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Image Processing Techniques for Improving Imagery from Remote Sensing Imaging Systems

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Outline

- **Motivation**
- **Super-Resolution**
- **Phase Diversity**
- **Summary**

Motivation

- **The performance of an optical systems is always limited, regardless of how perfectly it is designed and built.**
- **Limitations come from**
  - Physics (i.e., diffraction)
  - The optical design itself
  - Imperfections in alignment and assembly
  - Trades made during system design
  - Detector performance
- **Modern advancements in algorithms and computational power allow image processing techniques to mitigate these effects.**
- **Today I will present two classes of algorithms used for this purpose.**

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Sampling Theory

- **For an incoherent imaging system, the highest spatial frequency that can be transmitted is**

$$v_{opt} = \frac{1}{\lambda f^{\#}}$$ **where** λ: Optical wavelength; $f^{\#}$: f/number of the optical system (focal length divided by aperture diameter)

- **Spatial frequencies above v_{opt} are not transmitted by the optical system.**
- **The highest spatial frequency that can be sensed by the detector is**

$$v_{det} = \frac{1}{2p}$$ **where** p: Detector pixel pitch

  - Spatial frequencies above v_{det} are aliased back to lower frequencies.
- **When these two frequencies are equal we have**

$$\frac{\lambda f^{\#}}{p} = 2$$

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Sampling Theory

- **Define the sampling ratio Q as $Q \equiv \frac{\lambda f^{\#}}{p}$.**
- **When $Q \geq 2$ the system is Nyquist-sampled.**
  - The pixel pitch is small enough that all of the spatial frequencies up to the optical cutoff frequency are sensed without aliasing.
  - For a diffraction-limited Airy disk, there are at least 2.44 pixels across the first-null diameter.
  - The resolution of the system is limited by diffraction.
- **When $Q < 2$ the system is undersampled.**
  - The pixel pitch is relatively large compared to the optical spot. Spatial frequencies below the optical cutoff frequency and above the detector cutoff frequency are aliased.
  - The resolution of the system is limited by the pixel pitch.

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Undersampled Systems

- **Why not always design a system such that it is Nyquist sampled?**
- **Q depends on the focal length, aperture diameter, and pixel pitch. These parameters effect many other decisions in a trade study.**
- **For example, the pixel pitch directly impacts the field-of-view (FOV).**
  - Using smaller pixels but maintaining the same FOV requires more pixels.
    - Data processing needs will increase.
    - Power consumption will go up.
    - Data bandwidth needs will increase.
  - Using smaller pixels but maintaining the number of pixels reduces FOV.
- **Smaller Q values produce more energy on a single pixel.**
  - Increases signal-to-noise ratio.
  - Reduces integration time and hence motion-blur.
- **Smaller Q values often produce higher quality images despite the effects of aliasing[†].**

[†] R. D. Fiete, "Image quality and $\lambda FN/p$ for remote sensing systems," Opt Eng **38**, 1229-1240 (1999).

Examples of Undersampled Systems

- Consider the panchromatic bands of the following systems (designed to span a wavelength range of 0.45 μm to 0.90 μm.

Name	Focal Length (m)	Aperture Diameter (m)	Pixel Pitch (μm)	Q Range
Ikonos 2	10	0.70	12	0.54 to 1.07
Quickbird 2	8.8	0.60	12	0.55 to 1.10
GeoEye 1	13.3	1.10	8	0.45 to 0.91

Source: www.eoportal.org

- These systems are all considerably undersampled and would have improved resolution if Q were increased to 2. Other system trades impact the decision.
- There may be times when improved resolution is desired.

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Super-Resolution Imaging

- **Super-resolution techniques allow the sampling ratio Q to be effectively increased.**
- **Super-resolution refers to using a number of low-resolution images to create a single high-resolution image.**
  - The low-resolution images are usually laterally displaced by sub-pixel amounts.
  - Super-resolution algorithms have been implemented which use precise axial shifts.
    - Such algorithms are generally impractical in deployed systems due to vibrations and variations in the line-of-sight pointing angle.
- **Park, Park, and Kang have written an excellent overview article on super-resolution techniques[†].**

[†] S. C. Park, M. K. Park, and M. G. Kang, "Super-resolution image reconstruction: A technical overview," IEEE Signal Proc Mag **20**, 21-36 (2003).

Drizzle

- One commonly used super-resolution algorithm is Drizzle†.
- It was developed by Fruchter and Hook for use with the Hubble Space Telescope.

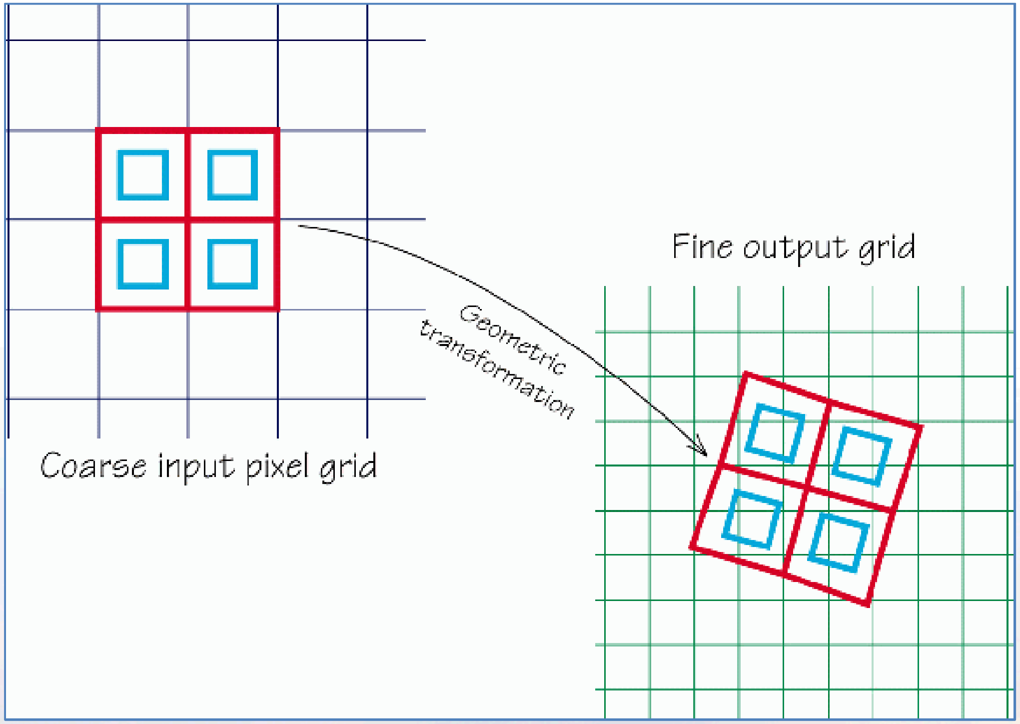
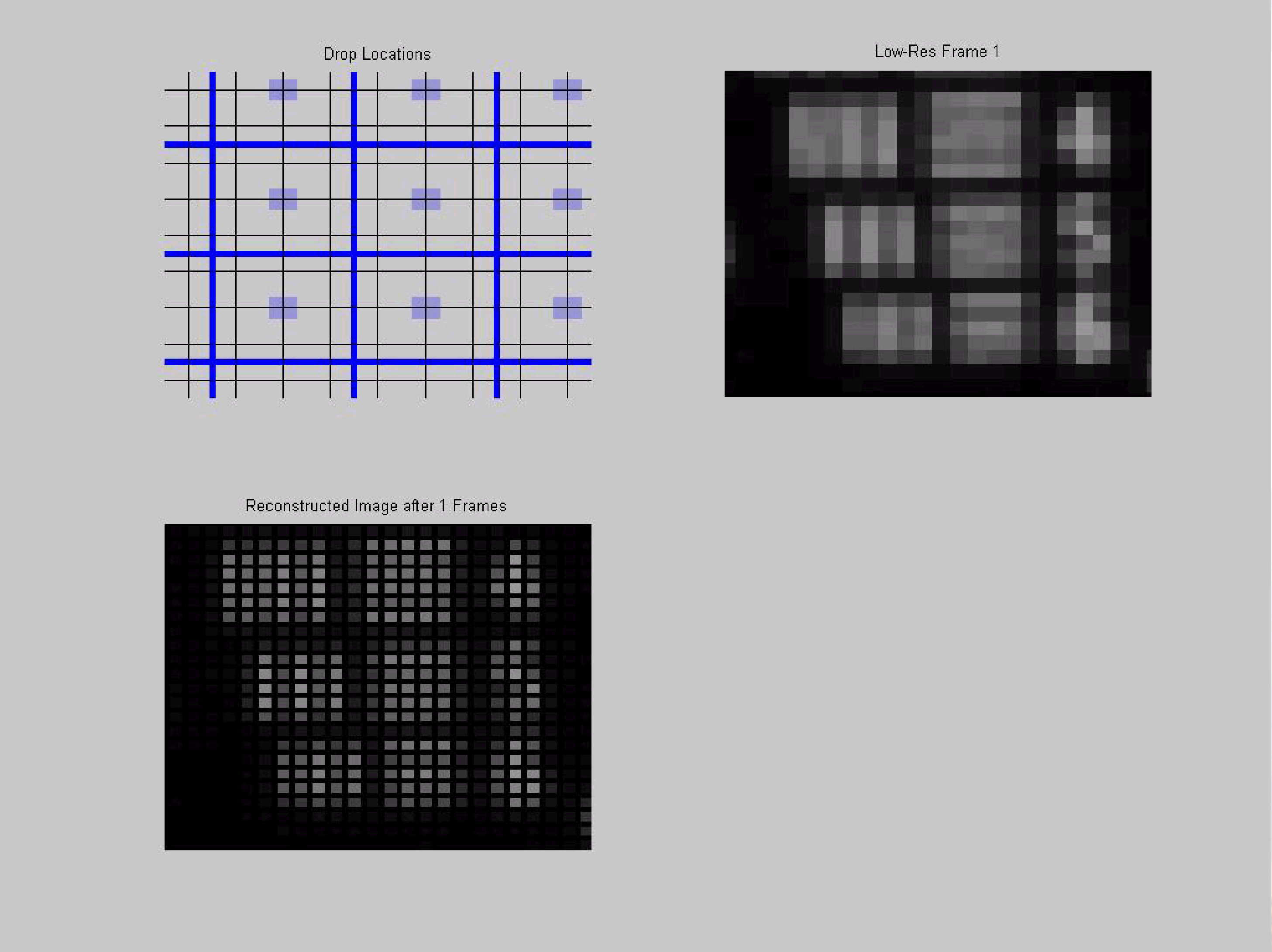


