Thoughts on Future Detectors: Signal Processing

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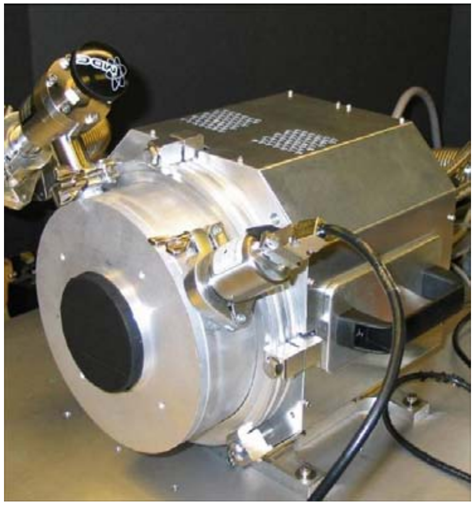
Why are CCDs still around?

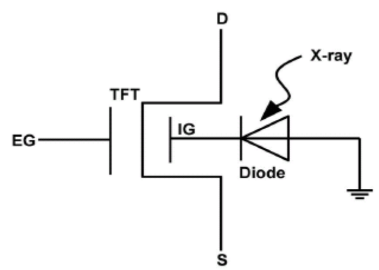


FCCD: J. Weizeorick et. al.

- Low noise output:
  - Tiny output capacitance from floating diffusion
  - A few electrons of noise
- Large number of pixels with simple readout.
  - A single ADC to read millions of pixels.
- Decent phosphors for x-ray detectors exist.
  - Reasonable efficiency (15% stopped x-ray energy converted to light)
  - Reasonable PSF (100um for powder GADOX).
- Improvements in CCDs
  - Thick silicon for direct detection. (200um FCCD)
  - Direct detect has reasonable energy resolution: (300eV FCCD)
  - Counting mode or integrating mode
  - Multiple readouts for 100 f/s
  - Structured phosphors- PSF down to 20um, Scint-X□

Why are CCDs still around? (2)

- Current pixel detectors solve some but not all the problems of CCDs.
  - Pilatus is fast, but no energy resolution.
  - Scientific CMOS- cannot have thick sensors.
  - Amorphous Si detectors such as GE flat panel- large area, can have small pixels, but much higher read noise than CCD.
- Future Pixel Detectors could replace CCDs
  - TFT readout (like on GE flat panel) on high quality semiconductor
- These are FUTURE detectors.
- Development of detector hardware is slow and expensive.
- In the end, we have a semiconductor sensor. Signal is read by charge transfer (CCD) or a “wire” (pixel detector).



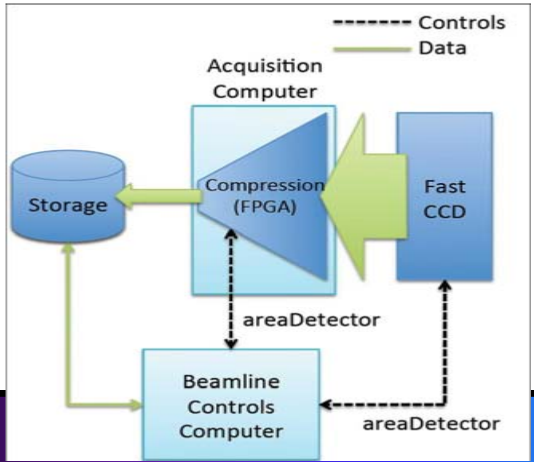
Wang, Karim, “Silicon X-ray Detector With Integrated Thin-Film Transistor for Biomedical Applications,” *IEEE Electron Device Letters, to be published.*

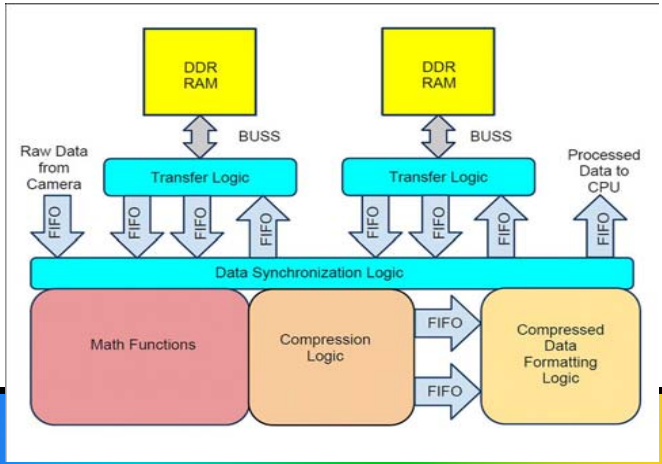
Signal Processing: Improvement of Detectors without Large R&D Projects.

