Computational Imaging for Extreme Fields of View

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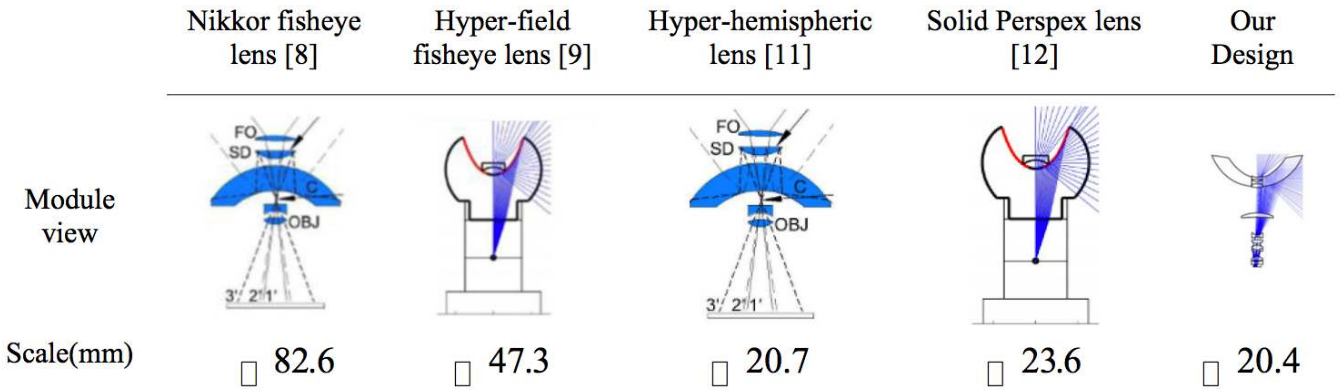
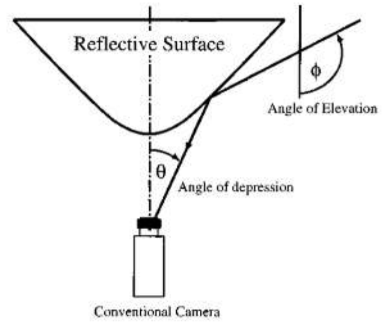
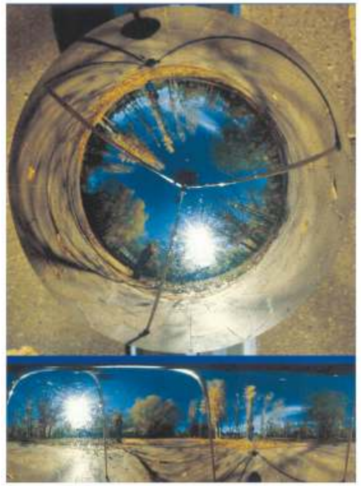
Outline

- Traditional approaches to extreme fields of views
- Computational imaging for
  - Wide field of view for single cameras
  - Combining cameras/optics into parallel channels offers
    - $4\pi/360°$ field of view
      - And high angular resolution
    - Multi-functionality

Traditional approaches to panoramic imaging



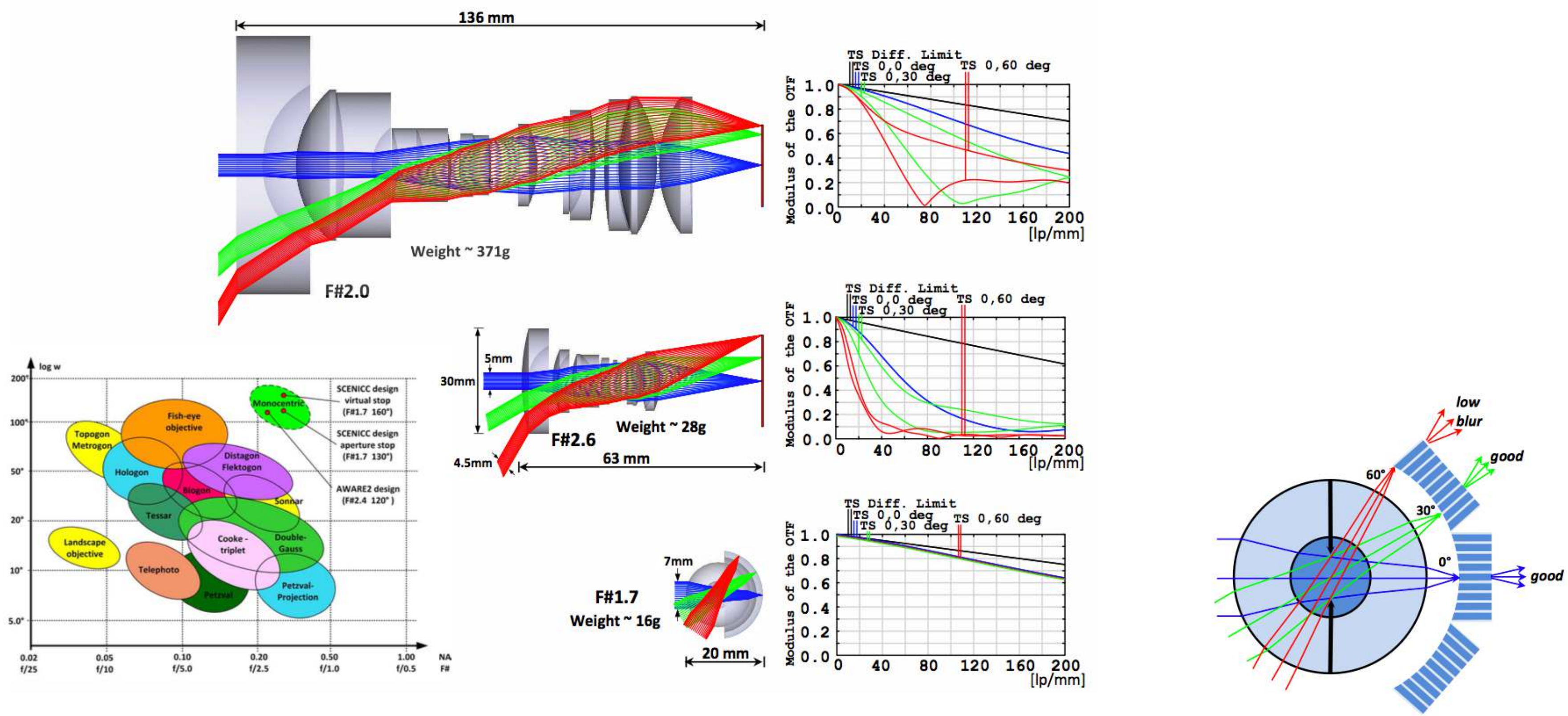




- Total pixel count limited by detector array
- Optical aberrations limit resolution

J. S. Chahl and M. V. Srinivasan, "Reflective surfaces for panoramic imaging," Appl Optics (1997)
1. C. Pernechele, "Hyper hemispheric lens," Opt. Express **24**, 5014–6 (2016).

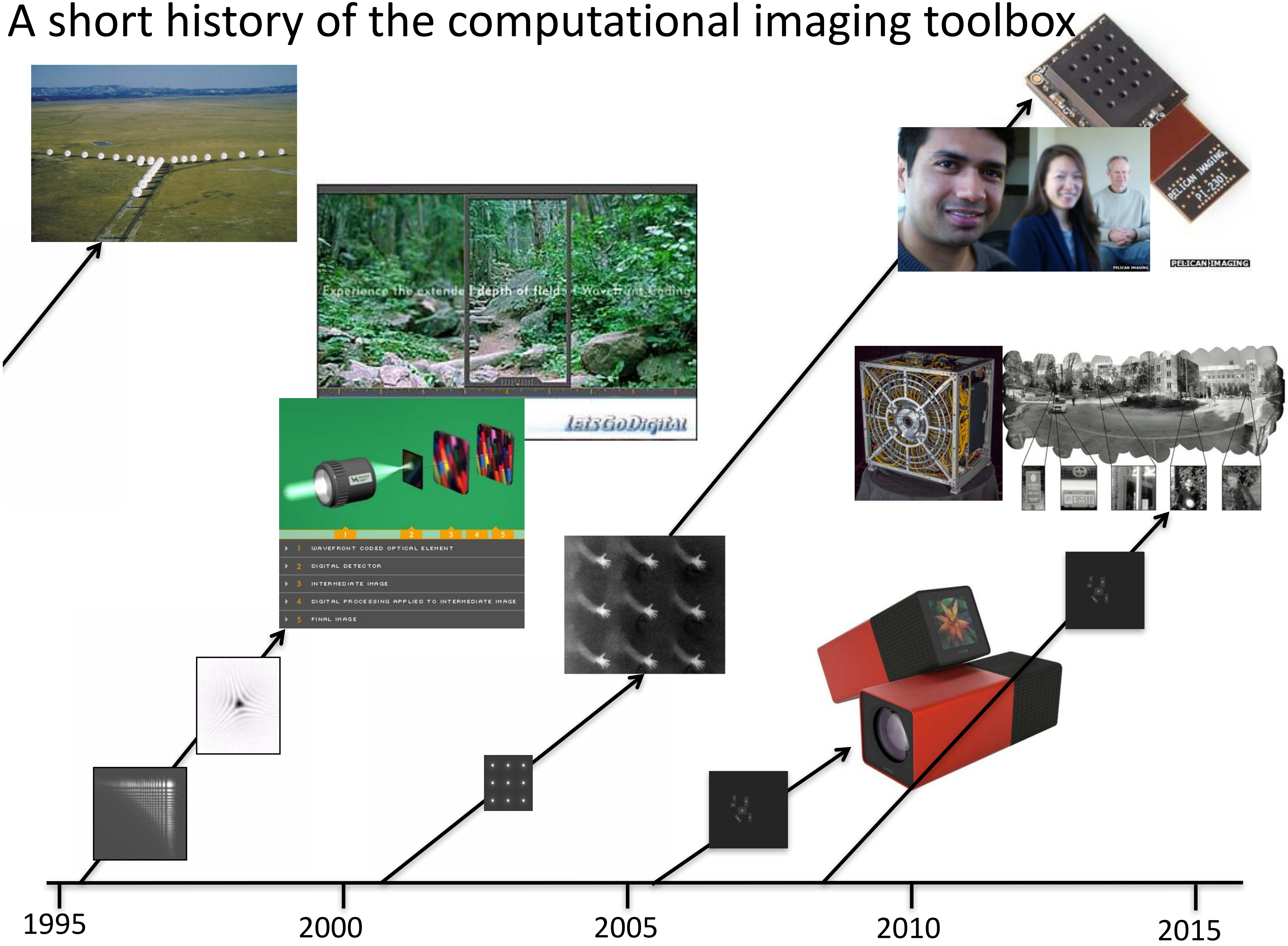
The curved detector array



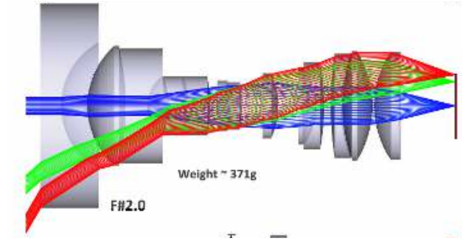
- Spherical detector reduces optical aberrations and enables simpler optics
- Single or multiple detectors?