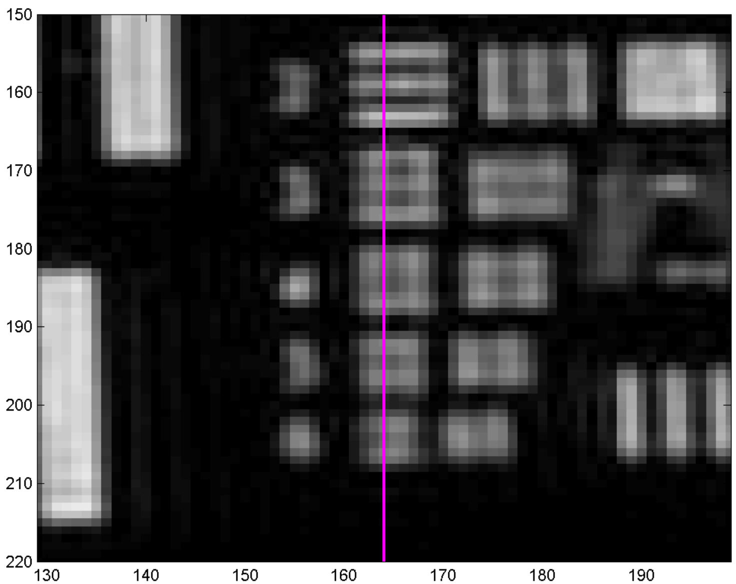
Image from http://www.stsci.edu/~fruchter/dither/drizzle.html

† A. S. Fruchter and R. N. Hook, "A novel image reconstruction method applied to deep Hubble Space Telescope images," Proc SPIE **3164**, 120-125 (1997).

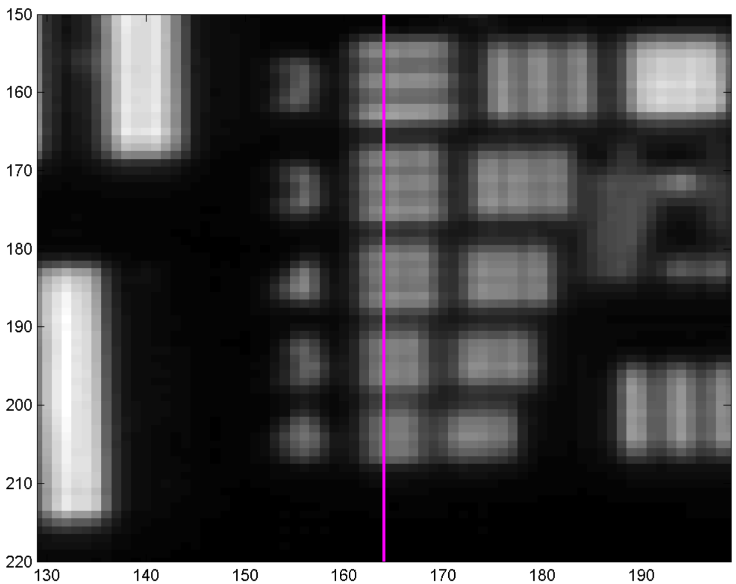
Drizzle Simulation



Drizzle Simulation

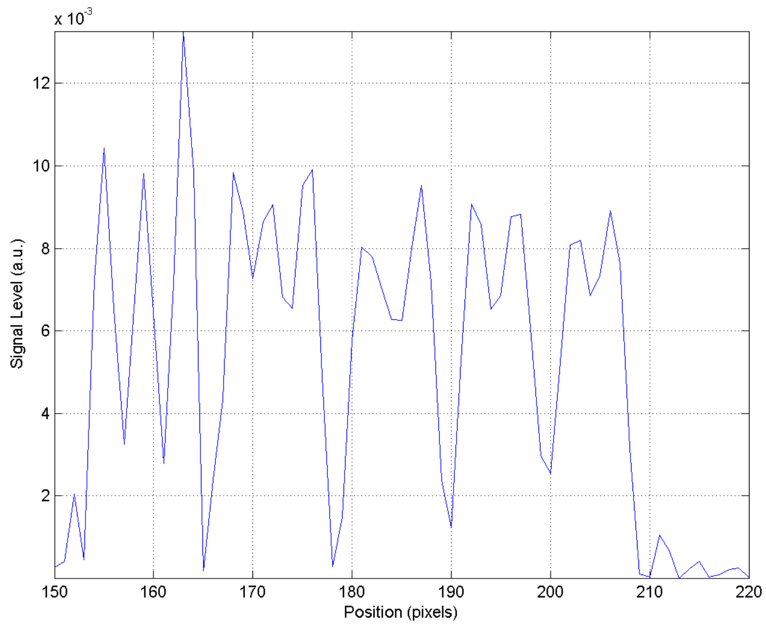


Reconstructed Image

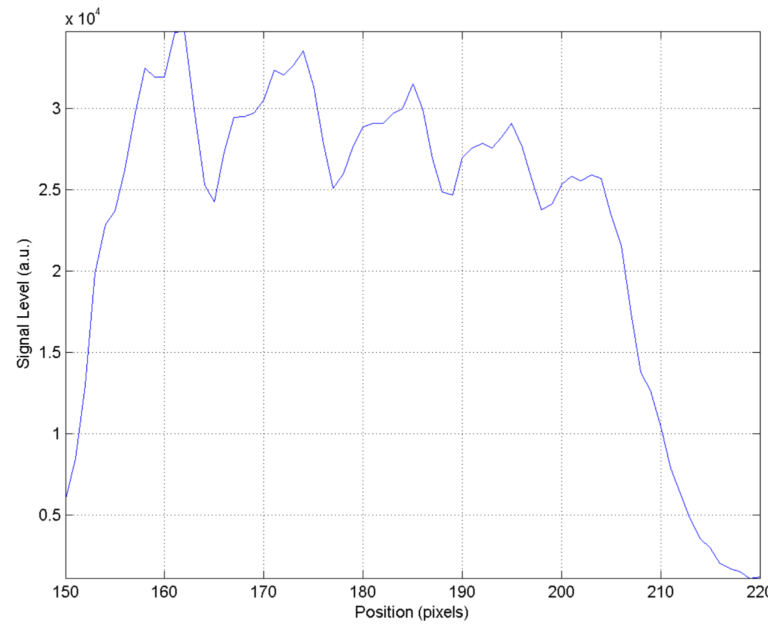


Best Focus Measurement

Drizzle Simulation – Slices



Reconstructed Image



Best Focus Measurement

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Outline

- **Motivation**
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- **Phase Diversity**
- **Summary**

