Trends in Multi-Aperture Imaging Systems

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Outline

1. Multi-aperture examples
2. Motivation for multiple aperture imagers
3. COMP-I and MONTAGE
4. Multiscale design and MOSAIC

Closeup imaging

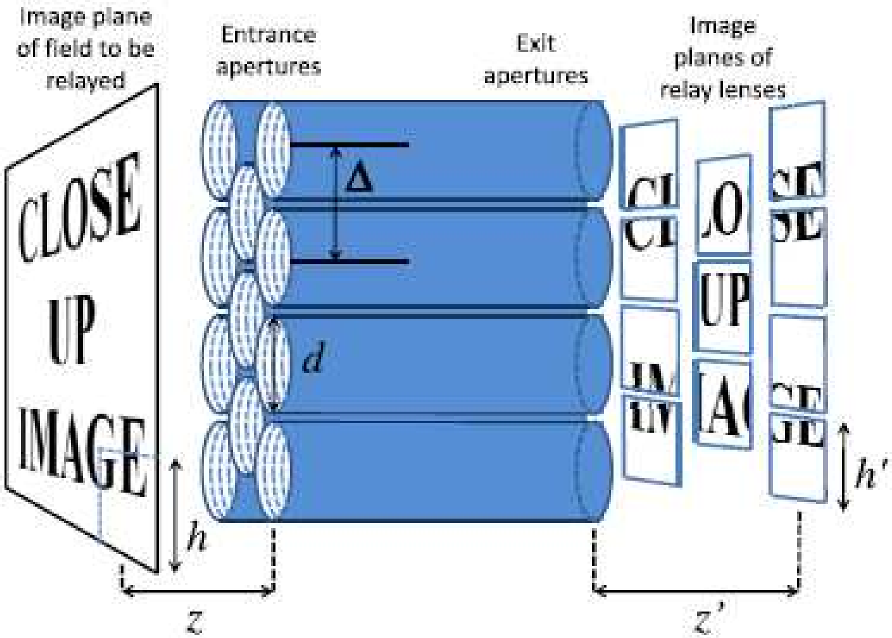


Fig. 1. Close-up imaging geometry.

Anderson Close Up Imager

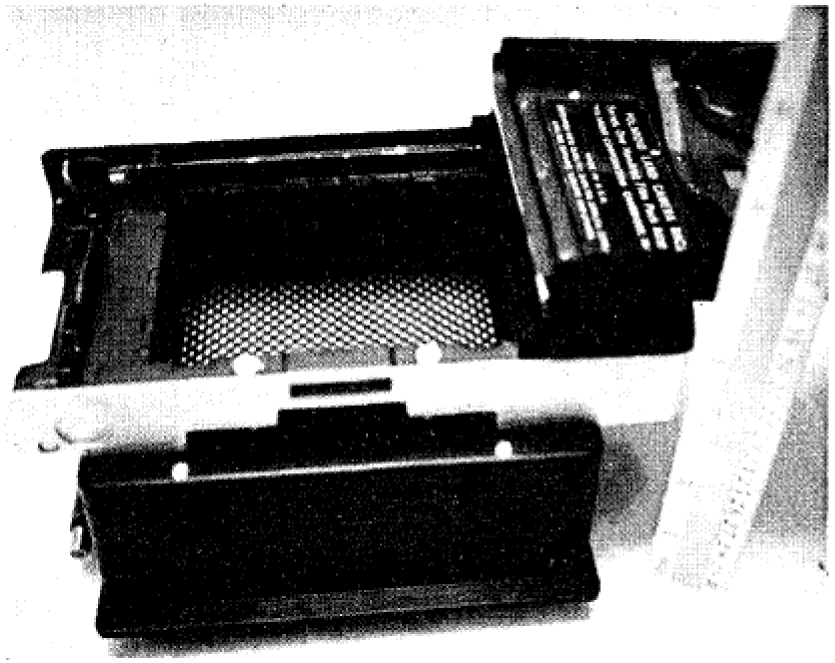


Fig. 8. The first fully developed lens-array oscilloscope camera has a demagnification of $\times 0.87$ and diagonal rows of lenses.

History of Close Up Imaging

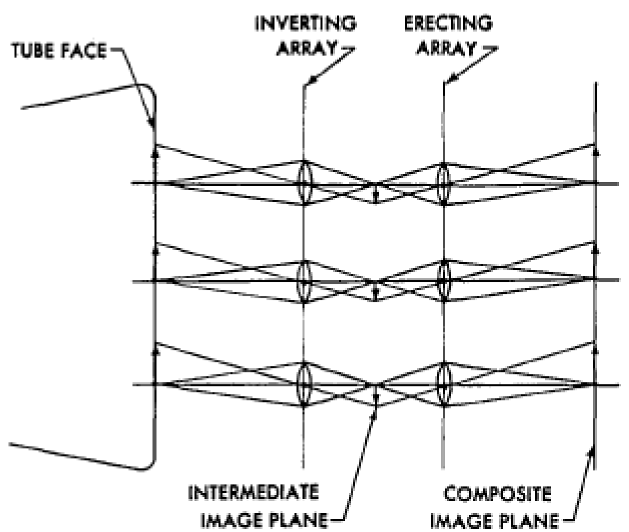
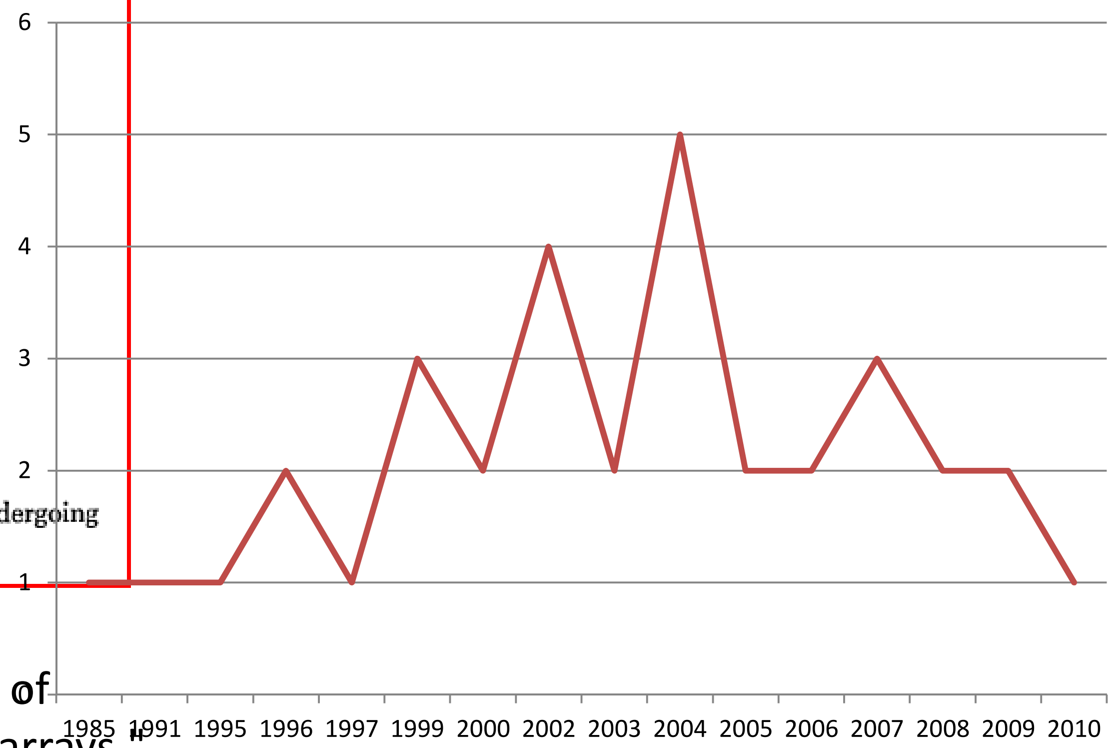


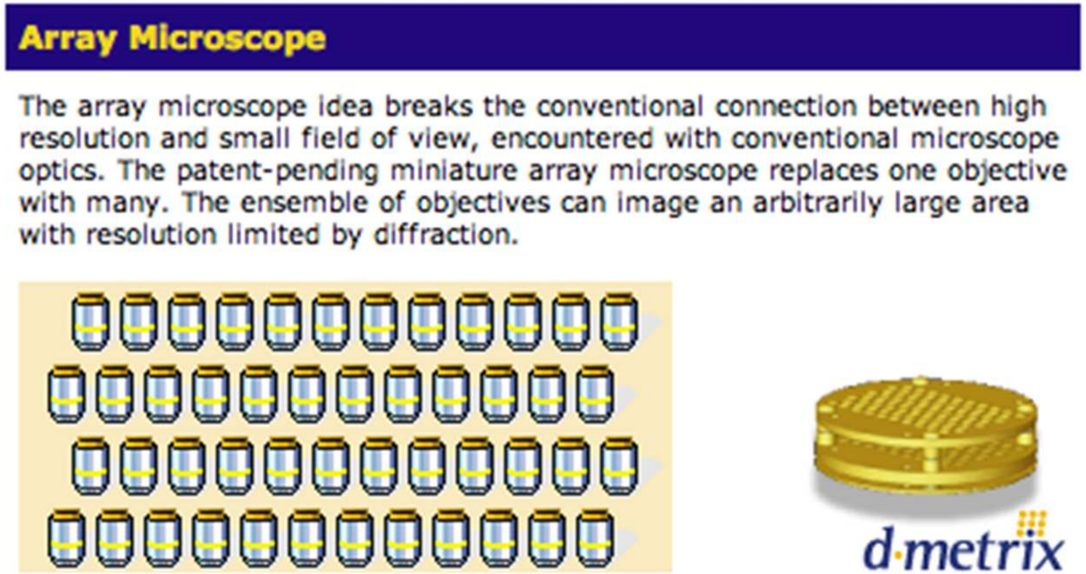
Fig. 1. The images are restored to an upright position by undergoing a second inversion.



R. H. Anderson, "Close-up imaging of documents and displays with lens arrays," Appl. Opt. **18**, 477-484 (1979)

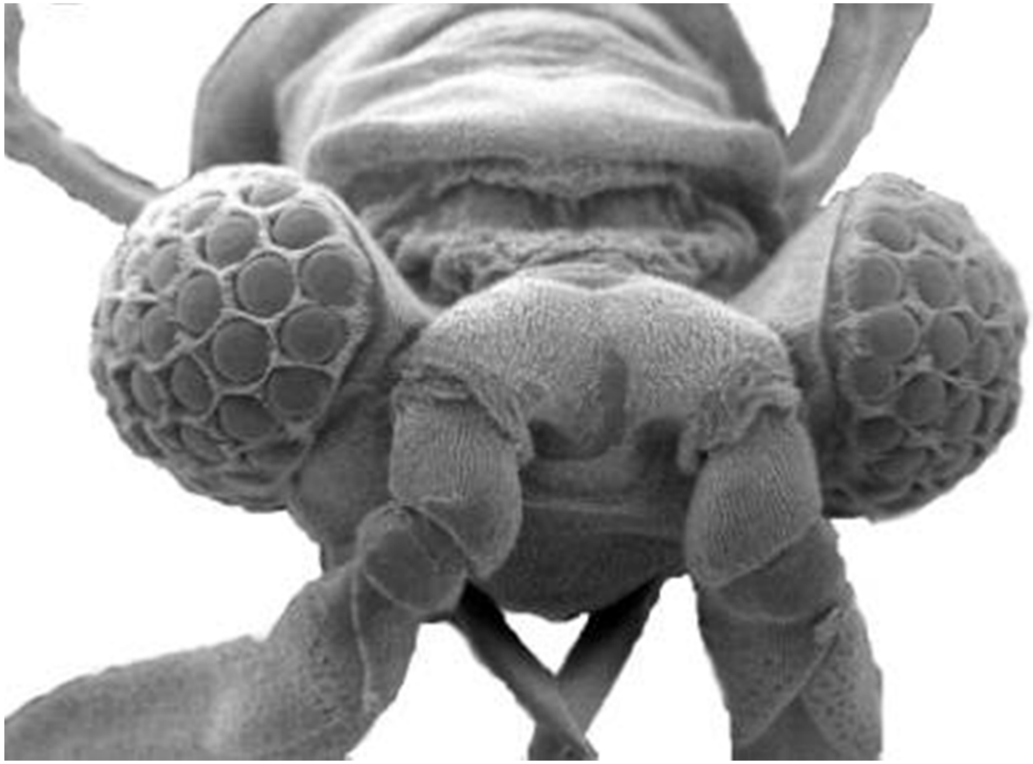
Citations to Anderson paper

Multi-aperture microscopy



http://www.dmetrix.net/techtutorial1.shtml

Multi-aperture in nature



Xenos peckii

Bug-inspired multi-aperture

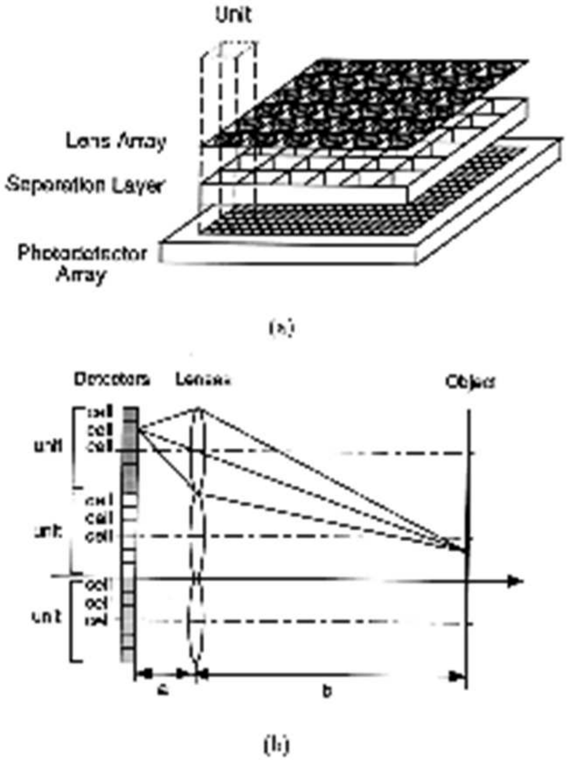


Fig. 3. TOMBO architecture: (a) system structure and (b) optical system.

Jun Tanida, Tomoya Kumagai, Kenji Yamada, Shigehiro Miyatake, Kouichi Ishida, Takashi Morimoto, Noriyuki Kondou, Daisuke Miyazaki, and Yoshiki Ichioka, "Thin Observation Module by Bound Optics (TOMBO): Concept and Experimental Verification," Appl. Opt. 40, 1806-1813 (2001)

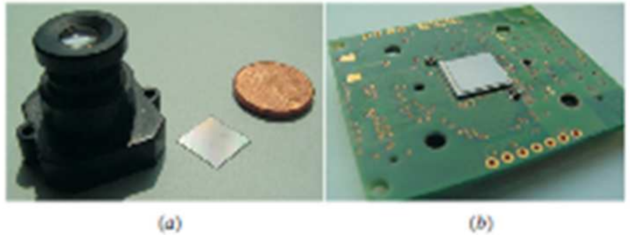


Figure 10. Diced artificial apposition compound eye. (*a*) Artificial apposition compound eye in comparison to 1 Euro cent and a traditional single lens objective with the same magnification and approximate length of 20 mm. (*b*) Artificial apposition compound eye attached to the CMOS sensor array (courtesy of Centre Swiss d'Electronique et de Microtechnique SA (CSEM) Neuchâtel, Switzerland).

