Sub-pixel spatial resolution interferometry (SSRI)

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Outline

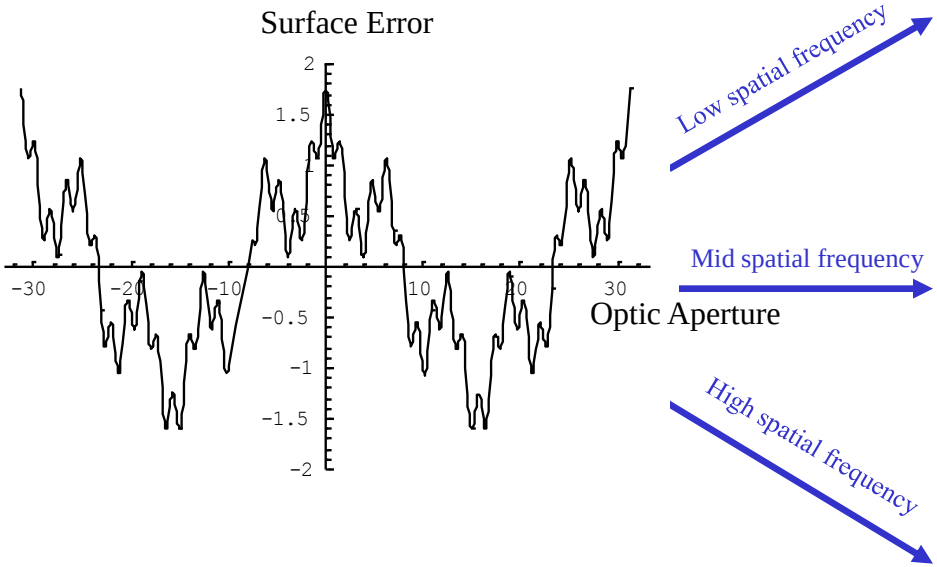
1. Problem
2. Interferometer Sampling
3. SSRI Method
4. Results

Problem Identification

The need for the sub-pixel spatial resolution interferometry method arises from:

- **Increased use of spatial frequency bands (including mid-spatial frequencies) for surface figure specifications**
- **Need for larger aperture imaging systems**
- **New advances in optical manufacturing that allow the mid-spatial frequencies to be deterministically corrected.**

Surface spatial frequency bands



Surface Figure Error

Spatial resolution for interferometers

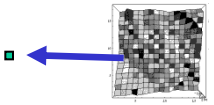
•Factors that limit the spatial resolution obtainable by interferometric measurements:

- **CCD pixel size and spacing**
  - Limited to resolve spatial frequencies of ½ the sampling frequency (i.e. a 1K x 1K detector could resolve 500 cycles per aperture)
- **Quality of the interferometer's imaging system**
  - Interferometer transfer function

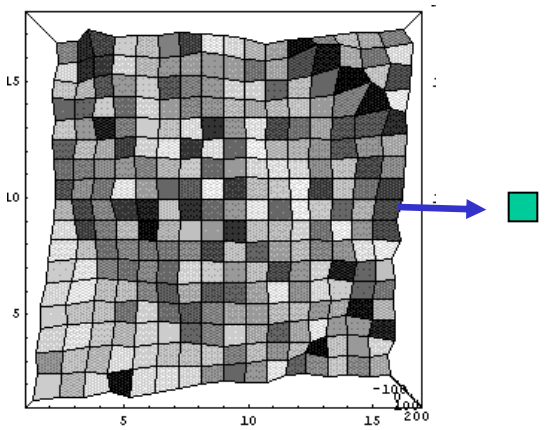
CCD scaling for larger optics

As aperture size increases for an interferometric measurement, the pixel size as projected onto the optical surface becomes larger, limiting the resolvable spatial frequencies.

