Summer at CDM

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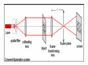
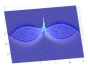
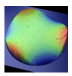
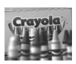
Agenda


The week-1 coherent optical reconstruction attempts

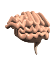

Wavefront Coded® system analysis

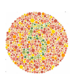

Optical Profilometry with Veeco Wyko NT8000



Experimental analysis of Wavefront coding


Occlusion detection in Wavefront Coding

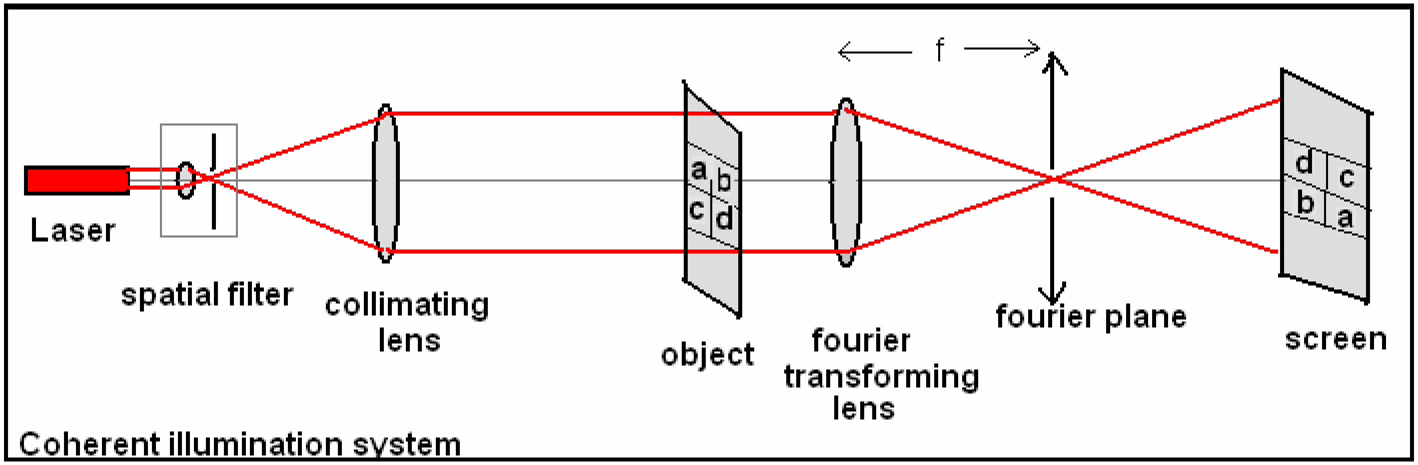

Real time pseudo 3D illusion in Wavefront Coding


Ishihara decomposition analysis

3D Future work

The week-1 coherent optical reconstruction attempts

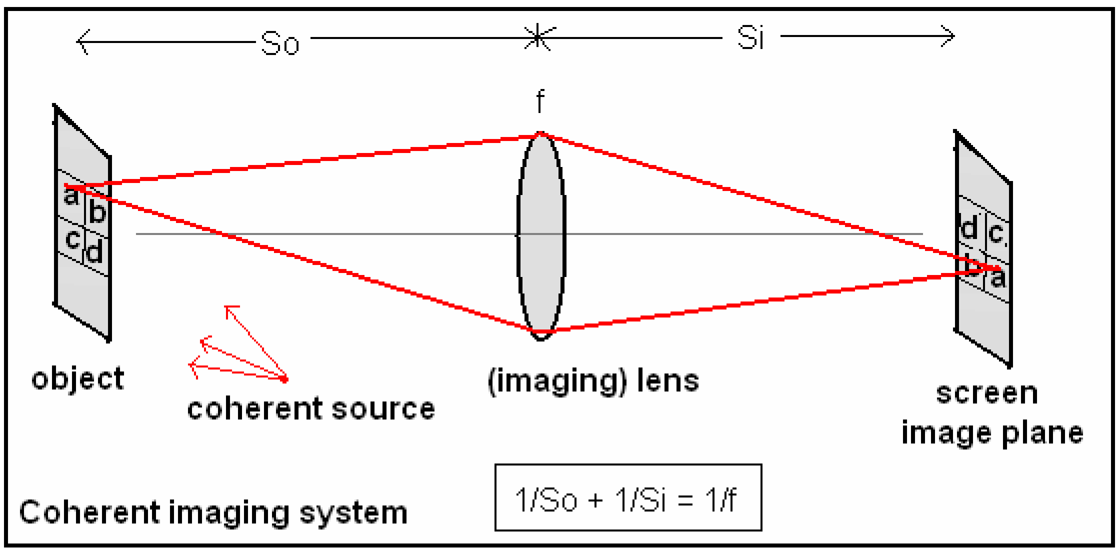
Coherent illumination system



A Coherent Illumination system has a Fourier plane

After the Fourier transforming lens, the wave front pretty much converges to a bright point (DC). Other spatial frequency components can also be seen in the Fourier plane if the bright DC is blocked.

Coherent imaging system



A coherent imaging system does not have a Fourier plane. At no location in space does the entire wave front converge to a point.

However, we do have a paraxial image plane, at a distance strictly defined by the lens equation

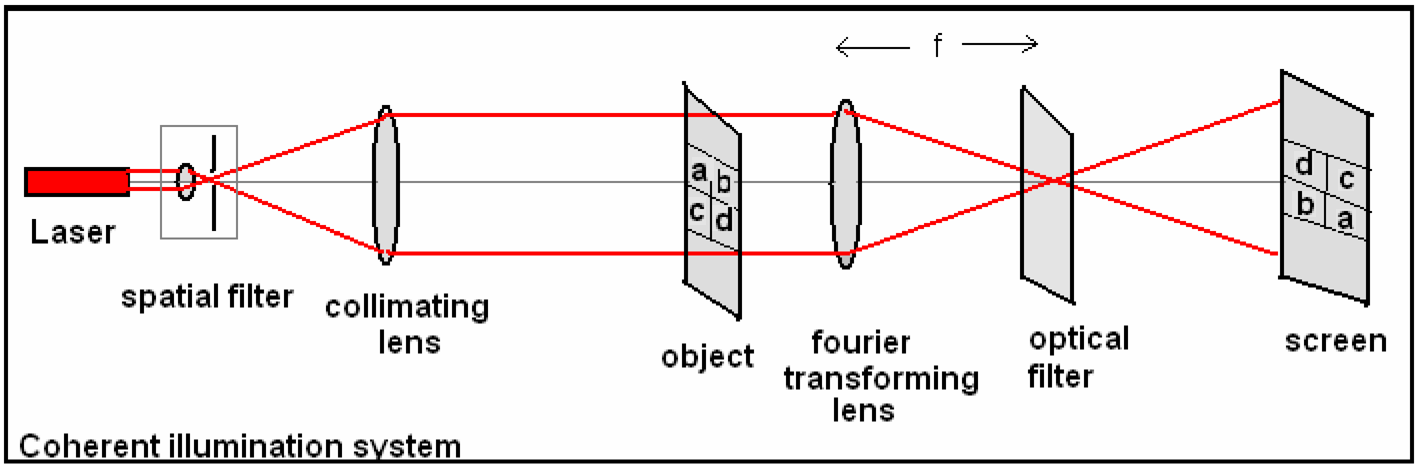
Optical signal processing (OSP) is easy in Fourier space (Multiplication).

Standard OSP techniques in real space (Convolution) involve mechanical motion. Not any more! See slides 5, 6

Reconstruction in a Coherent Illumination System

- The objective here is to see if we can do WFC reconstruction optically, at least in a coherent system. In an incoherent system, this is tricky, as we'll see in the later part of this presentation.

- In a Coherent illumination system, this can be easily accomplished by introducing an "optical filter" in the Fourier plane of the system



The optical filter can be designed to have phase in two ways

1. By varying the physical thickness according to the phase profile (3D physical structure)
2. Computer generated holography – Both amplitude and phase of the filter can be encoded in a 2D plane (transparency)

Realistic application: Transmission Microscopy

Reconstruction in a Coherent imaging system

Optical reconstruction in a coherent imaging system is not easy because there's no single plane where we can manipulate the spatial frequencies of the object. Some standard ways to accomplish this include:

1. Recording the intermediate image in a film, and using the film in a coherent illumination system…
2. Recording the intermediate image holographically; shine only the reference beam and direct the reconstructed object beam directly to a fourier transforming lens…
3. Using mechanical convolution techniques described in Goodman...

I am rejecting these three right away, as they don't seem practical. So, lets see what we really need..

Intermediate image = (Object) * (psf of the wfc optics) * → Convolution

Extended depth image = (Intermediate image) * (filter impulse response)

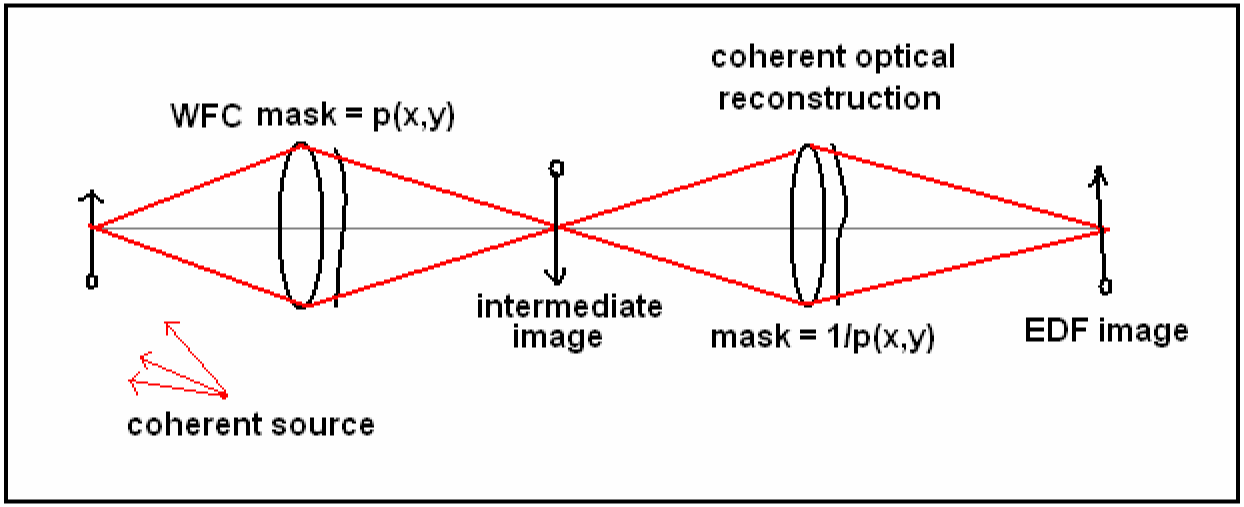
[Note that we can't do this in Fourier domain, as we don't have a Fourier plane in a coherent imaging system]

The need here is to come up with an optical convolution technique that does not require any mechanical motion.