Micro-optical artificial compound eyes
J W Duparré and F C Wippermann 2006 Bioinspir. Biomim. 1 R1

http://www.baesystems.com/Capabilities/Technologyinnovation/NewTechnologies/Bugeye/index.htm

Multi-aperture sampling diversity

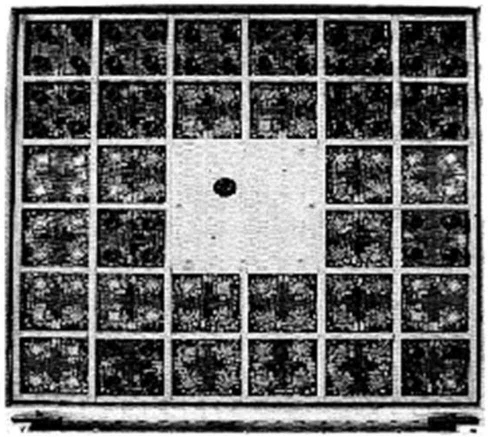


Fig. 19. Front view of the camera array. Each square holds an electronics board supporting four sensors. Fifty-six of the 129 sensors have lenses attached. The central area is devoted to interface electronics and a PC104 computer.

Premchandra M. Shankar, William C. Hasenplaugh, Rick L. Morrison, Ronald A. Stack, and Mark A. Neifeld, "Multiaperture imaging," Appl. Opt. 45, 2871-2883 (2006)

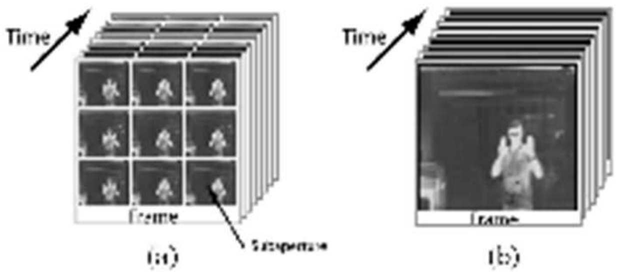


Fig. 1. Video frames from (a) a multichannel camera in which each frame consists of multiple nonredundant low-resolution representations of the scene and (b) a conventional camera.

Mohan Shankar, Nikos P. Pitsianis, and David J. Brady, "Compressive video sensors using multichannel imagers," Appl. Opt. 49, B9-B17 (2010)

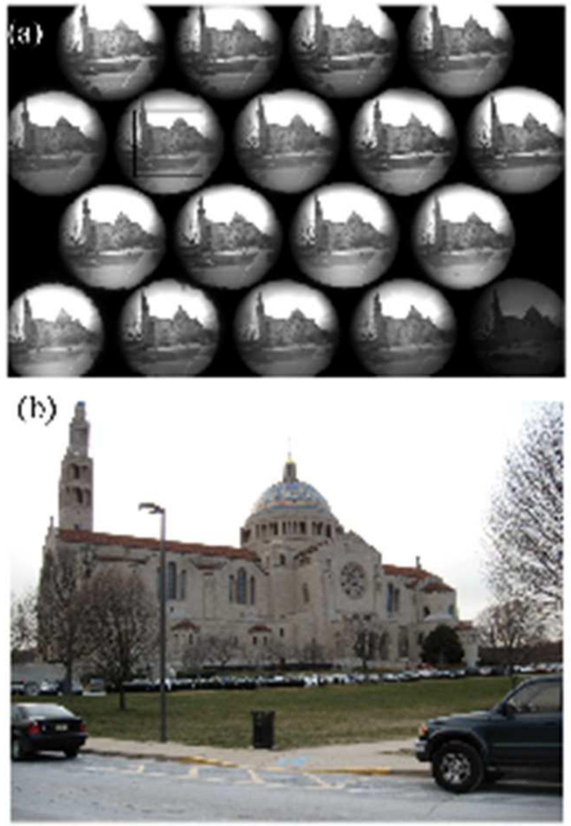


Fig. 3. (Color online) (a) Complete image of the National Shrine of the Immaculate Conception acquired with the multispectral camera. (b) The Shrine photographed with a conventional digital camera.

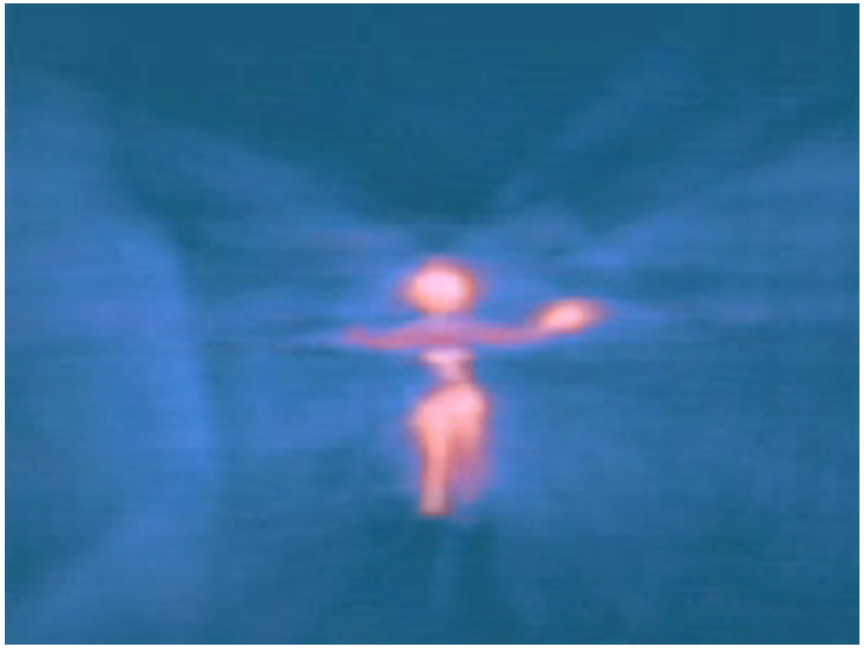
Scott A. Mathews, "Design and fabrication of a low-cost, multispectral imaging system," Appl. Opt. 47, F71-F76 (2008)

Wide field imaging

http://www.baesystems.com/Newsroom/NewsReleases/autoGen_107105142443.html

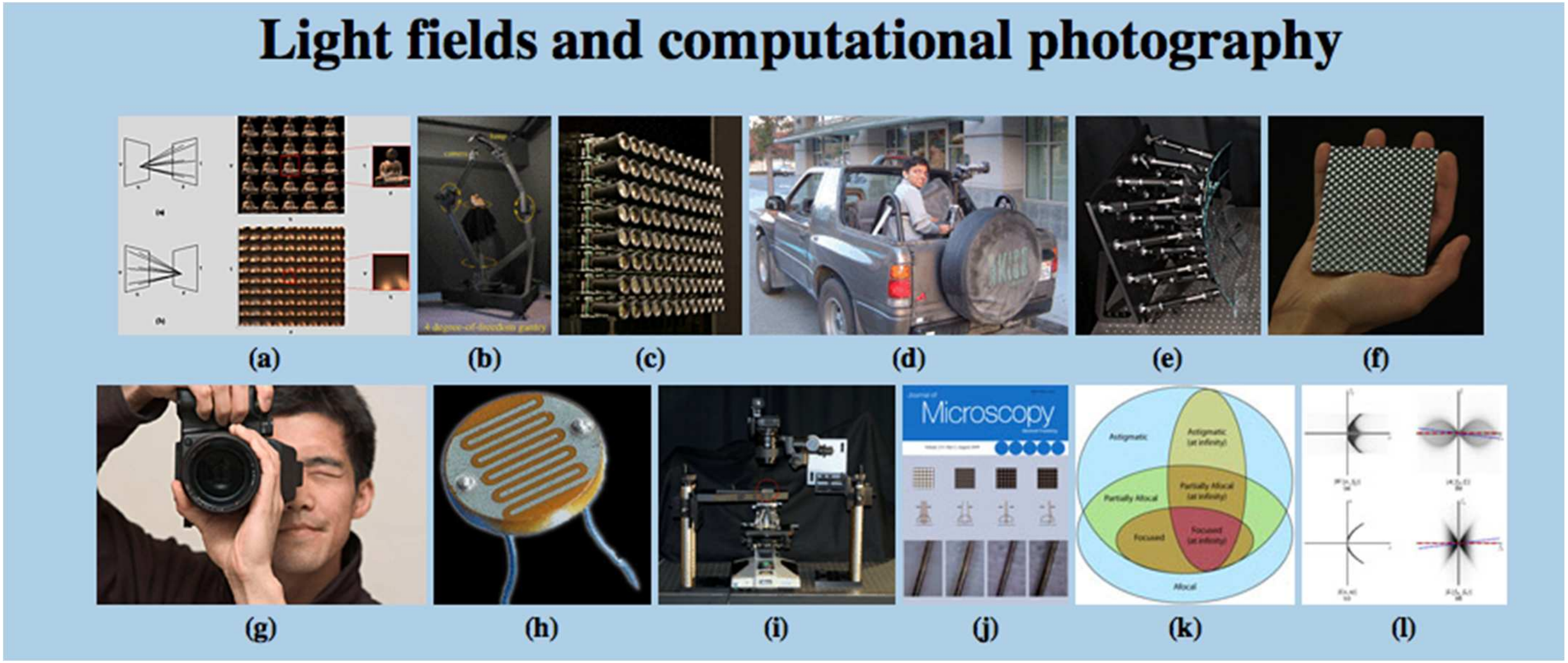
http://www.umich.edu/~rotse/camarray.htm

Stereo and Tomographic Imaging



Three dimensional imaging with the argus sensor array Evan C. Cull, David P. Kowalski, John B. Burchett, Steven D. Feller, and David J. Brady, Proc. SPIE 4864, 211 (2002)

Plenoptic imaging



http://graphics.stanford.edu/projects/lightfield/

Example of digital refocusing

http://graphics.stanford.edu/talks/lightfields-UVa-oct05/

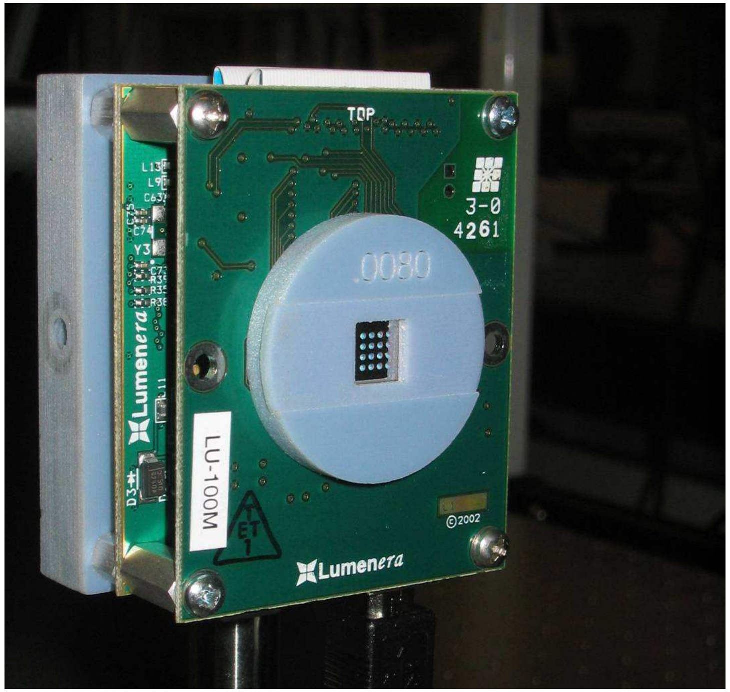
Why use multiple apertures?

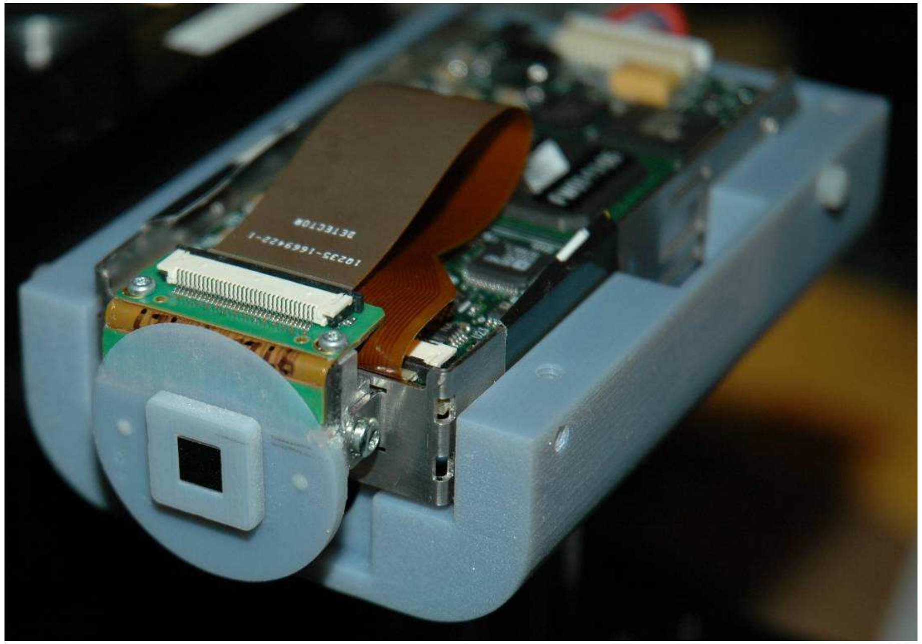
Metric	Multiple aperture solution
Volume	Thinner and simpler lenses per field and resolution
Mass	Thinner and more tightly integrated lenses
Power	Adaptive sampling reduces bandwidth per pixel
FOV	MA wide field simpler than SA
Ifov	Digital super-resolution
Range resolution	Tomographic arrays
Spectral range	Multiband coding, registration and fusion
Spectral resolution	Multispectral and hyper spectral coding
Cost	Thinner/more tolerant optics and lower power sensors
Depth of field	Adaptive multirange sensing
Pixel count	Generalized focal planes, power management and field stitching

Multi-aperture toolkit

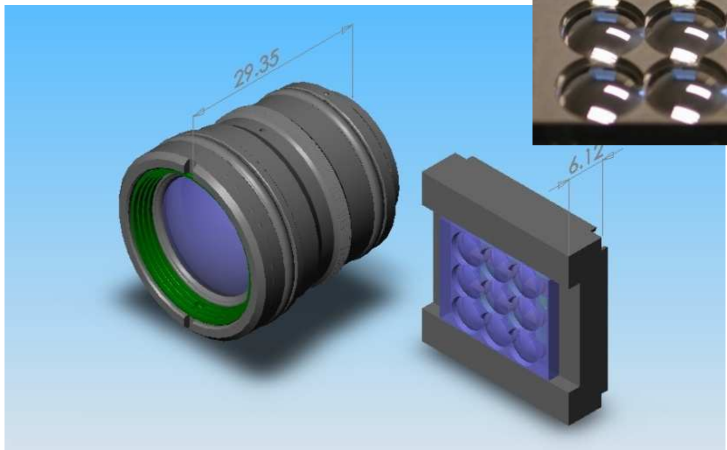
- Sampling diversity
  - Multi-focus, temporal asynchronicity, multispectral, multi-exposure, pixel phase diversity, FOV diversity
- Lens design
  - Smaller lenses and wafer-scale integration yield higher quality