Full aperture measurement of a 50 mm optic;
1000x1000 pixel CCD array:
Spatial Resolution= **0.1 mm features**



Small optic → small pixel →
high spatial resolution measurement



Large optic → large pixel →
low spatial resolution measurement

Full aperture measurement of a 5 meter optic;
1000x1000 pixel CCD array:
Spatial Resolution= **10 mm features**

Spatial frequency bands and interferometer resolution

Implement high spatial resolution techniques

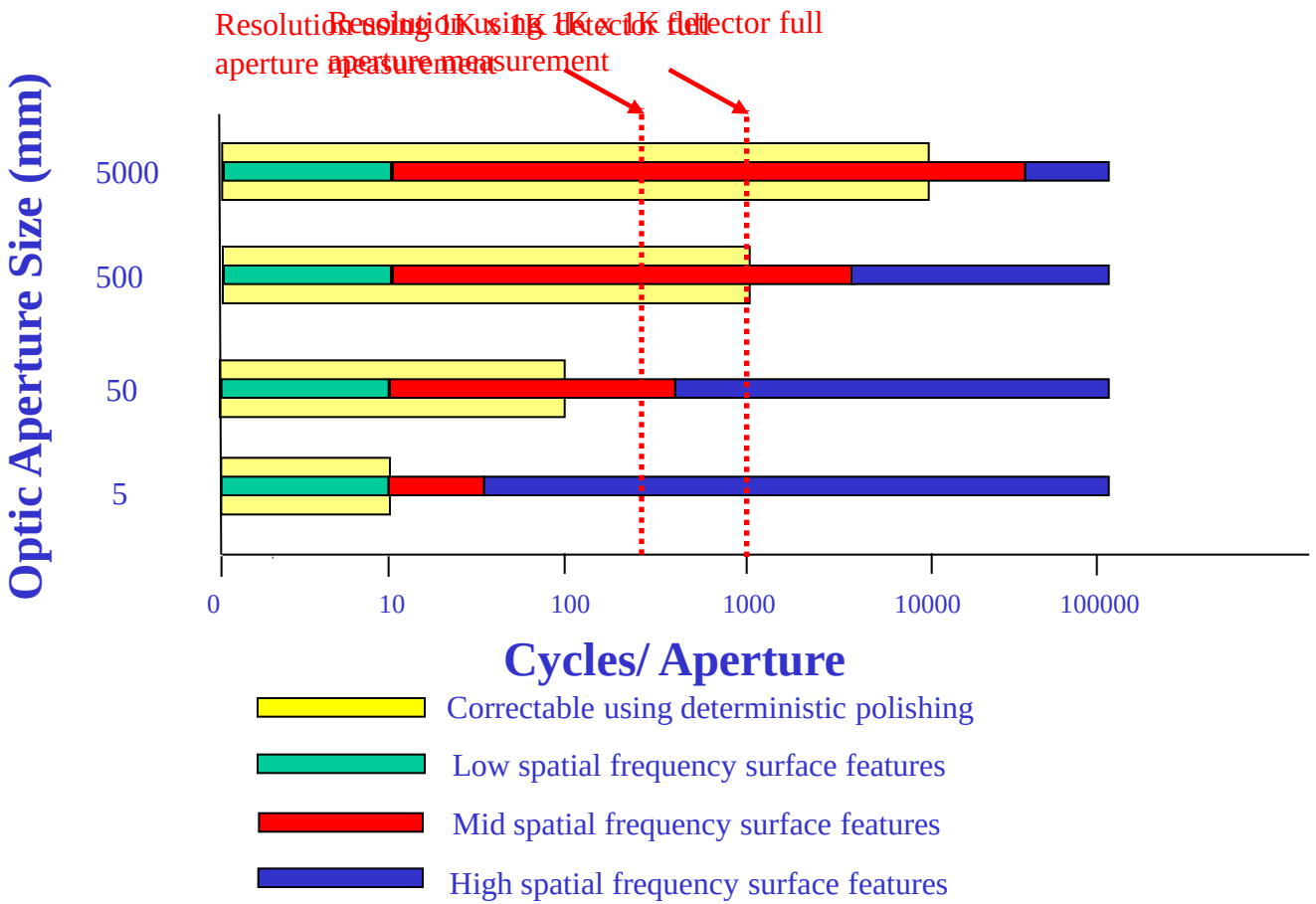
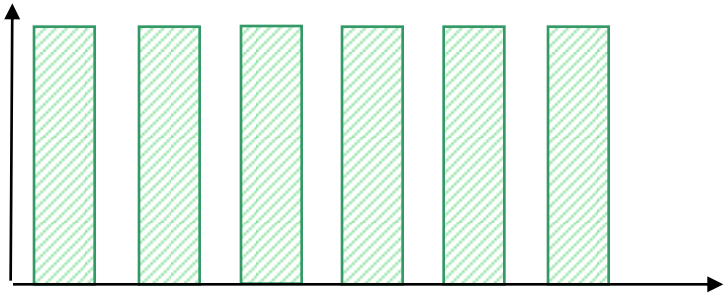