1. J. Ford, I. Stamenov, S. J. Olivas, G. Schuster, N. Motamedi, I. P. Agurok, R. Stack, A. Johnson, and R. Morrison, "Fiber-coupled Monocentric Lens Imaging," Imaging and Applied Optics CW4C.2 (2013).
2. I. Stamenov, A. Arianpour, S. J. Olivas, I. P. Agurok, A. R. Johnson, R. A. Stack, R. L. Morrison, and J. E. Ford, "Panoramic monocentric imaging using fiber-coupled focal planes," Opt. Express **22**, 31708–14 (2014).

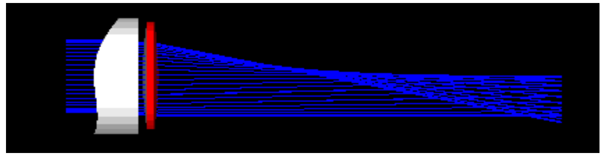
A short history of the computational imaging toolbox



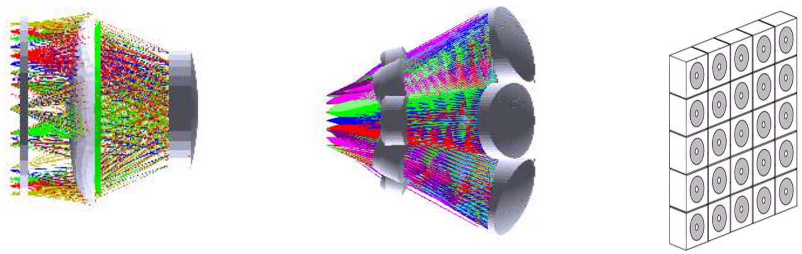
- The tradition: single lens and single detector array
  - Trade Field of View for angular resolution
  - Optical aberrations increase lens complexity, size, weight, cost



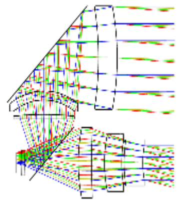
- Computational imaging: transfer complexity from optics to computation
- Promising Computational Imaging techniques
  - Wavefront coding
    - Increased FoV (x2 linear) from simpler optics



  - Parallelised imaging
    - Gigapixel, wide-field, scaleable
    - Single-aperture: Multiscale
    - Multi-aperture and integral imaging

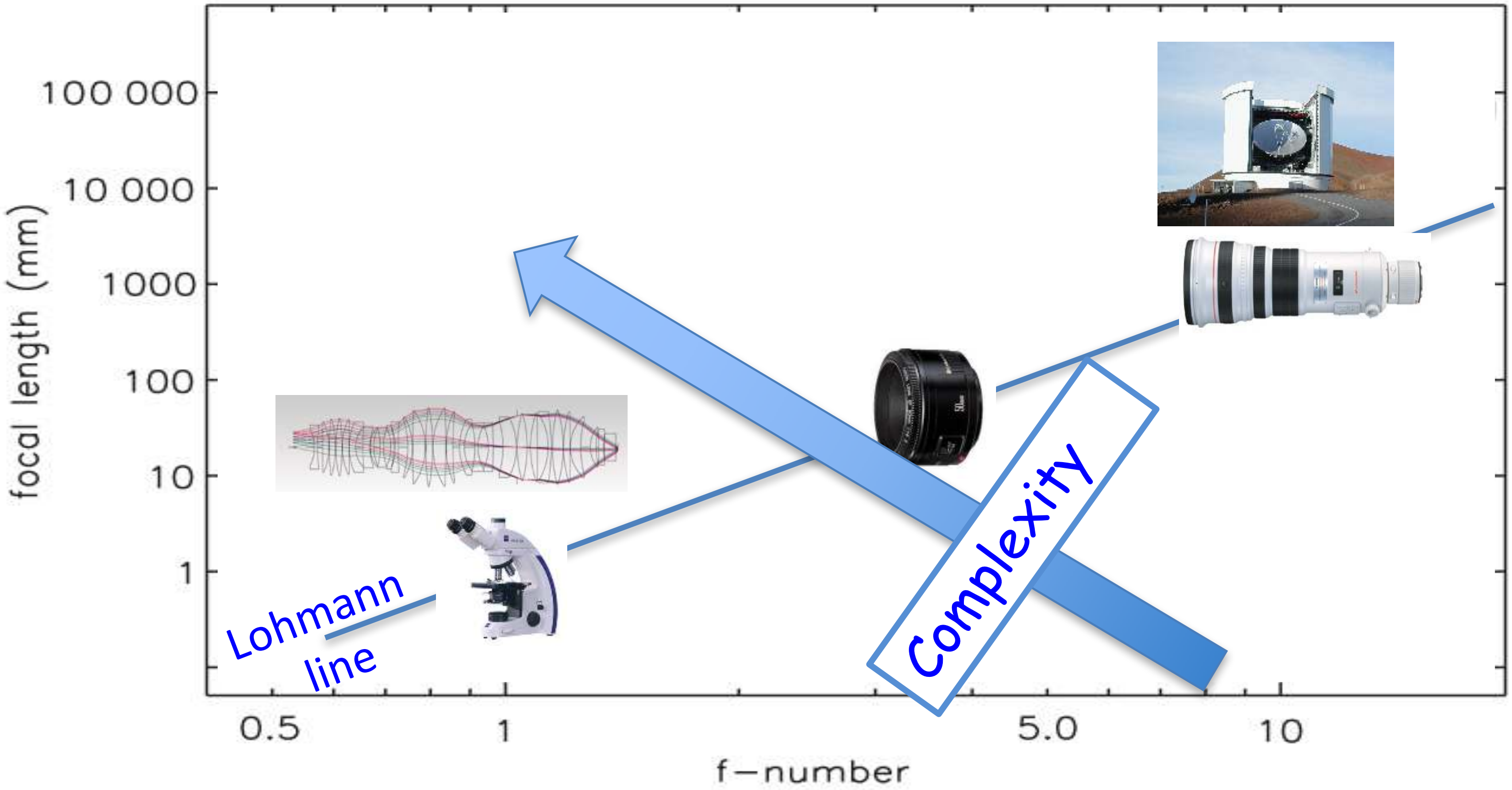


  - Superimposed imaging
    - Efficient use of high-cost (infrared) detector arrays



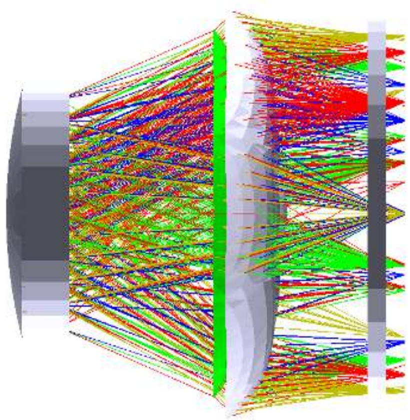
- Compact, scaleable architectures
  - High angular-resolution
  - Gigapixel imaging
  - High sensitivity (low f/#)

Optical aberrations

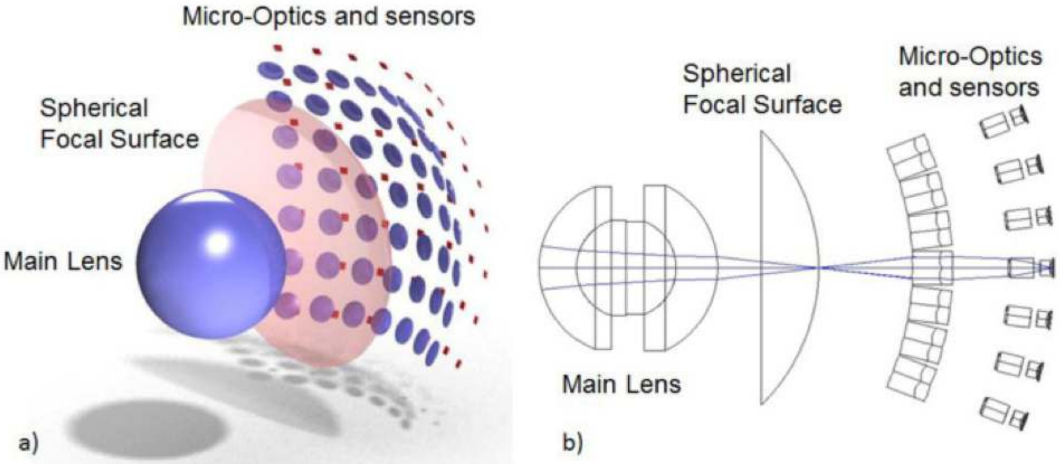


- Diffraction is scale invariant
- Geometric aberrations increase with dimensions and field of view
- Shannon Limit for a 1cm diameter lens
    - Visible: $N_{pix} \sim 10^9$
    - Thermal infrared : $N_{pix} \sim 2.5 \times 10^6$