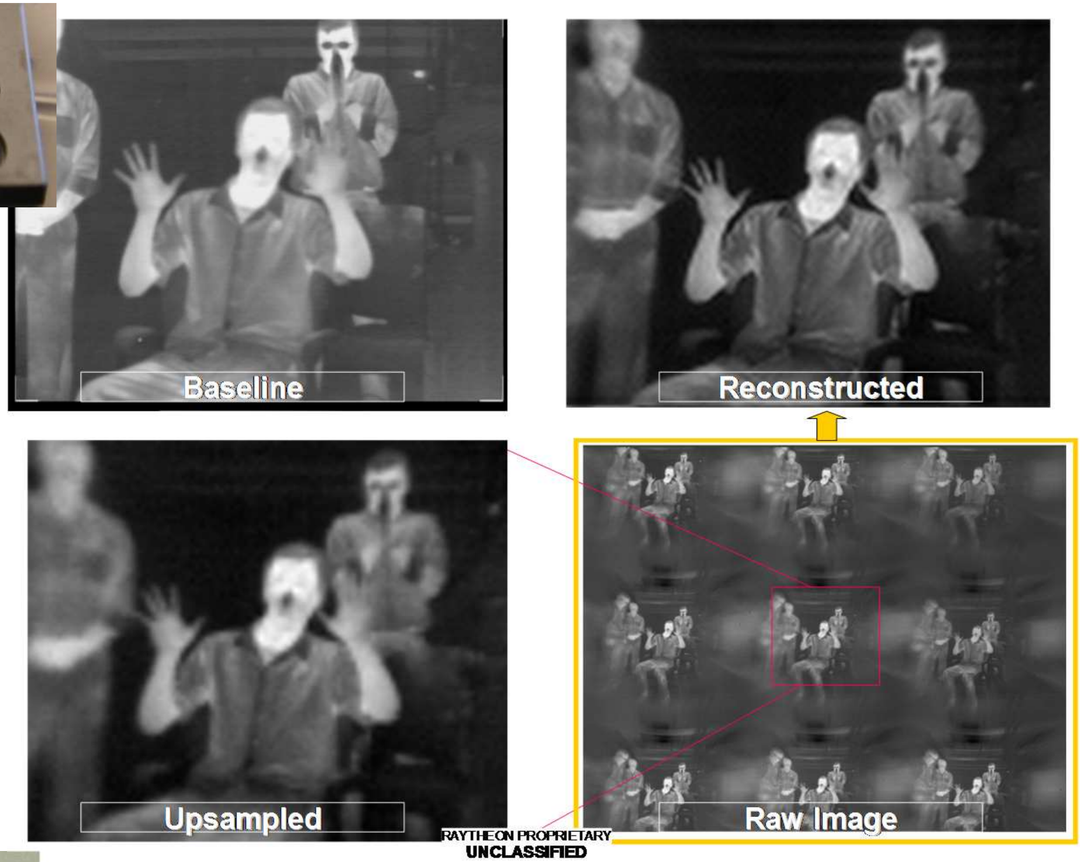
COMP-I, MONTAGE



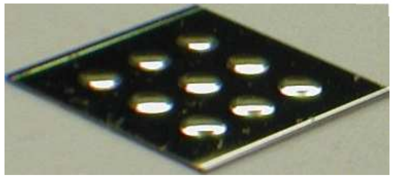


The Compressive Optical MONTAGE Photography Initiative





• COMP-I Uses lenslet array imaging and "compressive sampling" to reduce the thickness of night vision cameras by 5x, mass by 50 x, operating power by 2x



The Duke Imaging and Spectroscopy Program

Fixed Focus, Variable Target Distance

Single Aperture

Close-up (~50cm)

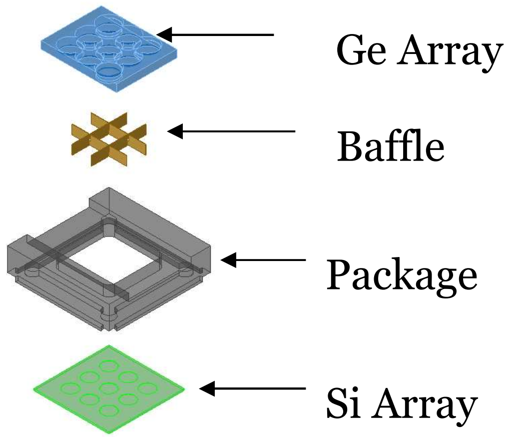
Mid-range (~150 cm)

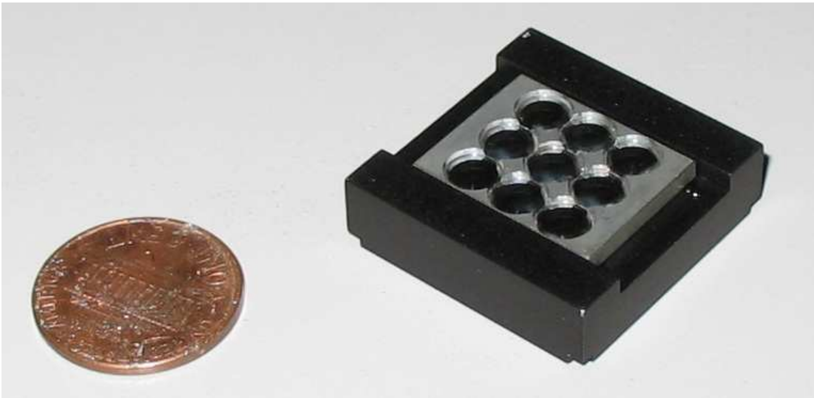
Far (~300 cm)

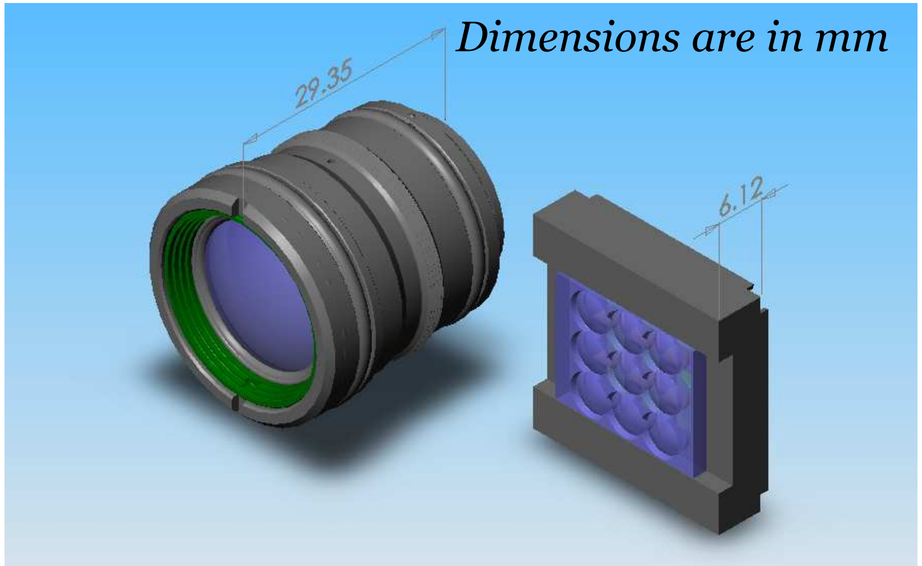
Multi-Aperture

COMPI Optic

- Lens Details
  - 3x3 Array
  - AR Coated
  - Nominal Pitch 5.108mm
  - Effective Focal Length 4.8 mm







Conventional vs Multichannel Optics

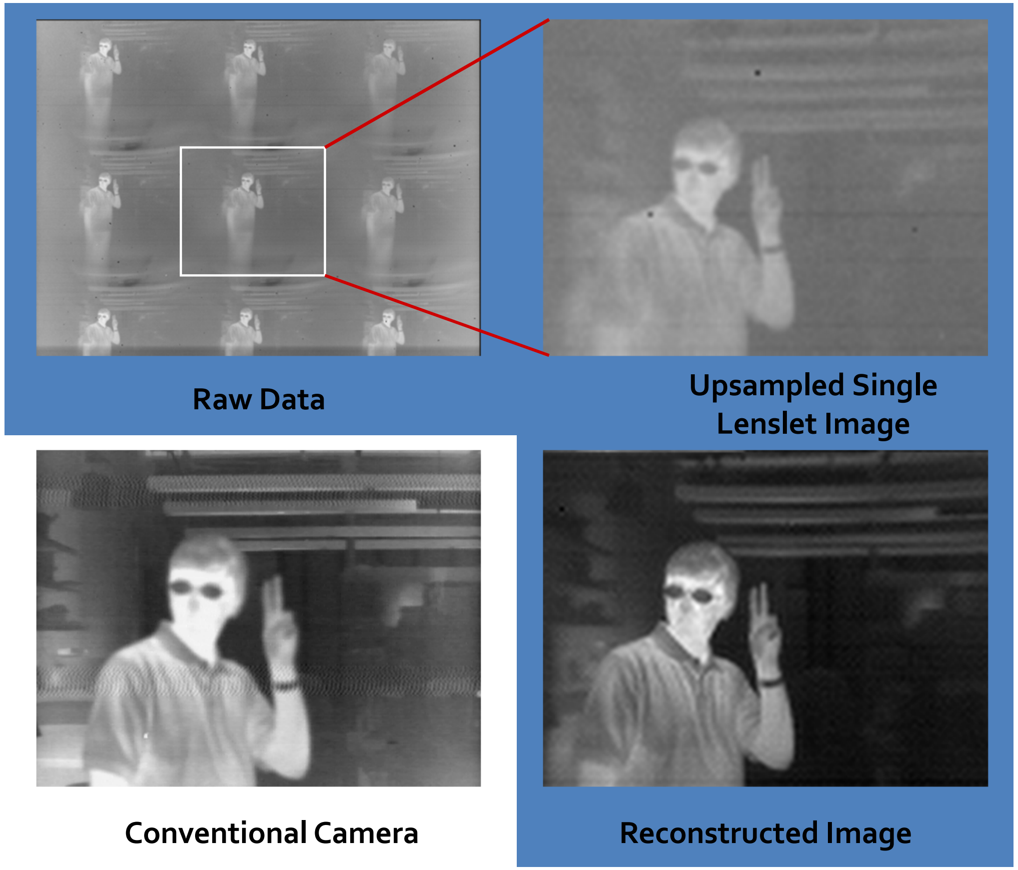
Camera Comparison

COMP-I Multiple Aperture Camera (left) vs. Single Lens Camera (right)

Reconstructed Image

- Resolution improves from single lenslet image to reconstruction.

- Comparable image quality is seen between reconstruction and the single lens (baseline) system.



Short Focal Length Lenses Mean Greater Depth of Field

Raw Image

Single Lenslet Image

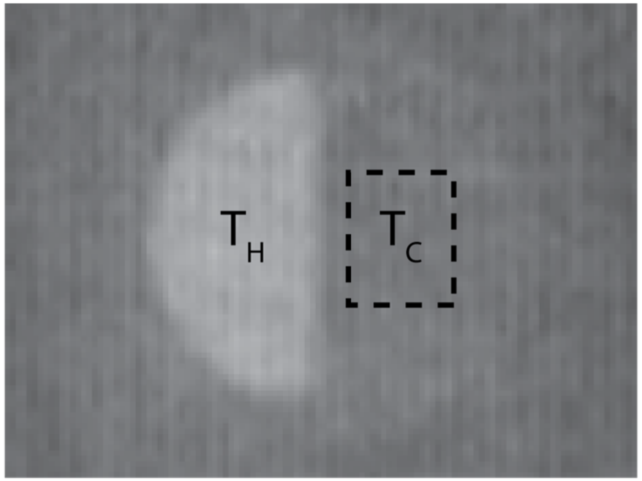
Baseline Image

Reconstructed Image

Person at a distance of 3 meters. Hand is at approximately 0.7 meter. The images were taken simultaneously; parallax is visible.

Statistically calculate NEDT from two temperature regions

- NEDT is the temperature at which the signal is equal to the noise fluctuations.
  - SNR = 1 (definition)
- NEDT translates pixel fluctuations resulting from system noise into an absolute temperature scale.
  - Quantifies the system's temperature resolution
  - Function of operating temperature
- Calculate NEDT by:
  - Mean pixel values from two constant T regions calibrate a linear response factor
  - Convert the standard deviation of pixel values to an equivalent T

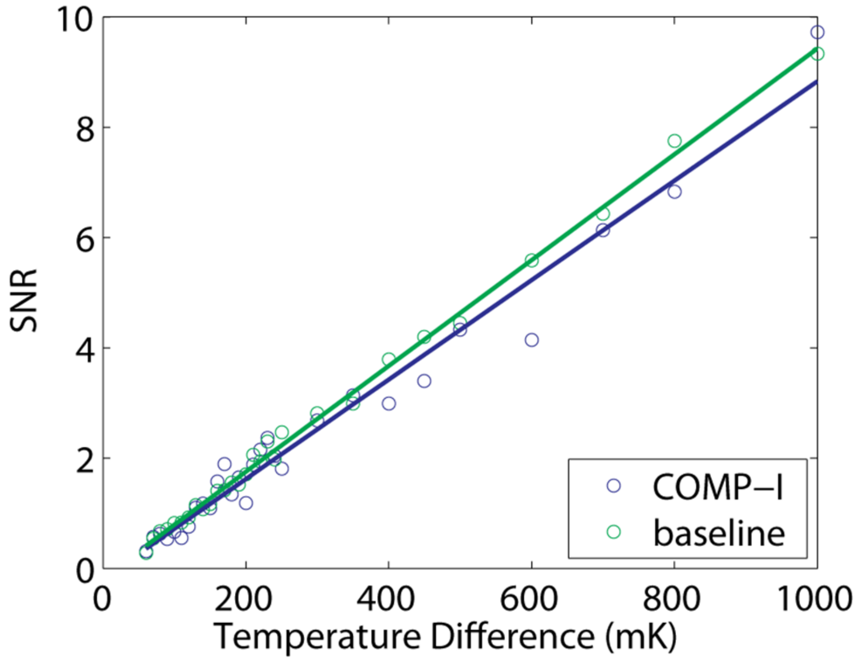


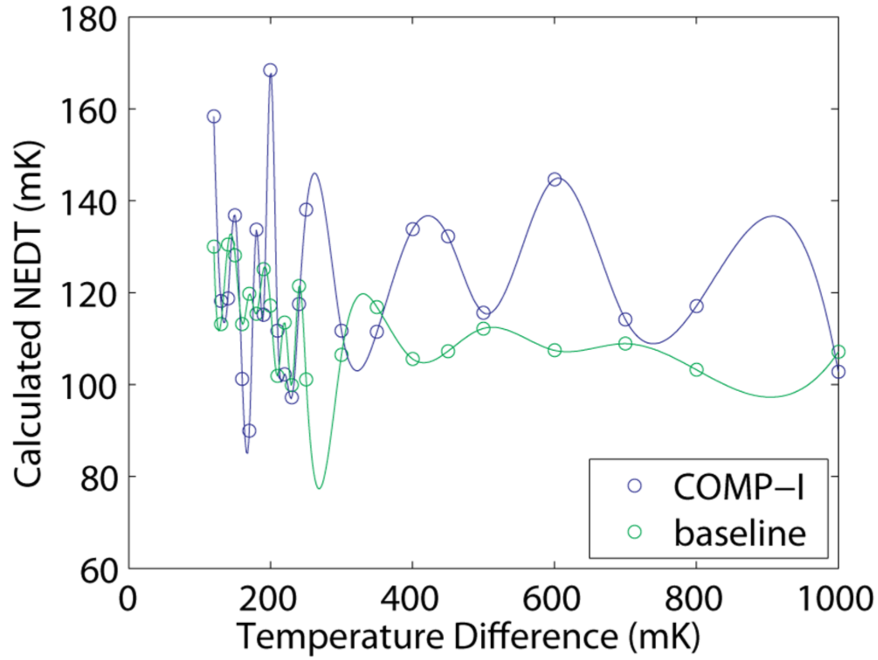
$$\mathrm{NE\Delta T} = \frac{(T_H - T_C) * \mathrm{std}(data \mid T_C)}{\mathrm{mean}(data \mid T_H) - \mathrm{mean}(data \mid T_C)}$$

calibration from pixel value to temperature

noise defined as std. dev. of pixel values in region of constant temperature

Comparable NEDT Results between cameras





Method 1:
Temperature at which SNR = 1

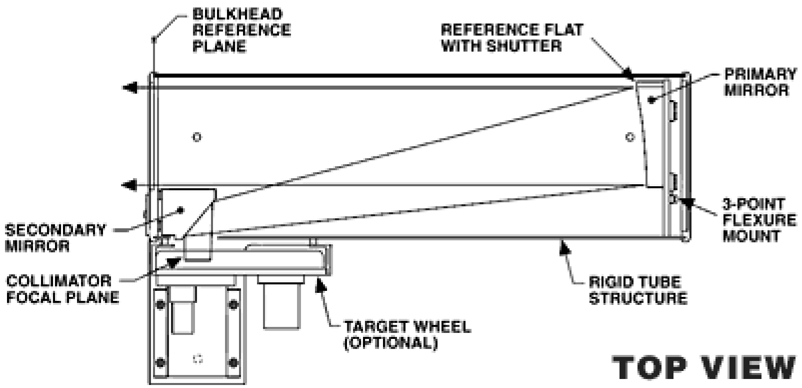
COMP-I: 131 mK
Baseline: 121 mK

Method 2:
Data Statistics on calculated Values

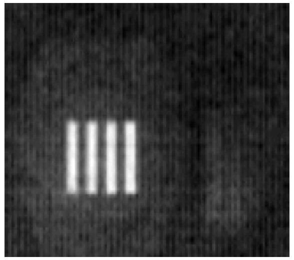
COMP-I: 121 mK (mean), 19 mK (st. dev.)
Baseline: 113 mK (mean), 9 mK (st. dev.)