We know that an imaging system essentially convolves an object with its psf. If we design a "reconstruction" imaging system whose psf is same as the impulse response of the filter, then, the extended depth image can be obtained using an all optical system.

Reconstruction in a Coherent imaging system

Since the intermediate image is essentially blurred by a wfc system, the reconstruction filter should be a high pass filter. Is possible to design an imaging system, whose transfer function is a high pass filter? The answer is **YES** in a coherent system.



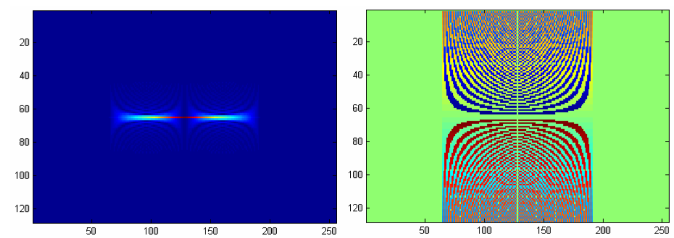
This cannot be accomplished in an incoherent system, since the OTF of an incoherent system always peaks at DC. Another way of thinking about this is

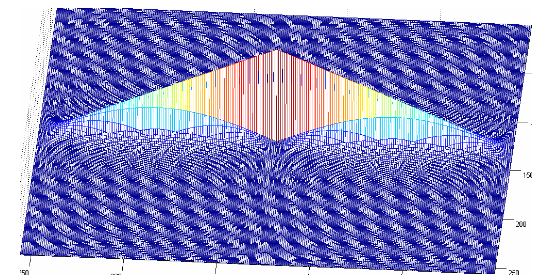
incoherent psf = |coherent psf|^2
implies, incoherent psf is all positive
implies, OTF is a low pass filter

Wavefront Coded® system analysis

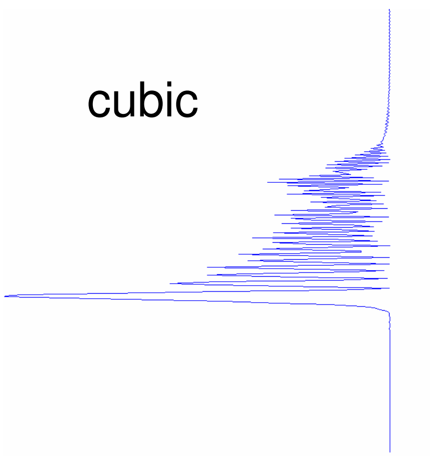
- Inorder to test the performance of a rubber phase mask, I had to understand a wavefront coded® system..

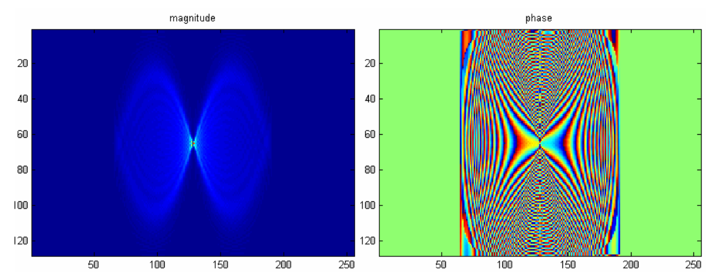
rect

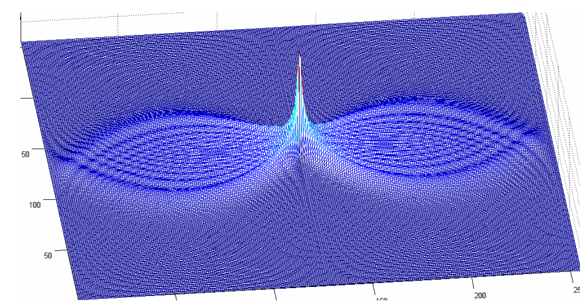




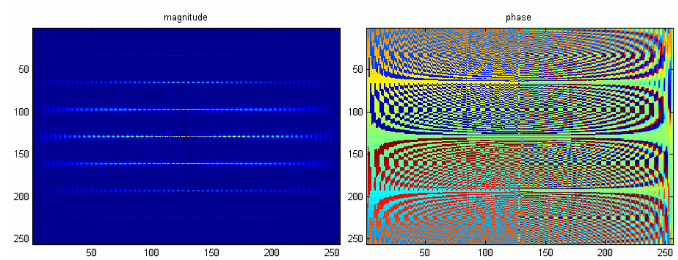
cubic

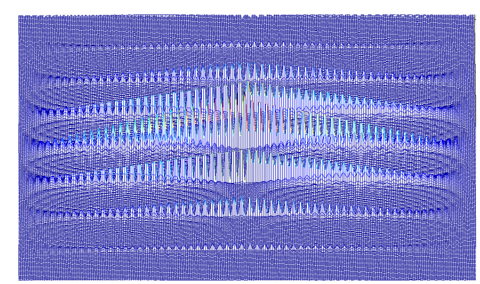






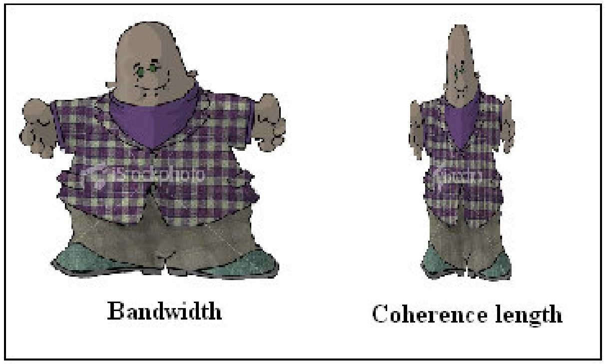
cosine

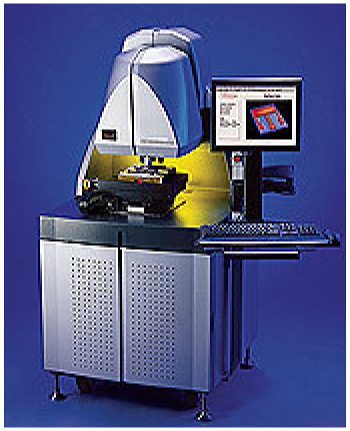




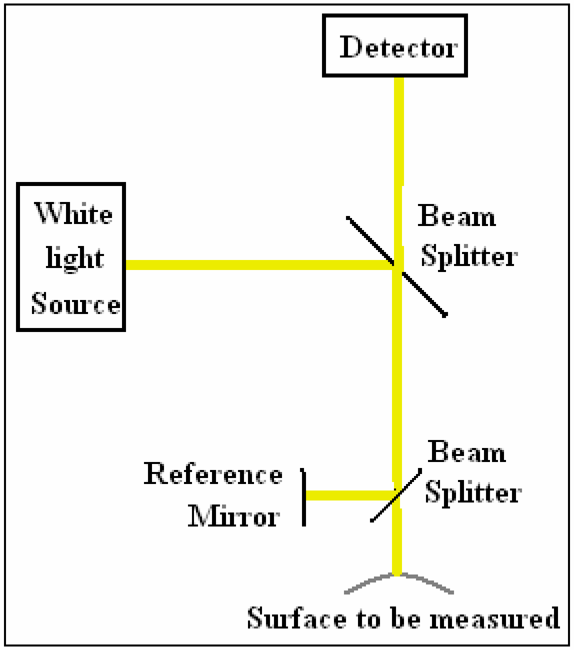
Optical Profilometry with Veeco Wyko NT8000

- A white light optical profilometer “accurately” determines the sag of a surface by measuring the interference between the light reflected off from the surface and an internal reference beam.
- Since the bandwidth of the source is large, its coherence length is extremely small.