Multiscale imaging



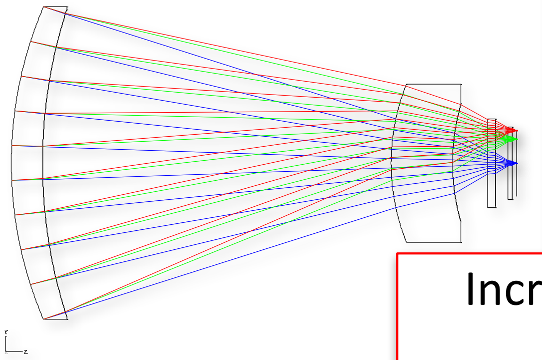
Multiscale imaging



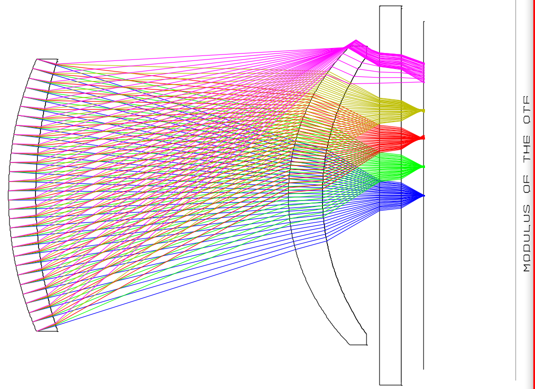
Hui S. Son et al, Optics Express, Vol. 19, No. 17 / OPTICS EXPRESS 16132 (2011)
Brady, D. J., et al. (2012). Multiscale gigapixel photography. *Nature*, *486*(7403) 2012
Daily Mail

Aberration correction
Multiscale – Imaging for extreme FoV

Baseline system 7°



Increase FoV to 35°



Multiscale: single-detector, f/2

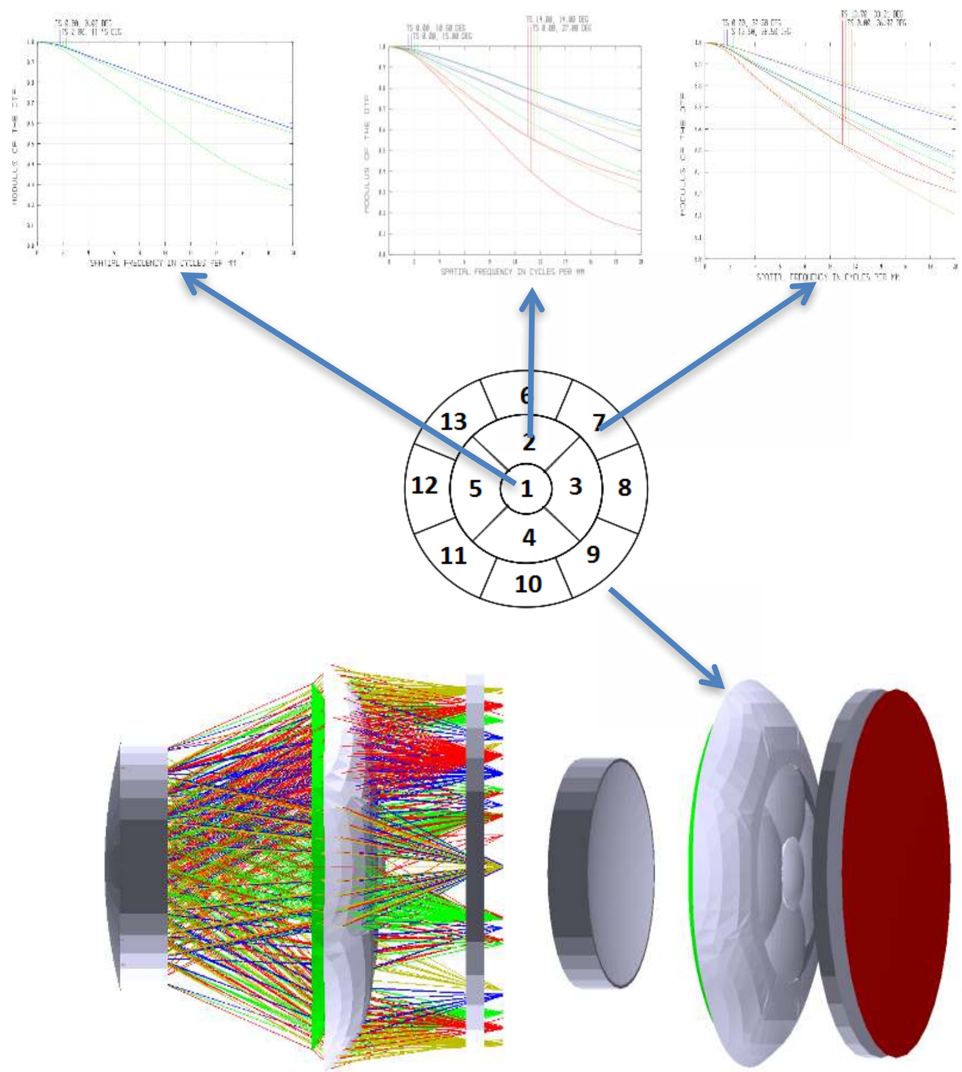
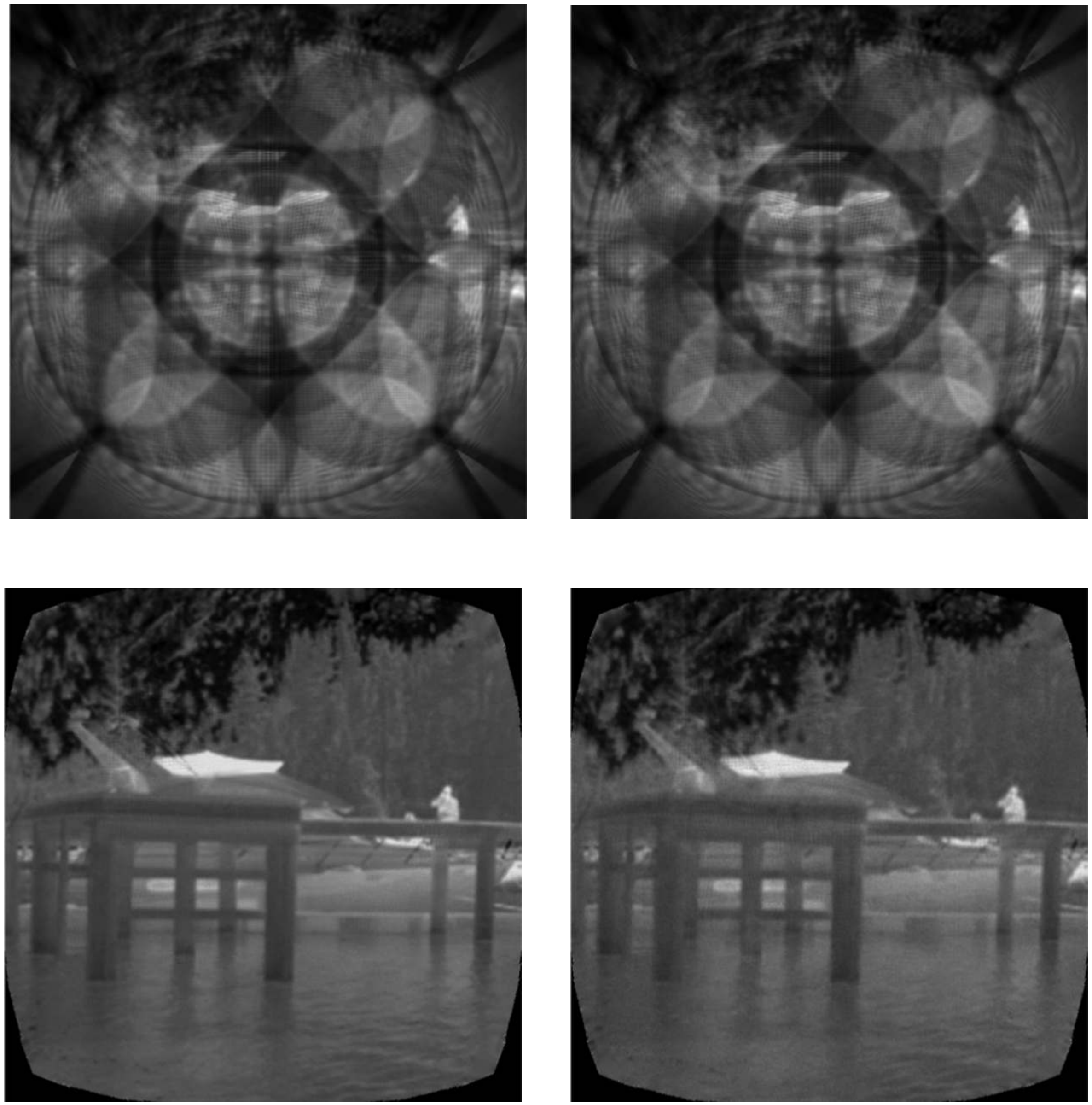


