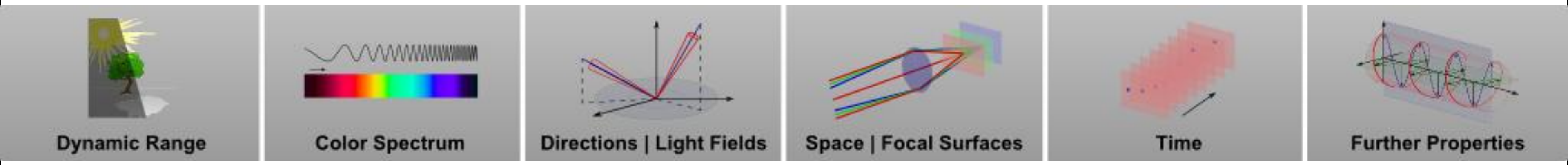
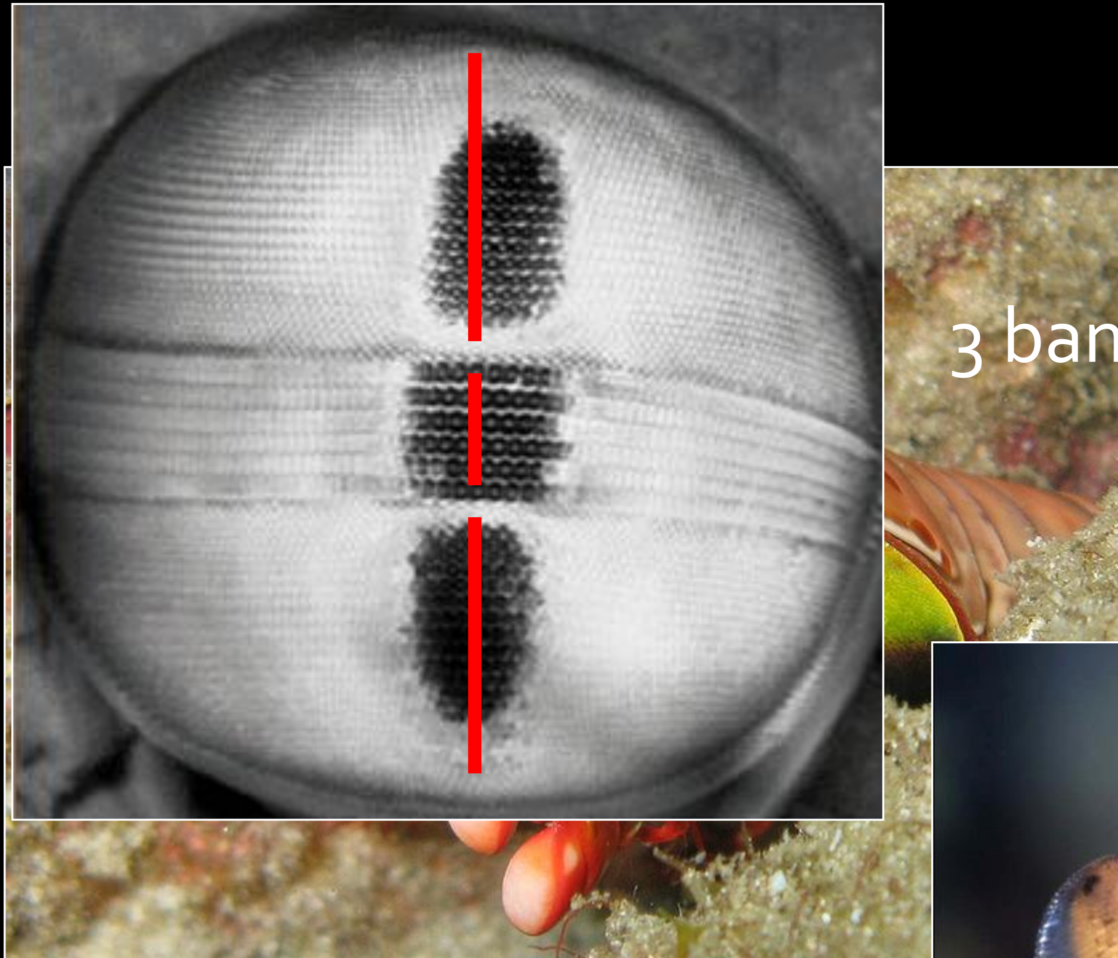
2015 – international year of light

Ivo Ihrke

Computational Imaging Modalities



Journées Nationales de la Recherche en Robotique, 22/10/2015

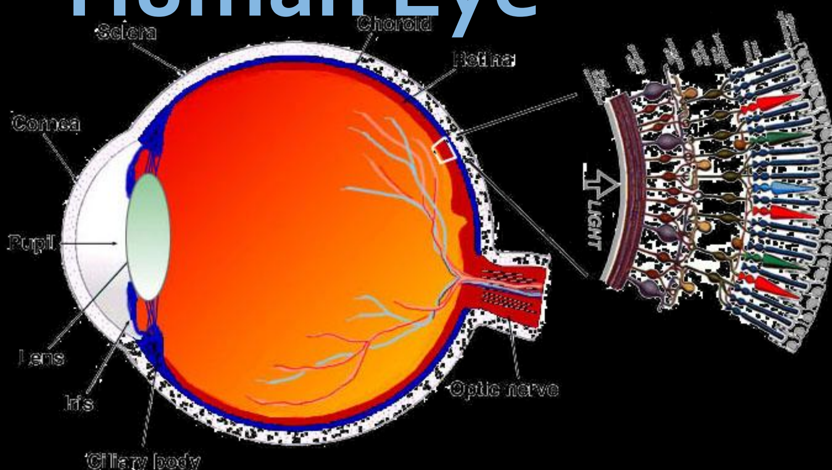


3 bands = trinocular vision with each eye!