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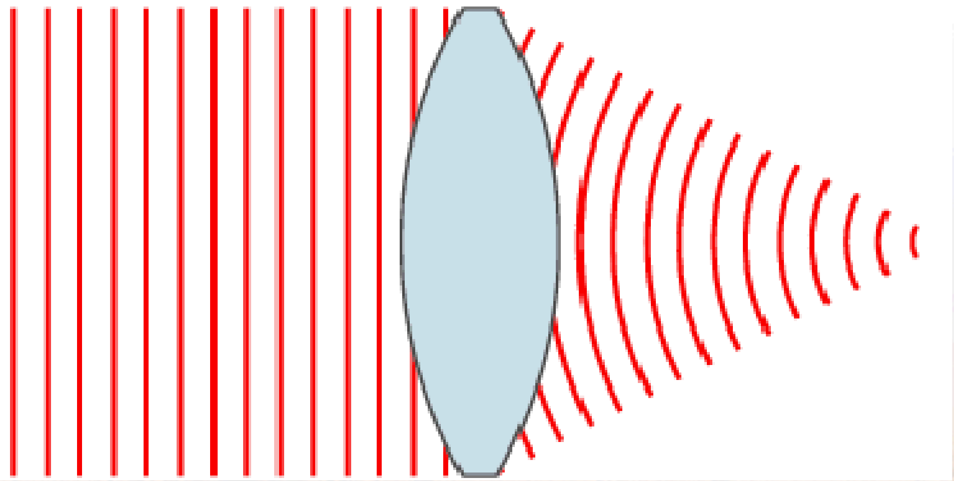
Optical Wavefront

- Wavefront is an important concept in optical engineering.
- A wavefront is a surface of points having the same phase for a propagating optical wave.
- Optical engineers often talk about wavefront error – the deviation of the wavefront from an ideal shape (usually planar or spherical).
- Wavefront error, also known as aberration, is usually measured with an interferometer.

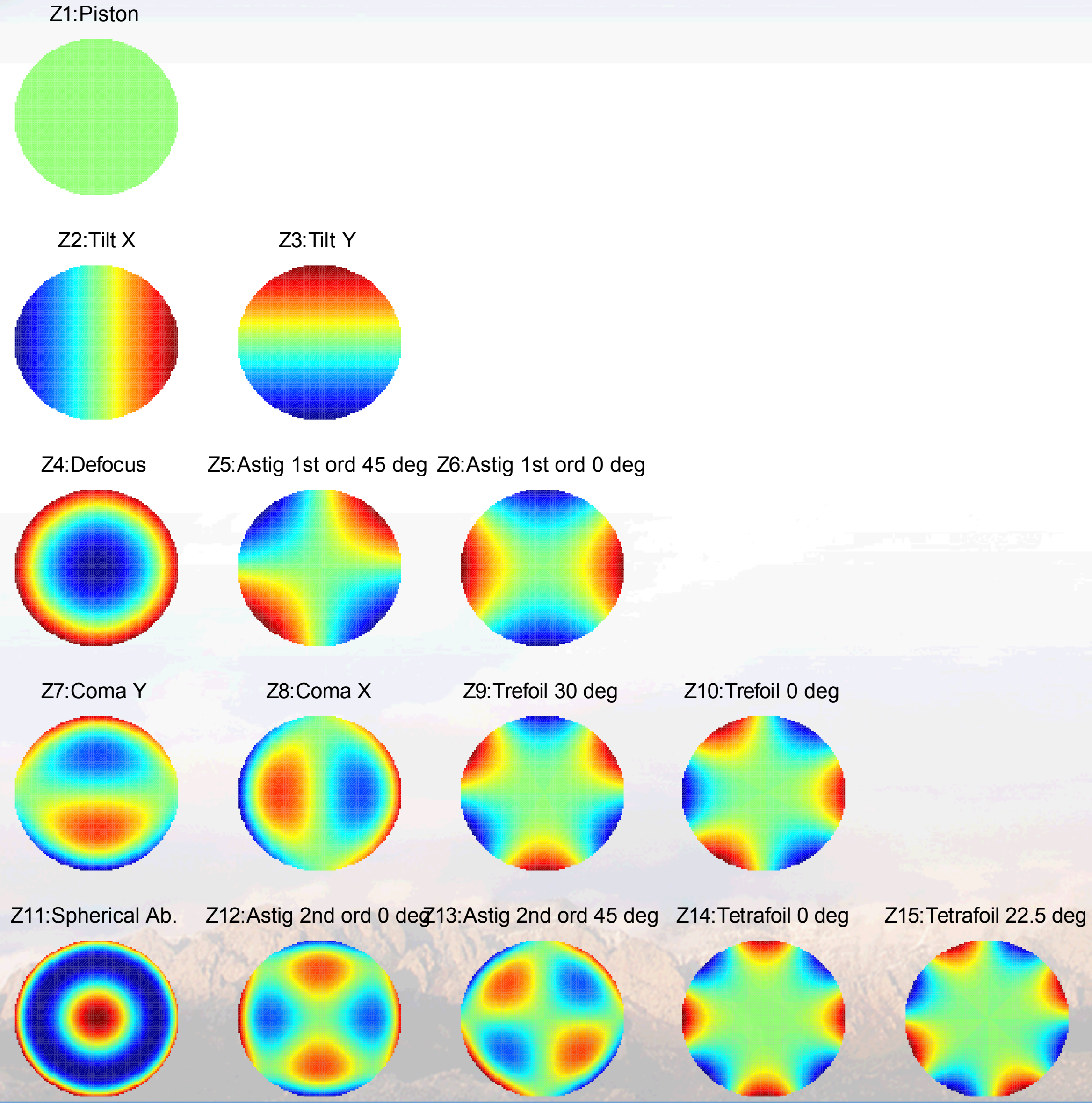


Video from https://en.wikipedia.org/wiki/Wavefront

Wavefront Error

- **Why is wavefront error useful?**
- **Wavefront error is the phase of the complex field amplitude at the pupil plane of an optical system.**
  - We generally know the magnitude of this complex field amplitude – it is simply unity wherever light is transmitted and zero where it is blocked.
- **The optical transfer function (OTF), which fully specifies the system performance at a particular wavelength and field angle, is equal to the autocorrelation of the complex pupil function.**
- **Thus if we know the wavefront error, we can fully model the performance of the optical system.**
- **For example, the image of an ideal point object is given by the square of the magnitude of the Fourier transform of the complex pupil function.**
- **Understanding wavefront errors is the basis of modern optical engineering.**

Common Aberrations



Interferometry

- **Wavefront errors are generally measured interferometrically.**
- **Interferometry can be a difficult measurement.**
  - You need an interferometer whose laser works for your system.
  - Vibrations may need to be very well controlled.
  - Interferometry generally requires a double-pass configuration – light must pass through the optical system twice so that it can return to the interferometer. Thus a precise, well-aligned return mirror is needed.
- **For an imaging system, once the detector is installed interferometric testing of the system cannot be performed.**
  - Any changes in optical performance are difficult to characterize or understand.
- **Other techniques for measuring wavefront do exist.**