Image reconstruction

Recorded image

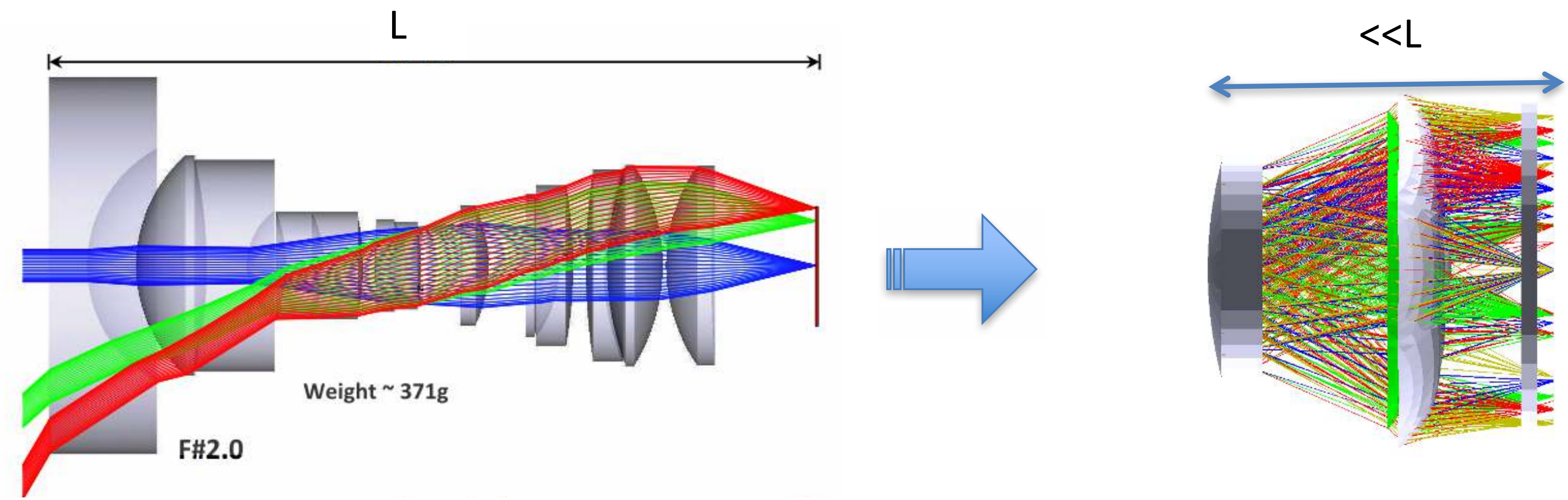
Reconstructed images



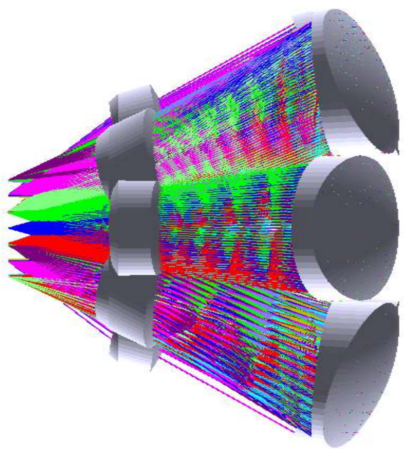
SNR=100 SNR=25

Principle advantage

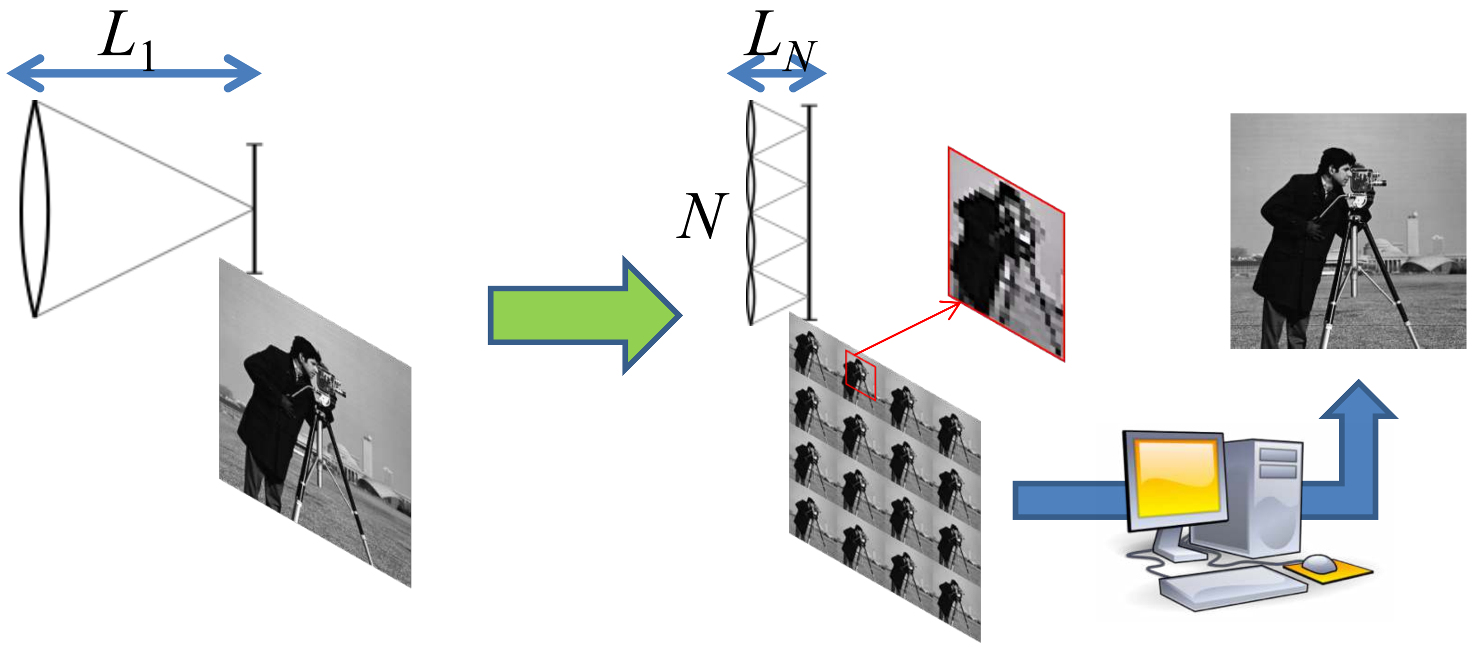
- Wide field of view from compact optics
  - Single detector array
  - High throughput (eg f/1)



Multi-aperture imaging



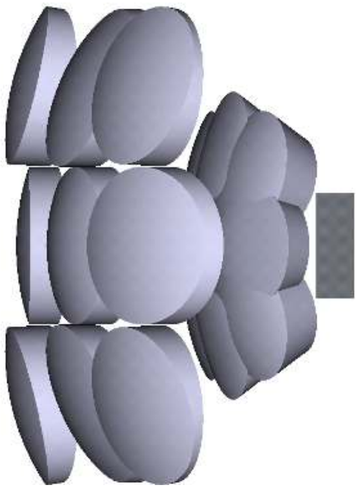
- Multi-aperture super resolution in snapshot
- Equivalent performance to conventional system
  - but with reduced length
  - Aliasing enables super-resolution



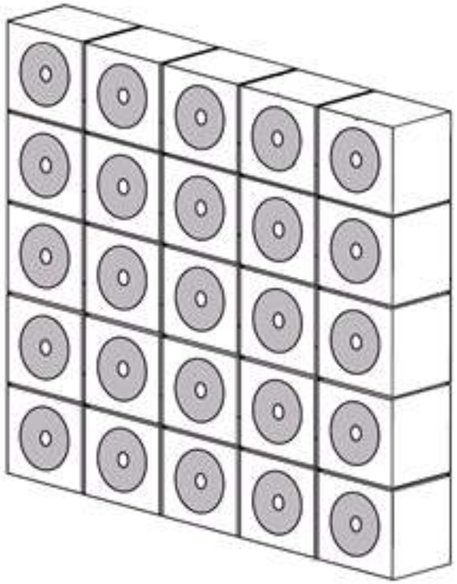
$L_N = L_1 / N$: Length reduction by a factor of N

HR Multi-aperture imaging

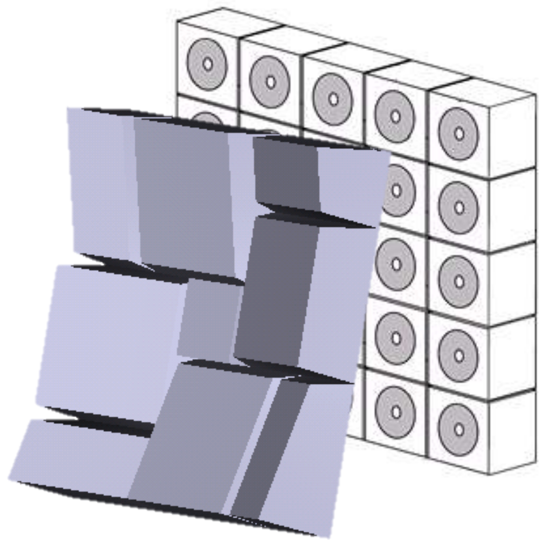
Solution 1
Free-form lenslet array



Solution 2
Multi-camera array



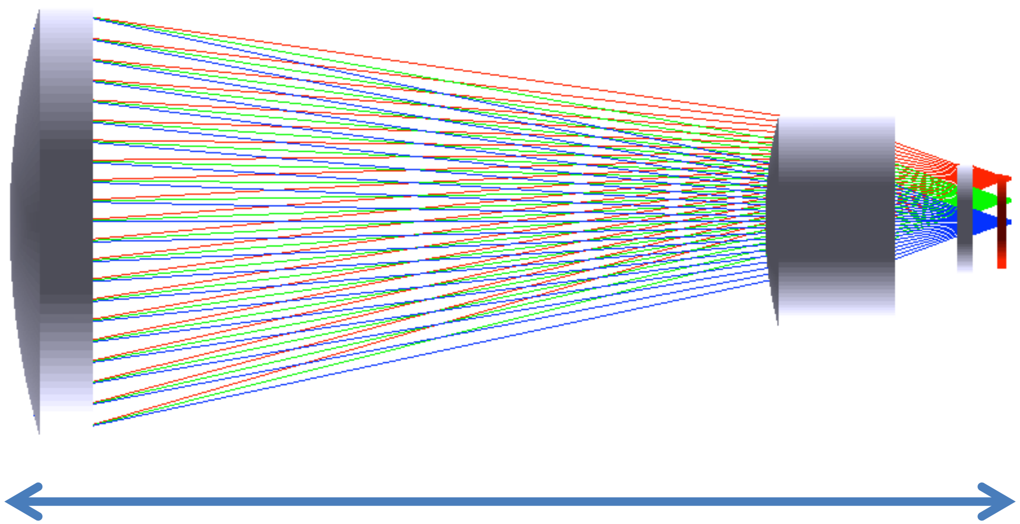
Solution 3
Multi-aperture mosaic



Solution 1: Free-form lenslets

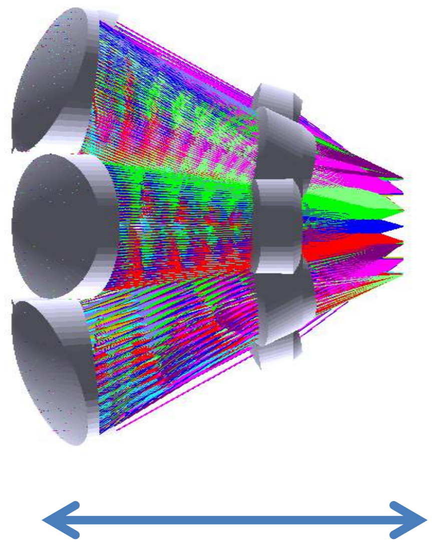
- 3x3 multi-aperture design with customized 2 elements
  - Single detector: 640x640 pixels @25µm pitch
  - Wavelength in the LWIR range: 8µm - 12µm
  - Non-redundancy achieved by design (varying distortions)