- Decades of development in signal processing
  - Communications systems
  - Image processing/ computer graphics
  - Military
  - Encryption
  - Machine Learning
- Intellectual "Divide"
  - DSP and Materials Science people do not talk to each other.
  - Different language- "LLD" versus "comparator" "Spectrum" versus "Histogram" "Reciprocal Space" versus "Frequency Domain"
  - 30 year old signal processing techniques are just starting to find their way into Synchrotron experiments.
  - Lack of trust that these DSP techniques actually work.

Future Detectors: High frame rates

- Data compression or huge disks?
- Sector 8 chose compression.
- Decades of development in image compression for photography
- Compressed image should look good to the *eye*.
- Not much work in compression tailored for scientific data.
- Sector 8:
  - Apply LLD to each pixel. Data values >> Noise□
  - Store pixel if above LLD. Discard otherwise
  - LLDs based on statistics of detector noise.
  - Works for sparse XPCS data. Compression rates 15 to 60X.



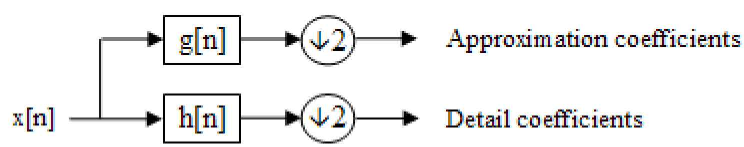


LLD in Transform Domain

- Steps to compression
  - Wavelet Transform (or your favorite transform)
  - Apply LLD
  - Quantize coefficients
  - Entropy coding (Huffman coding is common)

$$y_{\mathrm{low}}[n] = \sum_{k=-\infty}^{\infty} x[k]g[2n-k]$$

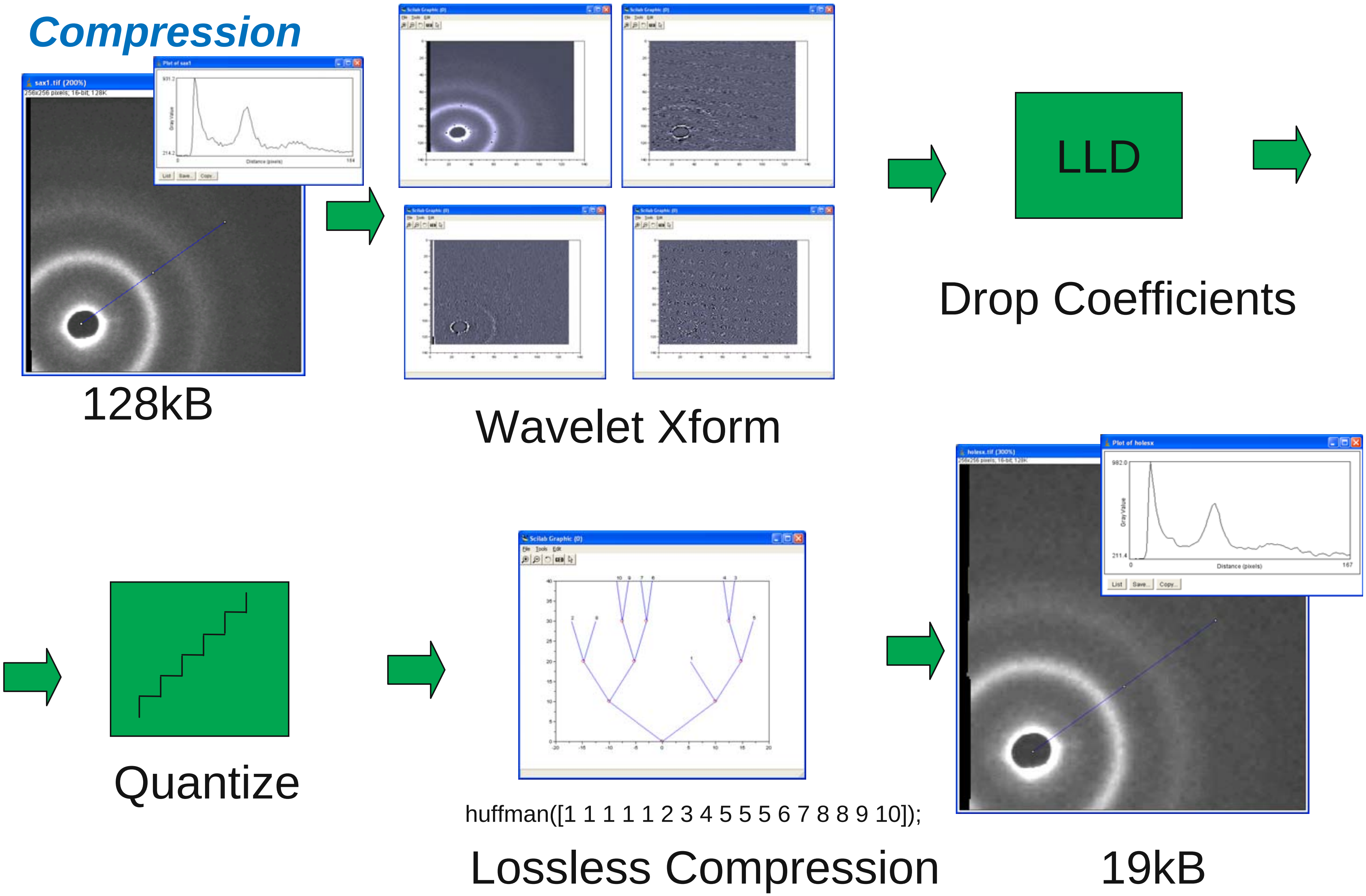
$$y_{\mathrm{high}}[n] = \sum_{k=-\infty}^{\infty} x[k]h[2n+1-k]$$