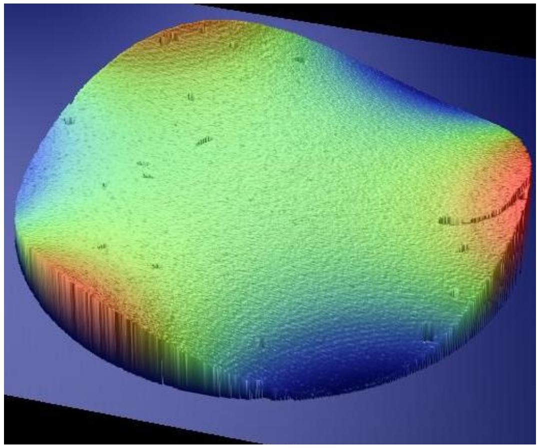




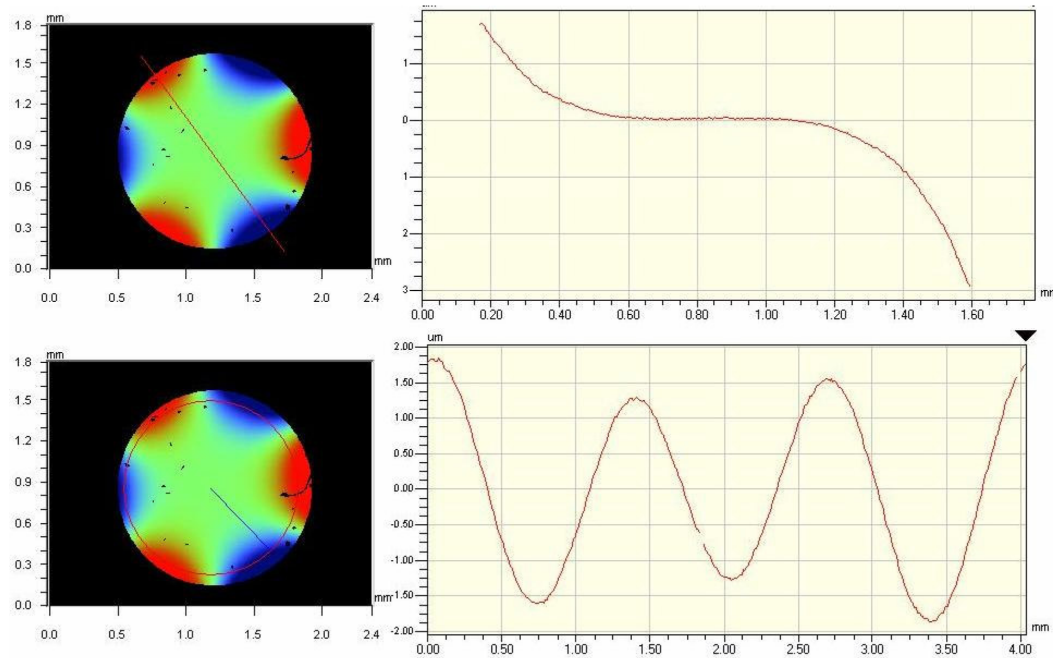
- Consequently, in a Michelson interferometer, fringes can be observed only when the optical path lengths of the two arm are the same.
- Since the distance between the reference mirror and the beam splitter is same as the working distance of the objective, interference fringes are visible only when the surface is in focus.
- In order to determine sag, the objective performs a z-scan (moves up/down) and records the position in z, where the fringe contrast is maximum.

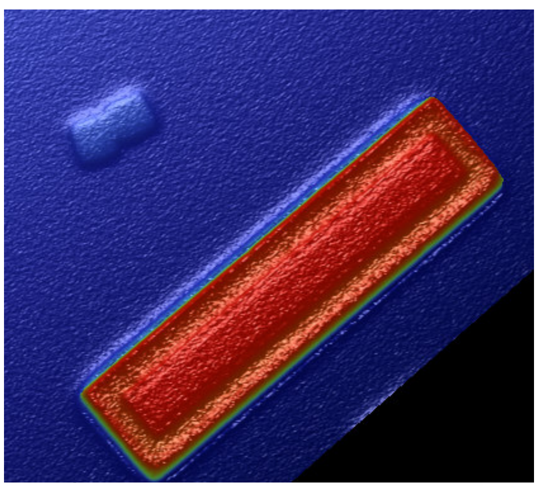


Some features of NT8000…

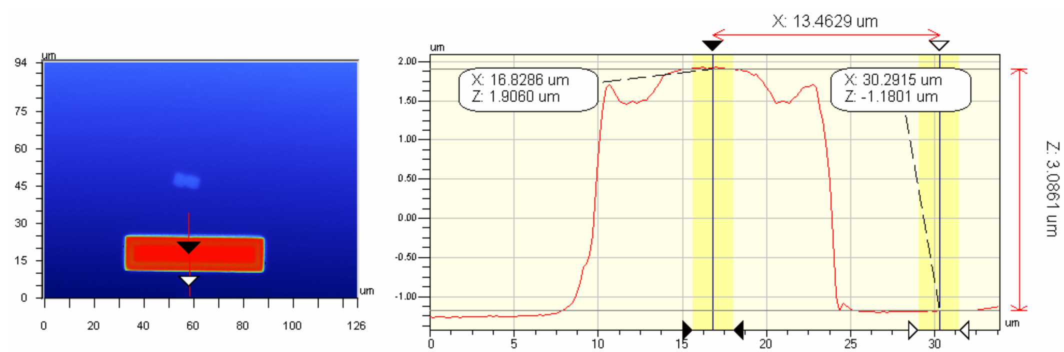


WFC Cosine form (~1.5mm diameter)
used in a cell phone camera



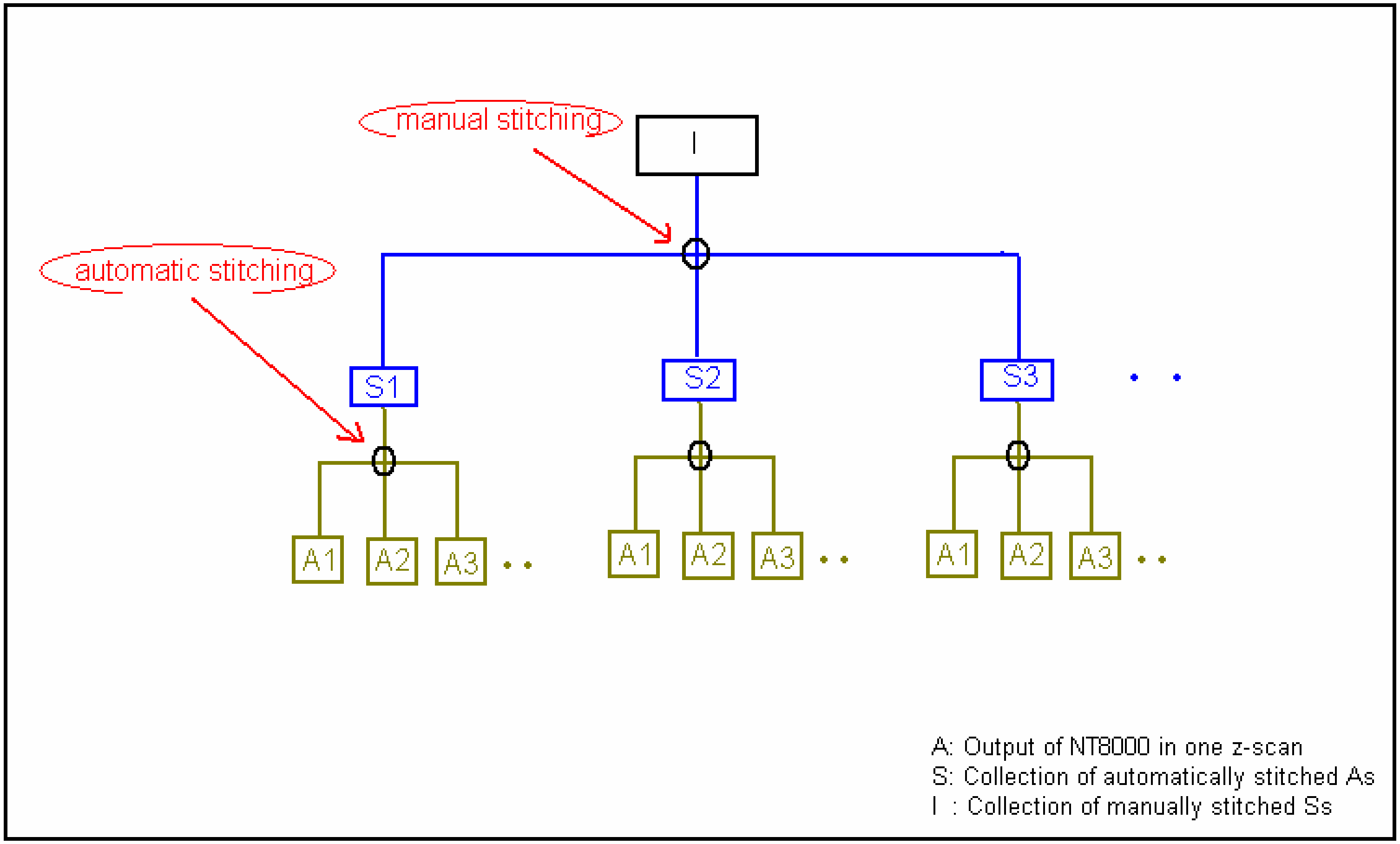


Prof. Carol's silicon wafer



NT8000 Problems

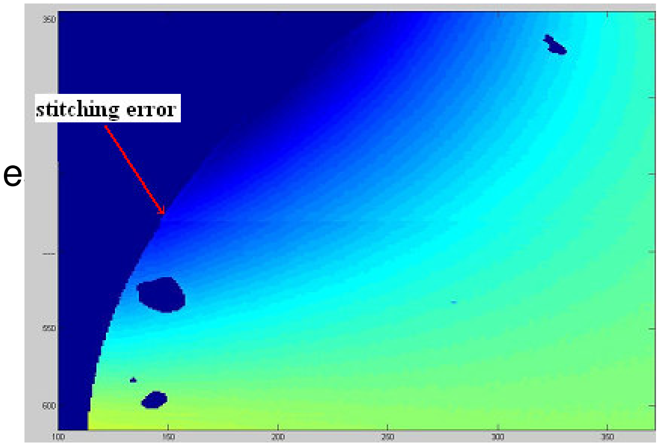
- As NA increases, the area of the region whose sag can be measured in one z-scan decreases. Consequently, for measuring the sag of large surfaces with high NA objectives, the sample is shifted (x/y translation) and multiple measurements are taken. Finally, these individual measurements are stitched together to form the final sag image.