Conventional design



L=185mm

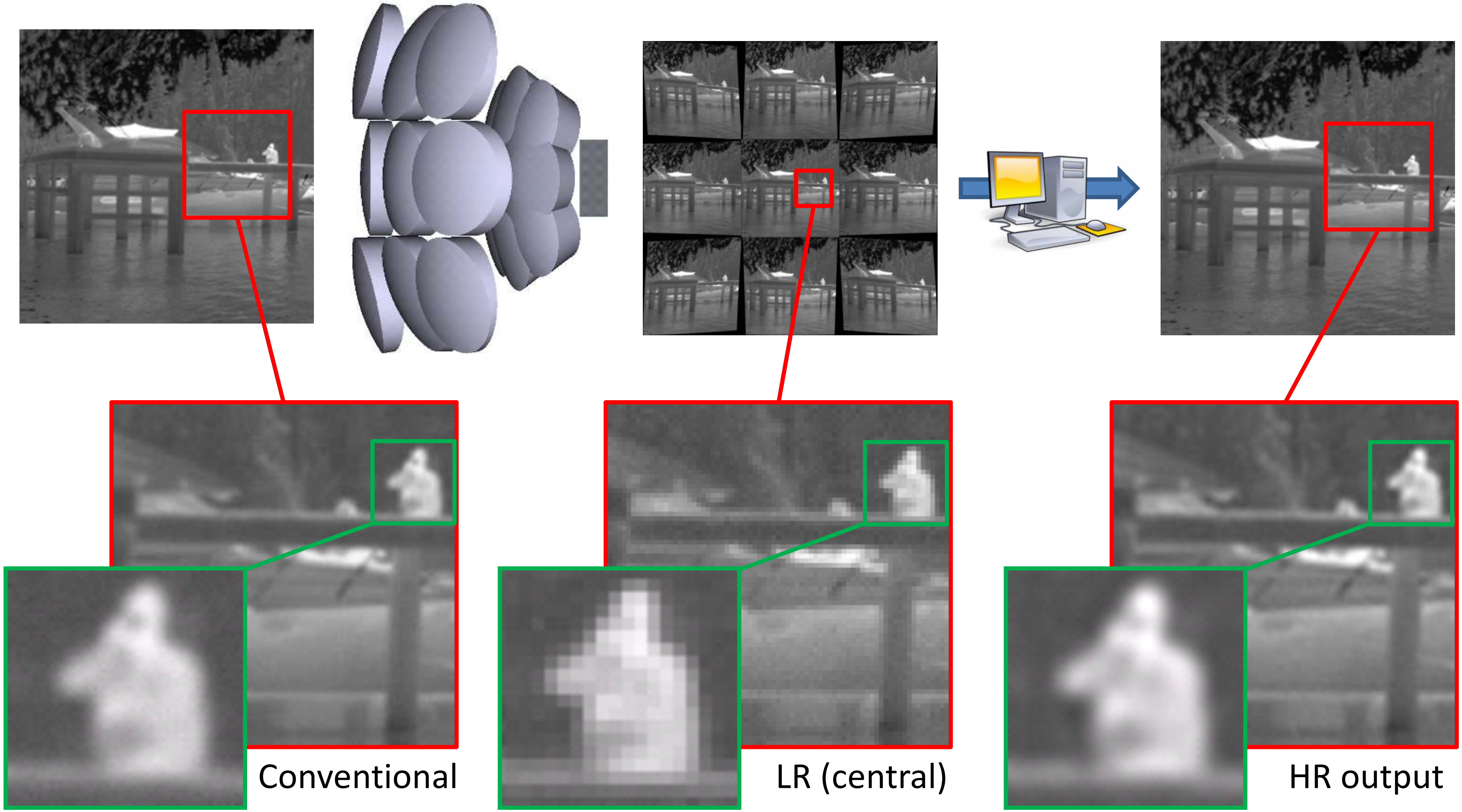
Multi-aperture design



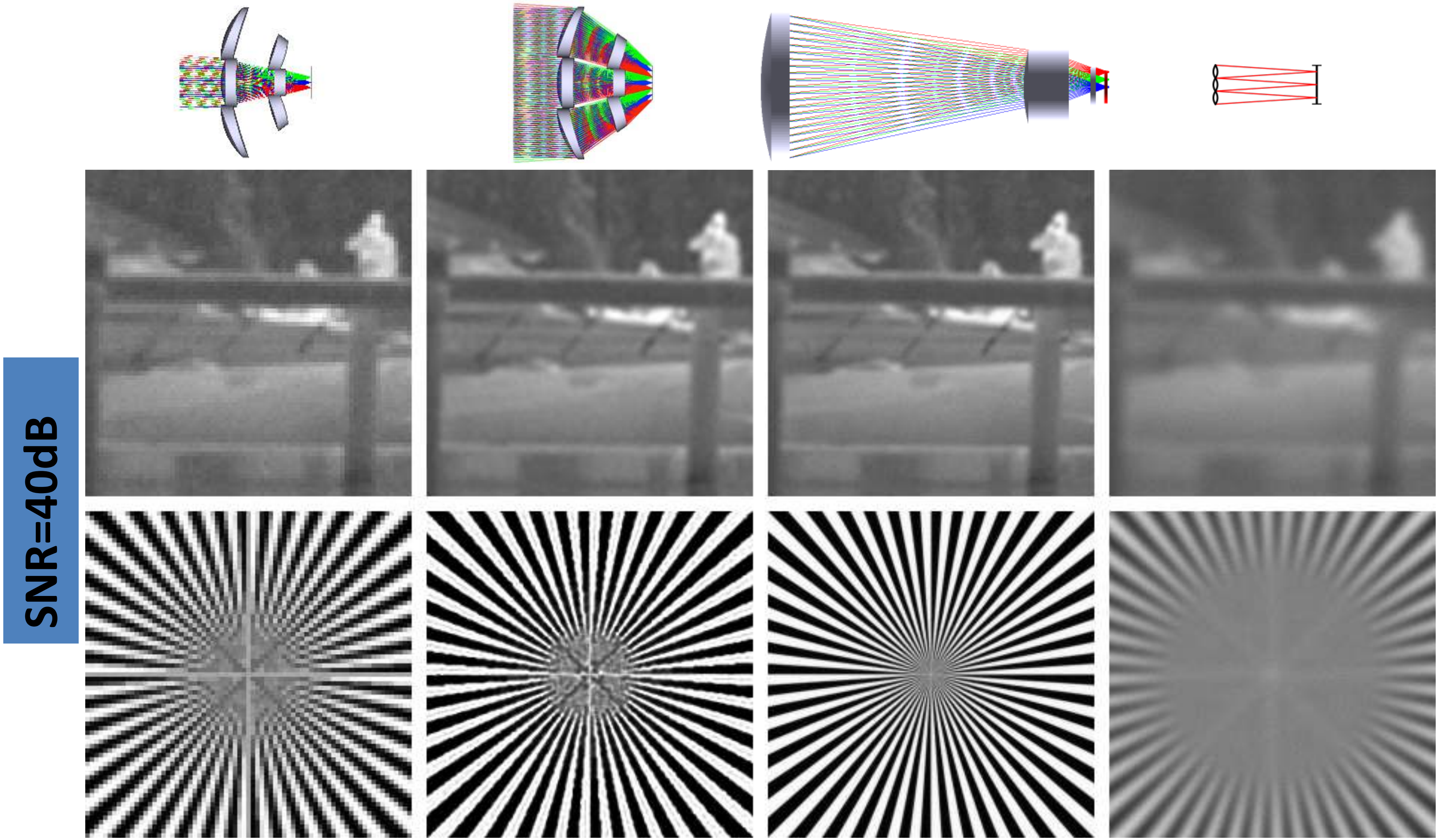
L=45mm

G Carles, G. Muyo, N. Bustin, A. Wood and A.R. Harvey, JOSA A- 32, 3, pp 411-419 (2015)