Wavelet Transform

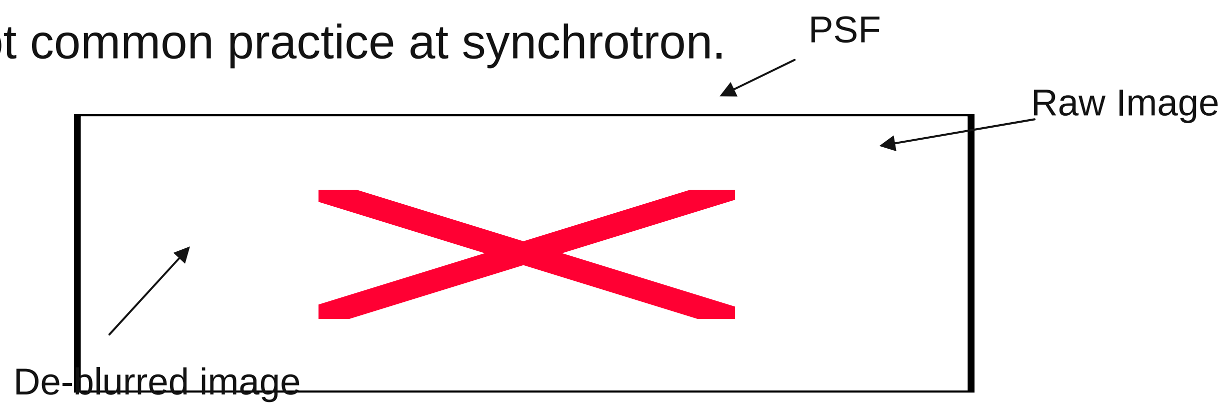
JPEG 2000 is based on wavelets. One could use JPEG library to add LLDs (not used in JPEG) and tweak quantization. JPEG 2000 has advanced entropy (lossless) encoding schemes that can be used alone.