Chart assumes that the interferometer optical system is not limiting the spatial frequencies.

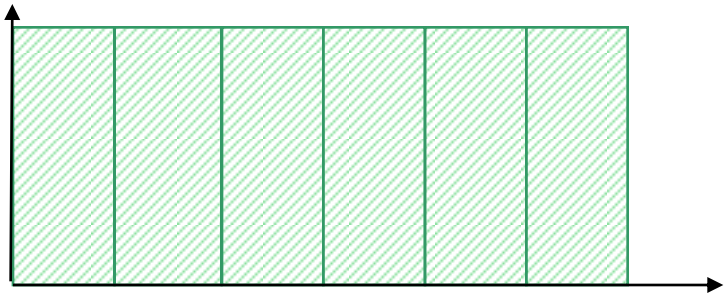
Interferometer Sampling

The "collecting area" of a CCD array can be described by the pixel function convolved with the sampling function:

$$p(x)*s(x)$$



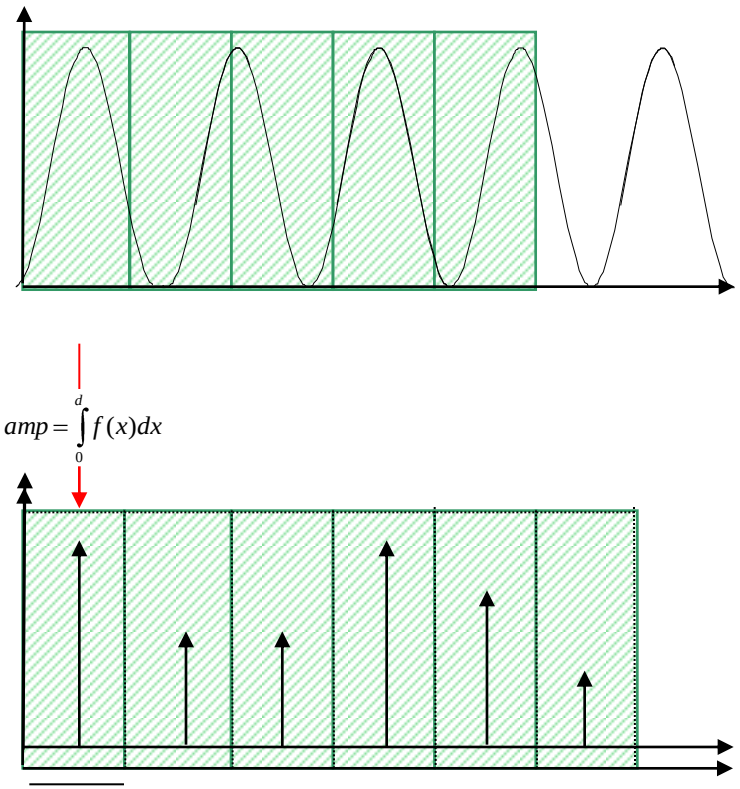
The width of p(x) is less than the delta function spacing of s(x)



The width of p(x) is equal to the delta function spacing of s(x)

Note: This equation does not represent what a CCD array actually "reports".