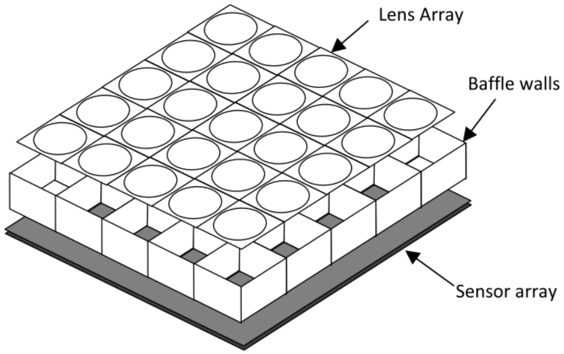
Solution 1: Free-form lenslets

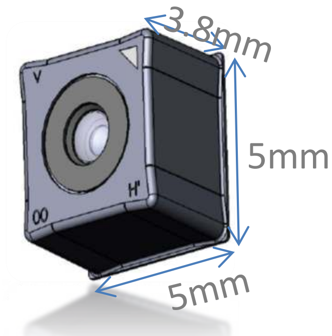


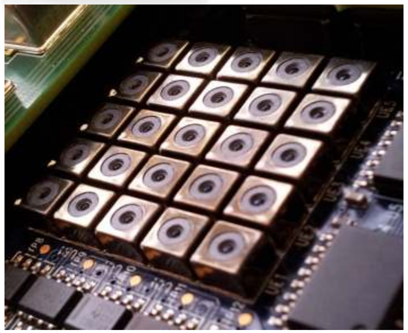
Solution 1: Free-form lenslets

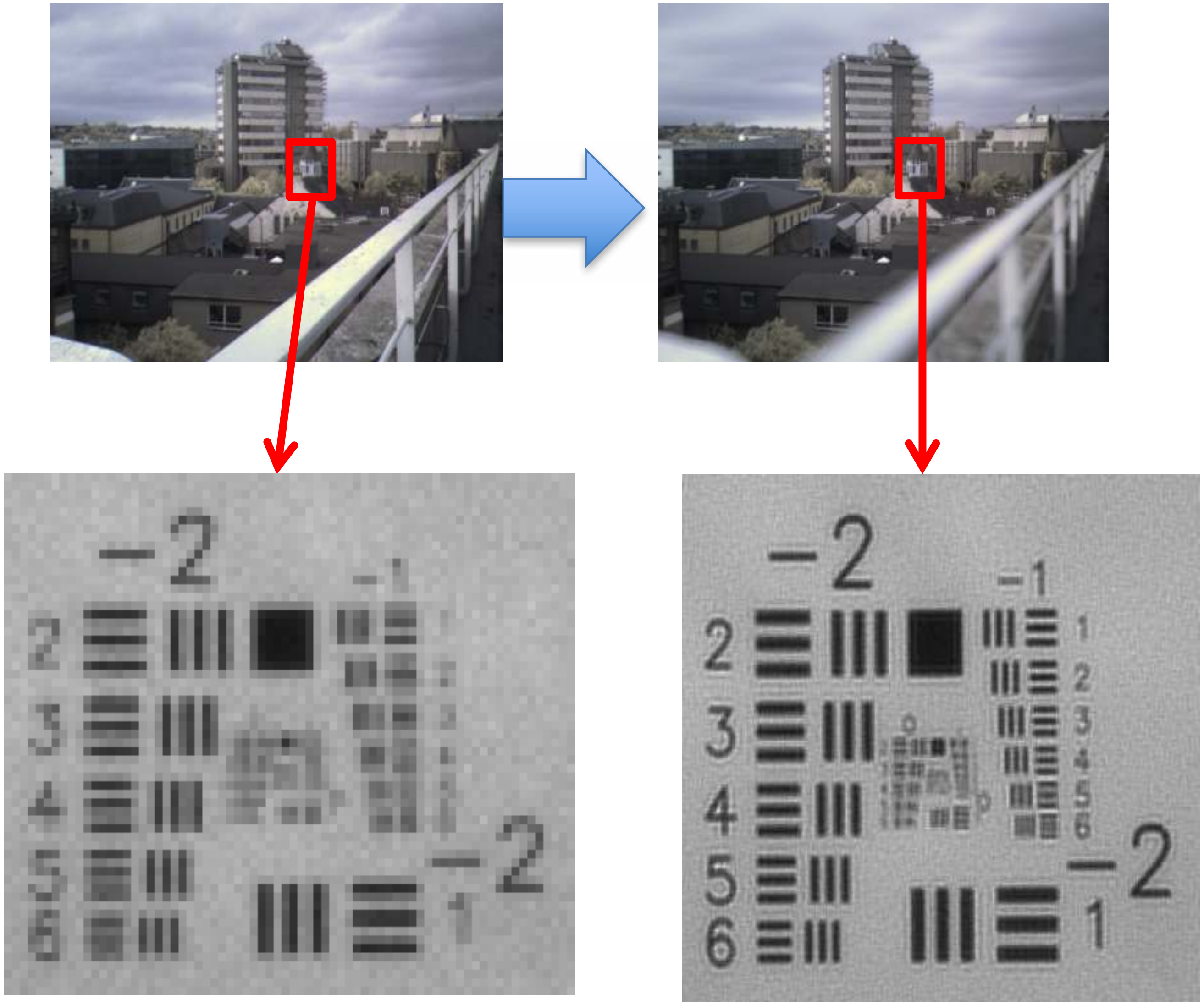


Solution 2: Multi-camera imaging: experimental 50-Mpixel imager (visible)







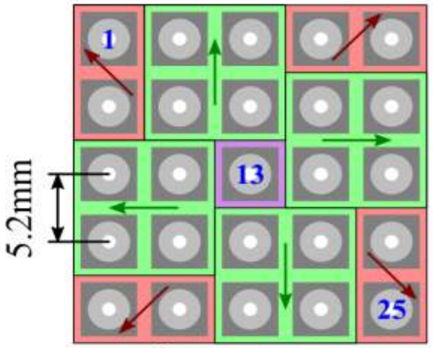


Carles, G., Downing, J. & Harvey, A.R., Opt. Let. 39(7), p.1889 (2014).

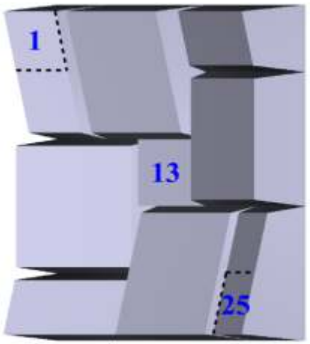

Image from one camera
25 images combined

Solution 3:Multi-aperture foveal mosaic

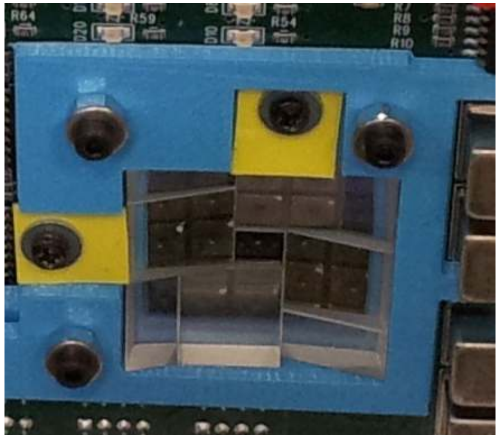
- Camera array with integrated multi-prism element
  - Super-resolution in biomimetic fovea PLUS FoV extension
  - 50°x40° ➔100°x80°