NT8000 problems

Some significant problems arise while measuring large surfaces

- Stitching errors
- Single pixel errors
- Horizontal sag profiles are not as good as the vertical sag profile
- Buggy software



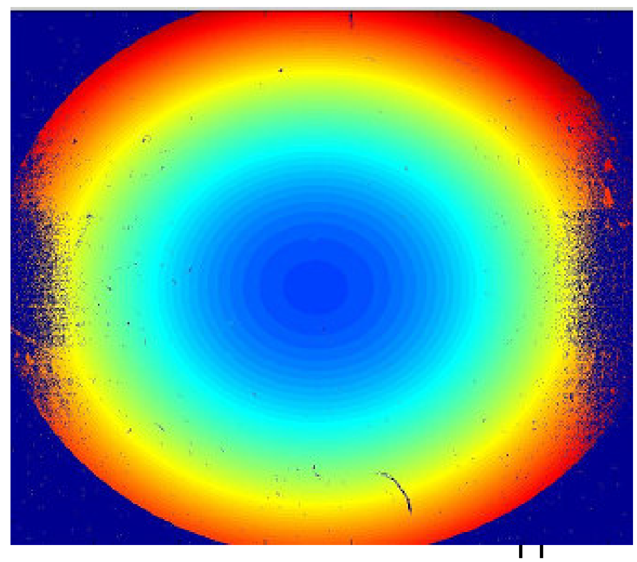
Stitching error

The probability of confronting severe software bugs (including crashing all of a sudden) seems to be a linearly increasing function of the size of the surface to be measured.

However, there are some workarounds that Regis and I figured out. Some recommendations on how to measure a large surface can be found in the following document.

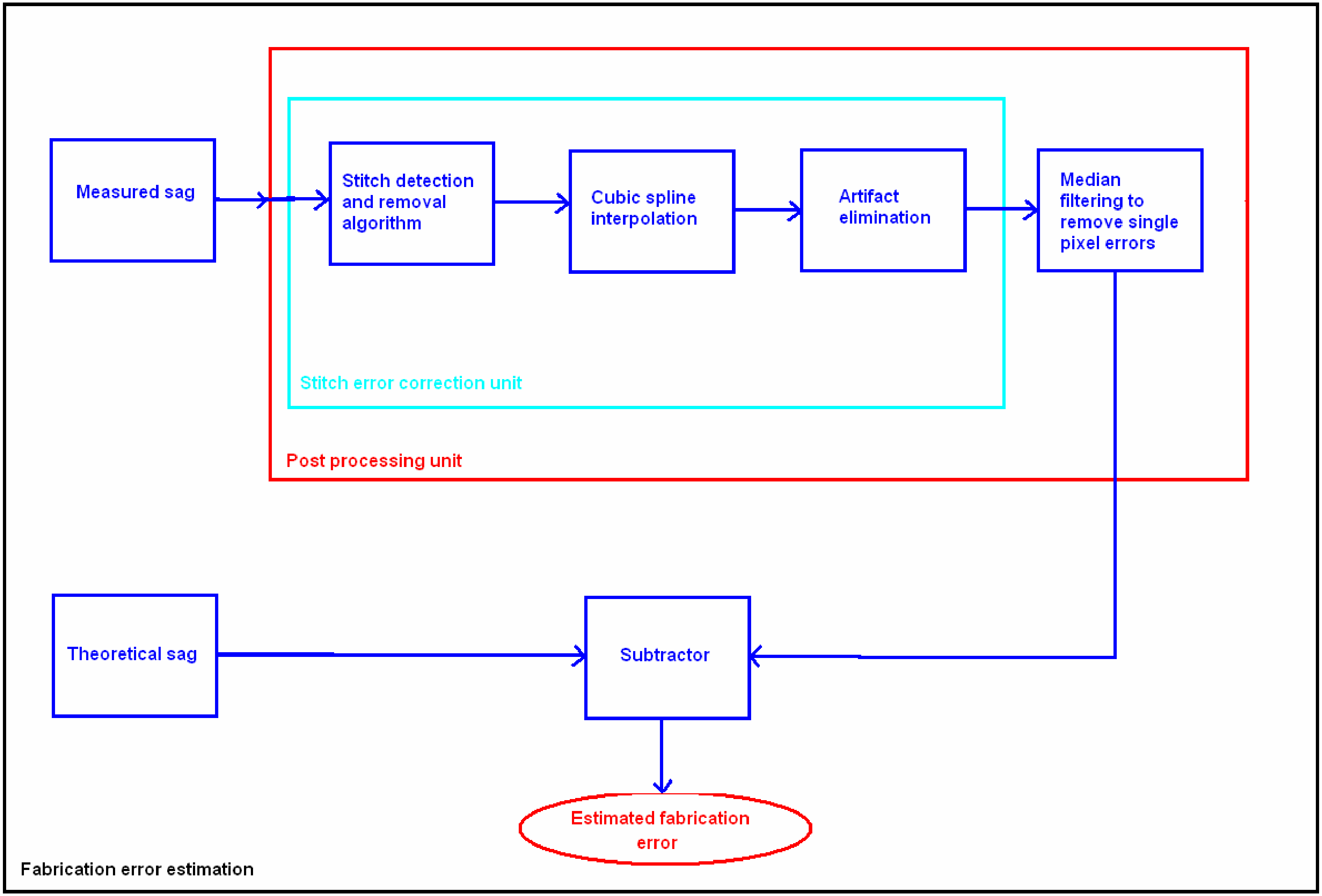
Adobe Acrobat 7.0 Document

How to use NT8000 for a large optic?



Bad horizontal profiles and single pixel errors

Solution to most NT8000 problems



Cubic spline interpolation and artifact correction

• Known information such as detector array size and sampling rate are used for detecting the location of the stitching errors. Once, detected they are “removed” – the entire stitching error region is zeroed out. [See images]

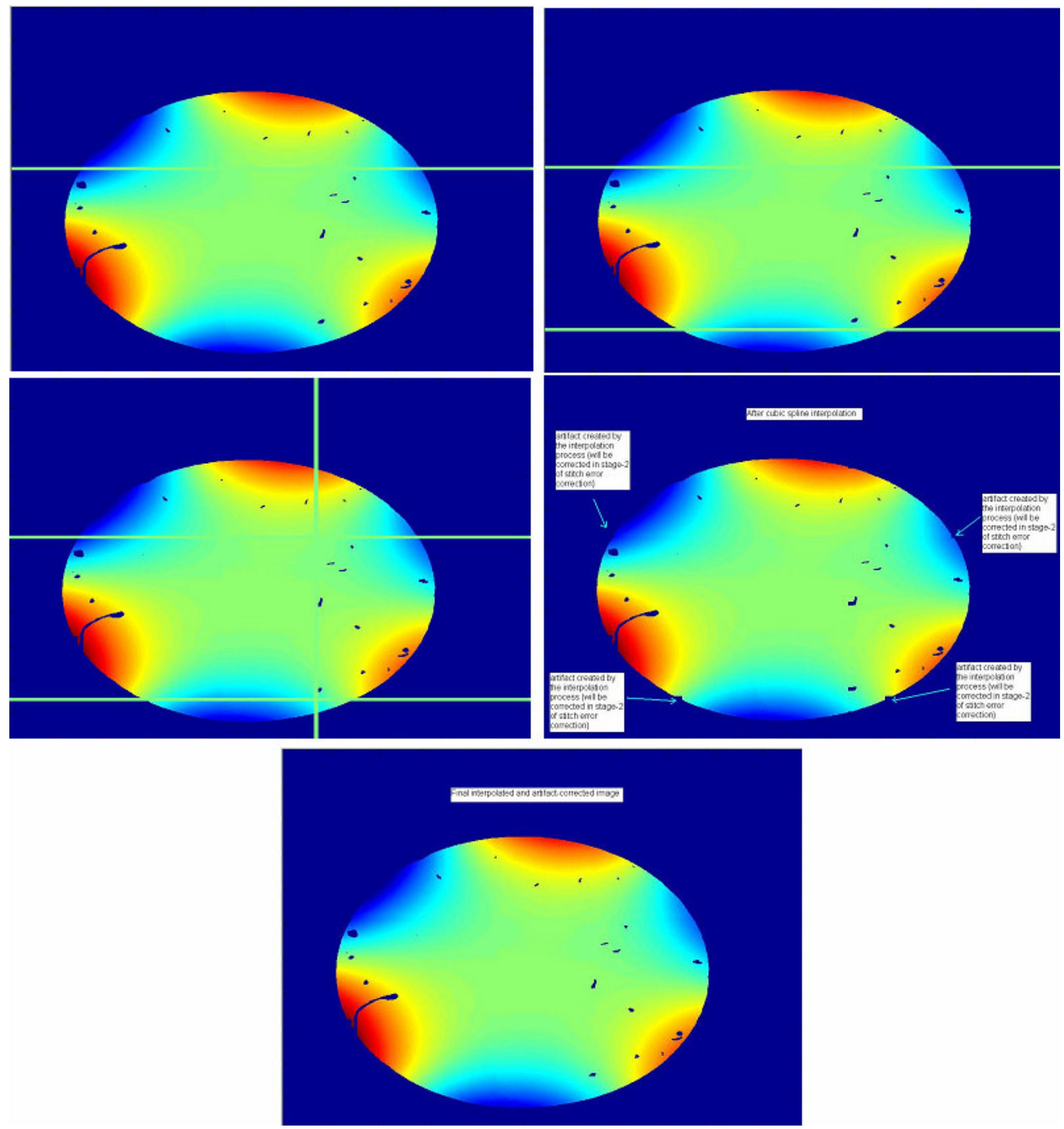
• From past projects, I learnt that cubic spline interpolation performs better than other interpolation techniques like zero-hold, sinc etc, in a mean squared sense.