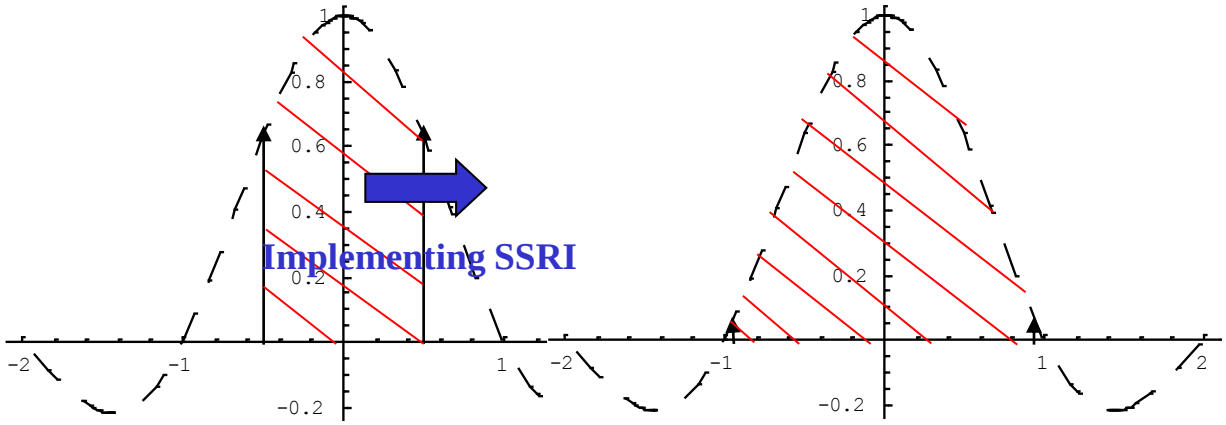
Sampling theory for interferometers



A linear CCD array will sample the function convolved with the pixel function at a spatial frequency defined by the pixel spacing.

Sampling theory for interferometers

If we assume that the pixel size equals the pixel spacing and we consider the function being sampled to contain all spatial frequencies, the resolvable frequencies can be described by the shaded region below:



Possible Solutions

- **High density CCD arrays**
- **Sub-aperture measurements and stitching methods**
- **Sub-pixel spatial resolution interferometry (SSRI)**
  - **Avoid high cost CCD arrays**
  - **Requires only small translations of the CCD detector or optic under test**

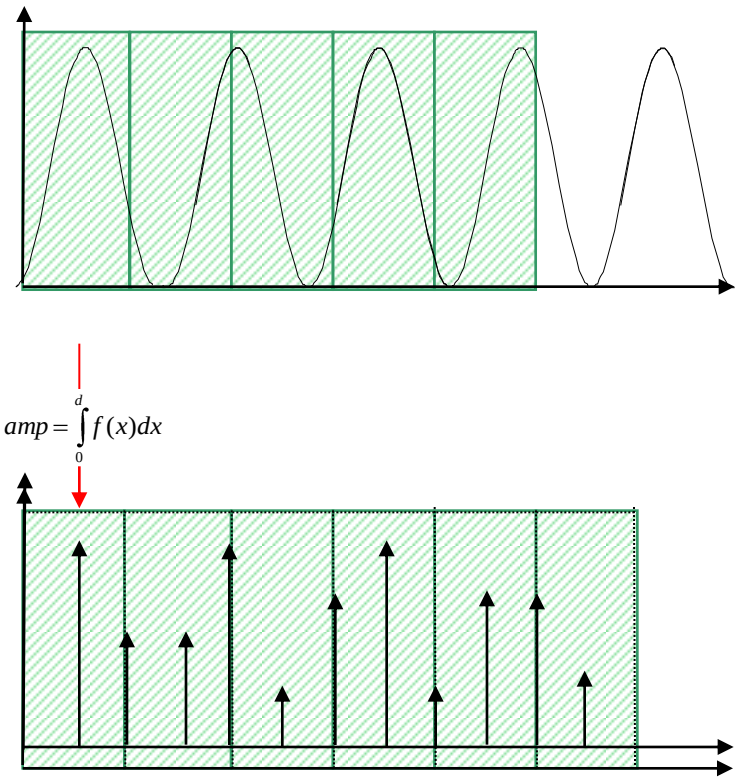
Sub-pixel spatial resolution interferometry

1. Perform multiple measurements with sub-pixel shifts of the CCD detector (or optic under test) between measurements.
2. Combine the measurements using an stitching and deconvolving algorithm.

This technique has been applied to imaging application such as the “jitter camera”*. This is the first attempt to implement the concept on interferometric measurements.