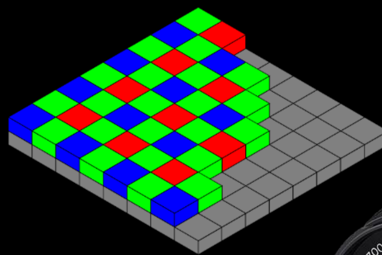
Up to 16 different photoreceptors:

- 12 for color (4 UV, visible, IR)
- 4 for polarization (linear & circular)

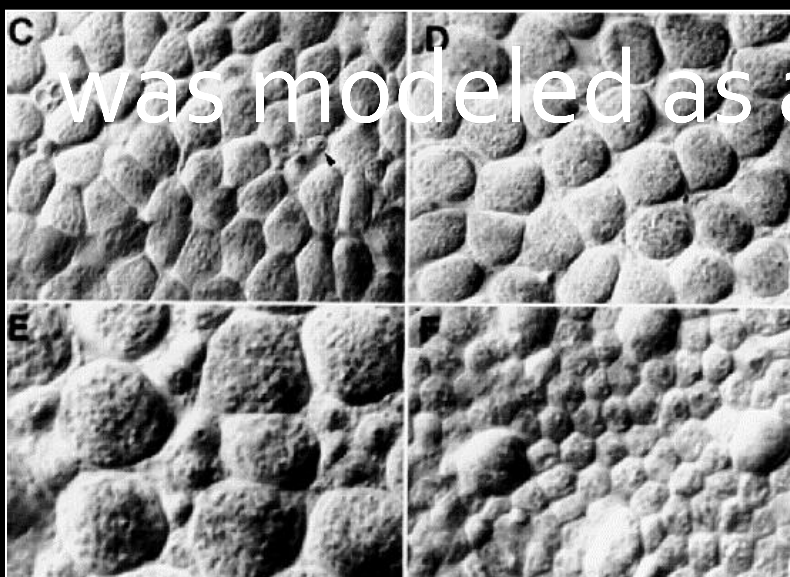
Cameras are modeled as one Human Eye



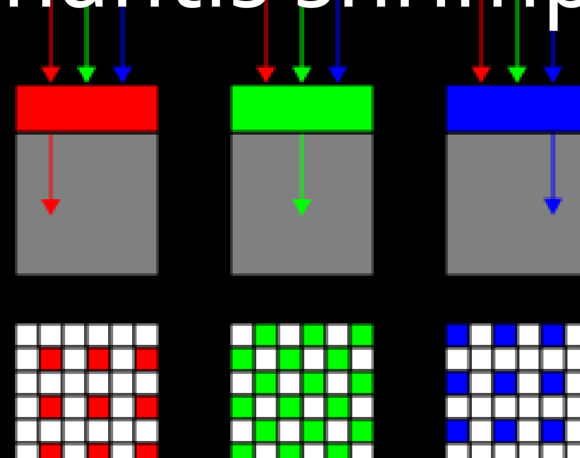
webvision.med.utah.edu



How would a camera look like if it was modeled as a mantis shrimp eye?



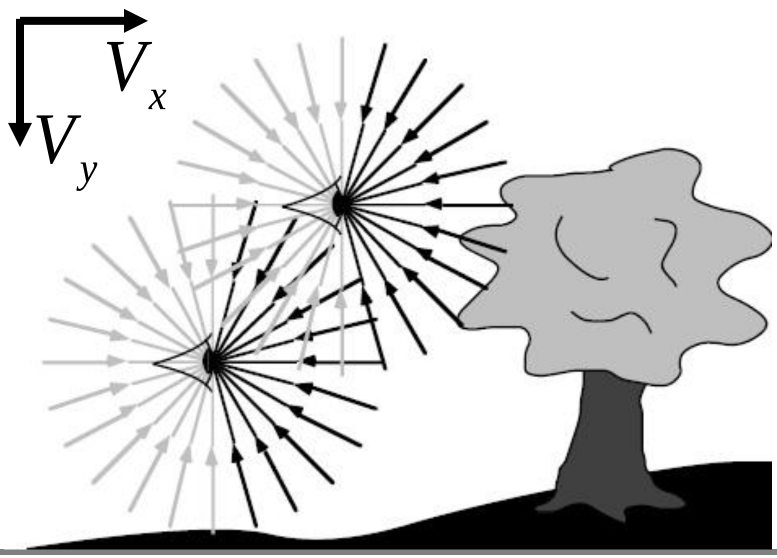
[Williams 91]



http://en.wikipedia.org/wiki/Bayer_filter

The Plenoptic Function

- Ray-based model for light
- Includes variations in space, time, wavelength, and directions $P = P(\theta, \phi, \lambda, t, V_x, V_y, V_z)$