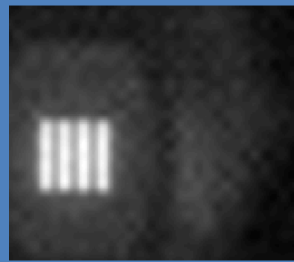
Bar Target Measurements

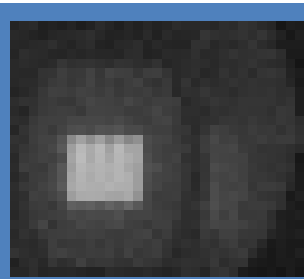
- A blackbody source uniformly illuminates a copper target.
- Reflective optics collimate the source.
- Images are acquired with both camera systems.
- The modulation depth is analyzed in a variety of configurations.
  - Width of target (spatial frequency)
  - Target temperature differential



Target 1





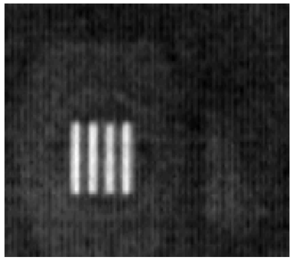


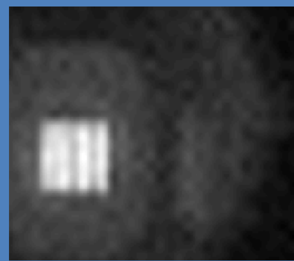
Conventional Single Aperture Camera

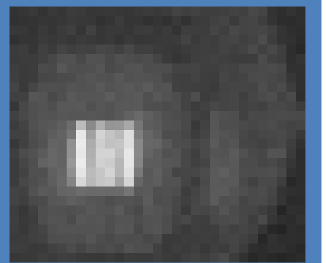
Multi-aperture camera reconstruction

Upsampled Lenslet Image from Multi-aperture camera

Target 2







Why is digital super res a good idea?

Each subimage represents a matrix of downsampled shifted copy of the scene.

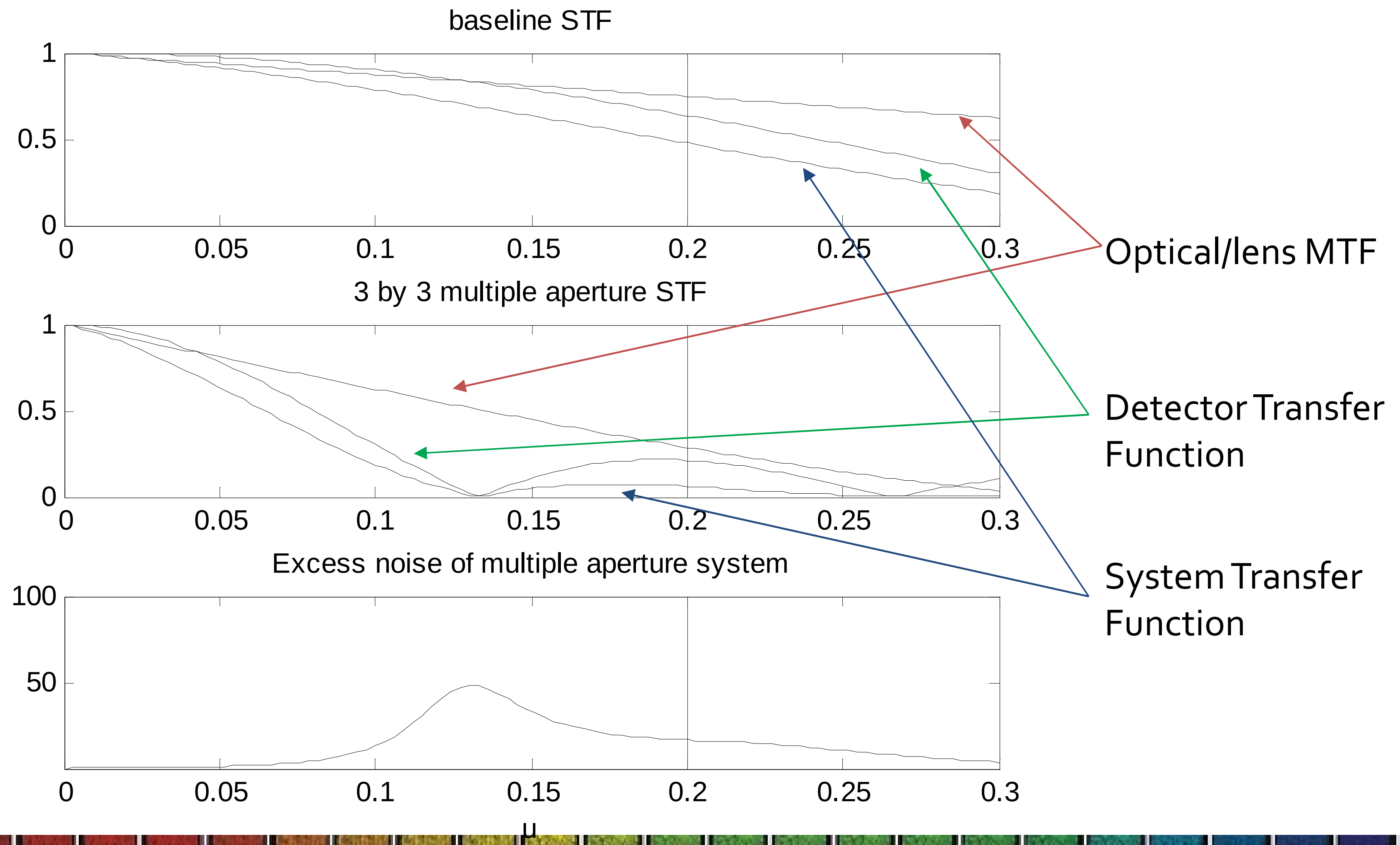
$$m_{ijk} = \underbrace{\iint rect(\frac{x'-ip-\delta_k}{p}) rect(\frac{y'-jp-\eta_k}{p})}_{\text{Pixel Sampling Function}} \underbrace{\iint f(x,y)h(x-x', y-y')}_{\text{Optical Impulse Response}} dxdydx'dy'$$

+ noise + time varying detector bias

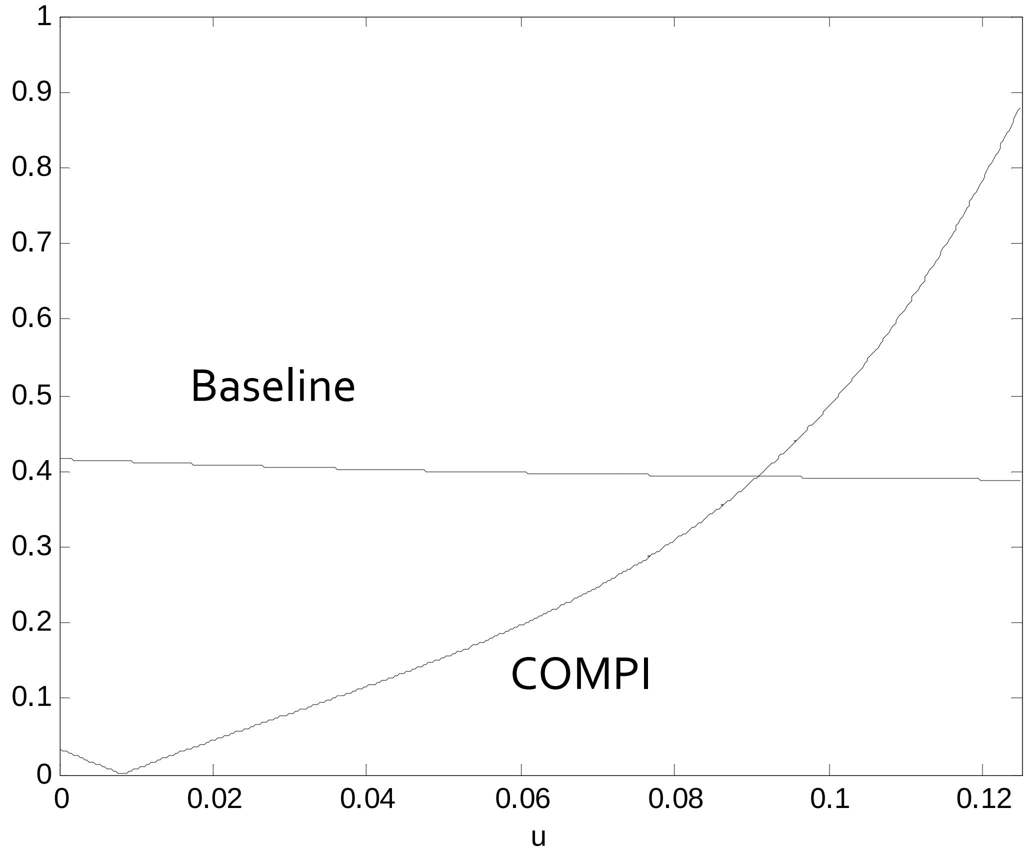
f :	source distribution	k :	subimage index
h :	optical PSF	p:	pixel pitch
m :	measurement	δ_k :	horizontal registration parameter
i,j:	pixel coordinates	η_k :	vertical registration parameter