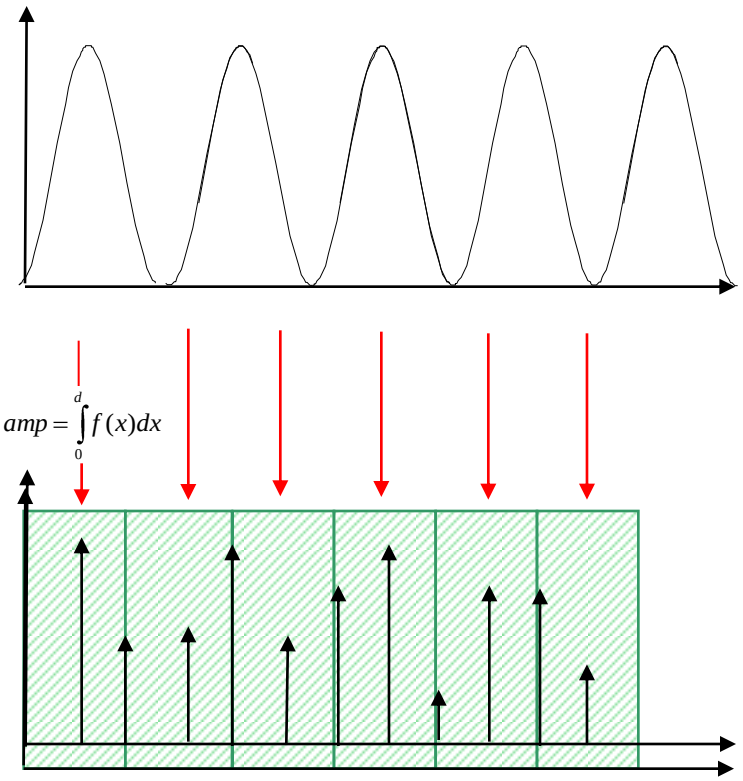
*M. Ben-Ezra, S.K. Nayar, "Jitter Camera: High Resolution Video from a Low Resolution Detector”, In Proc. of the IEEE Computer Vision and Pattern Recognition (CVPR), Washington DC, June 2004.

Sub-pixel spatial resolution interferometry



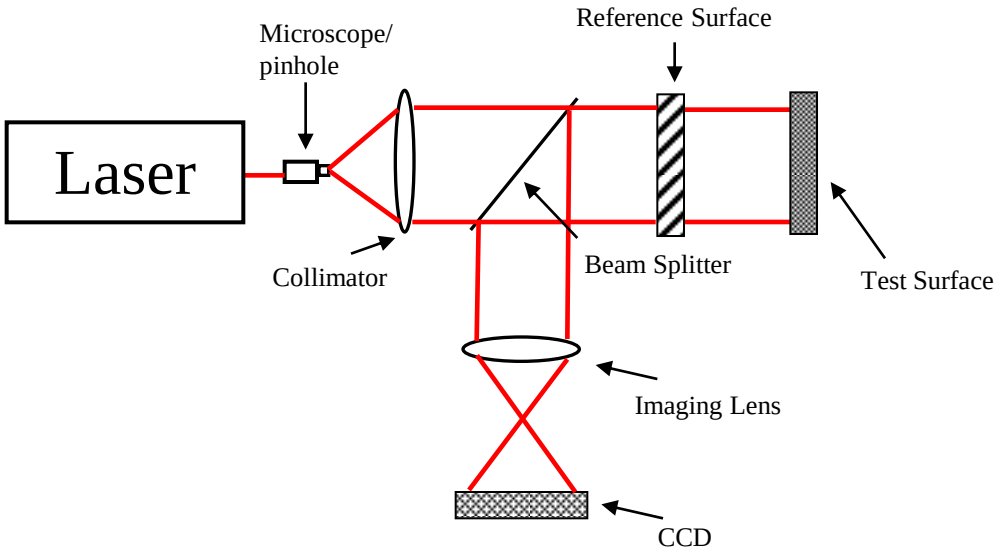
The pixel size does not necessarily define the sample spacing.

Sub-pixel spatial resolution interferometry



A half pixel shift can double the sampling of f(x)*p(x).