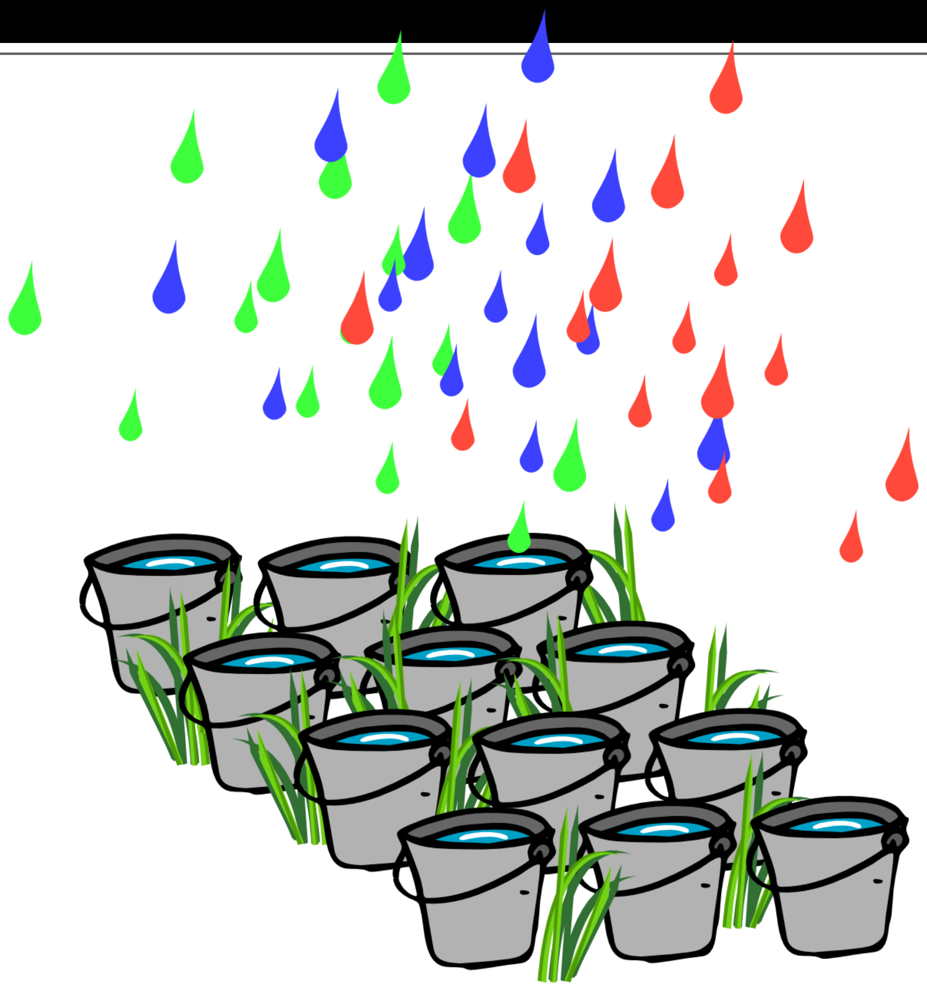


Adelson and Bergen: "The Plenoptic Function and the Elements of Early Vision", Computational Models of Visual Processing, 1991

How does a camera record light ?

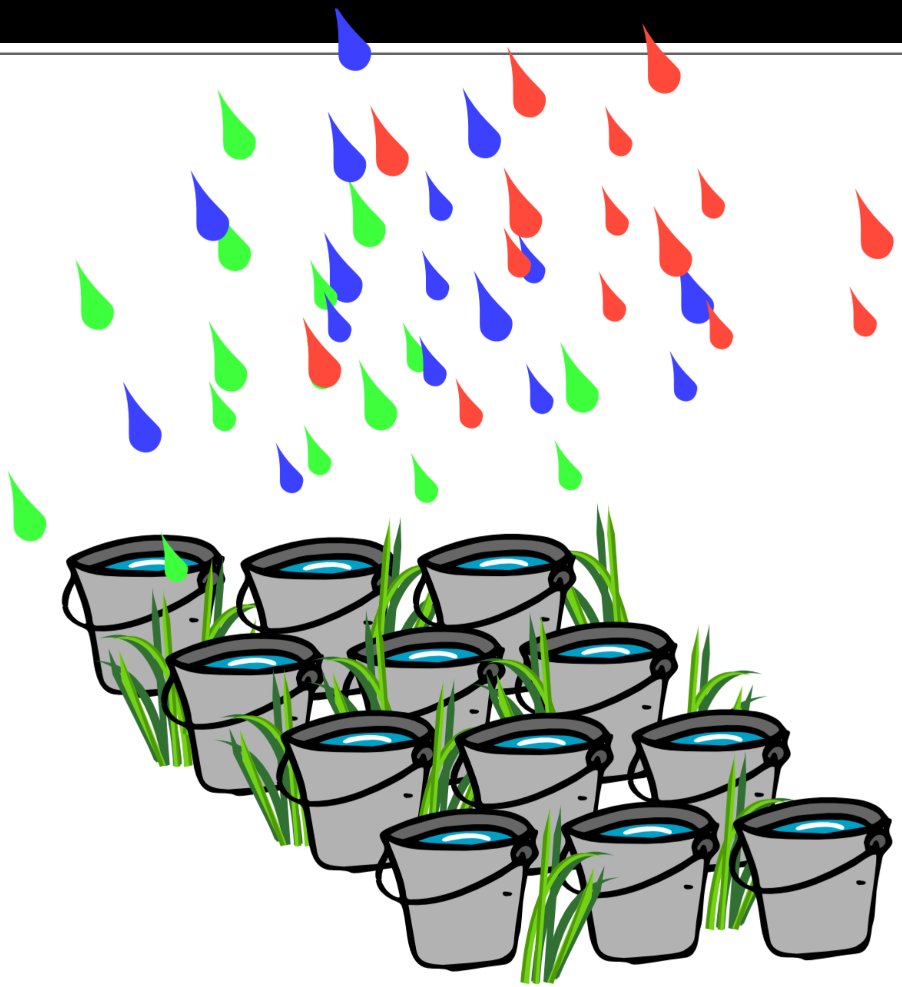
Ihrke et al.: "A Theory of Plenoptic Multiplexing", CVPR, 2010

How does a camera record light ?