System transfer function

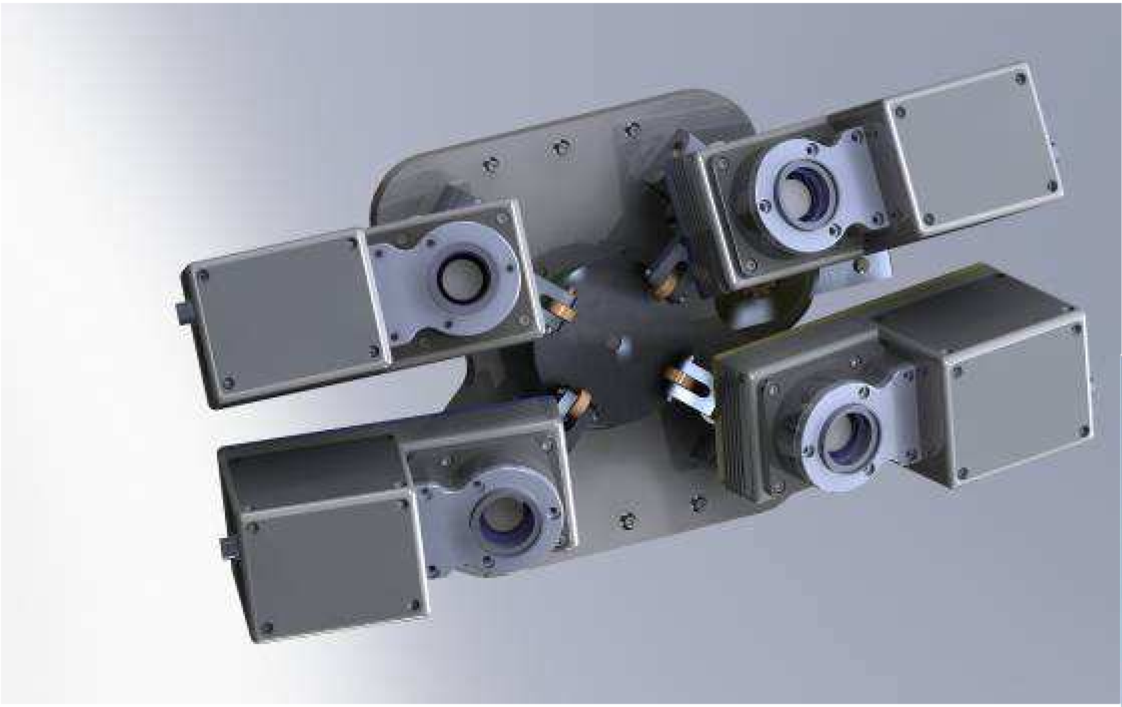
pixel pitch=2.5 $\lambda f/\#$

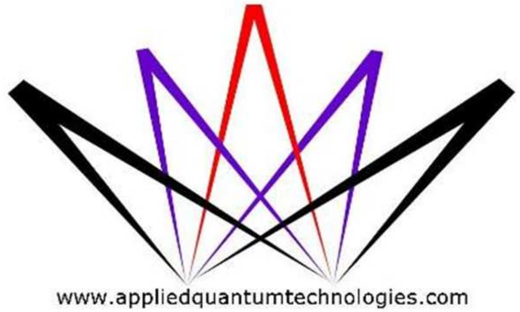


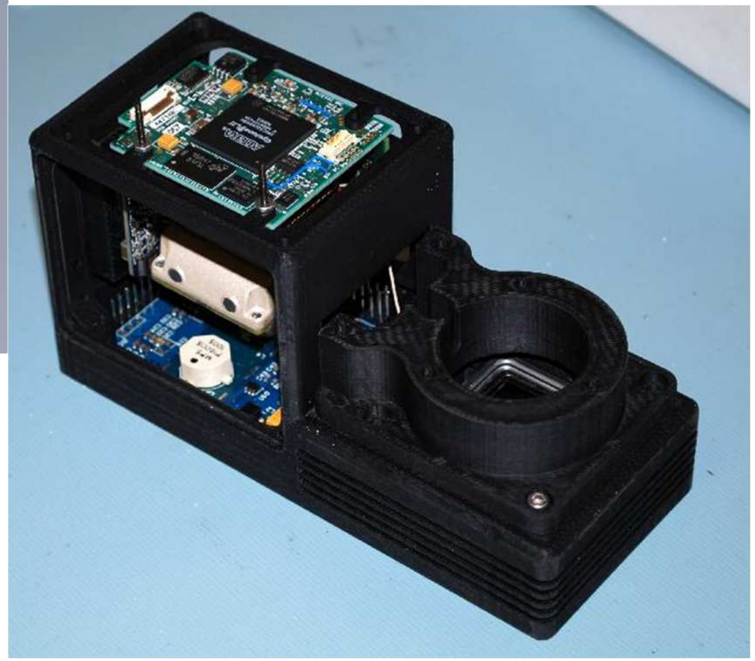
Aliasing MSE



MONTAGE Spinoffs





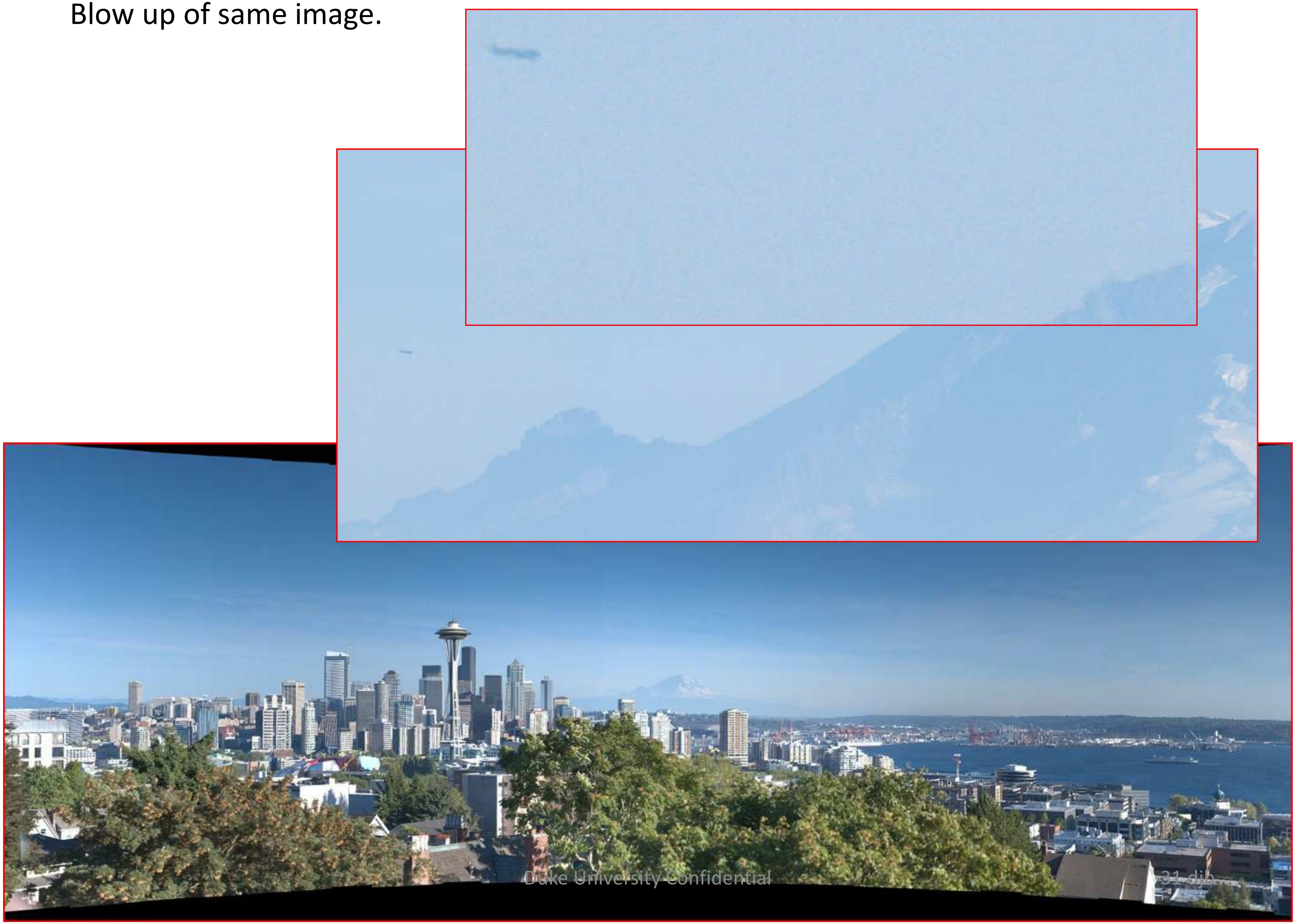


High resolution wide field intensified
SWIR

MOSAIC and Wide Field Imaging

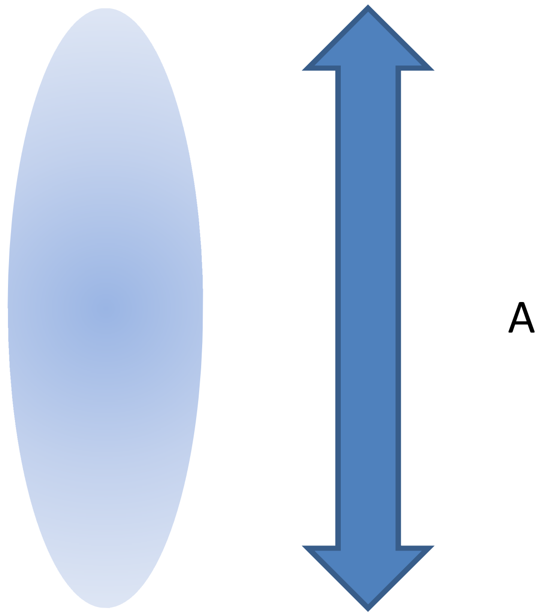
http://research.microsoft.com/IVM/HDView/HDGigapixel.htm

Blow up of same image.



Limits of Lens Capacity: Shannon Number

Shannon number S=SBP



2D imaging $S = \frac{\pi^2 A^2}{(2\lambda f/\#)^2}$

3D imaging $S = \kappa \frac{A^3}{\lambda^3 (f/\#)^4}$

Shannon Number

f/# | A	1 mm	1 cm	10 cm	1 m
1	9.9	990	99,000	9,900,000
2	2.5	250	25,000	2,500,000
4	0.6	60	6,000	600,000
8	0.15	15	1,500	150,000
16	.04	4	400	40,000

SBP in megasamples.

Multiply by 10-100 for 3D
Multiply by 10-100 for wavelength

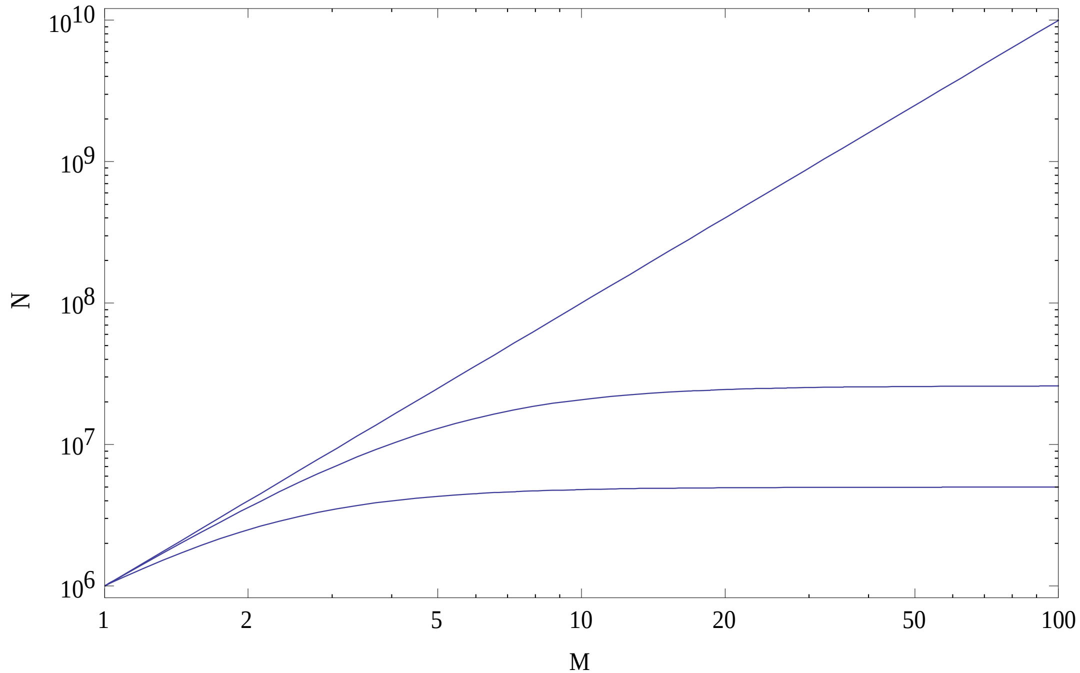
Barriers to Terapixel Imaging

A terapixel is a lot of detector elements

A terapixel is a lot of data

Conventional optical designs cannot capture a terapixel.

Pixel Count vs. Lens Scale



Resolvable pixels, N, as a function of imager scale, M.

- N is diffraction limited for apertures up to 1000 wavelengths (M=1). For M>1, geometric aberration limits N.
- The diagonal line is the diffraction limit.
- The middle curve assumes that the geometric blur spot size is 20% of the diffraction limit at M=1. The bottom curve assumes that the geometric blur is 50% of the diffraction limit at M=1.

High SBP lenses as a function of aperture

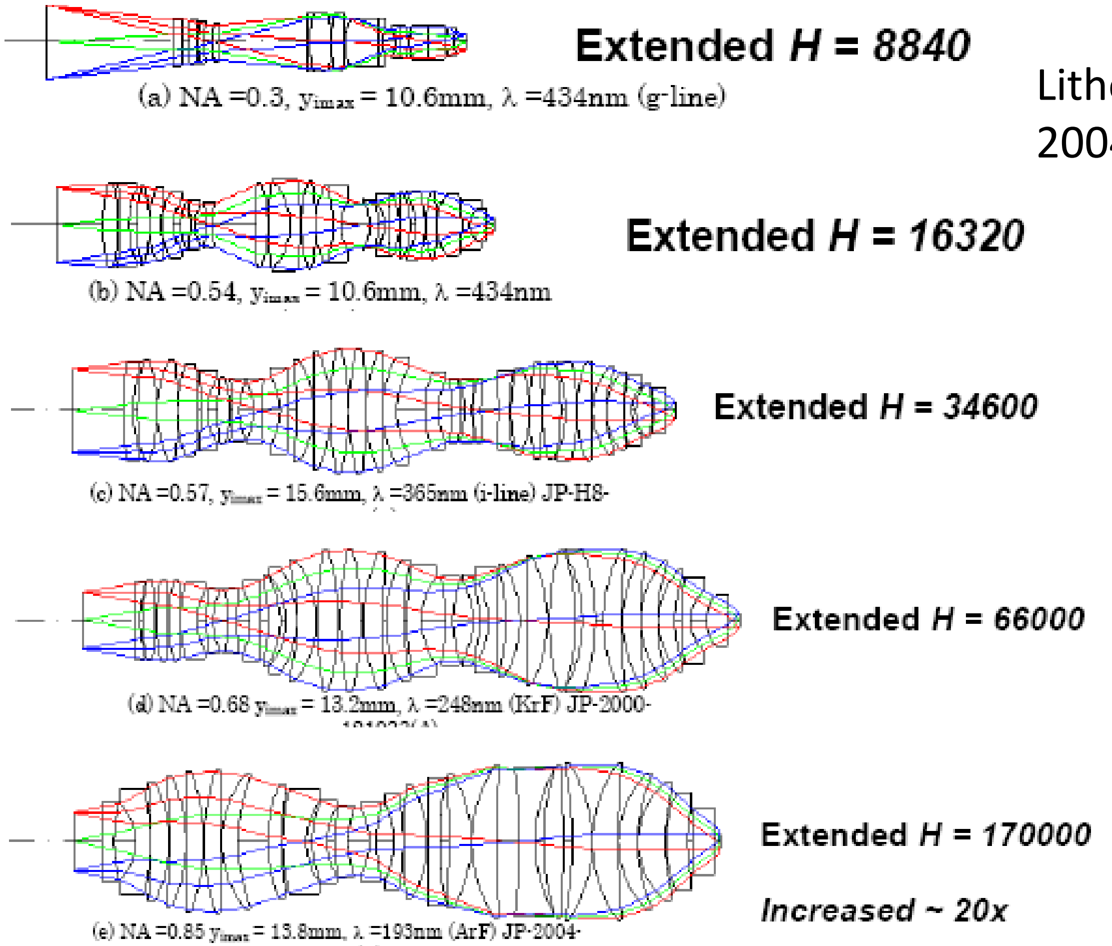
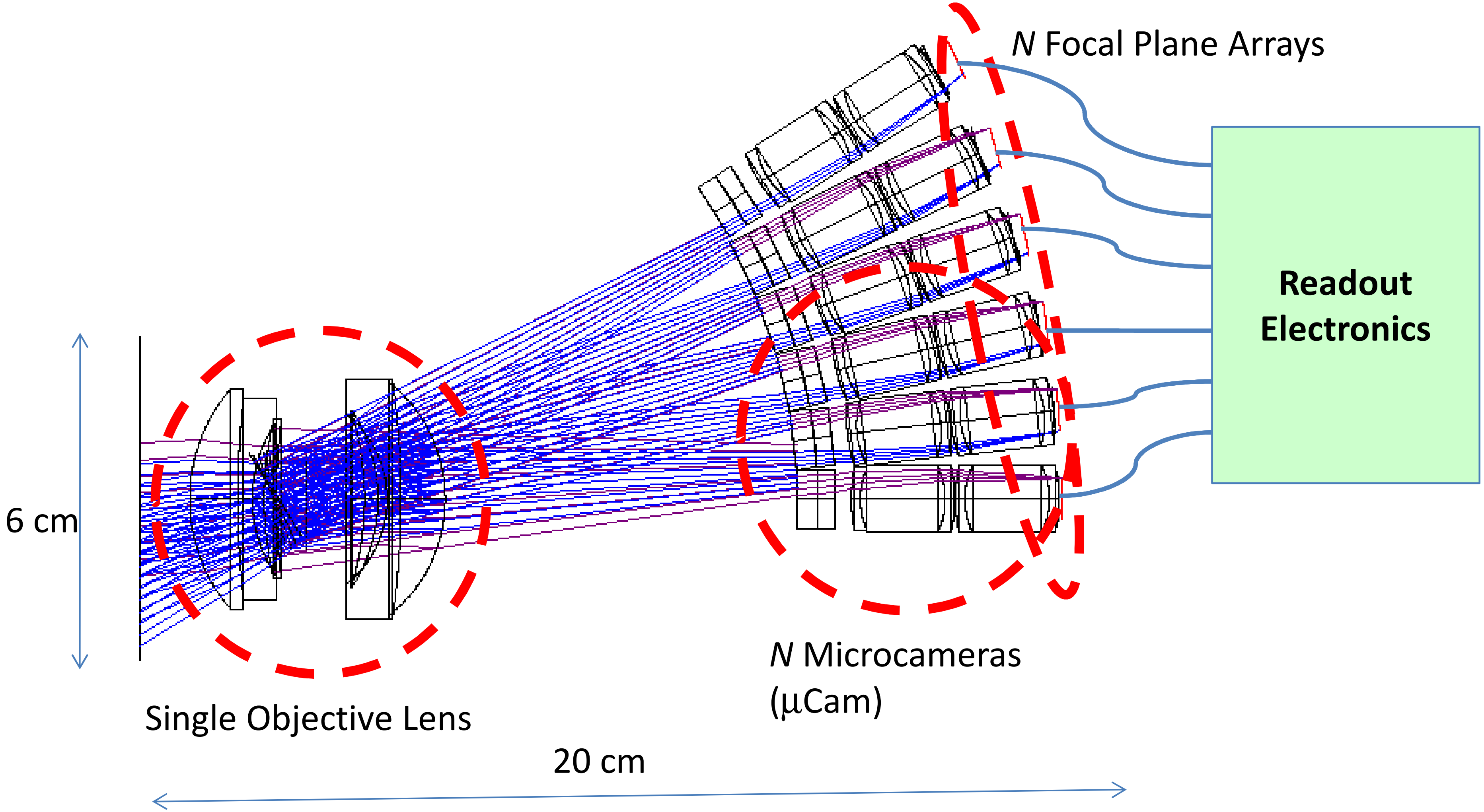


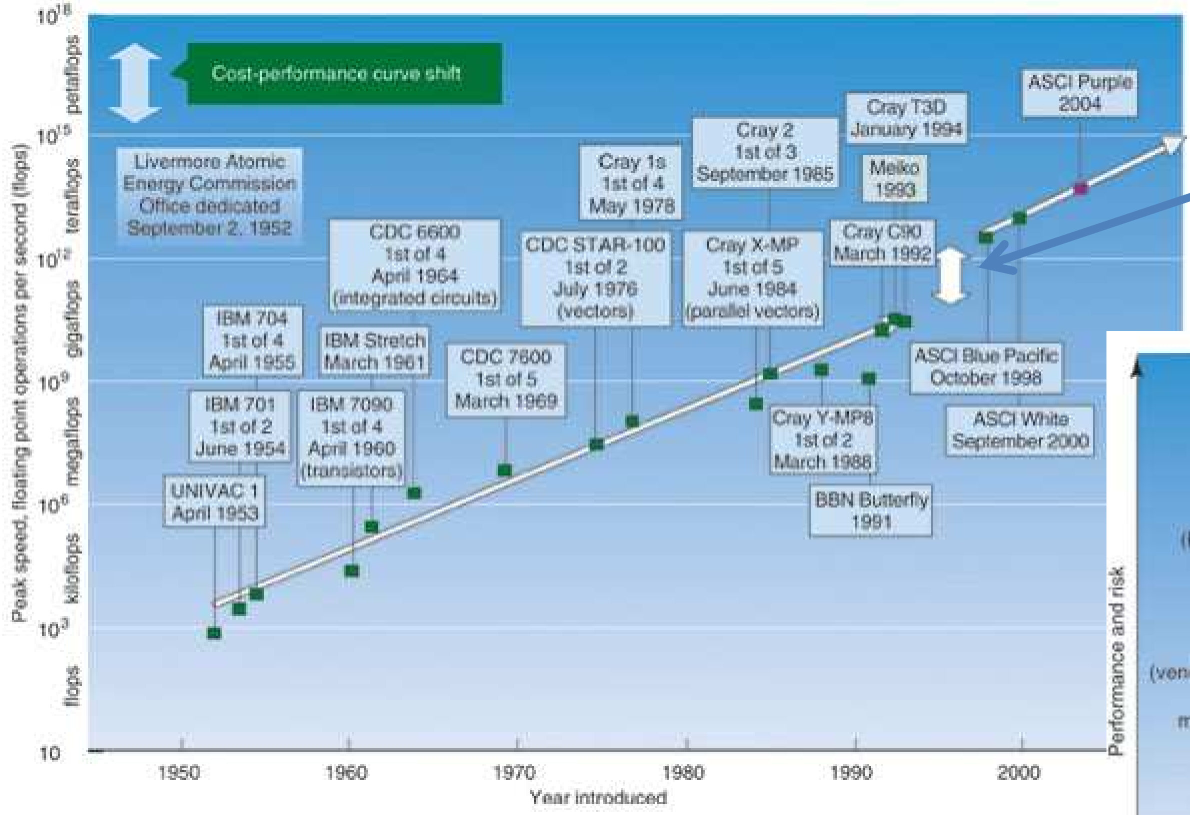
Figure 32. Some lithographic designs showing the parameters for each of the designs.