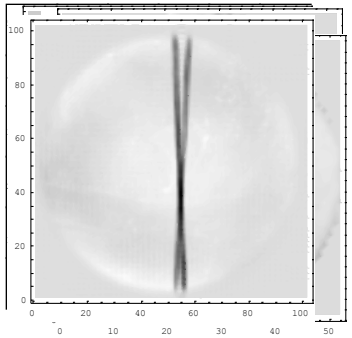
Sub-pixel spatial resolution interferometry



Simplified Fizeau Interferometer

Shifting can be performed on the CCD or the optic under test

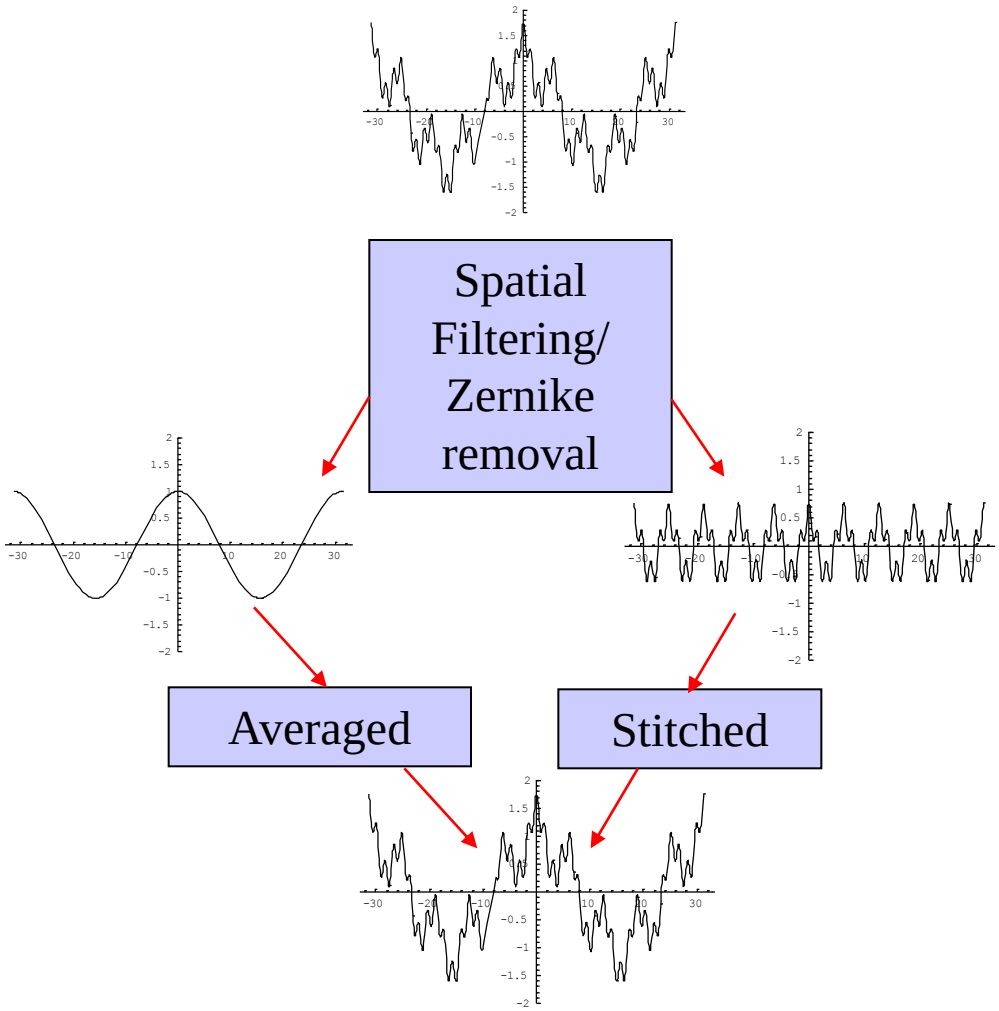
Sub-pixel spatial resolution interferometry