Ihrke et al.: "A Theory of Plenoptic Multiplexing", CVPR, 2010

How does a camera record light ?



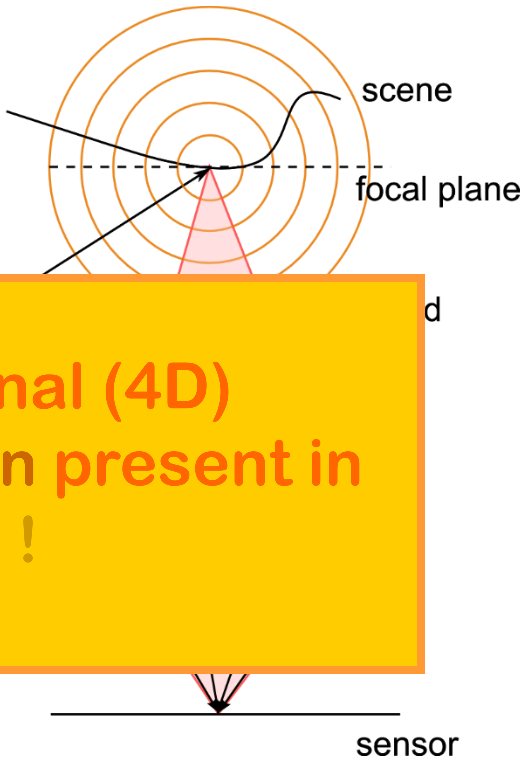
Ihrke et al.: "A Theory of Plenoptic Multiplexing", CVPR, 2010

How does a camera record light ?

Ihrke et al.: "A Theory of Plenoptic Multiplexing", CVPR, 2010

How does a camera record light ?

integrates



Integration is high-dimensional (4D)
It destroys significant information present in the plenoptic function !

Photons arrive at sensor from Scene through lens aperture (entrance pupil)

Ihrke et al.: "A Theory of Plenoptic Multiplexing", CVPR, 2010

Taxonomy and Overview

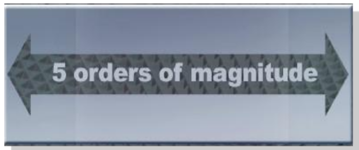
Acquisition Approach \ Plenoptic Dimension	Dynamic Range	Color Spectrum	Directions | Light Fields	Space | Focal Surfaces	Time
Single Shot Acquisition	Assorted Pixels Gradient Camera Adaptive DR Imaging	Color Filter Arrays Assorted Pixels Dispersive Optics	Plenoptic Cameras w/ Lenses, Masks, or Mirrors Compound Eye Cameras	Coded Apertures Focal Sweep Field Correction	Assorted Pixels Flutter Shutter Reinterpretable Imager Sensor Motion
Sequential Image Capture	Exposure Brackets Generalized Mosaics HDR Video	Narrow Band Filters Generalized Mosaicing Agile Spectrum Imaging	Programmable Aperture Camera & Gantry	Focal Stack Jitter Camera Super-Resolution	High-Speed Imaging Temporal Dithering
Multi-Device Setup	Split Aperture Imaging Optical Splitting Trees	Multi-Camera Arrays Optical Splitting Trees	Multi-Camera Arrays	Multi-Camera Arrays	Multi-Camera Arrays Hybrid Cameras

Wetzstein, Ihrke, Lanman, Heidrich: "Computational Plenoptic Imaging", Computer Graphics Forum, 2011