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Phase Diversity

- **(U) Phase diversity (PD) algorithms allow the system wavefront to be reconstructed from two or more measurements made at different defocus depths.**
  - (U) If the scene is a point source, the algorithm is referred to as phase-diverse phase retrieval (PDPR).
  - (U) For extended scenes, phase diversity algorithms also provide an estimate of the scene as if the wavefront were perfect (i.e., diffraction-limited).
- **(U) Phase diversity can be used to**
  - Characterize an optical system so its performance can be better understood, tracked, and accurately modeled.
  - Improve system resolution by both characterizing system aberrations and removing their effects from imagery

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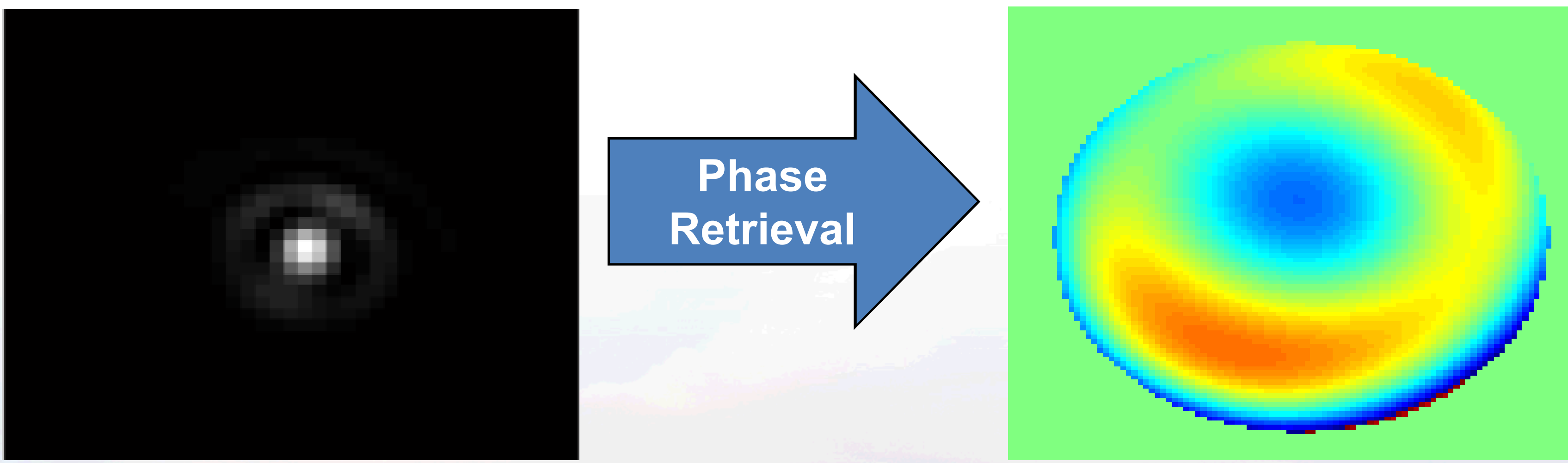
Phase Retrieval

- Phase retrieval refers to an algorithm that uses a measured spot to reconstruct the system wavefront error.
- Convergence and accuracy can be issues when using a single measurement.



Measured Spot

Wavefront Error

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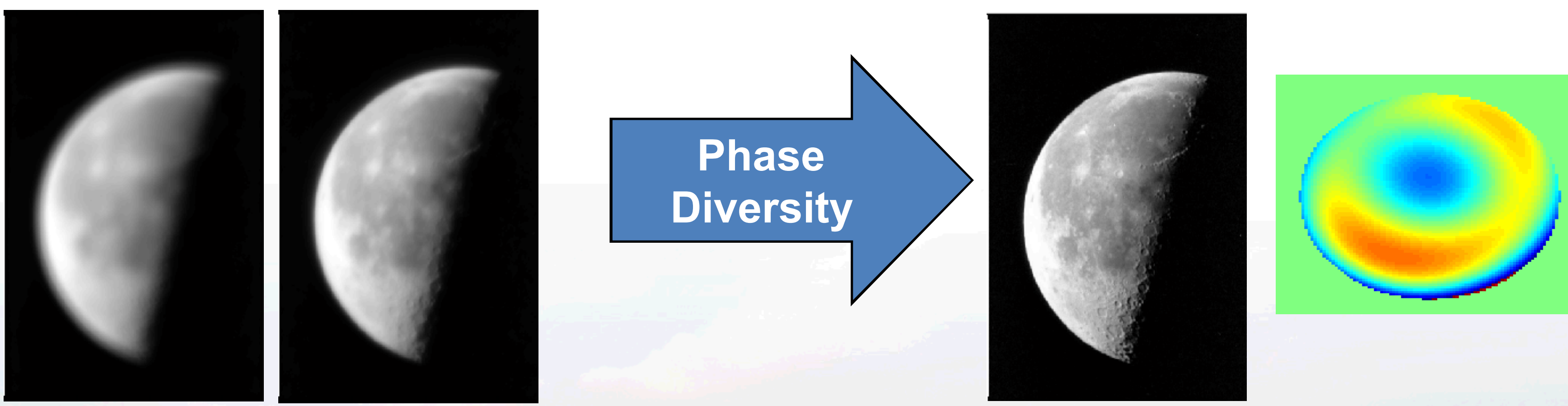
Phase Diversity

- Phase diversity refers to an algorithm that uses measured images at different defocus values to reconstruct both the scene and the wavefront.
- Measurements can be made at two or more defocus depths.

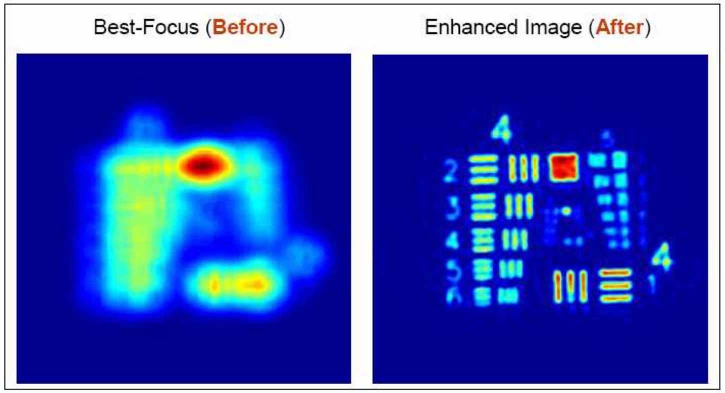


Measured Images

Scene and Wavefront Error

Applications

- **(U) In the early 1990s, phase retrieval was applied to images taken with the Hubble Space Telescope.**
  - The aberration content of the system was determined.
  - A misalignment of the Planetary Camera 6 (PC-6) subsystem relative to the main optical telescope was found.
- **(U) Phase diversity algorithms will be used to perform fine adjustment of the segmented mirrors in the James Webb Space Telescope.**
- **(U) Phase diversity is commonly used to perform real-time correction of optical systems that incorporate adaptive optical components.**
  - Boeing has demonstrated a system capable of reconstructing wavefront errors at 200 frames per second.†



† Dolne, J.J. et al, Proc. of SPIE, Vol 6712 (2007)

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Algorithms

- **Several algorithms for phase diversity and phase retrieval exist.**
- **All are essentially nonlinear optimization problems:**
  - Define an error metric based on predicted and measured images.
  - Define variables.
    - Wavefront (point-by-point phase or Zernike coefficients)
    - Lateral shifts (i.e., registration)
    - Axial shifts
    - Pupil amplitude
  - Search for variables which minimize the error metric.
  - More *a priori* knowledge is better.
- **Assumptions**
  - Light is monochromatic.
  - Extended scenes are narrow so wavefront error does not change as a function of field.
  - Appropriate sampling, $Q \geq 1$.
  - If $2 > Q \geq 1$, aliasing artifacts may impact the reconstruction.