Lithographic lenses from 1988-2004.

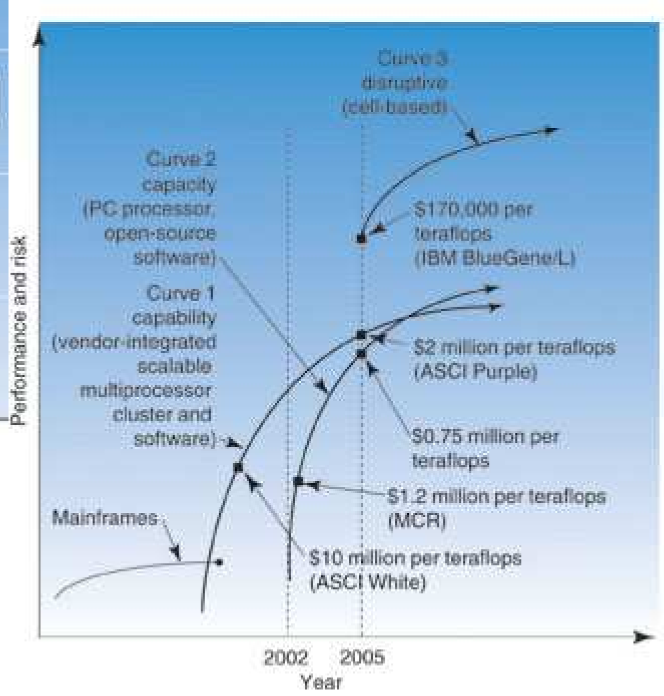
Multiscale High Pixel Count Imaging



Multiscale Design and Computation



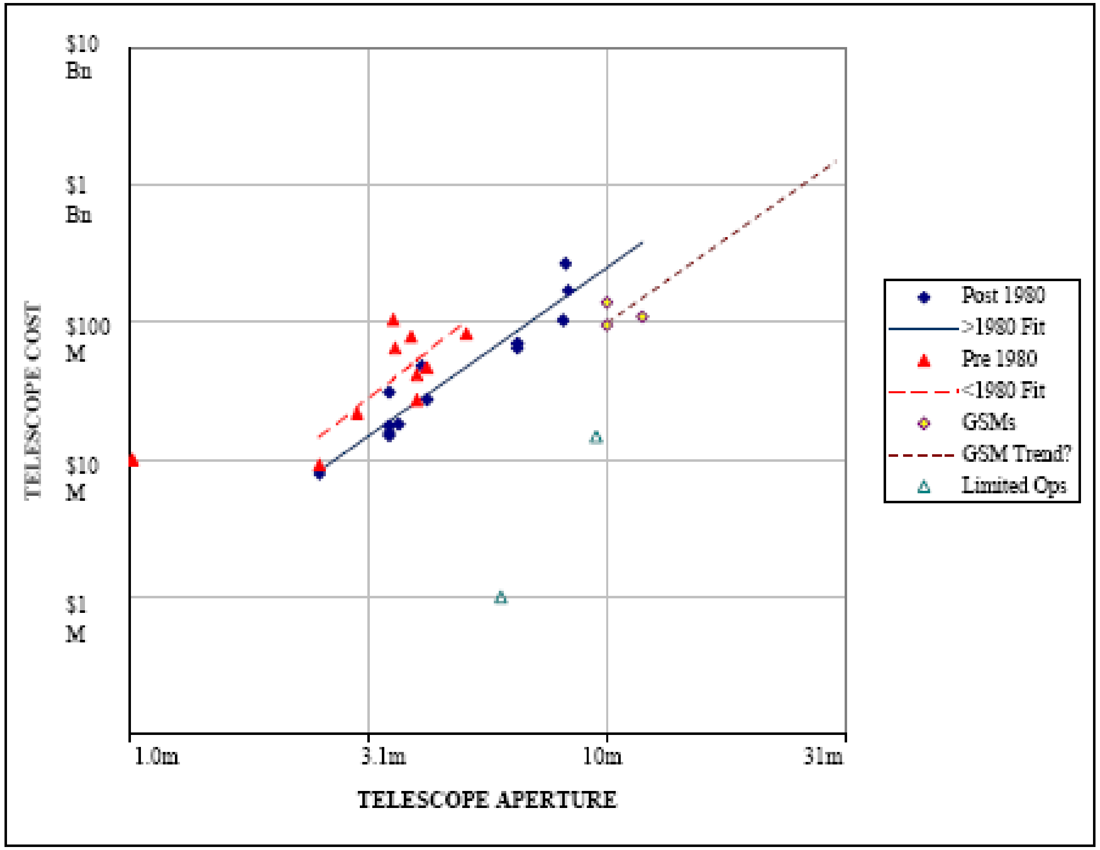
Shift from vector to parallel architectures



Shifts from mainframe/vector based processing to parallel architectures enabled disruptive changes in computer processing capacity

https://www.llnl.gov/str/June03/McCoy.html

Multiscale Design and Optics

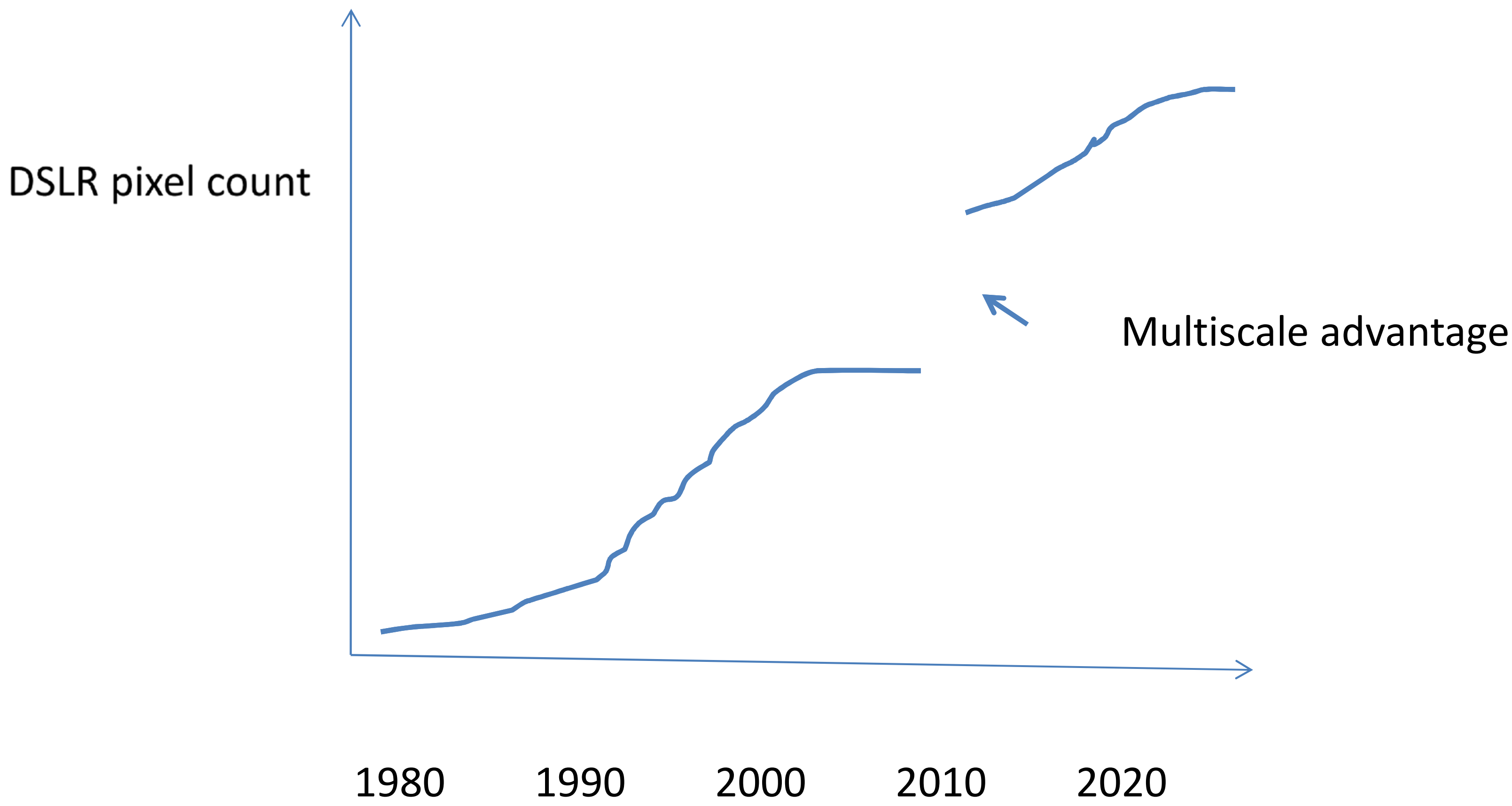


Move to segmented mirrors (e.g. multiscale optics) transformed aperture cost.

Figure 1. Cost versus aperture diameter for optical telescopes built before and after 1980. For the pre-1980 fit, cost $\propto D^{2.77}$, and for the post-1980 fit (exclusive of the giant segmented mirrors), cost $\propto D^{2.48}$. The two limited operations telescopes plotted are the UBC 6-m liquid mecury telescope and the 9-m (effective) HET.

The scaling relationship between telescope cost and aper… es Gerard T. van Belle, Aden B. Meinel, and Marjorie P. Meinel, Proc. SPIE 5489, 563 (2004)

MOSAIC Concept



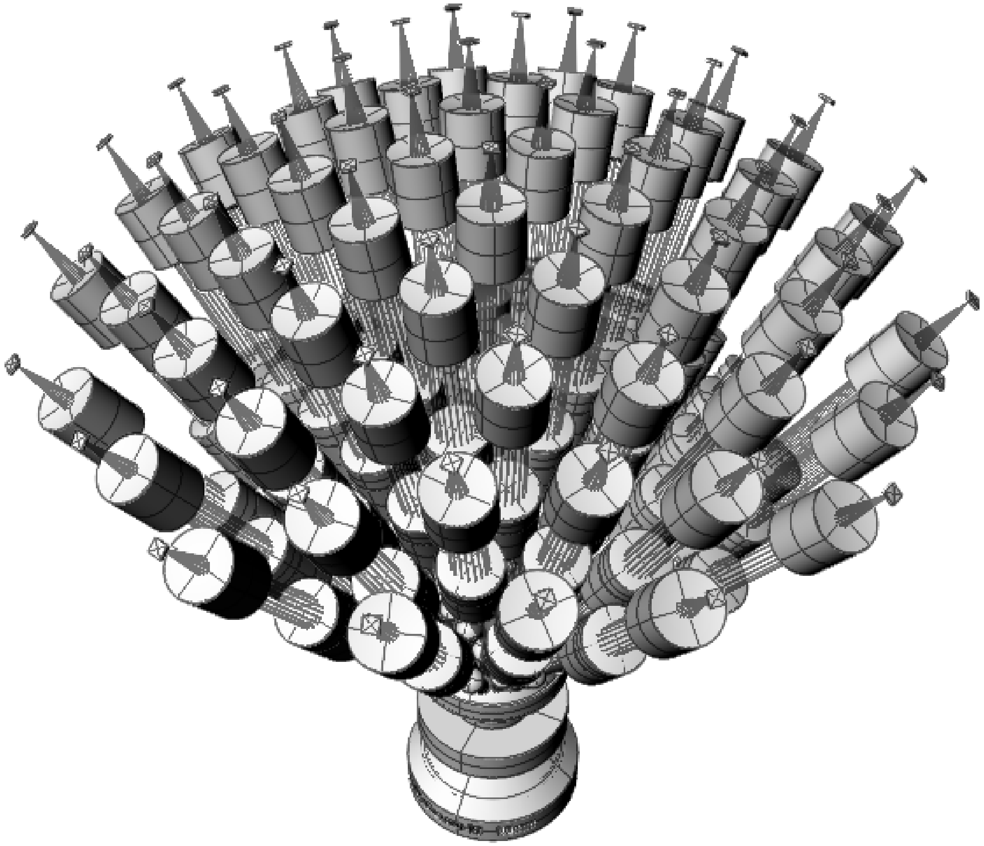
MOSAIC Specifications

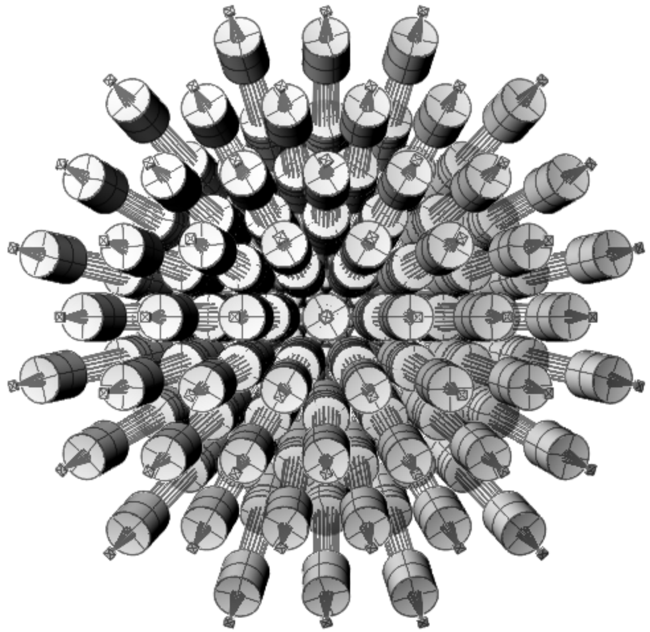
Specification	BAA Spec	MC3
Integrated optical and opto-electronic prototype volume	0.08 m^3	0.08 m^3
Prototype mass	10 kg	10 kg
Field of view	2 rad	2 rad
Instantaneous field of view	8 μrad	8 μrad
Image size	50 gigapixels	51.8 gigapixels
Operating mode	full frame	full frame
Operating mode	100 frame seq	100 frame seq
Image quality	Comparable to baseline	Comparable to baseline
Motion and turbulence artifacts	Comparable to baseline	Comparable to baseline
Frame rate	10 Hz	10 Hz
Frame buffer	100 frames	100 frames
Image formation latency	< 1 second	< 1 second

