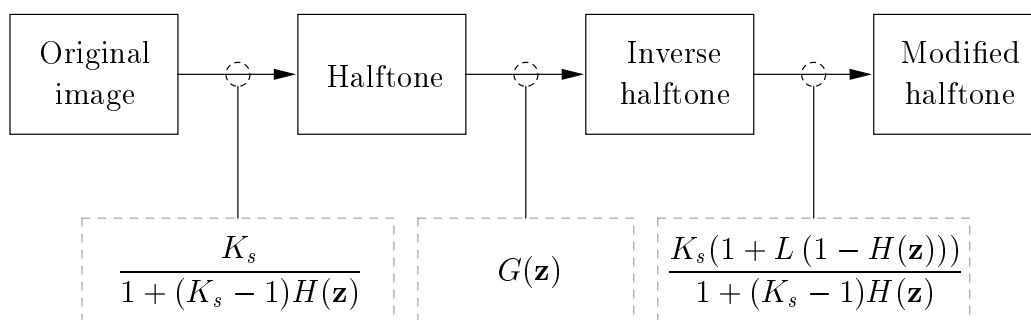


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REHALFTONING

- Halftone conversion, manipulation
- Assume input and output are error diffused halftones
- Fixed lowpass inverse halftoning filter, compromise cut-off frequency
 - ▶ Noise leakage masked by halftoning
 - ▶ Blurring correctable by modified error diffusion
 - ▶ Computationally efficient



- Use linear gain model to design L for flat response
- Use approximation for digital frequency: $e^{j\omega} \approx 1 + j\omega - \omega^2/2$

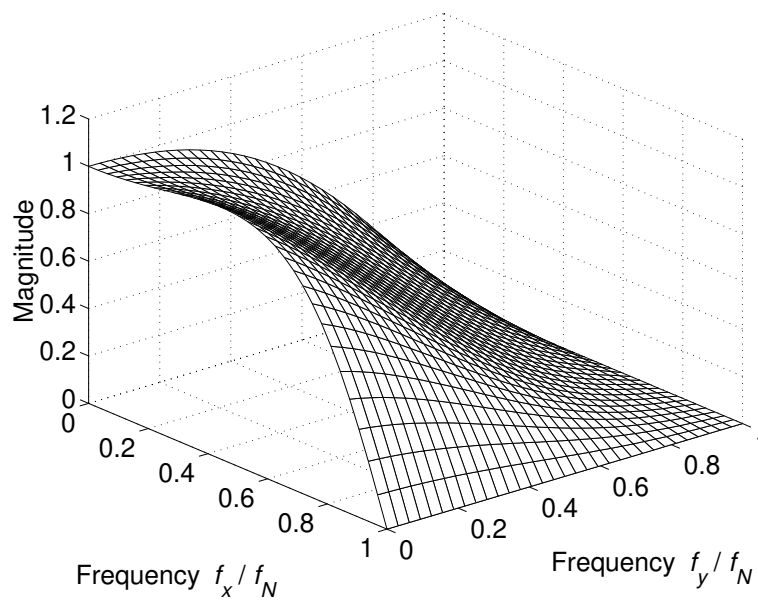
REHALFTONING RESULTS



Original image



Rehalthtone



Signal transfer function

INTERPOLATION

- Image resizing
- Different methods (increasing cost)
 - ▶ Nearest neighbor
 - ▶ Bilinear
 - ▶ Bicubic, cubic splines, lowpass filtering
- Nearest neighbor, bilinear methods
 - ▶ Low computational cost
 - ▶ Artifacts masked by quantization noise in halftone
 - ▶ Blurring correctable by modified error diffusion
- Examine $\times 2$ interpolation; method applies to any scaling factor
- Design L for flat transfer function using linear gain model
- L constant for given interpolation scheme

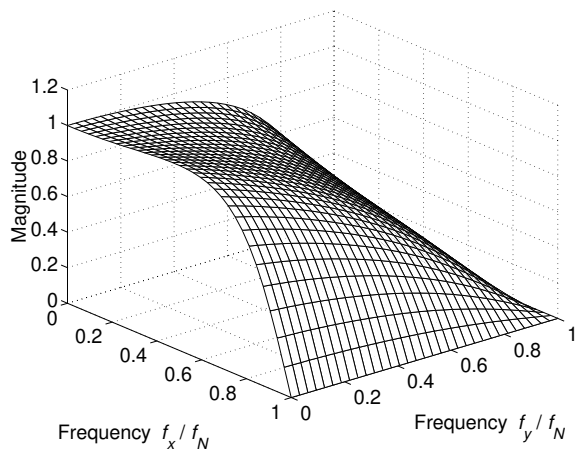
INTERPOLATION RESULTS



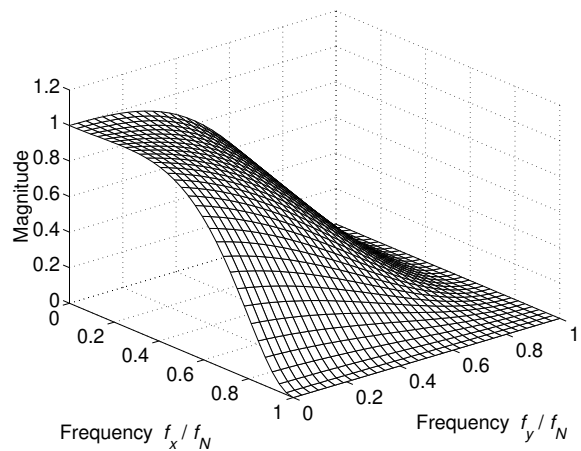
Nearest neighbor $\times 2$



Bilinear $\times 2$



Transfer function
 $L = -0.0105$



Transfer function
 $L = 0.340$

CONTRIBUTIONS

- Visual quality metrics for forward and inverse halftones
 - ▶ Restriction on correlation for accuracy of WSNR metric
- Linear gain model of error diffusion
 - ▶ Accuracy of model established
 - ▶ Tonality metric for artifacts
 - ▶ Link between filter gain and signal gain
- Inverse halftoning
 - ▶ New efficient method, suitable for hardware and embedded software
 - ▶ Model for inverse halftoning
 - ▶ Quality metrics for inverse halftones
- Rehalftoning and interpolation
 - ▶ Efficient algorithms
 - ▶ Verifies validity of linear gain model