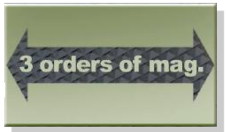
High Dynamic Range Imaging

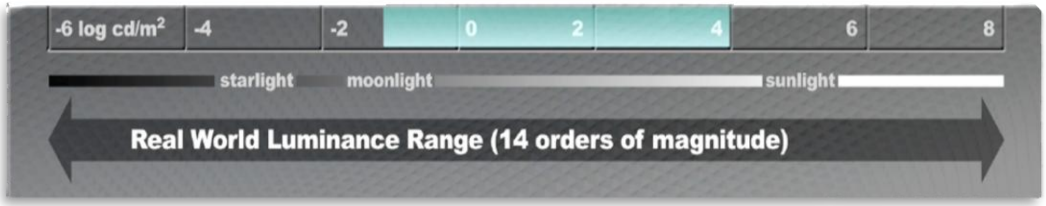
High Dynamic Range Imaging

HUMAN VISUAL SYSTEM



CONVENTIONAL CAMERAS



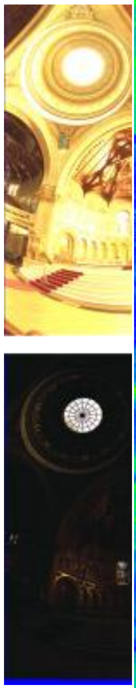


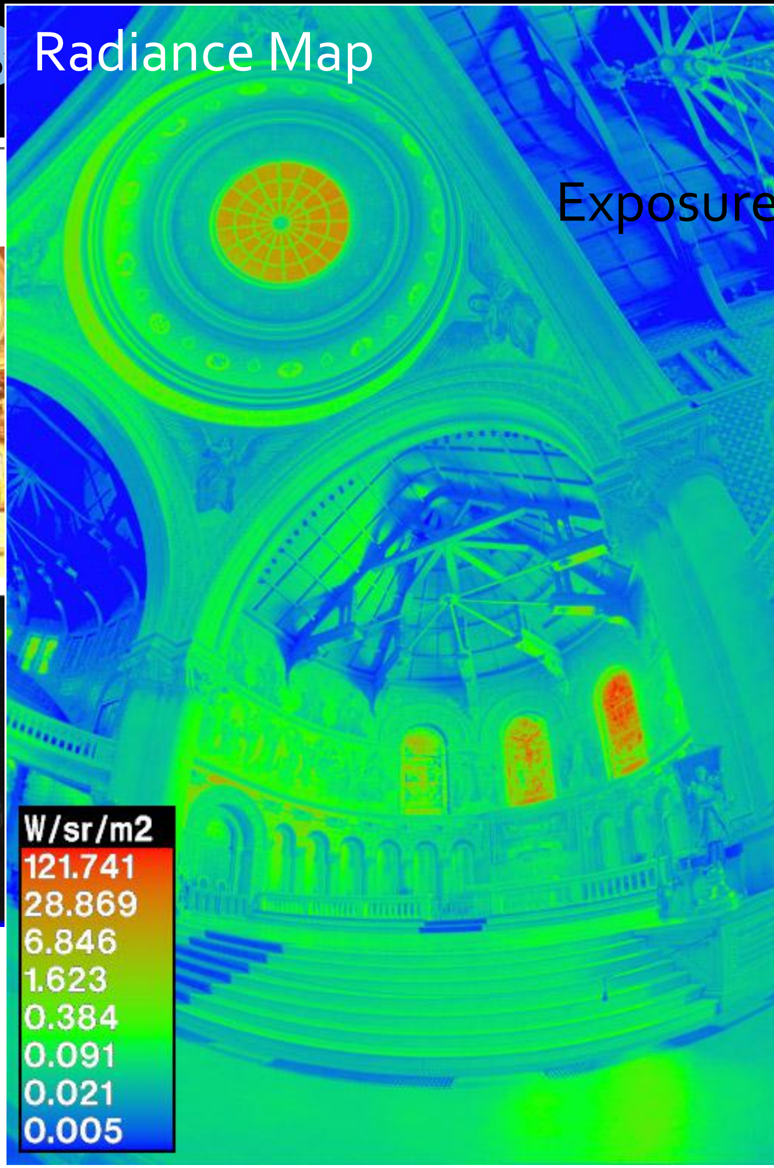
REAL_WORLD IRRADIANCE

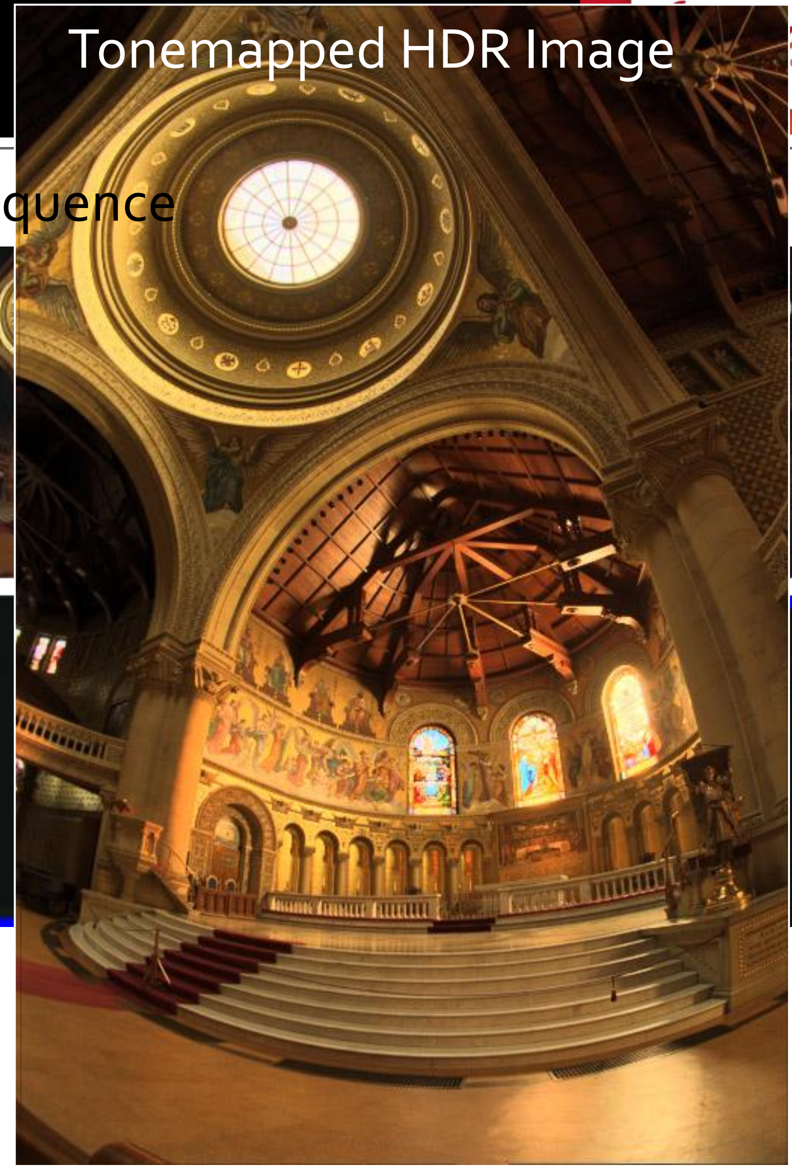
http://en.wikipedia.org/wiki/High-dynamic-range_