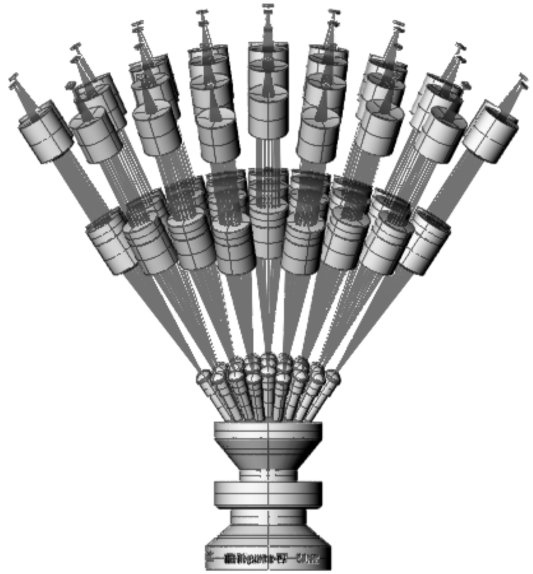
MOSAIC Project Plan

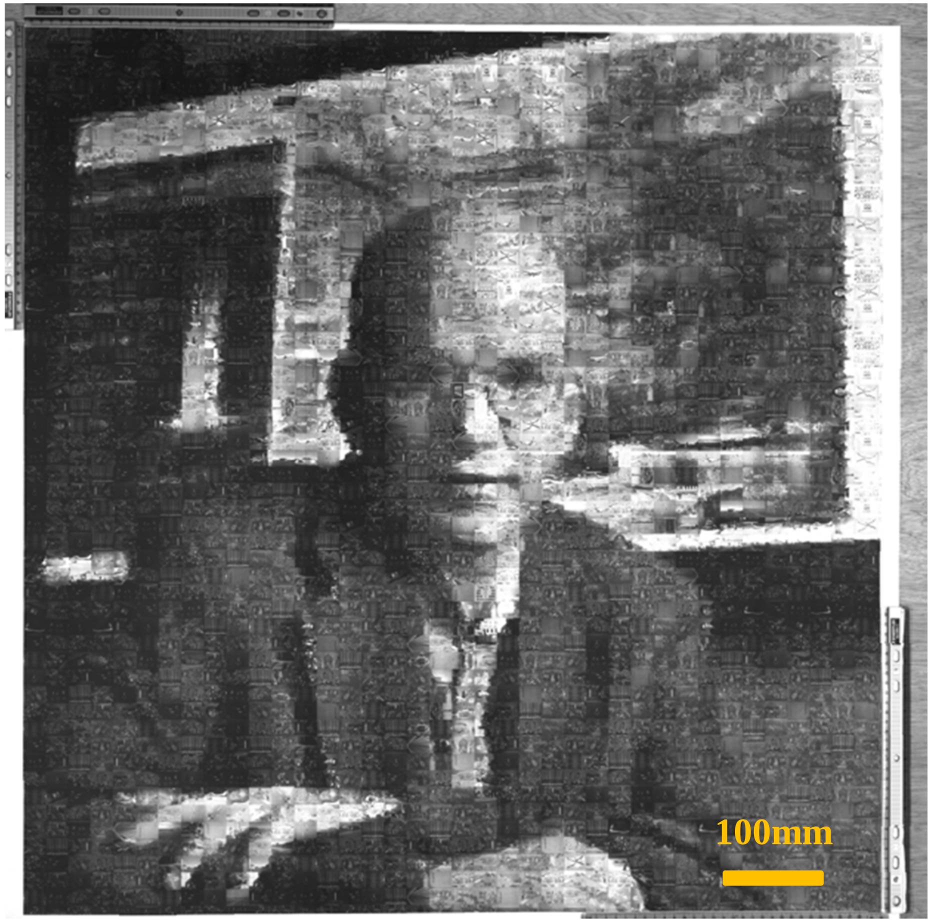
Camera	Completion	Specifications	Comments
MOSAIC Camera 0.a	Dec. 2010	500 MPx, 60 degree FOV	Monocentric objective breadboard electronics
MC0.b	May 2011	1.5 GPx 120 degree FOV	Monocentric objective, 2^{nd} genmicrocamera modules
MC1	Dec. 2011	1, 2 and 50 GPx	Design studies
MC2	June 2013	1, 2 and 50 GPx	Integrated system
MC3	Dec. 2014	1, 2 and 50 GPx	TRL8

Assembly of 55 micro cameras MC0A.10.8



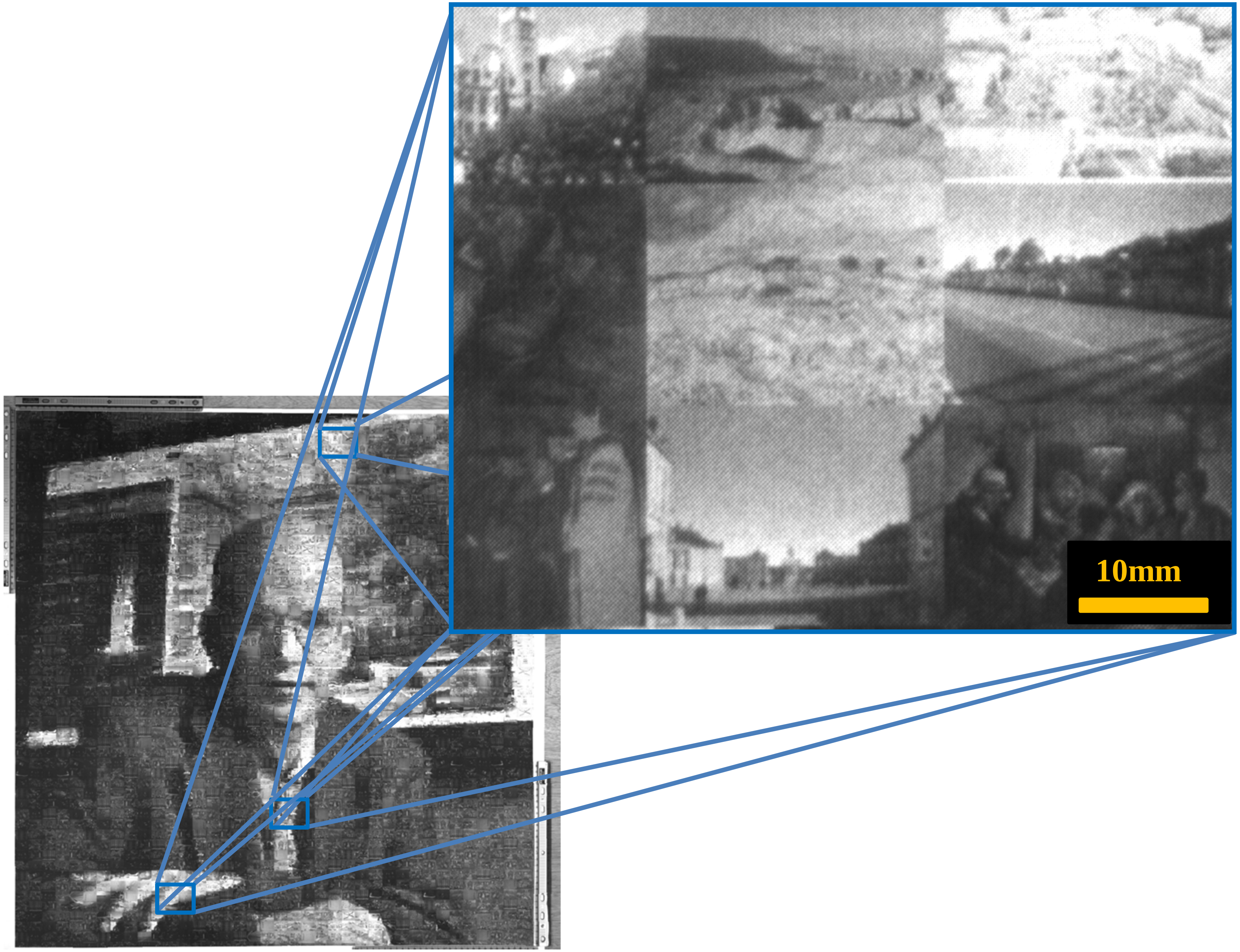


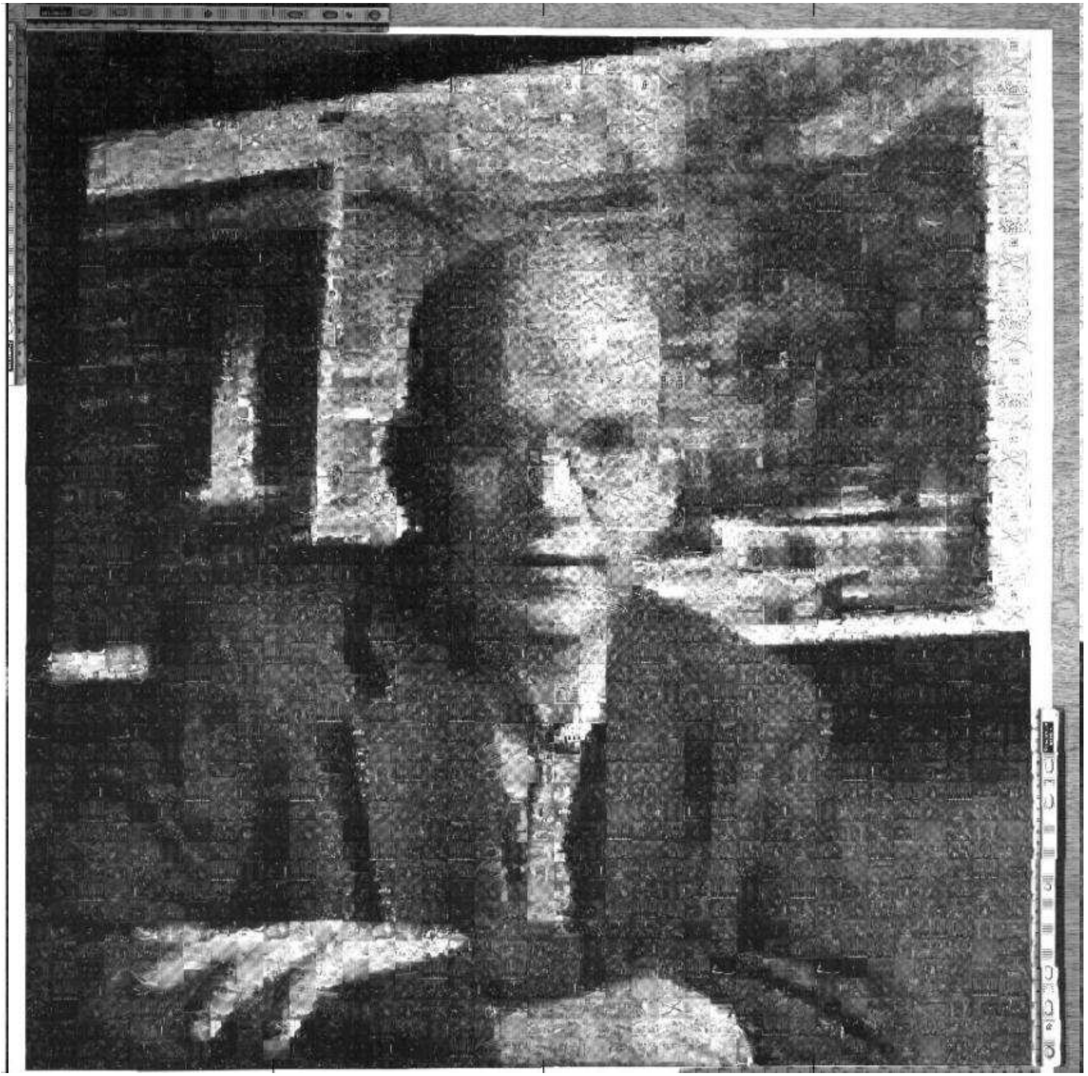


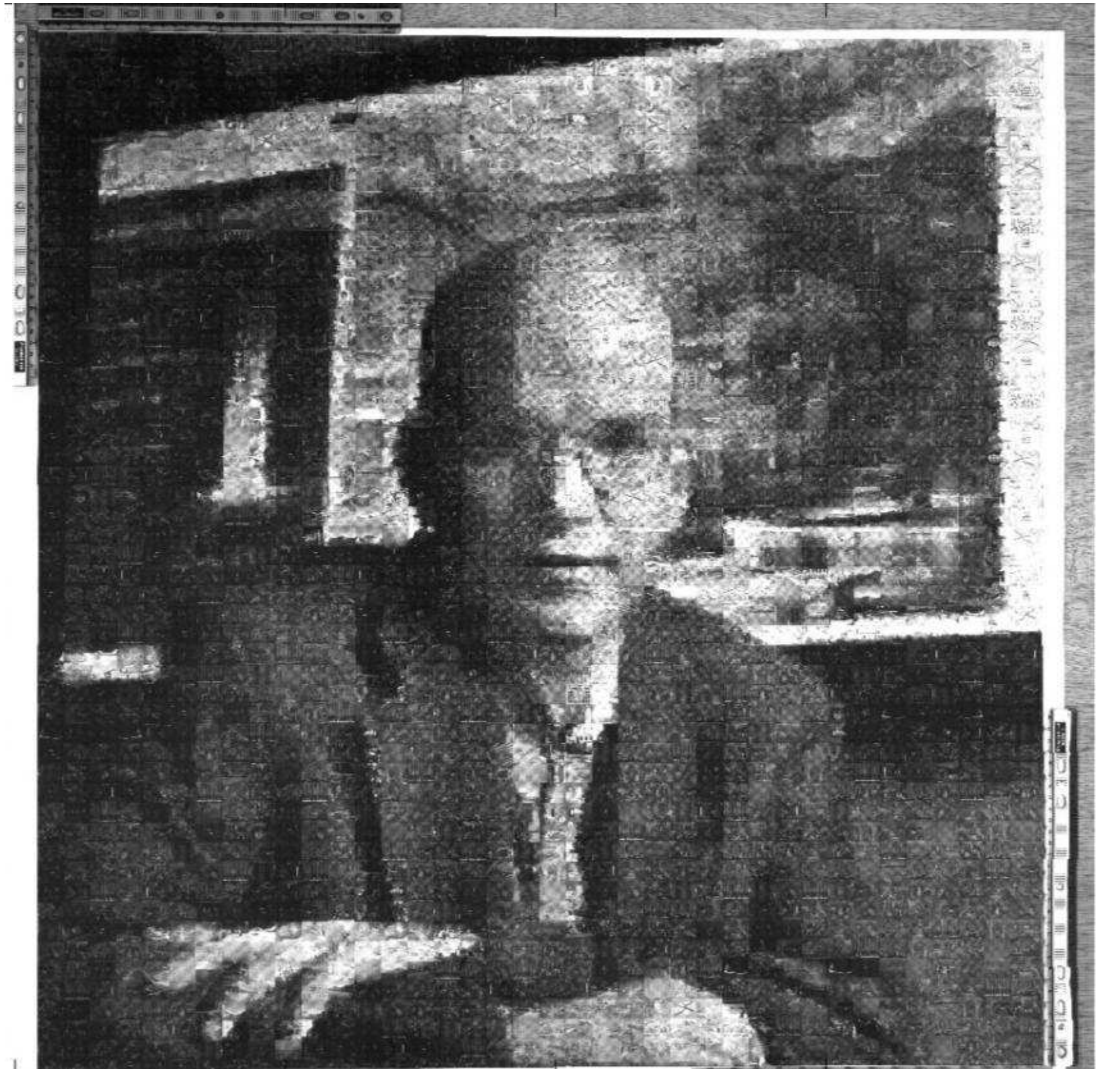


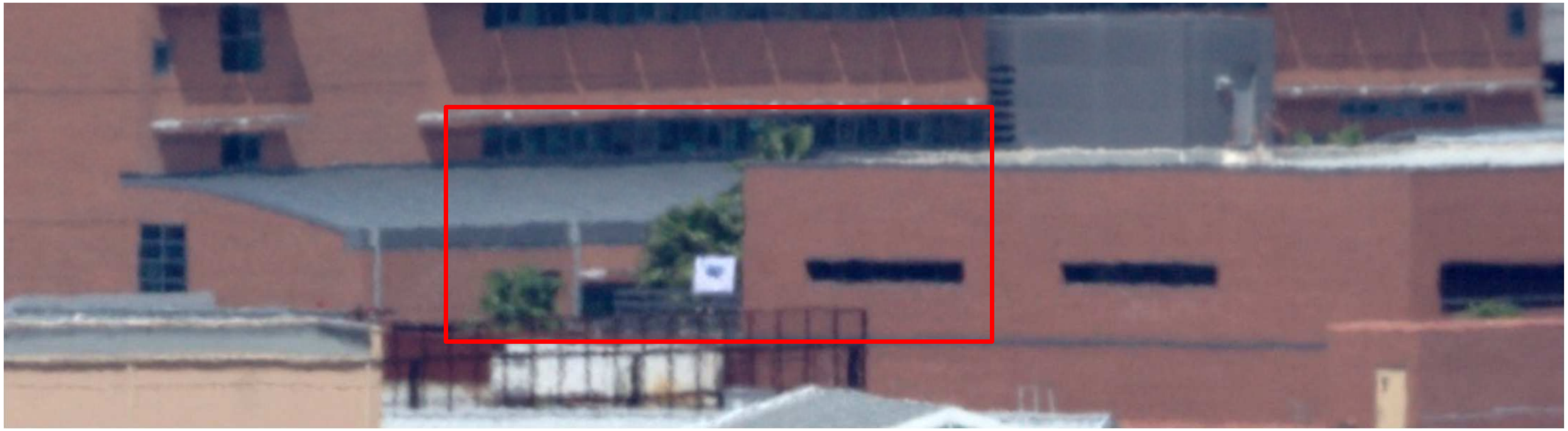
This image is constructed with 16(H)x20(V) small images with 1280x1024 resolution. Every adjacent images are overlapped by 32 pixels with each others.