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Benefits

- **Wavefront errors can be measured much later in integration and during operational use.**
  - Interferometric methods are not possible once focal planes are installed.
- **Wavefront errors can be measured at any wavelength where a source and filter are available.**
  - Interferometry is limited to laser lines of available tools.
- **Wavefront errors can be measured from images of extended scenes with phase-diverse phase retrieval.**
  - Improved image quality is possible.
  - No point object is needed.

Phase Diversity for Undersampled Systems

- **Algorithms exist for implementing phase diversity on undersampled systems, but they have limitations:**
  - Restricted to point objects[1]
  - Restricted to point objects and requires subaperture scanning[2]
  - Works with extended scenes but is intolerant to line-of-sight jitter[3]
- **An algorithm that works with extended scenes in a deployed environment is needed.**

[1] S. T. Thurman and J. R. Fienup, J Opt Soc Am A **26**, 2640-2647 (2009).
[2] G. R. Brady, M. Guizar-Sicairos, and J. R. Fienup, Opt Express **17**, 624-639 (2009).
[3] X. J. Hu, S. Y. Li, and Y. L. Wu, Appl Optics **47**, 6079-6087 (2008).

New Algorithm for PD with Undersampled Systems

- **The Drizzle algorithm is used for super-resolution at each defocus depth.**
  - Low-resolution images are used to create a single high-resolution image.
  - Effects of pixel size and algorithm “pixfrac” parameter are deconvolved from measured data.
- **Two phase-diversity algorithms are used on super-resolved data.**
  - PD1: S. T. Thurman, R. T. DeRosa, and J. R. Fienup, J Opt Soc Am A **26**, 700-709 (2009).
  - PD2: R. G. Paxman, T. J. Schulz, and J. R. Fienup, J Opt Soc Am A **9**, 1072-1085 (1992).
- **PD2 is modified to optimize lateral shifts of each measured image.**
- **Results are presented here for PD2 with an extended scene.**
- **PD1 assumes a point object.**
  - Results are presented in the literature[1-3].

[1] E. A. Shields, *Opt Lett* **37**, 2463-2465 (2012).
[2] E. A. Shields, *Computational Optical Sensing and Imaging*, OSA Technical Digest (online) paper CTu2B.4 (2012).
[3] E. A. Shields, *Proc. of SPIE,* Vol 8499 *(2012).*

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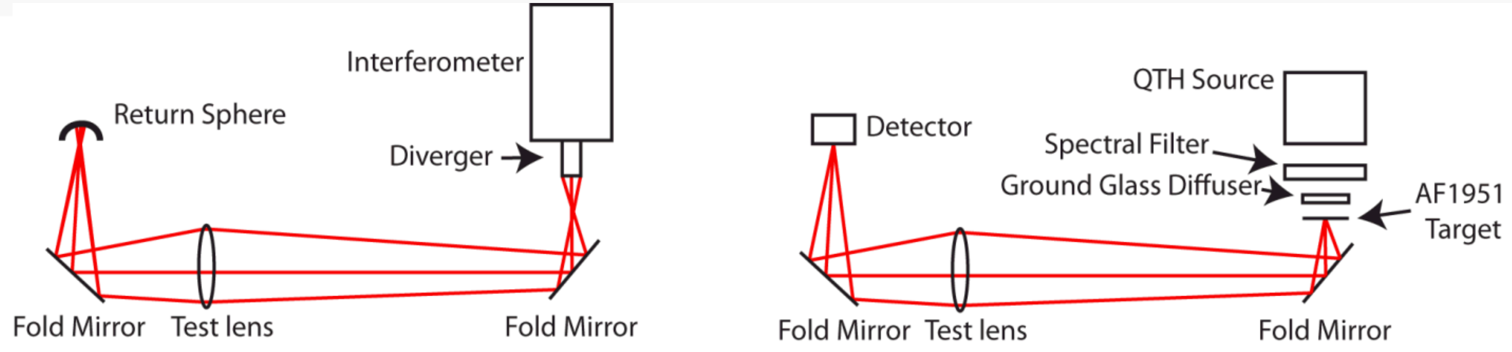
Extended Scene Configuration



Interferometric Configuration

Phase Diversity Configuration

- **The phase diversity configuration uses a filtered quartz-tungsten-halogen (QTH) source to mitigate speckle.**
- **A ground glass diffuser is used to improve scene uniformity.**
- **The extended scene is an Air Force 1951 resolution target.**
- **The detector is mounted on stages allowing lateral motion in all three directions.**

Experimental Test Parameters

- **20 single-shot wavefronts were collected, averaged, and fit to 15 Zernike polynomials[†].**
- **Wavelength:**
  - Interferometry: 632.8 nm
  - Phase Diversity: 650 nm center wavelength with bandwidth of 40 nm
- **Aperture Diameter: 1.6 inches**
- **Focal Ratio: f/16**
- **Defocus depths of -1, 0, +1 mm (defocus Zernike coefficients[†] of -0.22, 0, +0.22 waves)**
  - Peak-to-valley defocus errors are 0.76, 0, and 0.76 waves.

[†]R. J. Noll, "Zernike Polynomials and Atmospheric-Turbulence," J Opt Soc Am **66**, 207-211 (1976).

Extended Scene Parameters

- **Data were collected in two modes: Nyquist-sampled and undersampled.**
- **Comparisons of the two reconstructions provides information on the impact of the super-resolution pre-processing step.**

Parameter	Nyquist-Sampled Case	Undersampled Case
Frames per defocus depth	1	64 (spatially jittered)
Pixel Pitch	3.45 µm	13.8 µm
Sampling Ratio Q	3.0	0.75
Super-Resolution Factor	N/A	3

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Extended Scene Scanning

- The camera is scanned laterally at each defocus depth for the undersampled case.
- Image registration via cross-correlation is used to align images.
- The following plot shows calculated image locations for the 64 frames at best focus.