HDR Acquisition – Exposure B

Exposure Sequence



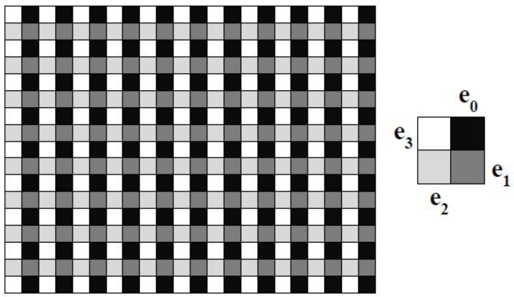


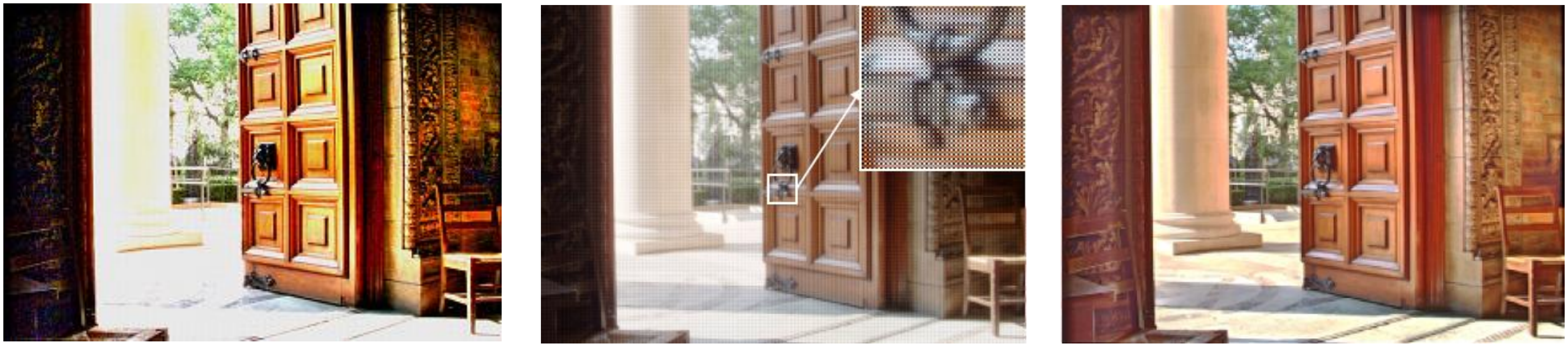


Debevec and Malik: "Recovering High Dynamic Range Maps from Photographs", Siggraph 1997

Assorted Pixels

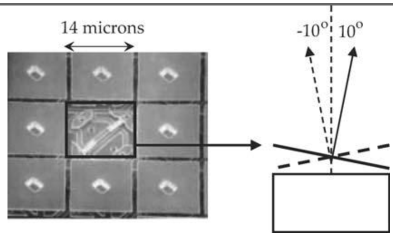
- ND filter arrays

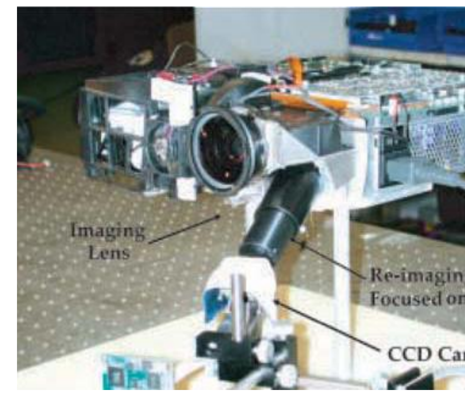


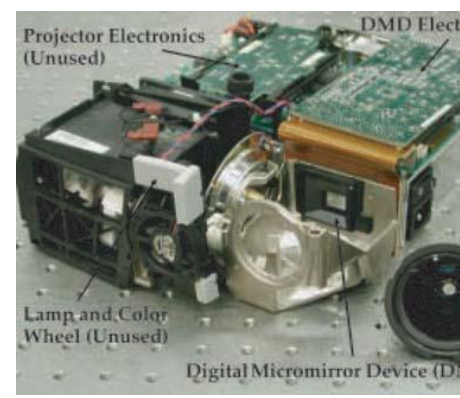


Nayar and Mitsunaga: "High dynamic range imaging: Spatially varying pixel exposures", CVPR 2000