Compression



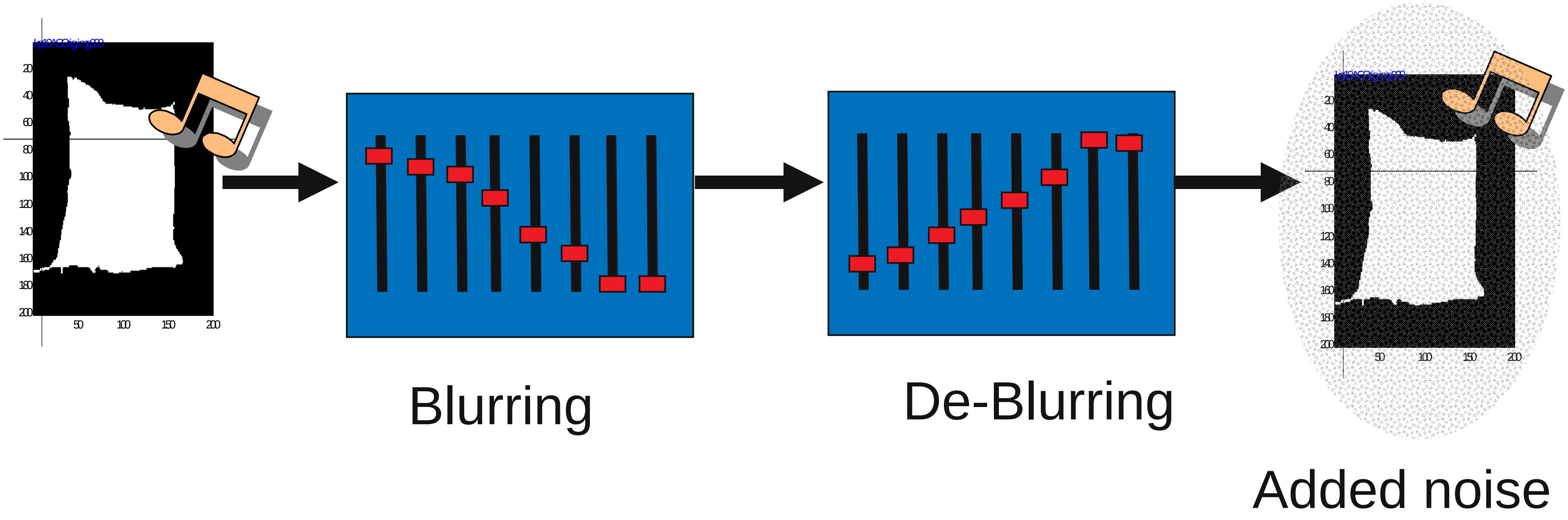
Improving PSF

- Using DSP to "De-blur" an image
- Blind Deconvolution
  - Essentially inverting a matrix (with singularities). Hard to do.
- Richardson-Lucy Algorithm, when PSF is known.
  - Developed in 1972, based on Bayes' Theorm
  - Common practice for de-blurring photographic images.
  - Iterative, so it could work in real-time as data is taken.
  - Not common practice at synchrotron.



Limits to De-blurring: Information Theory

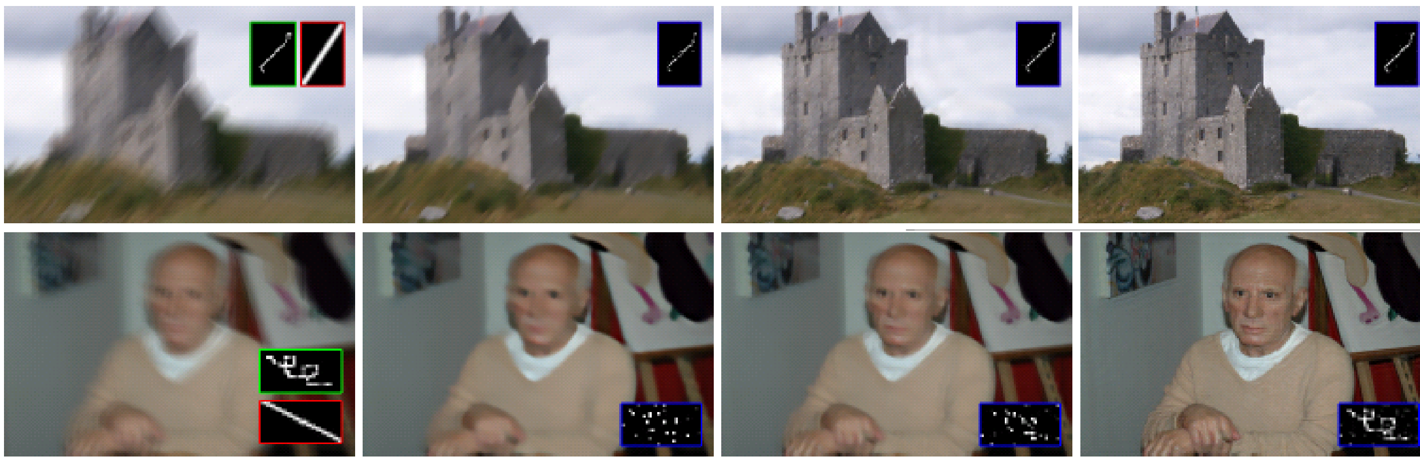
- Once energy is lost, it is gone.
- Say we have a fancy stereo system. We feed one graphic EQ into another. What comes out? It should ideally be the original signal.