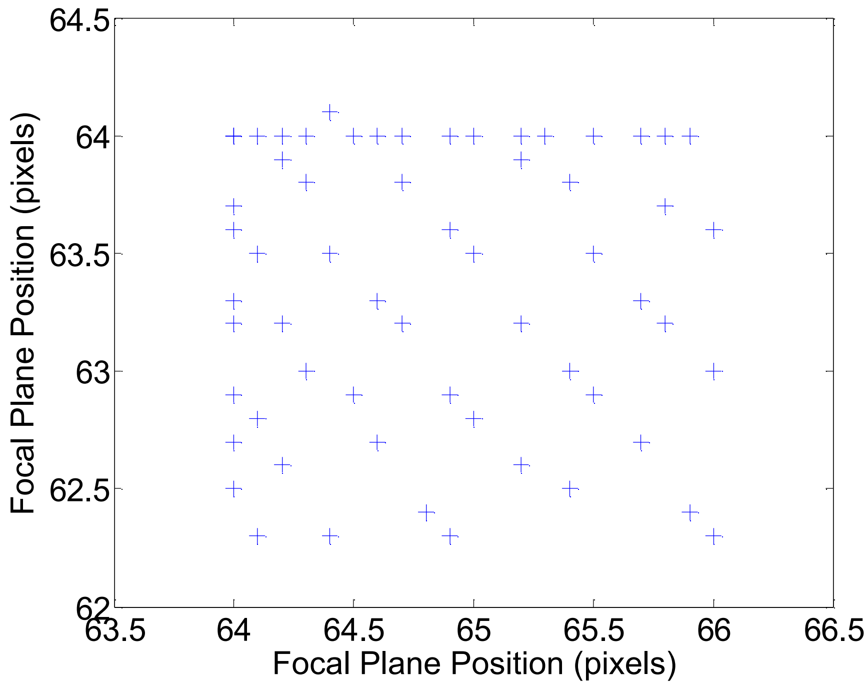
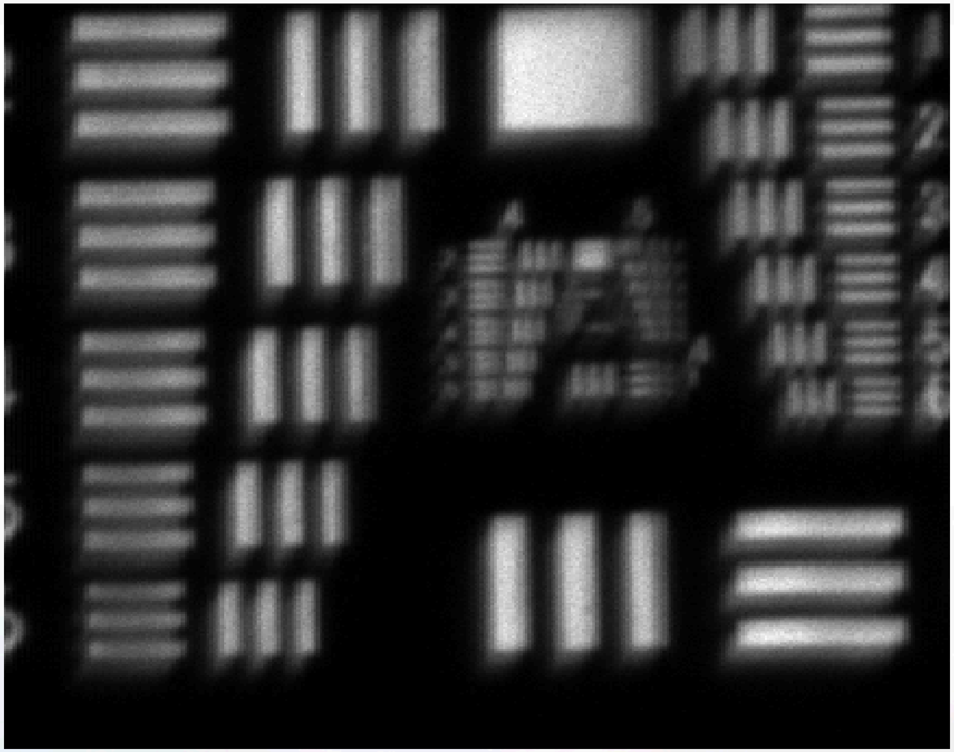
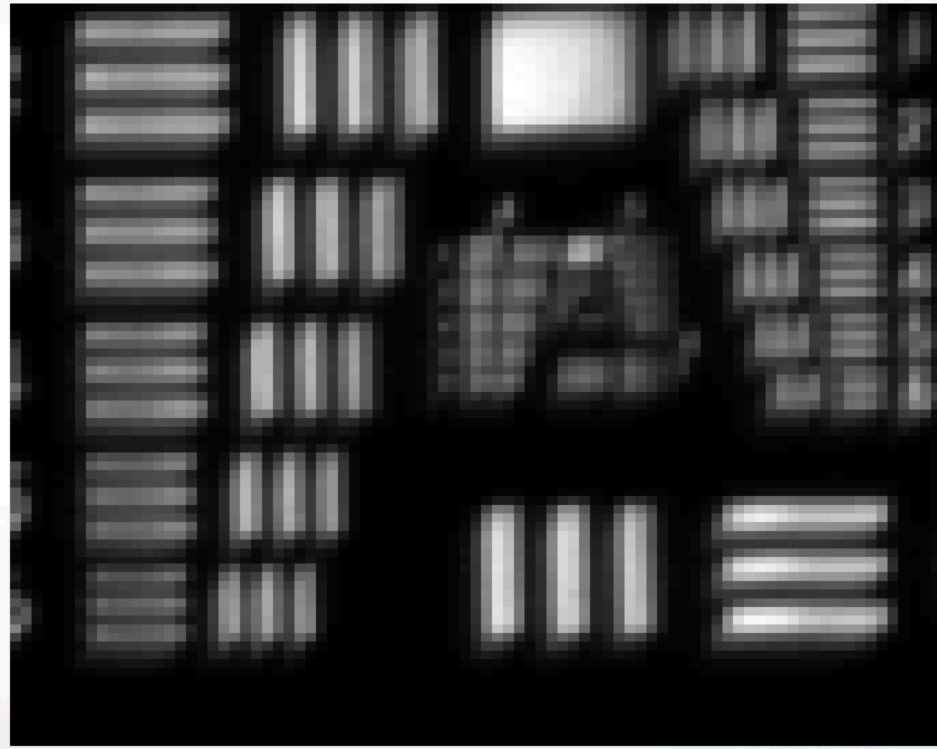


Image Locations at Best Focus

Sample Scenes at Best Focus

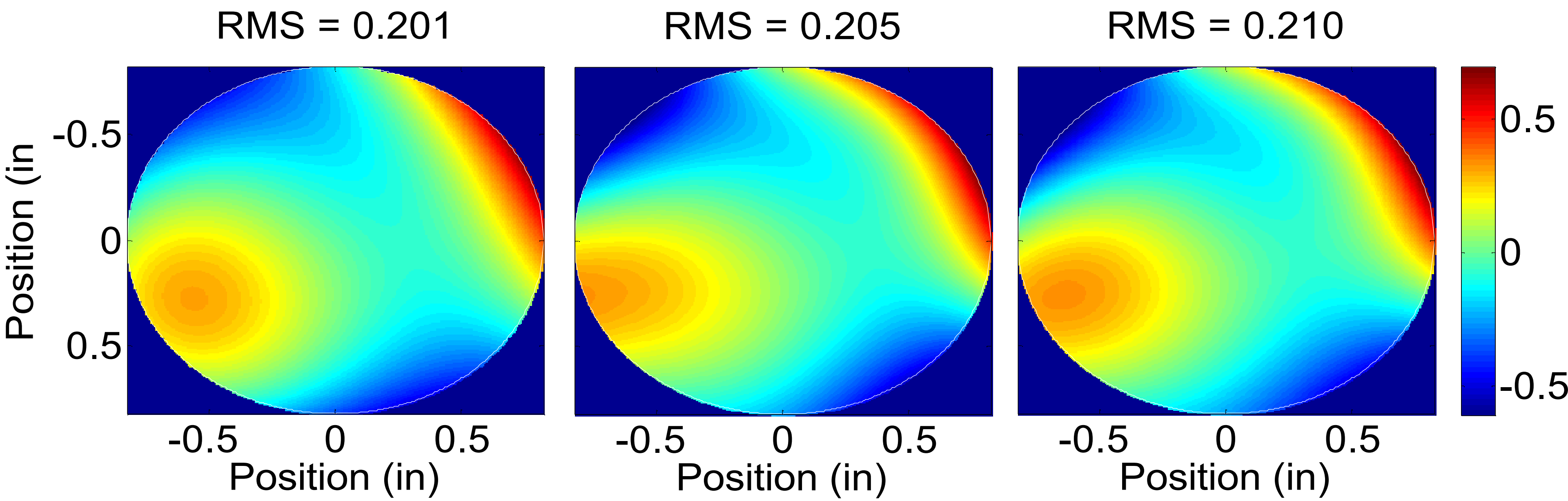


Nyquist-Sampled Scene



Undersampled Scene

Wavefront Results



Interferometric Measurement

Nyquist-Sampled Reconstruction

Undersampled Reconstruction

- **Wavefronts and root-mean-square (RMS) values are shown in waves.**
- **The reconstructed wavefronts agree well with the interferometric measurement.**