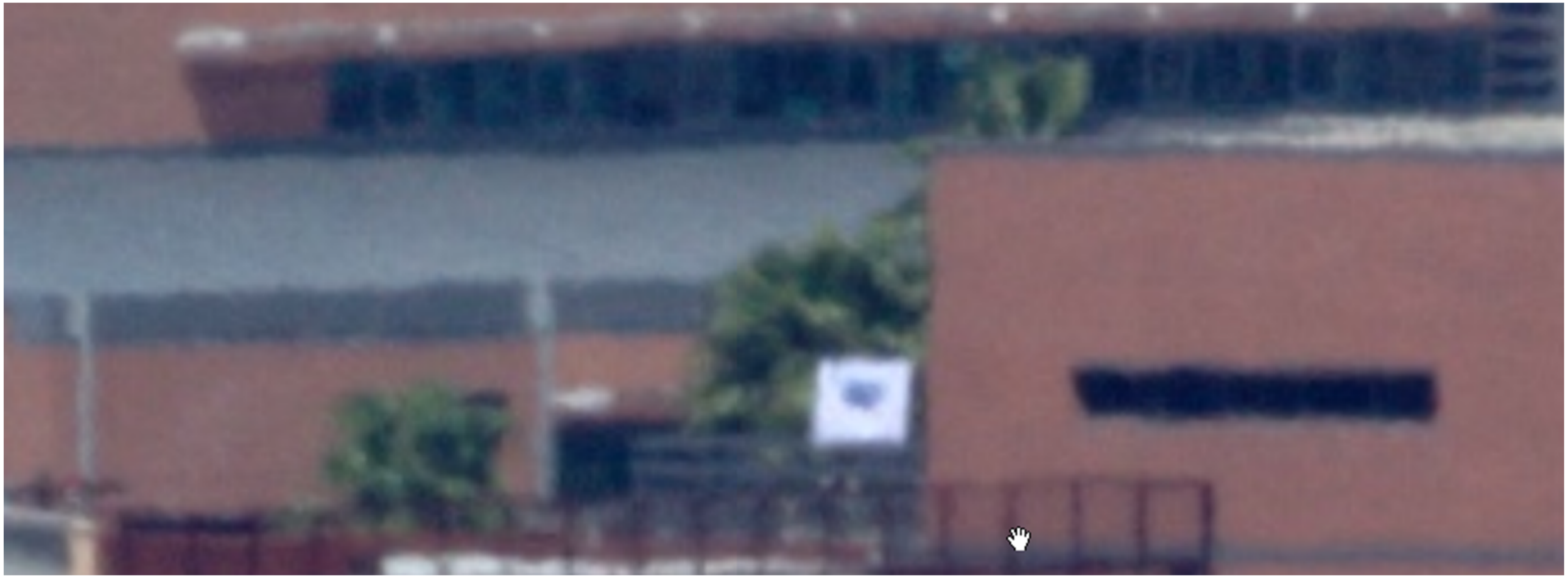
19968(H) x19840(V) pixels= 396,165,120 pixels


10mm







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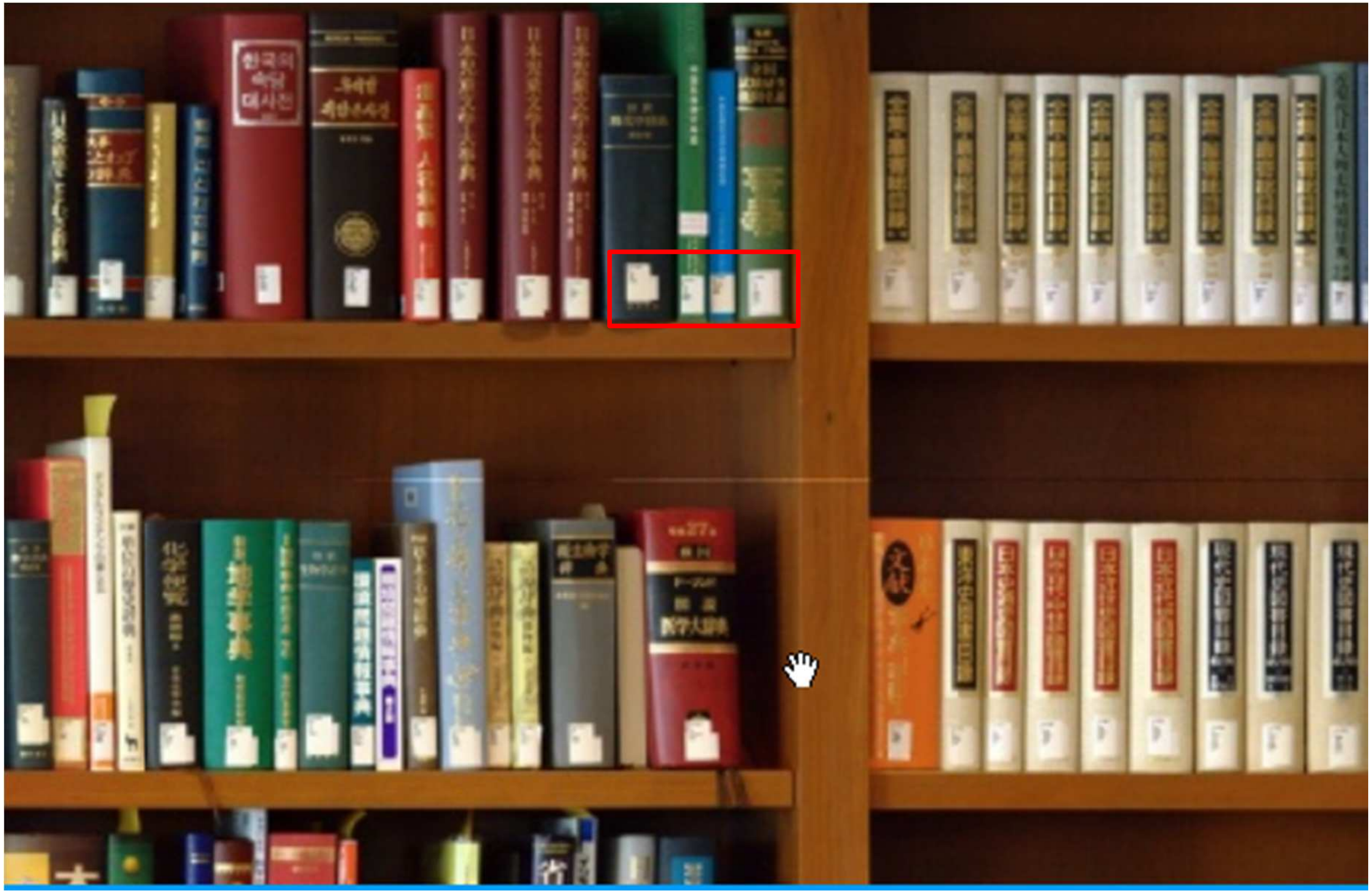


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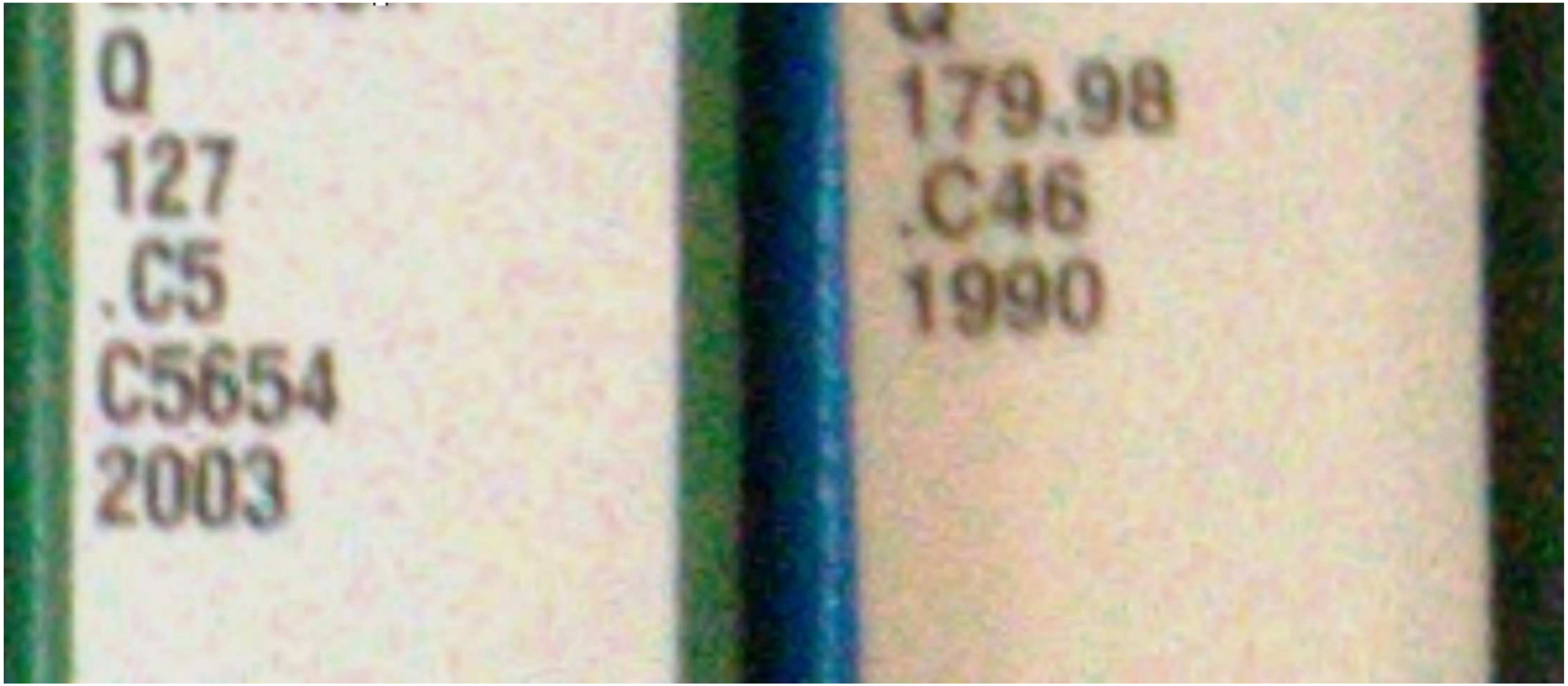
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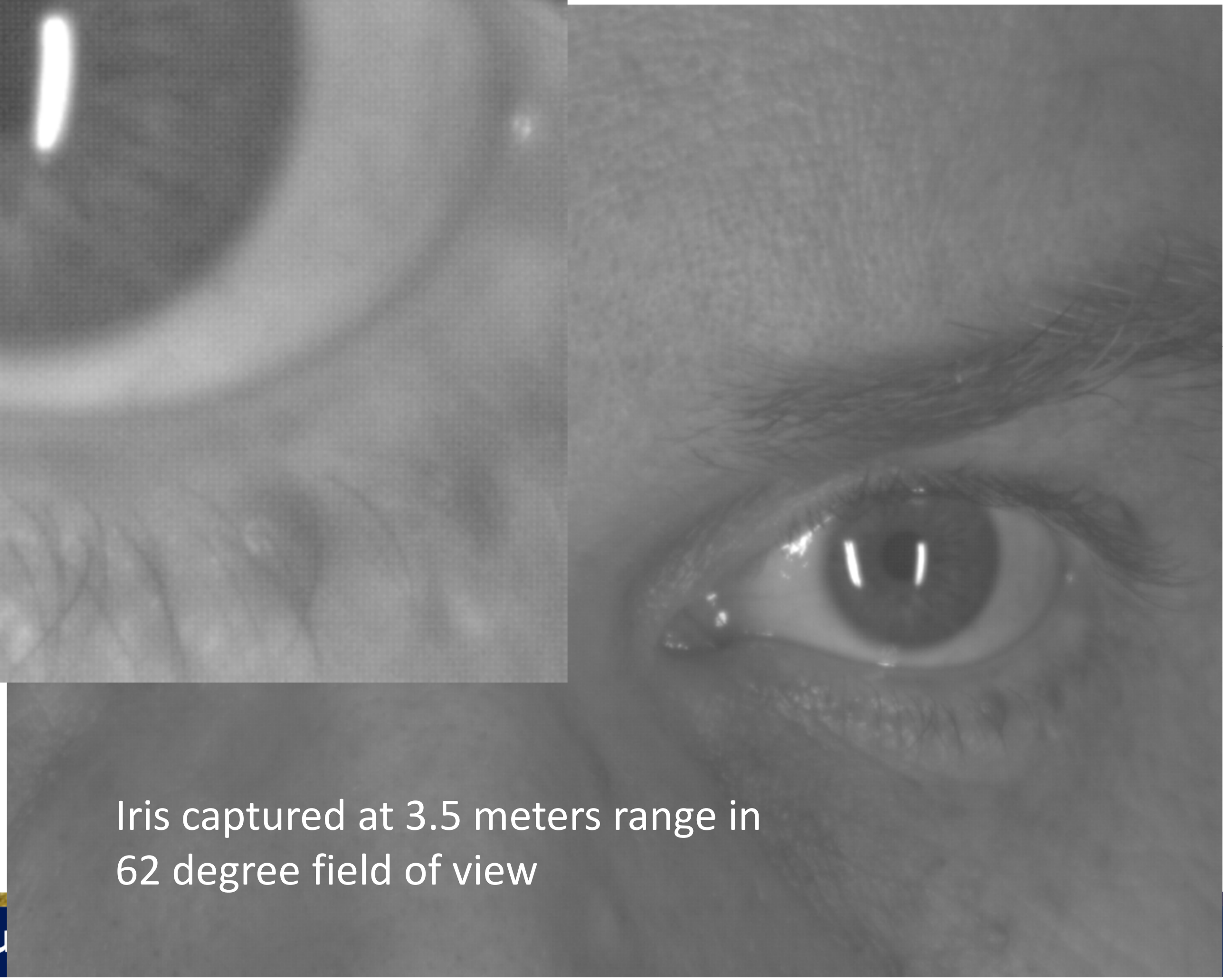

Iris captured at 3.5 meters range in 62 degree field of view

Summary

- Multi-aperture design is a useful tool to manage sampling and signal diversity in imaging systems
- Military and security multi-aperture systems are coming to market now
- Consumer multi-aperture for wide field, close-up scanning, multispectral imaging, HDR may be expected in next 5 years
- Consumer and military very high pixel count cameras also coming using multi-aperture arrays.