[See http://eces.colorado.edu/~pavani/sampling.pdf]

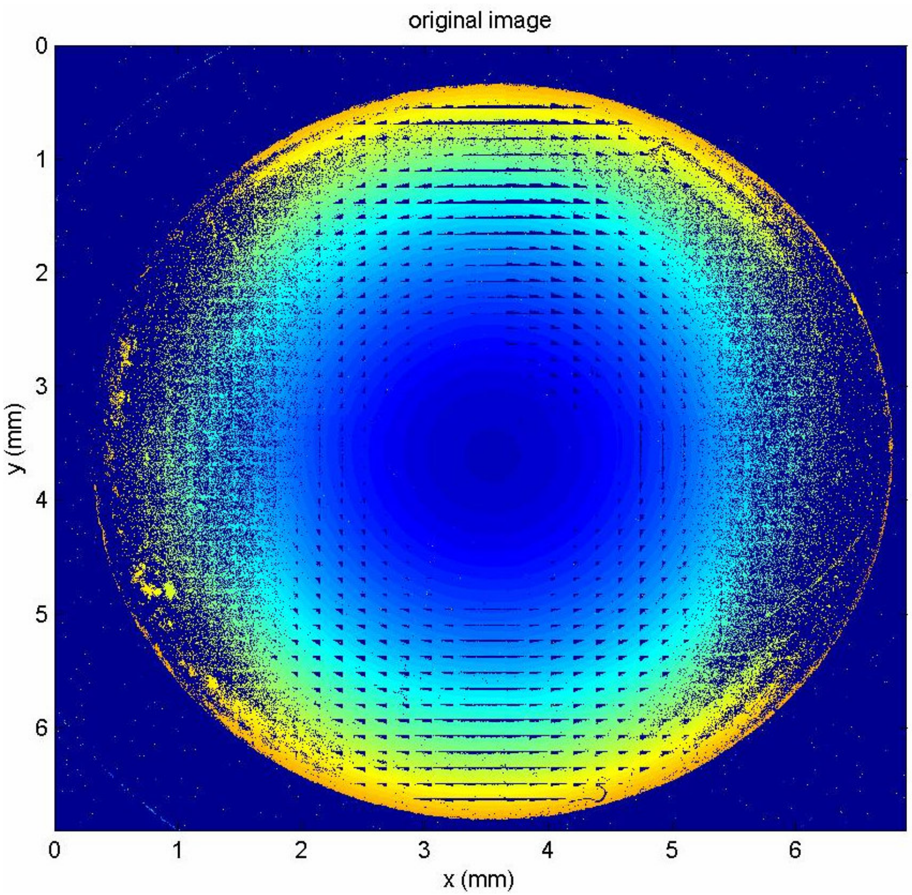
• The cubic spline interpolation algorithm creates artifacts, particularly near the edges, which is corrected by the artifact correction algorithm.

• Finally, median filtering is done to get rid of single pixel errors.

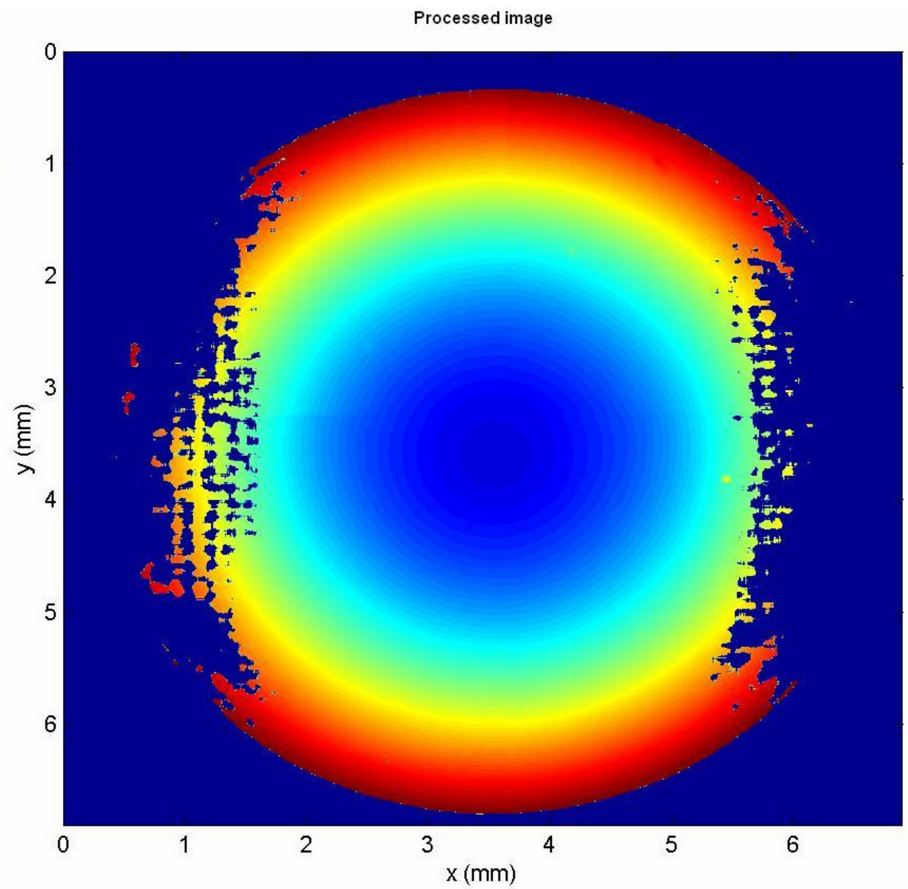
• No loss of spatial resolution as these region based algorithms work in real space.



Robustness of the processing algorithms



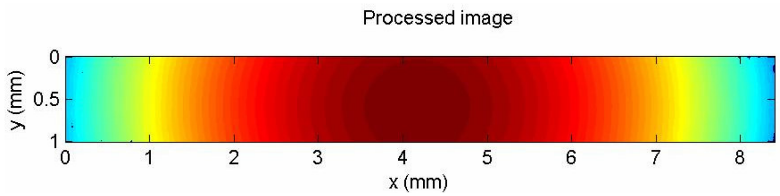
Before Processing

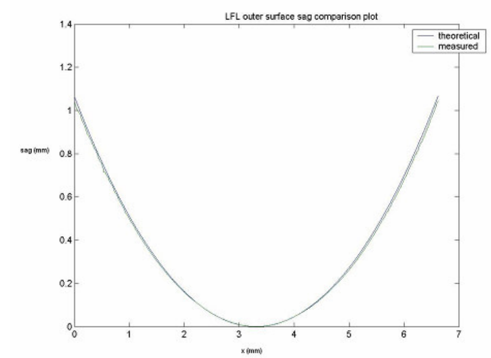


After Processing

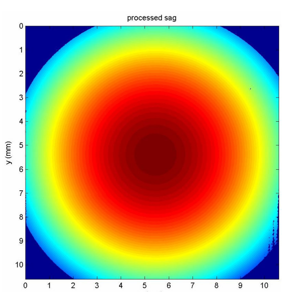
Profilometry in some key CDM projects

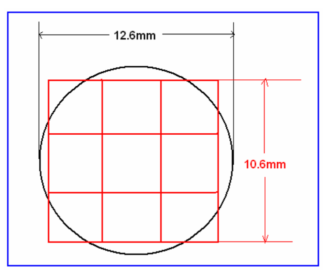
- **LFL:** Sag of the LFL IR lens was measured before and after Anti-Reflection (AR) coating. Results indicated that there was an overall increase of about ~70u after coating
- **LFL:** The outer surface of the LFL IR lens was found have a peak deviation of ~30.2u from the theoretical specifications.

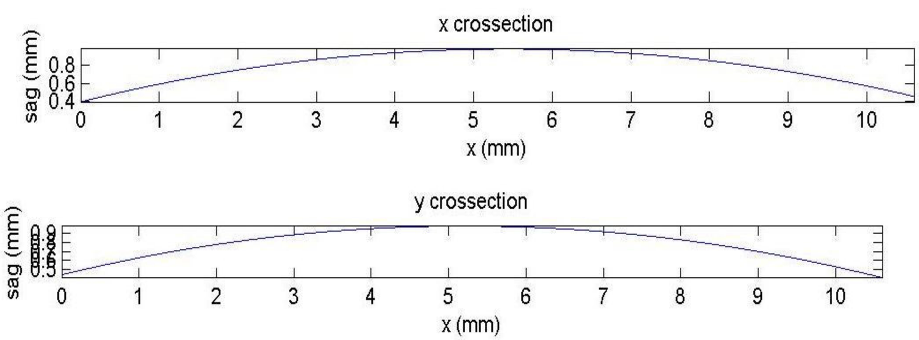




- **ASPEN:** The uncertainty in the ability of NT8000 to measure the profiles of large surfaces (>10mm) was laid to rest – A 10.6mm x 10.6mm area of a test lens was successfully measured.