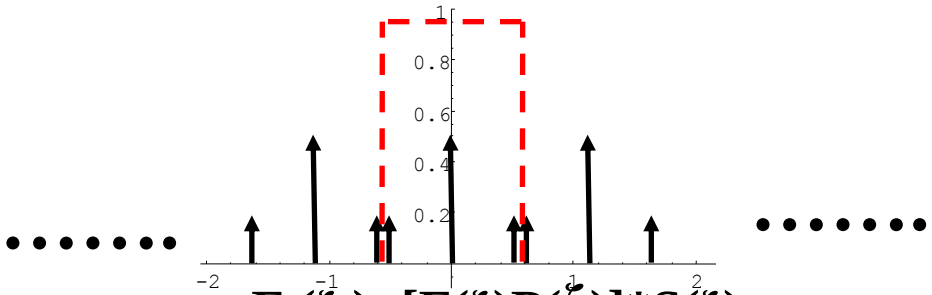
Data stitching

1. Raw data stitching (interlace stitching)
2. Pre-stitching spatial filtering
3. Pre-stitching low order Zernike removal
4. Averaging algorithm

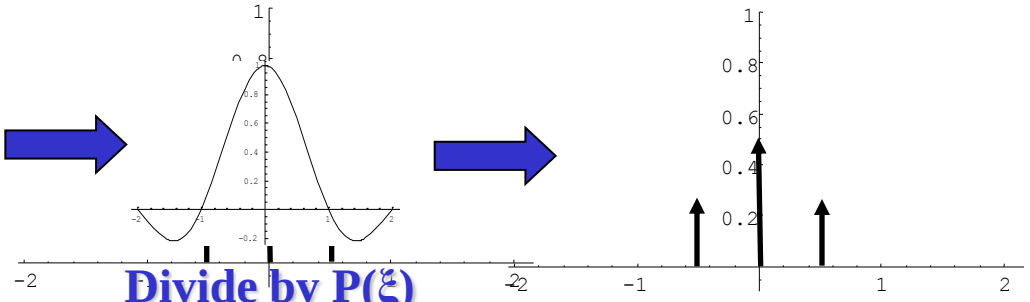
Pre-stitching spatial filtering/ Zernike removal



Pixel deconvolution



$$F_s(\xi) = [F(\xi)P(\xi)] * S(\xi)$$

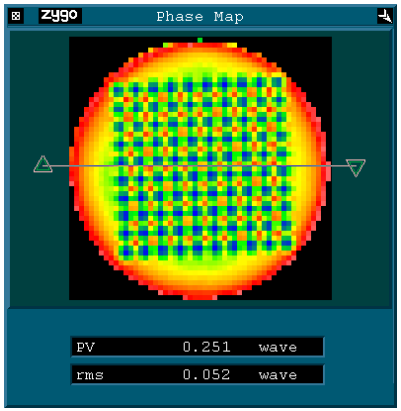


Divide by P(ξ)

$F(\xi)P(\xi)$ $F(\xi)$

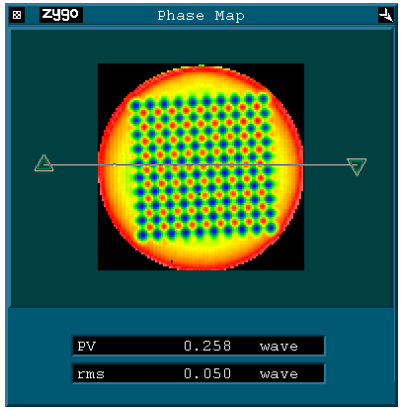
SSRI Results

A



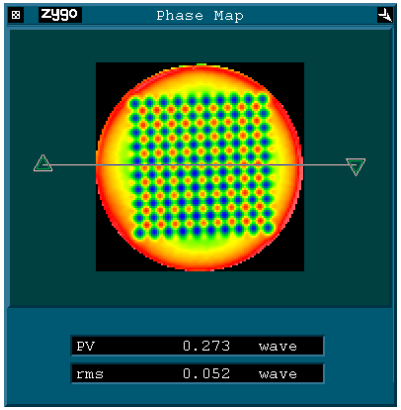
Low Resolution Measurement

B



Reconstructed "high" Resolution Measurement

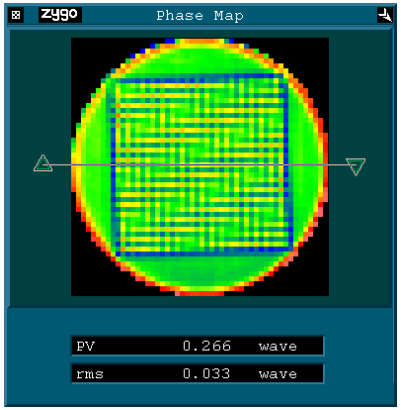
C



Measurement at twice the resolution of (a)