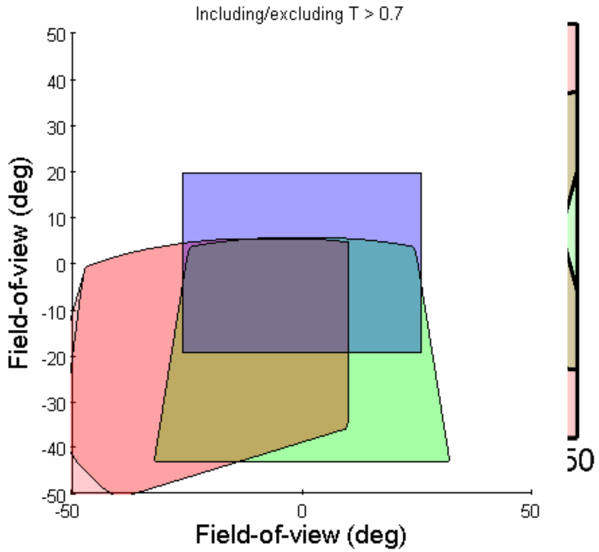


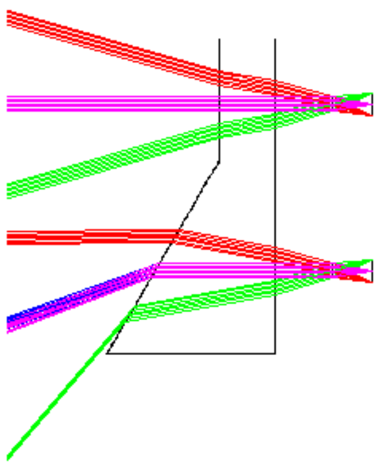
Camera array

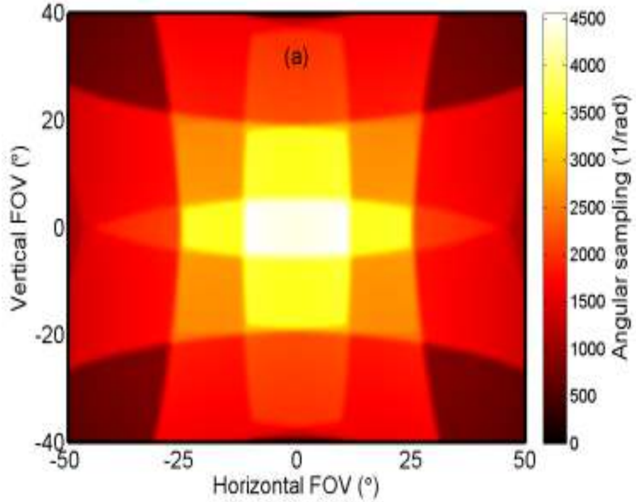


prism array









Solution 3. Multi-aperture mosaic

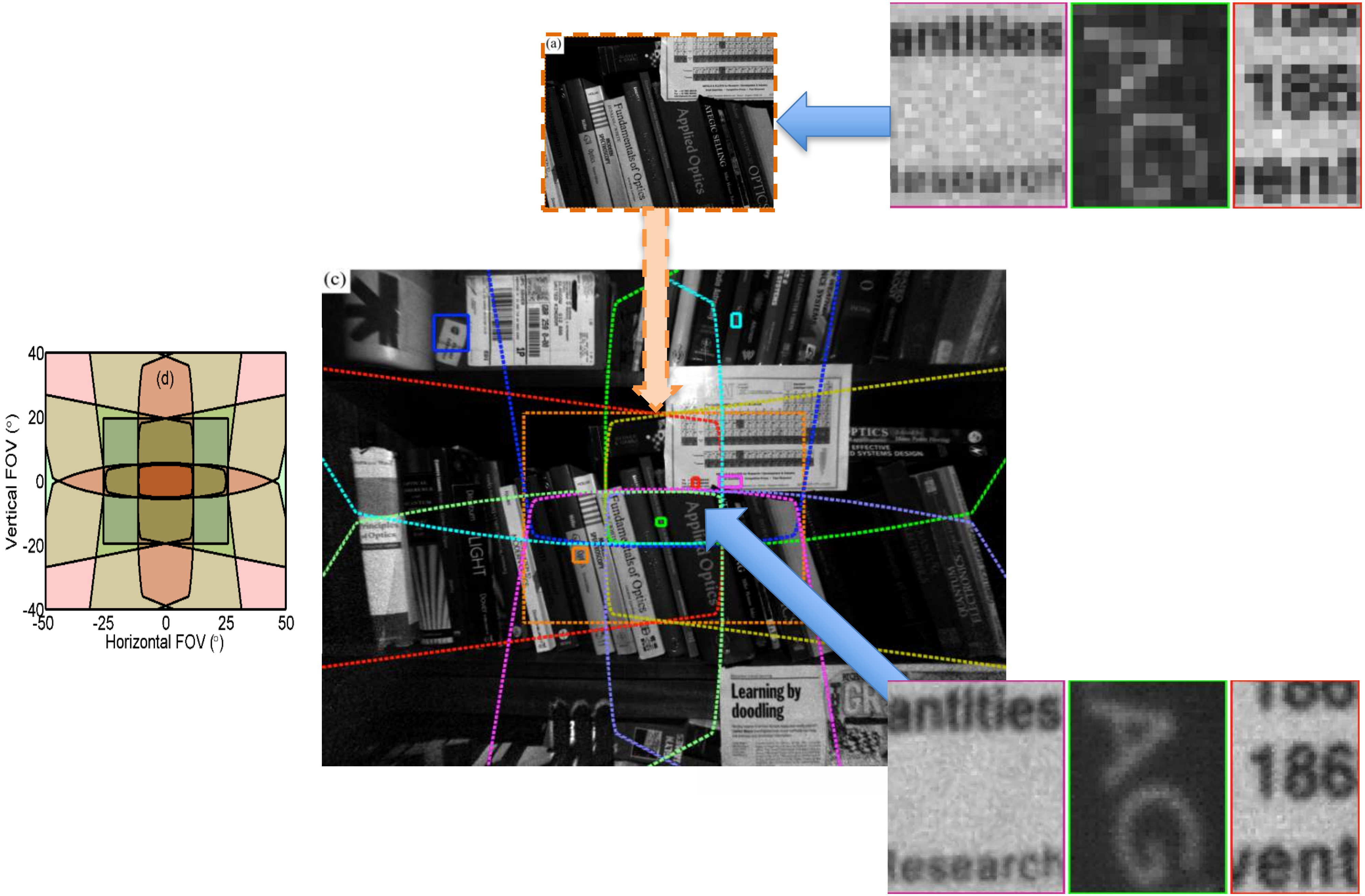
- Simulation using Zemax warp calculation

Central camera

All cameras

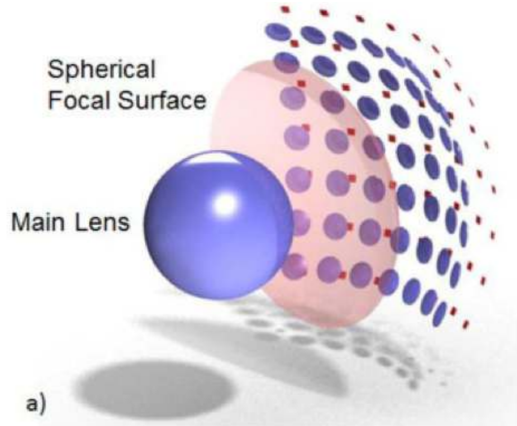
Reconstructed image

Foveal multi-aperture: a bookcase

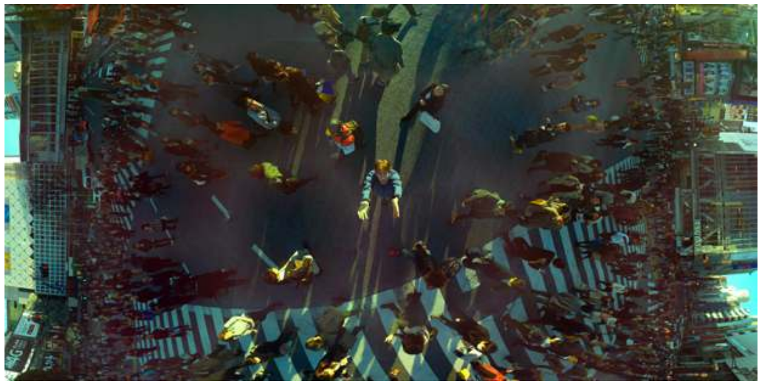


Spherical camera arrays

- Now available as consumer products

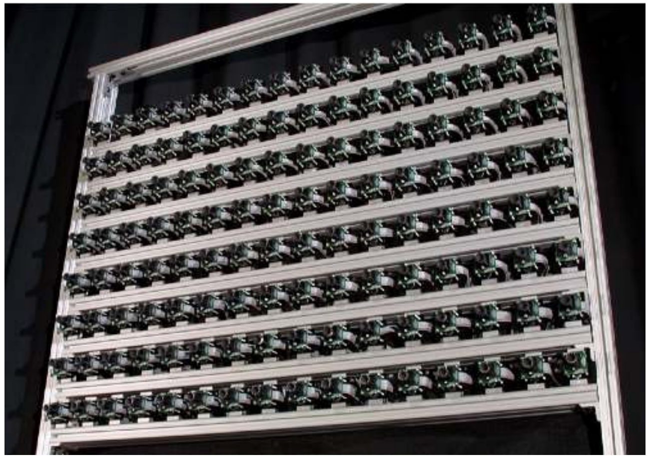


Note similarity to
Multiscale imaging

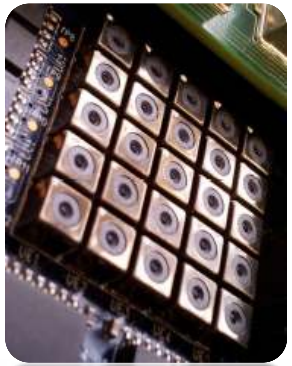


108 Mpixel snapshot

- Multi-aperture imaging (with field overlap) introduces parallax…
  - 3D imaging and ranging
  - Seeing through obscurities

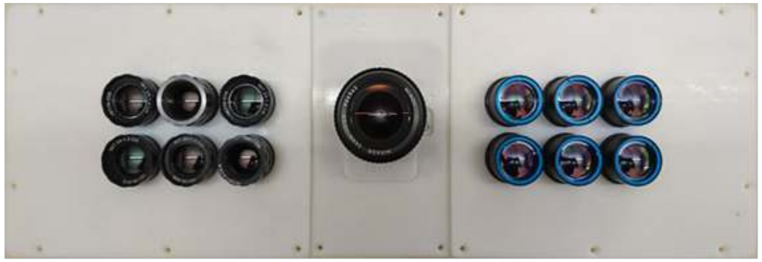


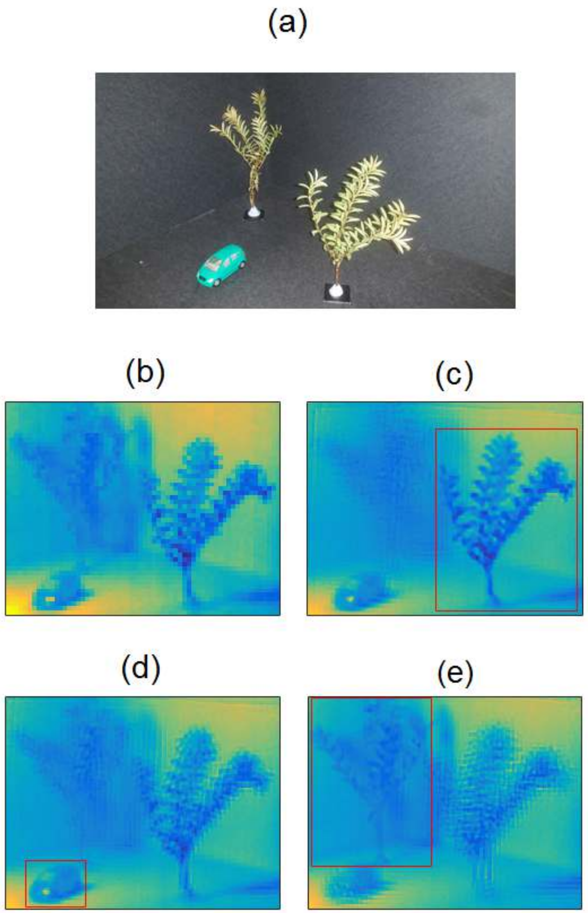
  - And multi-functionality
    - Multi-spectral
    - Foveal
    - …