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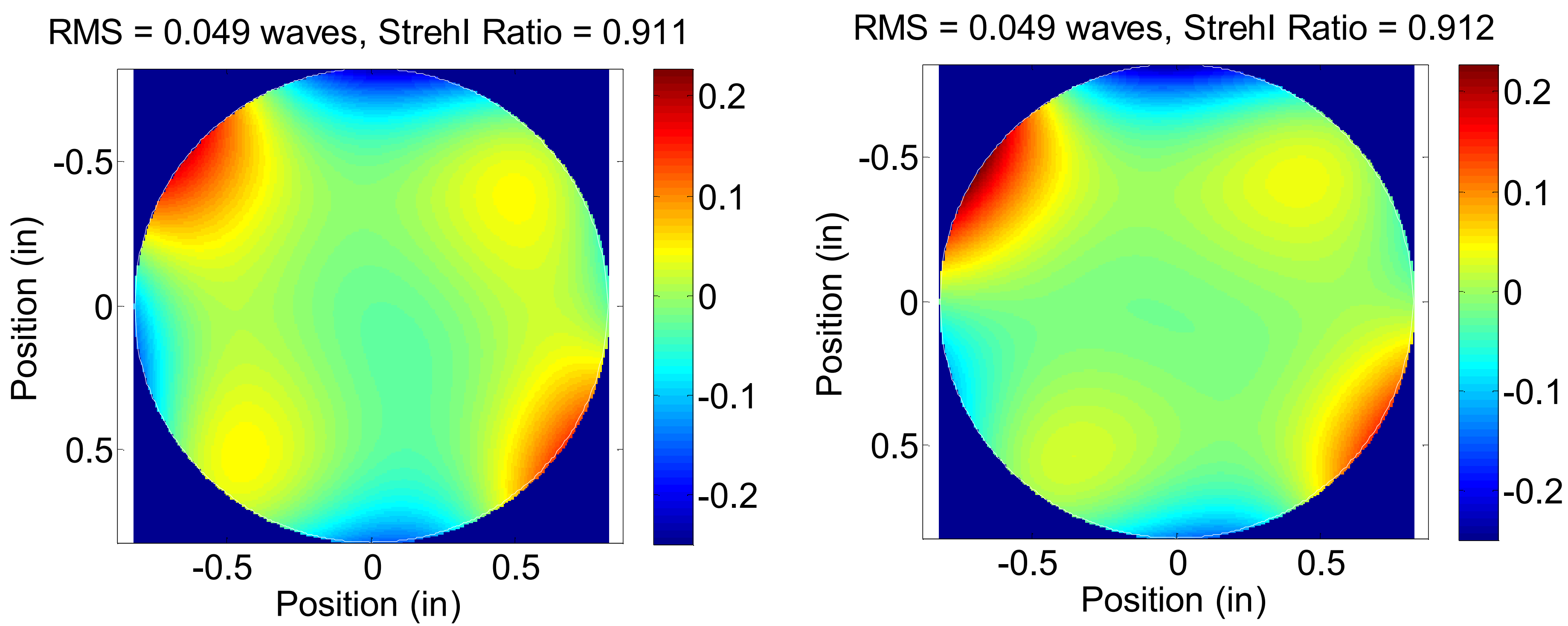
Difference Wavefronts



Nyquist-Sampled Difference Wavefront **Undersampled Difference Wavefront**

- **The RMS errors of the difference wavefronts are lower than $\lambda/20$, demonstrating good agreement.**
- **Reconstruction errors are inline with those in the literature for this magnitude of wavefront error†.**

†J. J. Dolne et al, Appl Optics **42**, 5284-5289 (2003).

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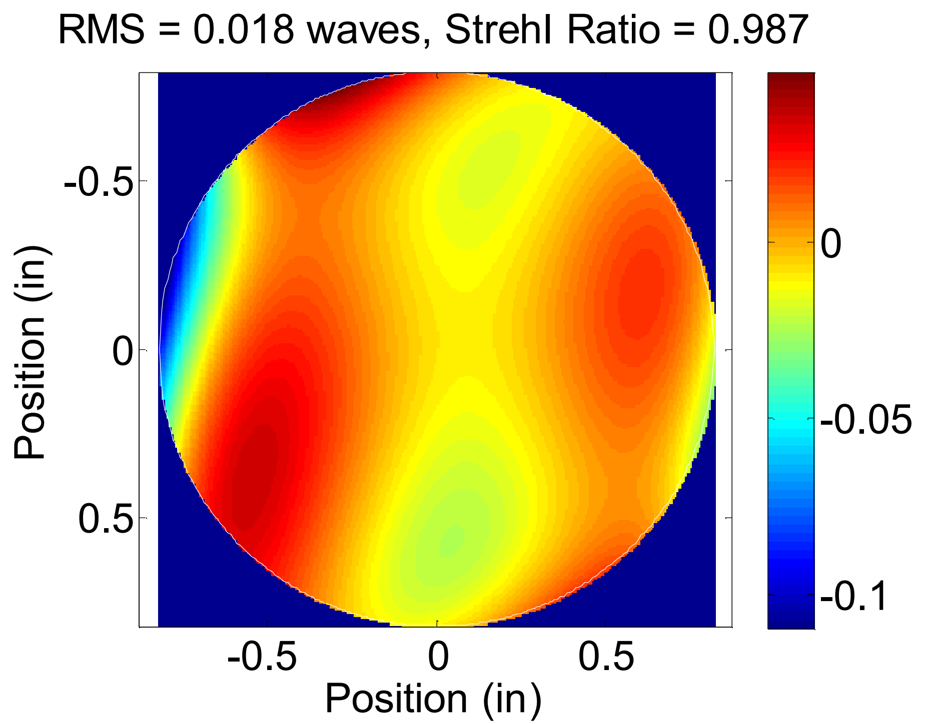
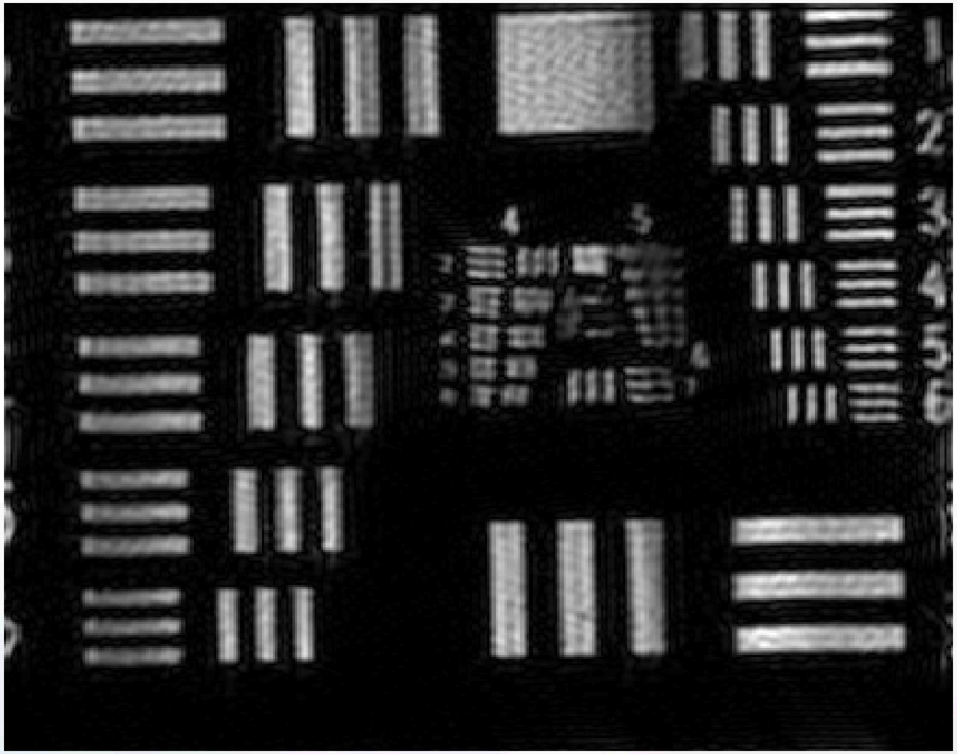
Impact of Super-Resolution Pre-Processing

- The difference between the reconstructed wavefronts is shown.
- This characterizes the impact of the super-resolution pre-processing.
- The reconstructions agree to better than λ/50, demonstrating excellent agreement.