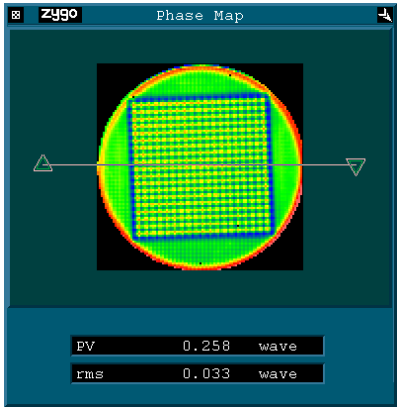
SSRI Results

A



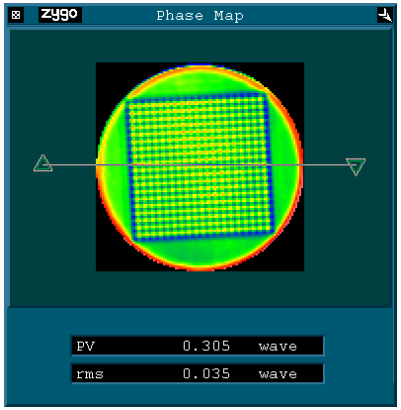
Low Resolution Measurement

B



Reconstructed "high" Resolution Measurement

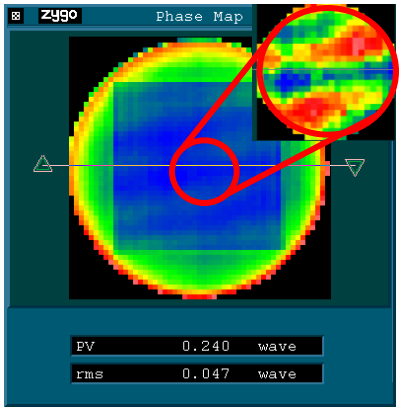
C



Measurement at twice the resolution of (a)

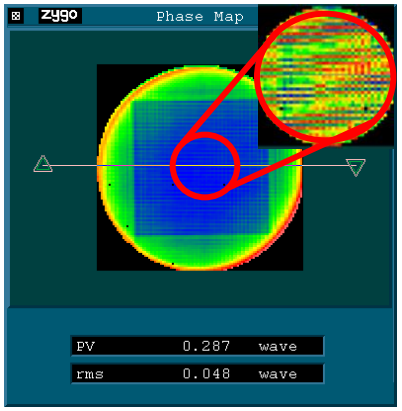
SSRI Results

A



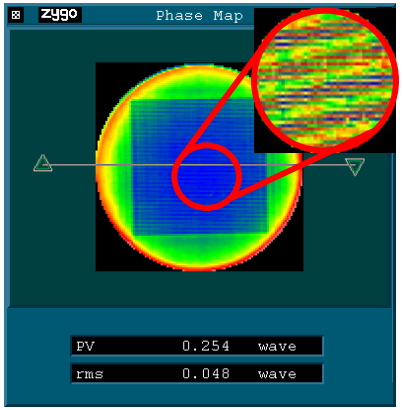
Low Resolution Measurement

B



Reconstructed "high" Resolution Measurement

C



Measurement at twice the resolution of (a)

Summary

- **The SSRI process has been developed to address a metrology "gap" created by:**
  - **Increased use of spatial frequency bands (including mid-spatial frequencies) for surface figure specifications**
  - **Need for larger aperture systems**
  - **New advances in optical manufacturing that allow the frequencies to be deterministically corrected.**
- **The SSRI was developed to increase the sampling limitation in interferometric measurements due to pixel spacing.**
- **The initial results obtained demonstrate the capability of the process to resolve aliasing issues due to under sampling.**