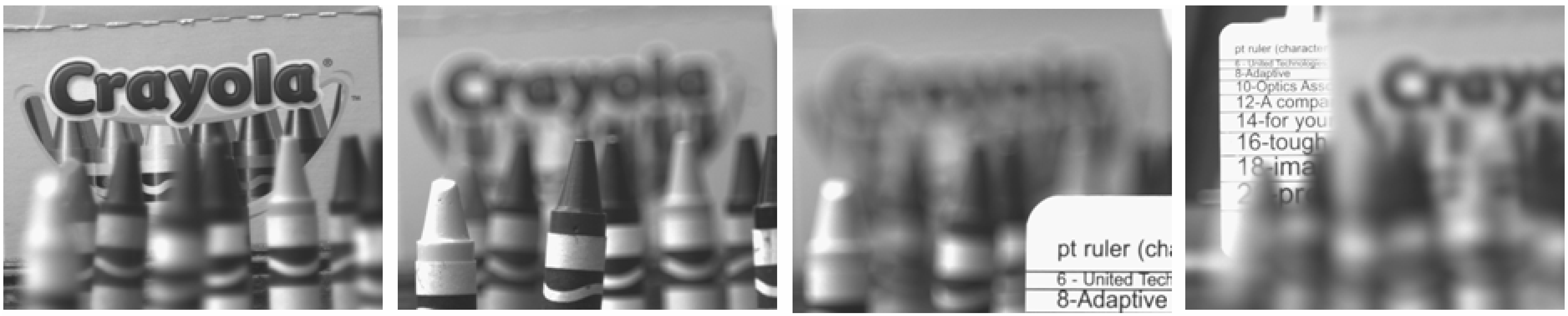




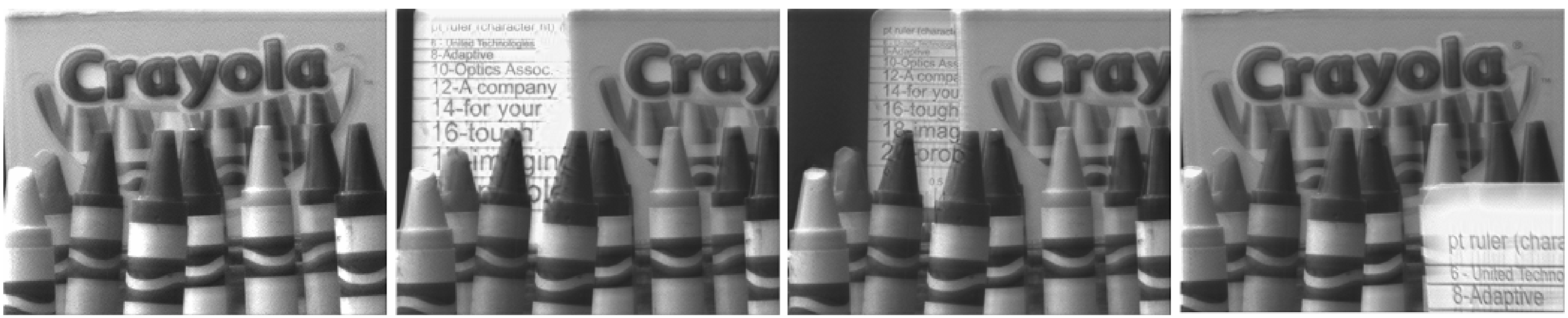
Experimental analysis of Wavefront coding

- Used EDF Demo to acquire psfs of a cubic, cosine form, circular caustic with a 2u pinhole.
- Obtained psfs over a 30cm range with more weight to the central psf.
- Built Least Square reconstruction integer filters and saw EDF images in ~real time.
- Compared the performance of different masks

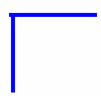
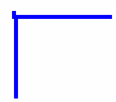
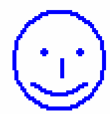
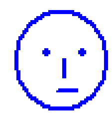
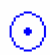
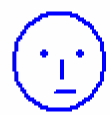
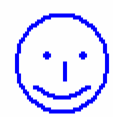
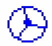
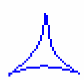
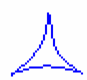
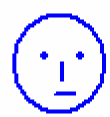
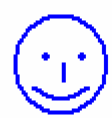
Traditional:

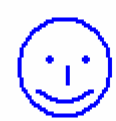
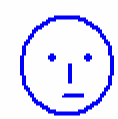


EDF with cubic mask:



Comparison of Cubic, Circular caustic, and cosine form

Mask	PSF			Depth of field	Intermediate image quality	Analysis
	infocus (z=0)	defocus (z>0)	defocus (z<0)			
Cubic						Good candidate for EDF, but would boost diagonal frequencies of the object.
Circular Caustic (CC)		 circle expands with misfocus	 circle expands with misfocus			Bad for EDF, but the intermediate image quality is good.
Cosine Form (CF)		 expands with misfocus	 expands with misfocus			Bad for EDF and the intermediate image is better than Cubic but worser than a CC

 = Good  = Bad

Occlusion detection in Wavefront Coding

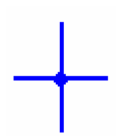
- All of the above EDF images (with cubic mask) have a peculiar feature in common – **Occluded objects are visible in front of the objects occluding them!**

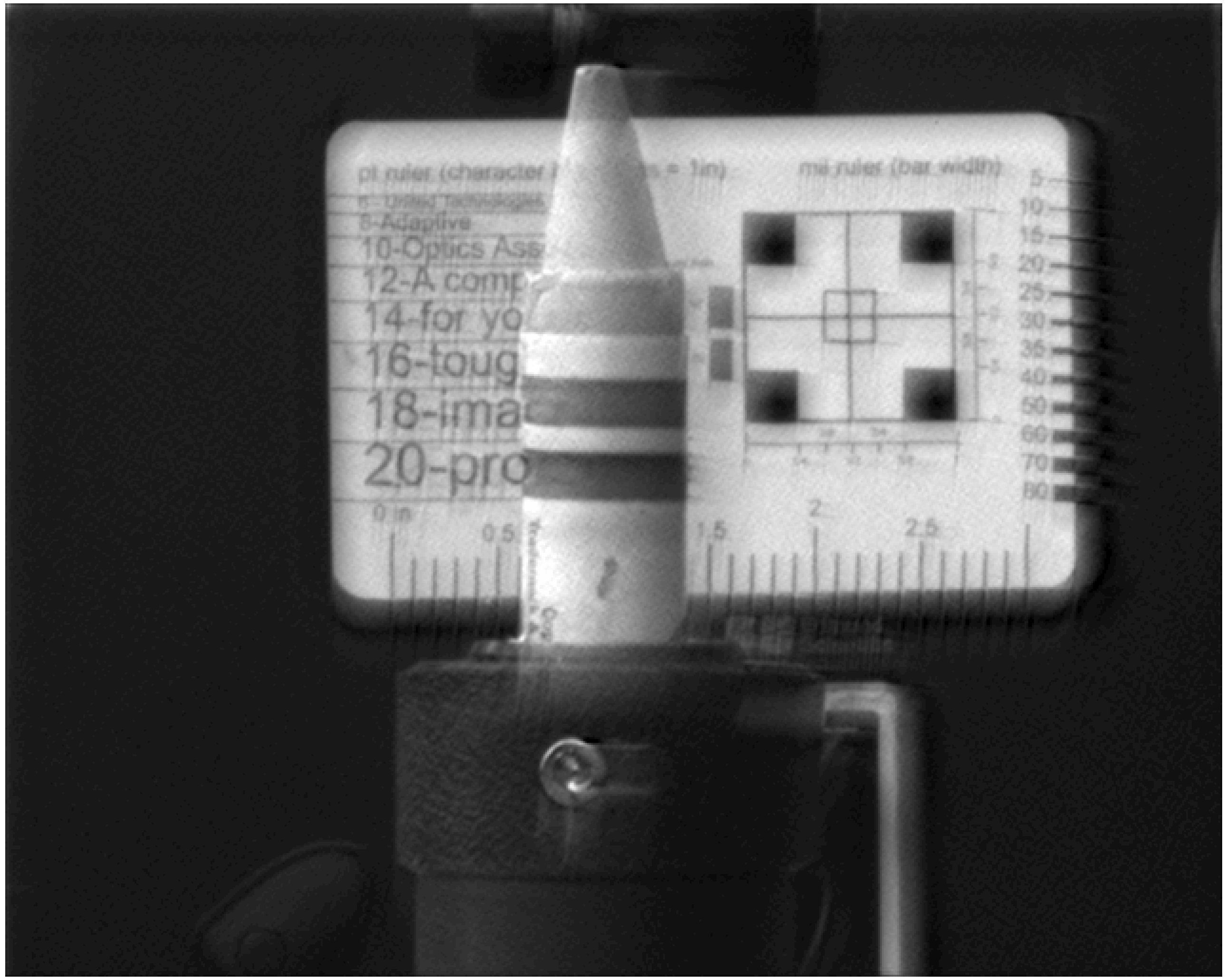
- For example, in the first image, see the fourth crayon from the left. The letter “b” of the card (behind the crayon) seems to be in front of the crayon!

- The direction of occlusion visibility is depends on the orientation of the cubic mask. In the above images, the cubic was oriented in a way such that the psf was like . If the mask is rotated such that the psf is , then the “b” in the above example would not be visible any more. Instead, occluded objects to the right of the crayons would be visible.

Occlusion detection - Analysis

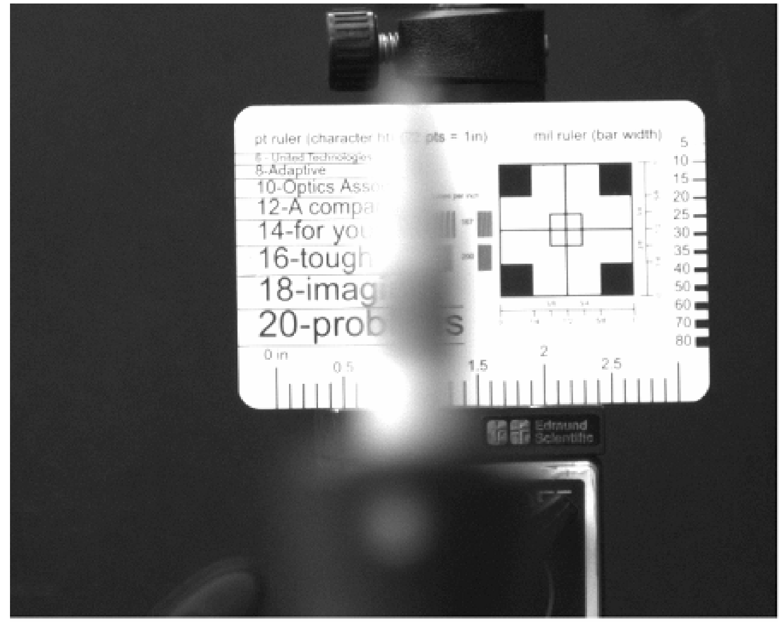
- Notice that “g” of the “18-imag” and ”b” of the “20-prob” are visible **on** the crayon. They seem to be “stretched” by the surface of the crayon.
- Occlusion detection is possible with a cubic, but not with a circular caustic or with a cosine form.
- For occlusion detection, the psf should be stretching horizontally and for vertical occlusion detection, the psf should be stretching vertically. The ideal psf for occlusion detection is probably some thing like