Programmable Imaging

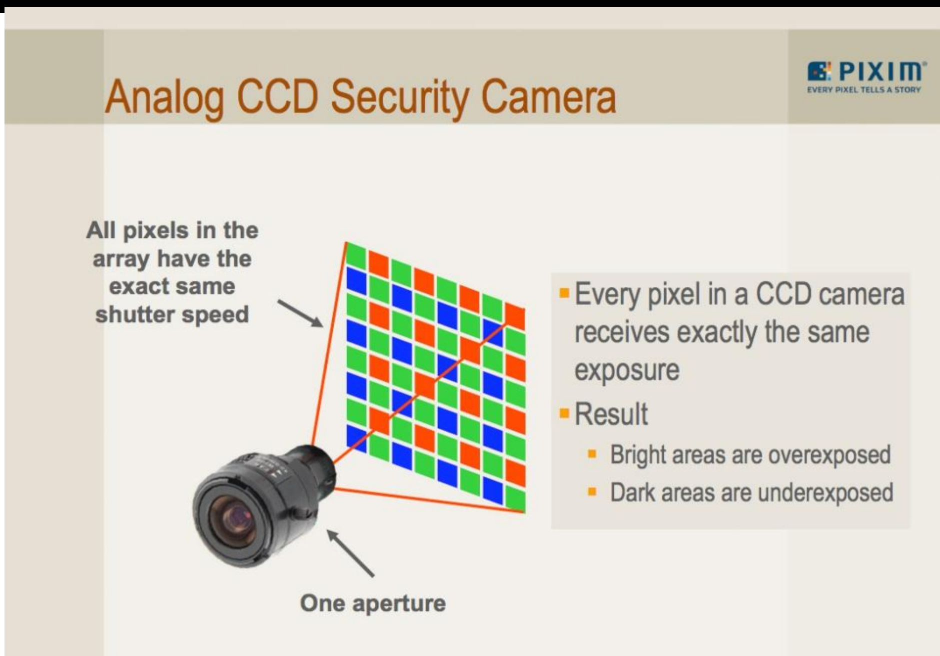


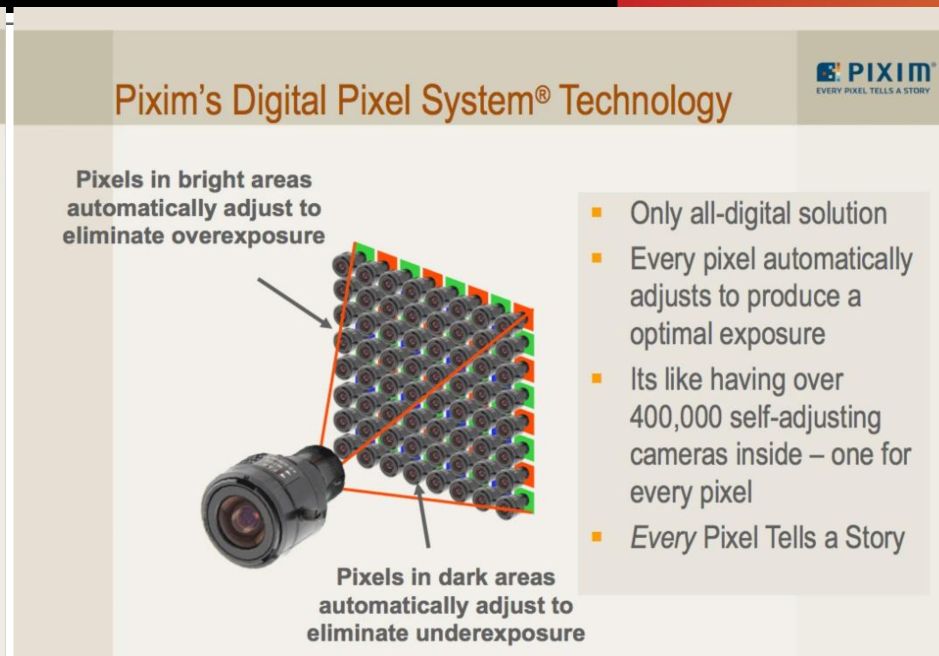




Nayar and Branzoi: "Programmable imaging using a digital micromirror array", CVPR, 2004

Per-Pixel Exposure Control



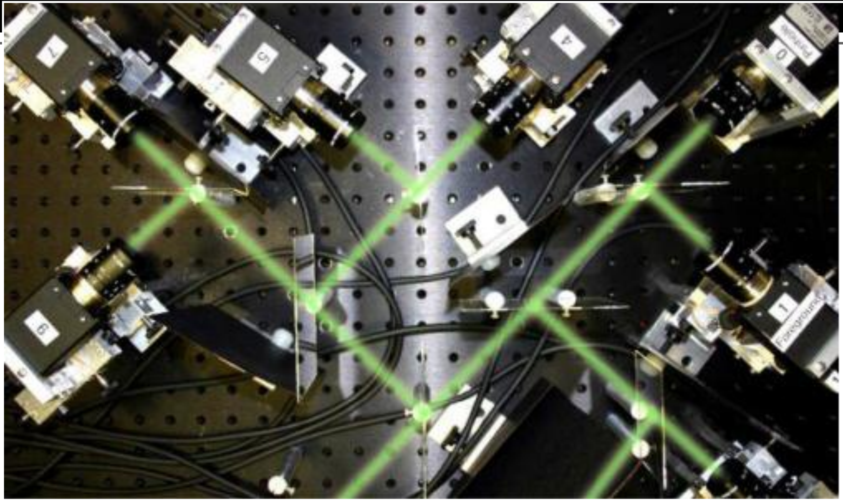


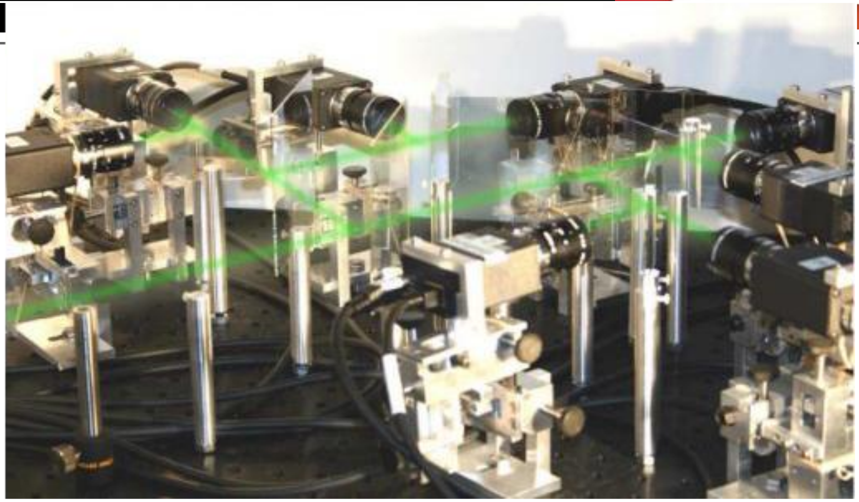
[Pixim] (now Sony)