Modern De-blurring Algorithm

Below are results of algorithm by Shan et. al. in which both the image is restored and point spread function is discovered. PSF is not initially known with great accuracy. Developed for photograph restoration when camera is moved during exposure.

73:6 • Q. Shan et al.



(a) Blurred image (b) Iteration 1 (c) Iteration 6 (d) Iteration 10

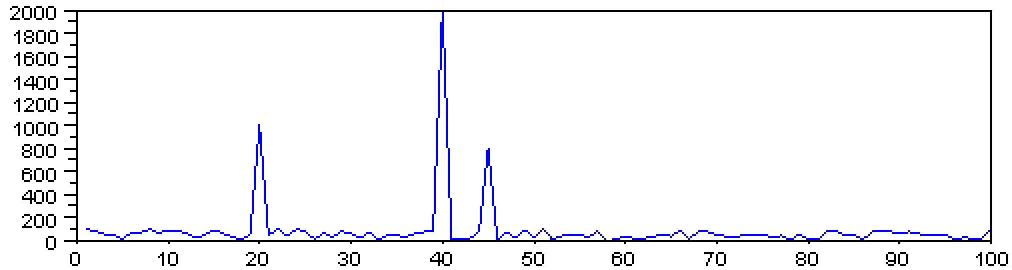
Figure 10 Illustration of our optimization in iterations. (a) The blurred images. The ground truth blur kernels are shown in the green rectangles. Our simple initialized kernels are shown in the red rectangles. (b)-(d) The restored images and kernels in iteration 1, 6, and 10.

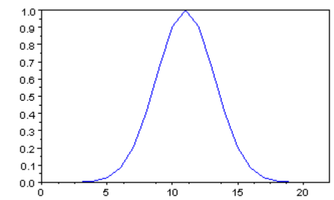
Apply De-blurring to a Dispersive Energy Spectrum

- All research developed for image de-blurring can be applied in 1 dimension to “de-blur” an energy spectrum
- Richardson-Lucy Algorithm useful if *Detector Energy Resolution* is known.
- R-L Algorithm used by Fister et. al. at APS.
- R-L could be an EPICS AD plug-in for any spectroscopy detector.
- More advanced de-blurring algorithms exist.