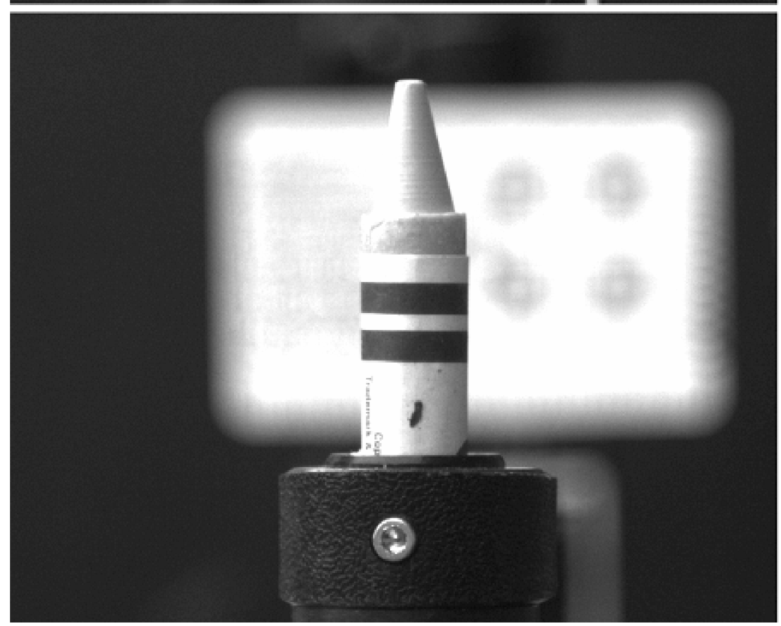




Occlusion detection - Analysis

- These are two traditional images of the same object.
- Careful observation of the top image would reveal that the “g” in “18-imag” and the “b” in “20-prob” is seen clearly. In the EDF image of the previous slide, we noticed that two letters were imaged in front of the crayon.
- In the “bottom” image, only the crayon is visible and the card is totally blurred out.
- So, clearly, for any one plane of focus, a traditional imaging system cannot resolve both the card and the crayon. However, as the wavefront coded system collects information from the entire depth of field, it is able to resolve “g” and “b”
- Finally, note that the cubic phase mask is **not** the optimum mask for occlusion detection. A mask with psf + would probably do better as we would be able to see occluded objects in all four directions.





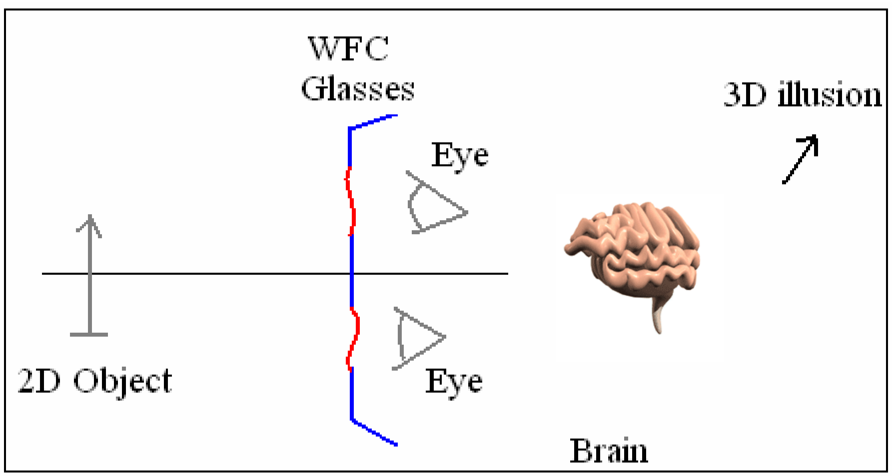
Real time pseudo 3D illusion in Wavefront Coding

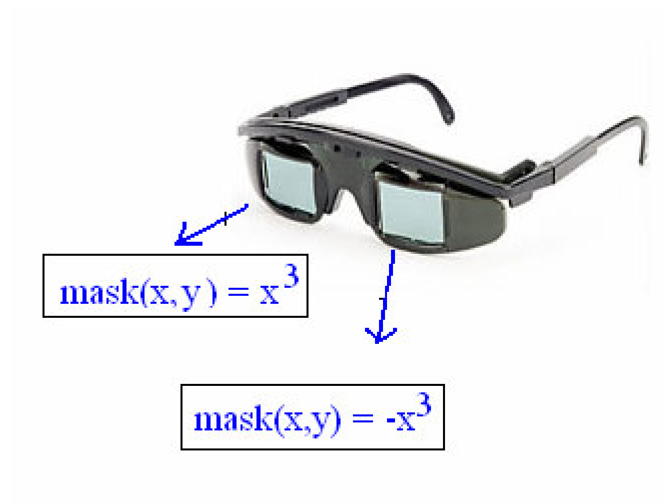
- The objective is to create a 3D realtime "illusion" from a 2D object using wavefront coding. In order to see the 3D illusion, the viewer should wear wavefront coaded spectacles

- mask in left eye = lm(x,y) = x^3
  mask in right eye = rm(x,y) = -x^3

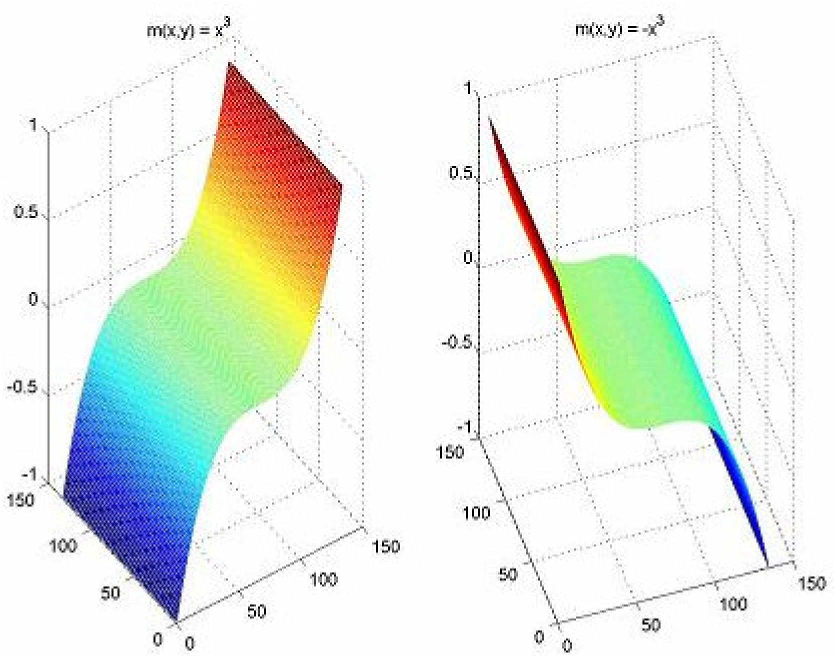
- These masks create opposite "motion blurs" in the horizontal direction, thereby providing two different views of the 2D object to each of the eyes. The brain perceives a pseudo 3D as the left and right eyes see different images of the same object.

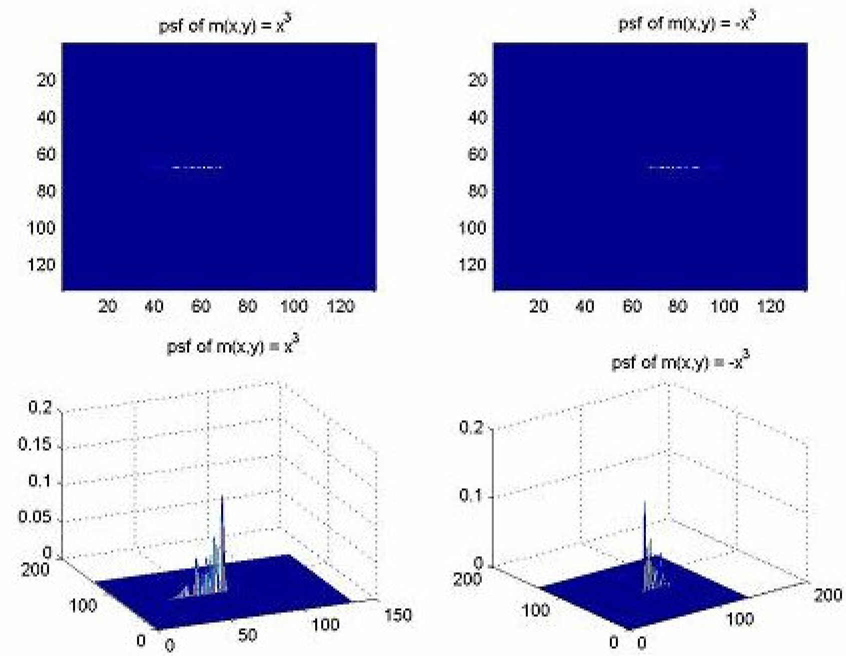
- Application: **Entertainment industry**  (kids toys etc)





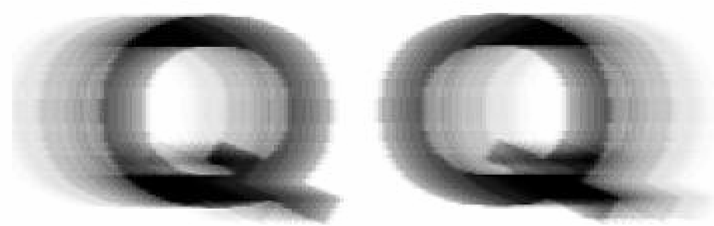
Real time pseudo 3D illusion - Analysis





2d object:

Right/Left eye images:



Ishihara decomposition analysis

- My last research at CDM for the summer!

Problem

Monochrome cameras cannot differentiate between two different colors with the same brightness.