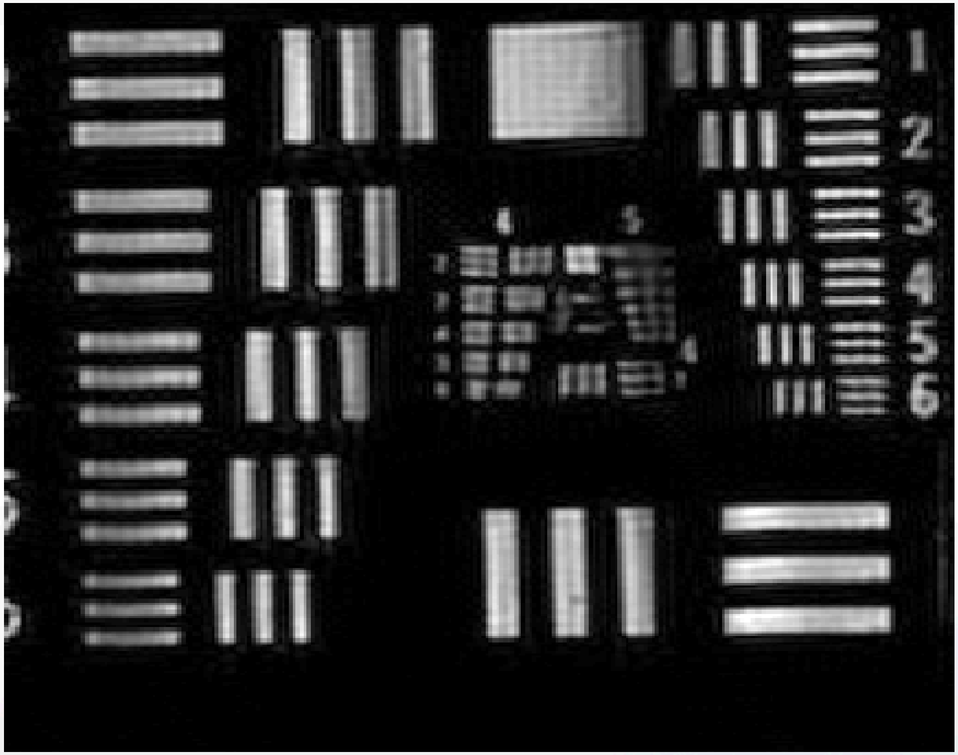


Difference between Reconstructed Wavefronts

Reconstructed Scenes

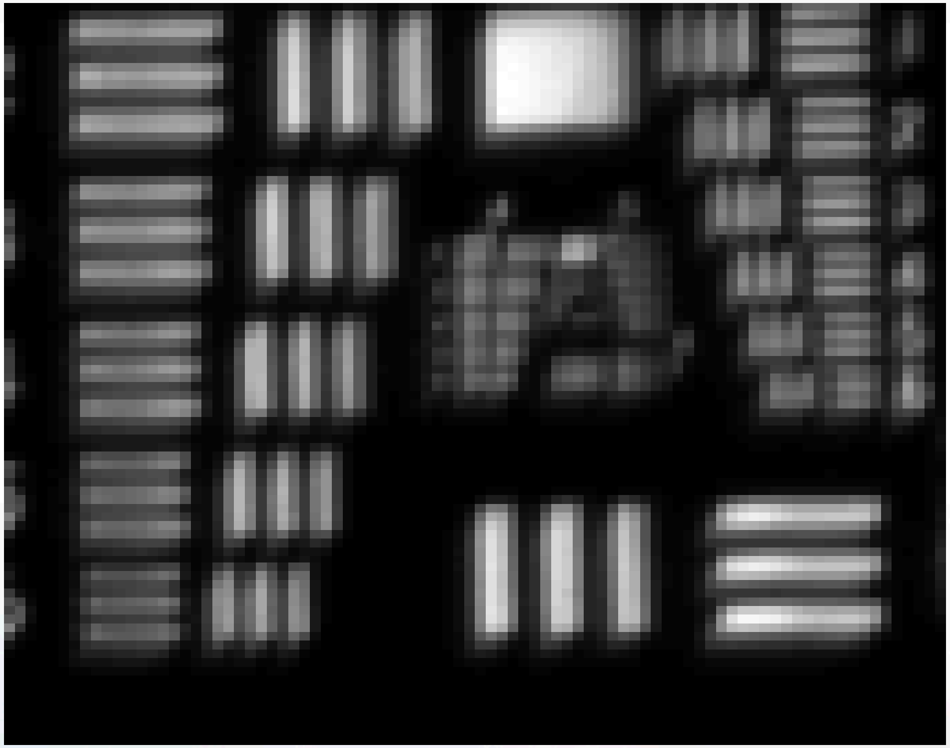


Reconstruction from Nyquist-Sampled Measurements

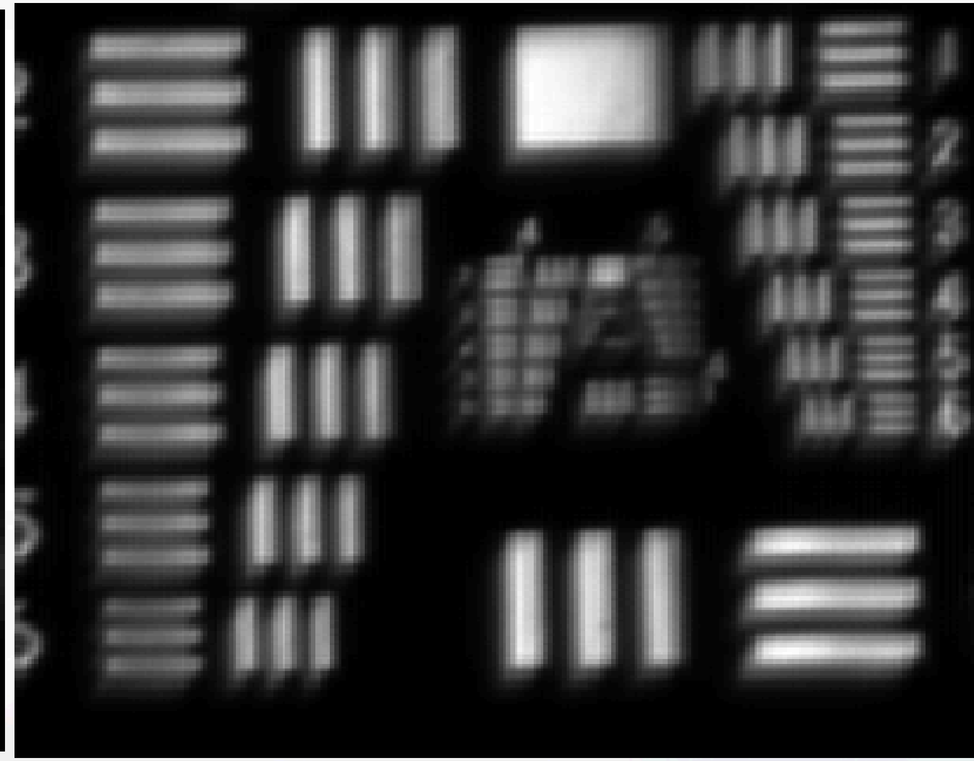


Reconstruction from Undersampled Measurements

Reconstructed Scenes



Single Undersampled Scene



Phase Diversity Reconstruction
Drizzle Only

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Summary

- **Many remote sensing imaging systems are designed such that the pixels are relatively large compared to the size of the optical spot.**
  - Such systems are called undersampled.
  - The resolution of undersampled systems is limited by the pixel size.
  - Aliasing artifacts may be present in undersampled systems since the optical system transmits spatial frequencies that exceed what the detector can measure.
- **Super-resolution techniques can be used to improve the spatial sampling.**
  - Increased resolution is not free. Costs include:
    - Considerably more data need to be collected.
    - The image must somehow be moved by small amounts on the detector.
    - Image registration is required.
    - Considerable processing may be necessary for the super-resolution algorithm itself.

Summary

- The optical wavefront error is critical to understanding the performance of an optical system.
- Interferometry can be used to measure wavefront error, but it has limitations.
- Many of those limitations can be overcome through the use of phase diversity.
- Phase diversity imaging from a deployed, undersampled system is possible by using super-resolution techniques as a pre-processing step.
- Modern image processing techniques can be leveraged with great utility to improve system resolution and image quality.

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