Scilab simulation- Improving energy resolution without improving detector sensor

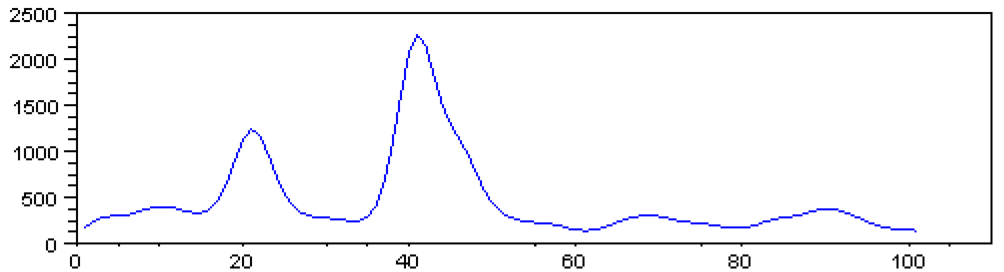
Ideal Spectrum



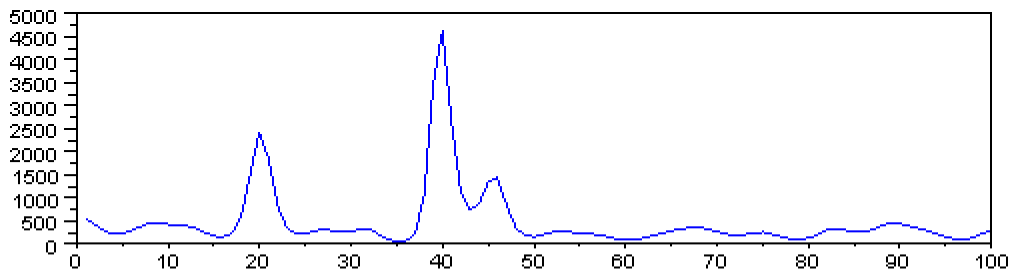


Detector Resolution

Detector Output

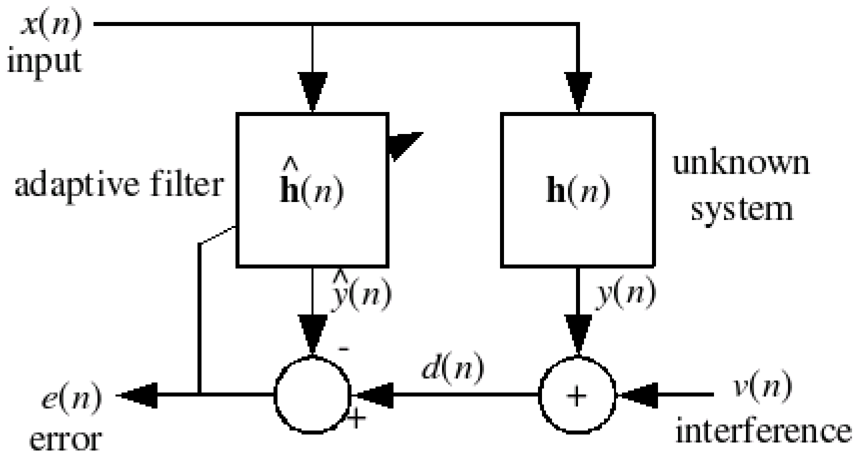


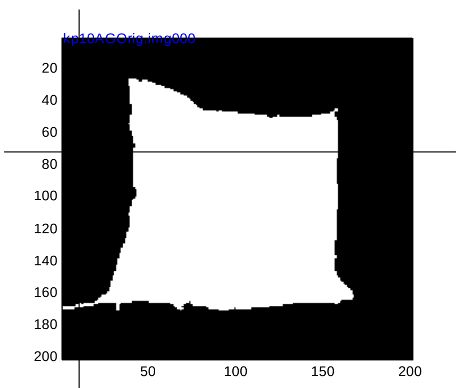
After deconvolution



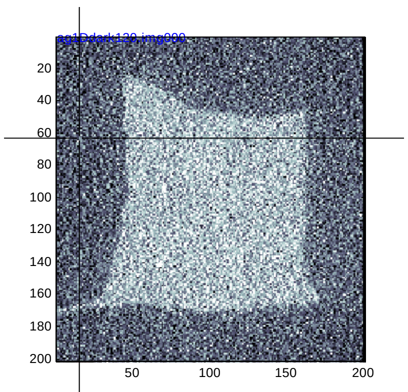
Removal of Ghosting

- In hardware ghosting is solved by using better detector crystals, Frisch grids, small pixel effect, etc.
- DSP algorithm: LMS Adaptive Filter- solves least square problems.
- Echo Canceller- cell phones, speaker phones.
- Ghosting more complex problem than acoustic echo canceller because of nonlinearity.





Bright image on Kodak CCD



Ghost image

Adaptive filters for complex problems

- New twist on adaptive filters: Difference Map Algorithm. Elser et. al.
- Solves phase problem.
- Run Difference Map Algorithm in real time as data is collected?
- Difference Map algorithm could be used for solving a large variety of problems. (even Sudoku puzzles)

Elser, “Solution of the crystallographic phase problem by iterated projections,” *Acta Cryst*. (2003). A59, 201-209

Summary

- Detector hardware will slowly improve.
- DSP can be used to make detectors work better
  - Data Compression
  - Point Spread Function
  - Energy Resolution
  - Ghosting
  - Solving complex problems
- DSP slowly being adopted in synchrotrons.