Consequence

Edges between equi-bright colors cannot be detected. For instance, A colored text on a differently colored background will be completely invisible to a monochrome camera if the two colors have the same brightness.

Solution

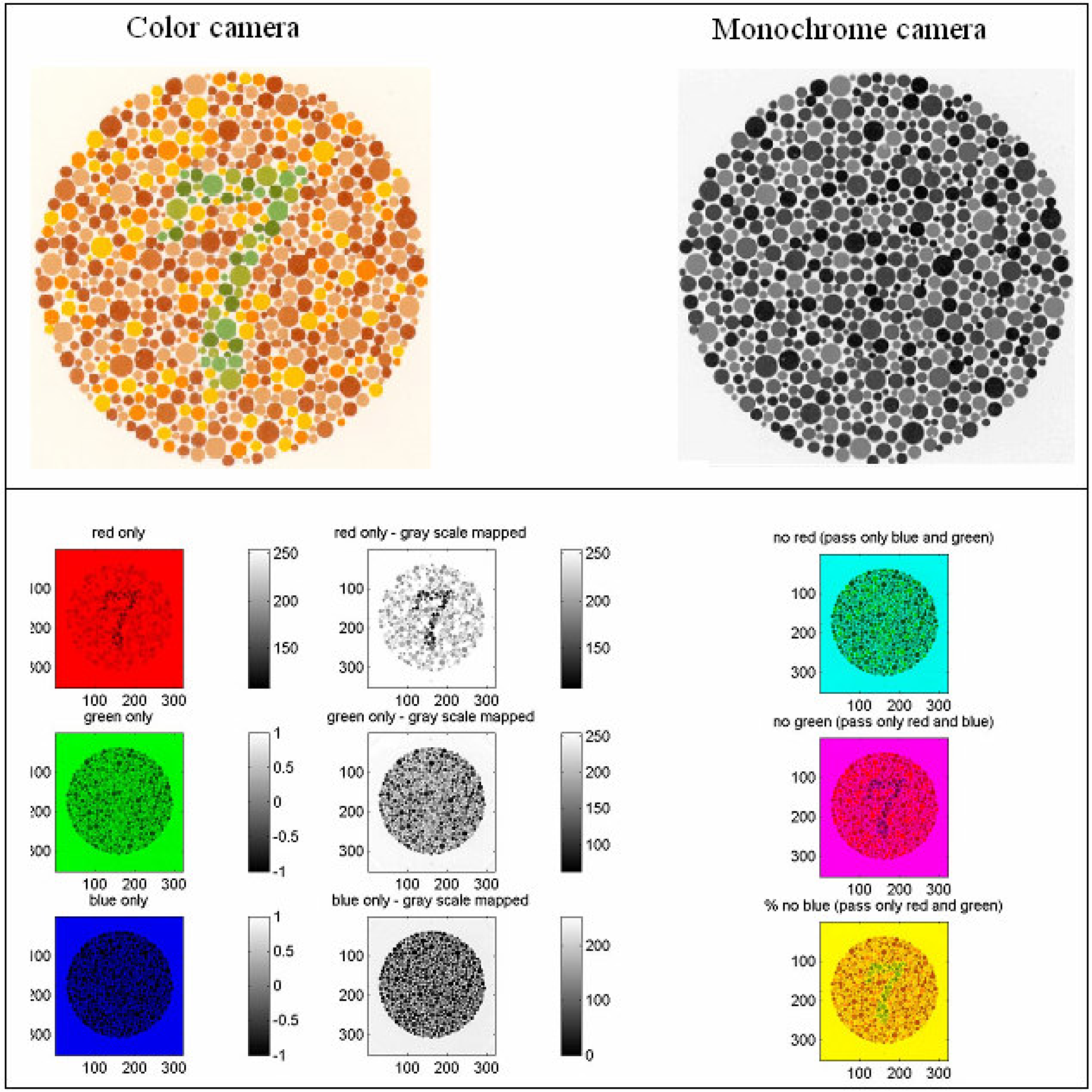
Use color filters? What colors?

Ishihara test

- A standard test for detecting red-green color identification deficiency in humans.
- I am going to extend the same test to a monochrome camera.
- Since a monochrome camera is completely colorblind, by itself, it would definitely fail in the test.
- The goal here is to design a technique for making a monochrome camera to pass the ishihara test
  - Make a monochrome camera to differentiate between two equi-bright colors. Can we?

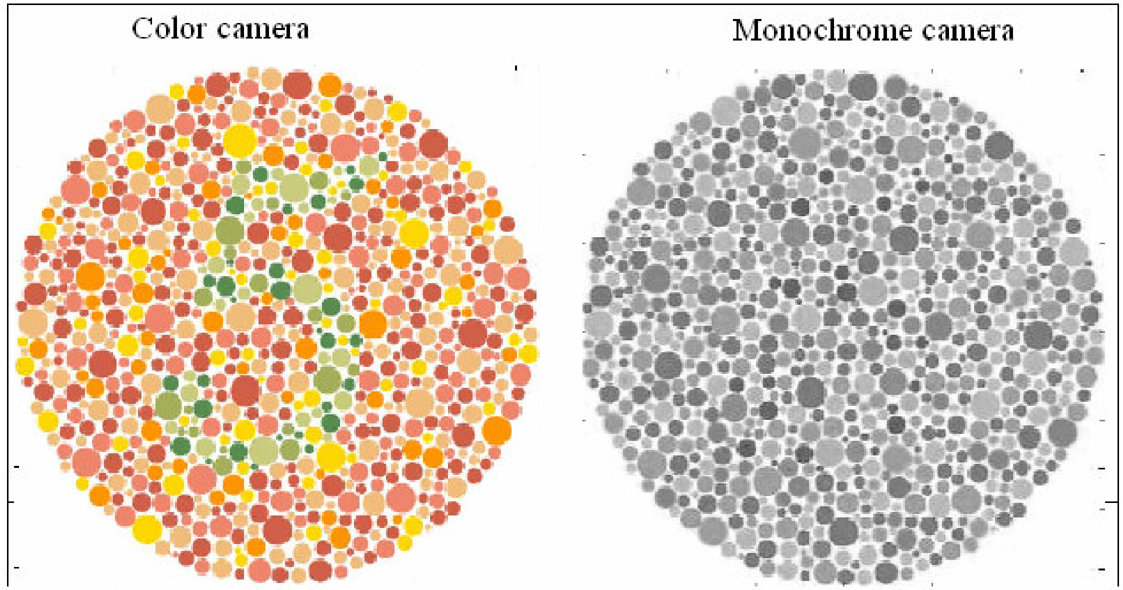
Ishihara decomposition analysis

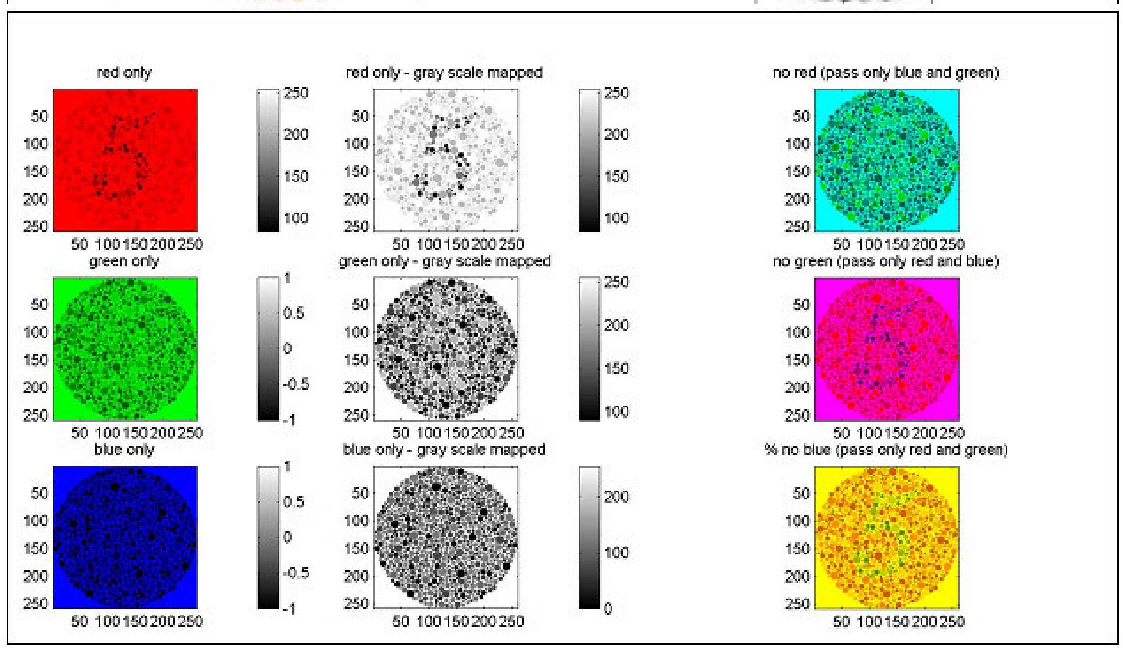
Red and purple color filters can make a monochrome camera to differentiate between equi-bright red and green patterns



Ishihara decomposition analysis

Red and purple color filters can make a monochrome camera to differentiate between equi-bright red and green patterns





Future work

3D WFC imaging system

- Most 3D imaging systems available in literature either use coherent scanning for depth determination or use many lenslet arrays before the detector. These systems typically are very expensive and they have stringent limits on achievable resolution. Depth from stereo suffers from many known problems like correspondence problem.

- Wavefront coding clearly can extend the depth of field.

- Ed and Greg showed in their PhD research that wavefront coding can be used for range determination.

- I would like to investigate if there are ways obtain both range and extended depth image from a single WFC imaging system. If this becomes a reality, there seems to be a possibility to design reasonably priced 3D imaging systems, that do not have stringent resolution limits.

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