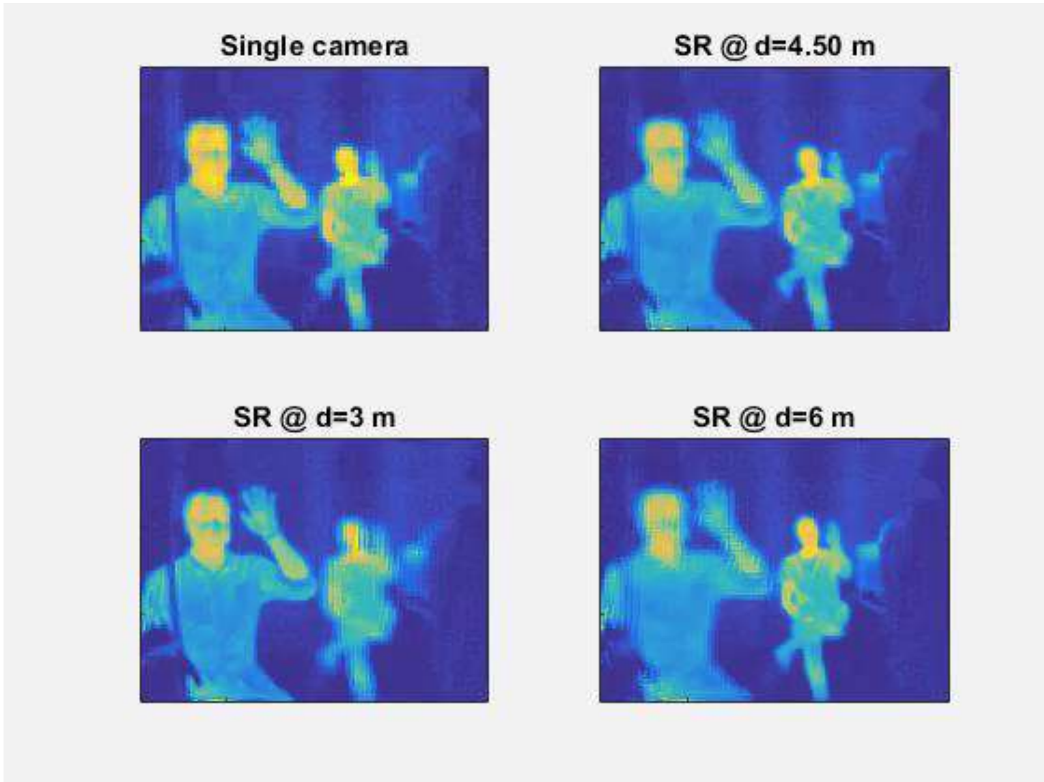
Vaibhav Vaish, PhD thesis Stanford University, 2007

And in the infrared?



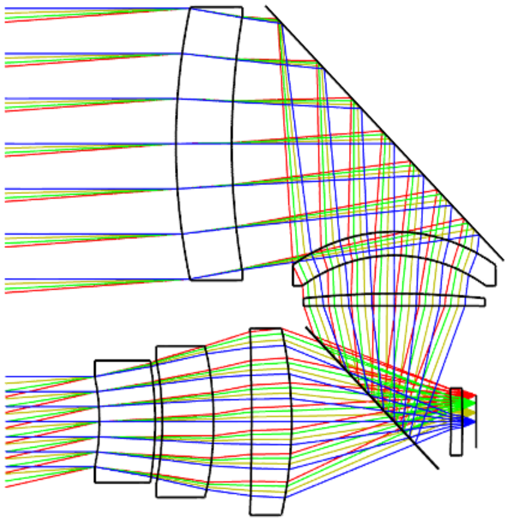


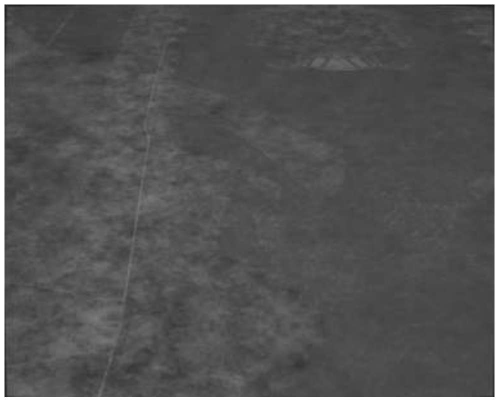
- Low-resolution consumer thermal infrared cameras offer low-cost Camera arrays
  - Spherical-camera Thermal Imaging
  - 3D imaging
  - Imaging through obscurations
  - Convenient deployment



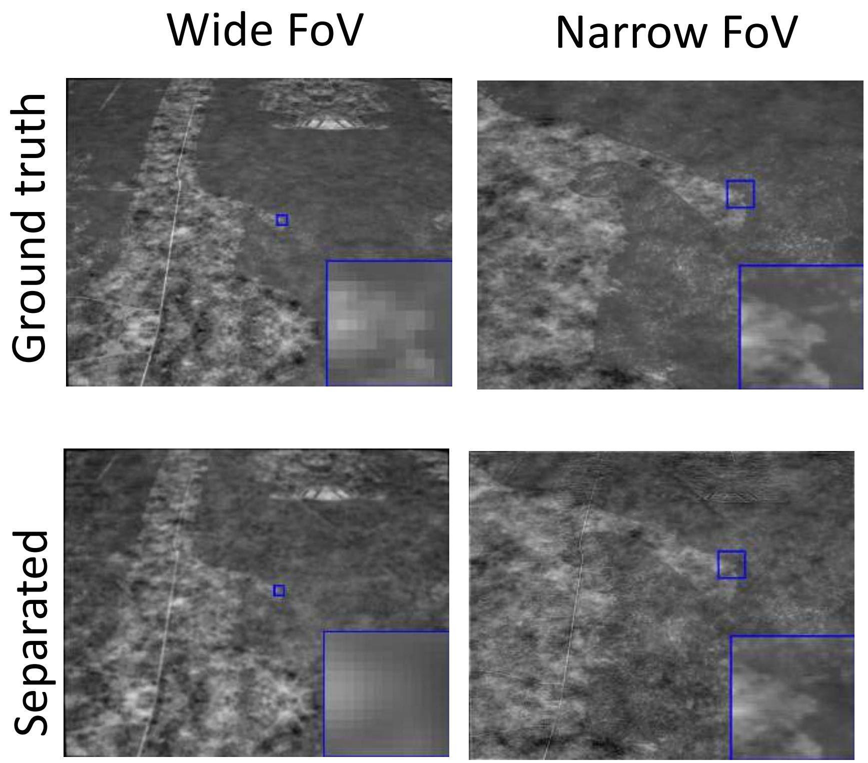
Superimposed imaging: dual field of view

- High-performance detector arrays in the thermal infrared can dominate system cost
  - Multiple channels share a single detector array?
- Multiple images superimposed onto a single detector array can be computationally separated

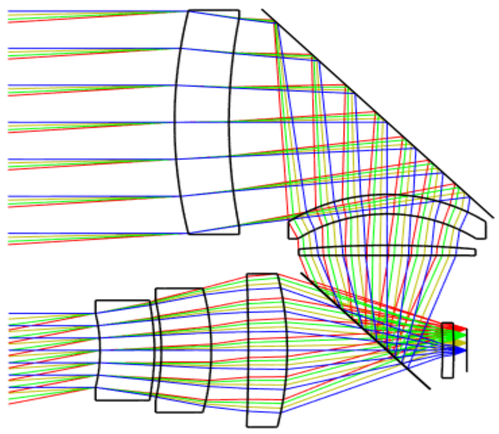


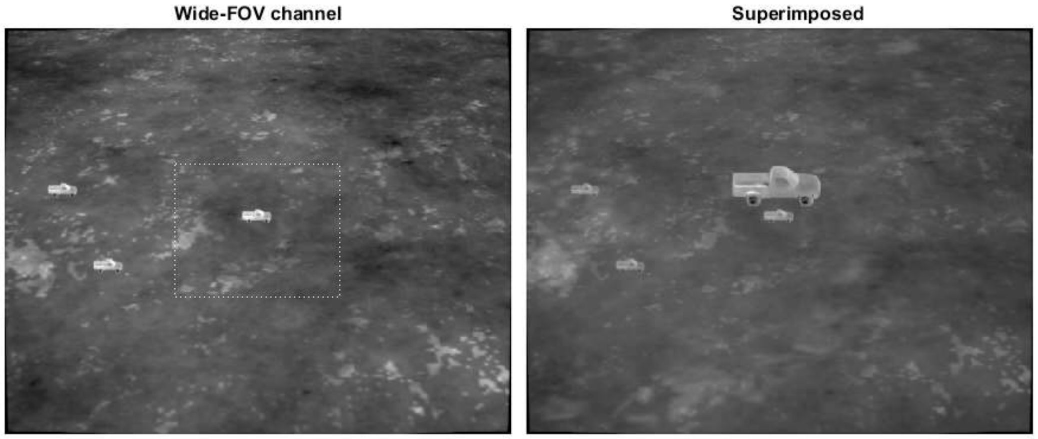


Superimposed video

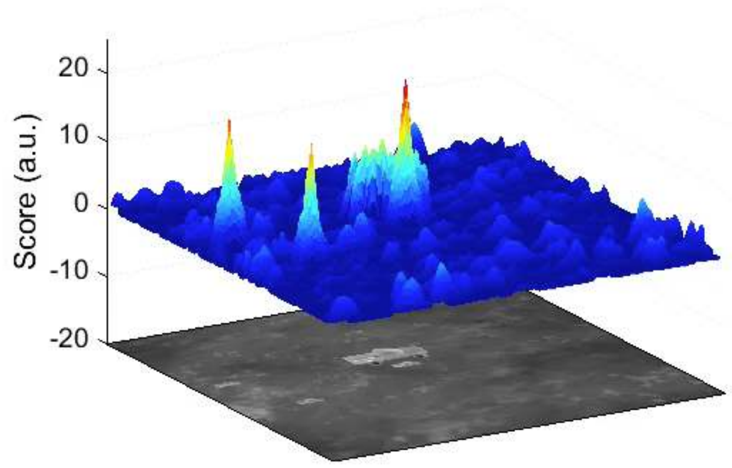


Superimposed imaging with ATR





- ATR can perform directly on superimposed images



Conclusions

- Single detector array computational imaging
  - Wavefront coding, multiscale/multi-aperture
  - More compact, lower weight wide-field cameras
- Multi-detector array
  - Multiscale and Multi-aperture
  - Scaleable spherical or part-spherical cameras
  - Multi-aperture offers multi-functionality
    - 3D imaging and ranging
    - Seeing through obscurations
    - Multi-spectral
    - Foveation
    - ….
- The role of the optics is to transfer information to the detector
  - It does not need to look like an image
  - The computer does the rest
    - Image reconstruction
    - ATR