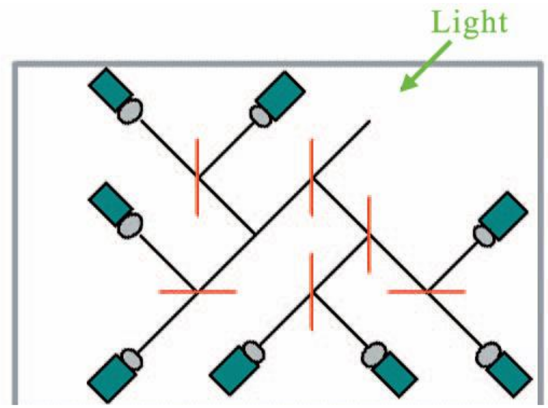
no pixim

with pixim

Optical Splitting Trees







Exposure Sequence & Tonemapped Image

McGuire et al.: "*Optical splitting trees for high-precision monocular imaging*", *Computer Graphics and Applications, IEEE, 27(2), 32-42.*

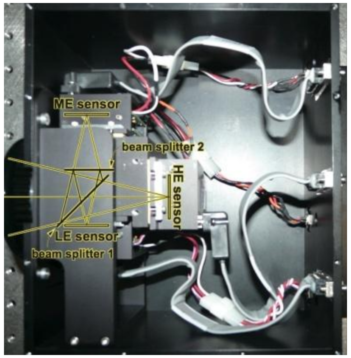
Commercial Systems

Large Pixels

Grass Valley Viper

Panavision Genesis

Optical Splitting



ContrastOptical

Scanning

Spheron

Spectral Imaging

The spectral data cube

- spectrometer

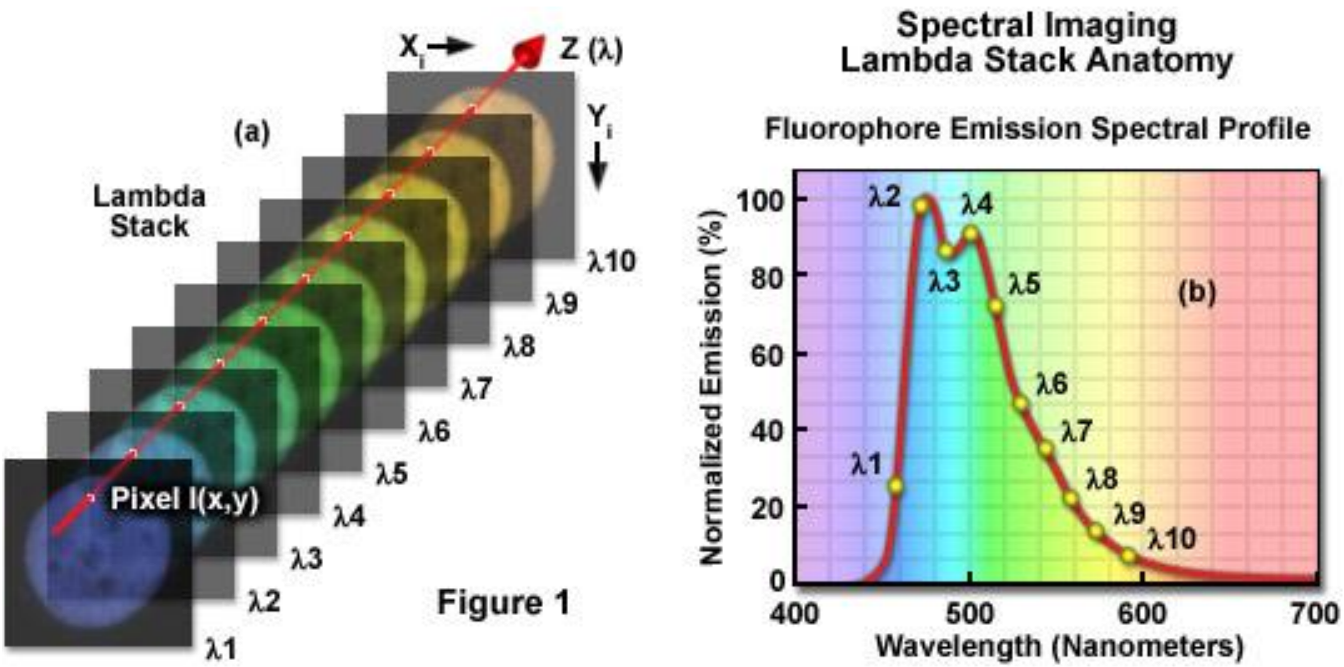
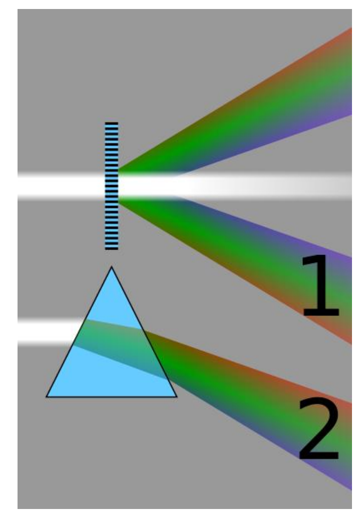
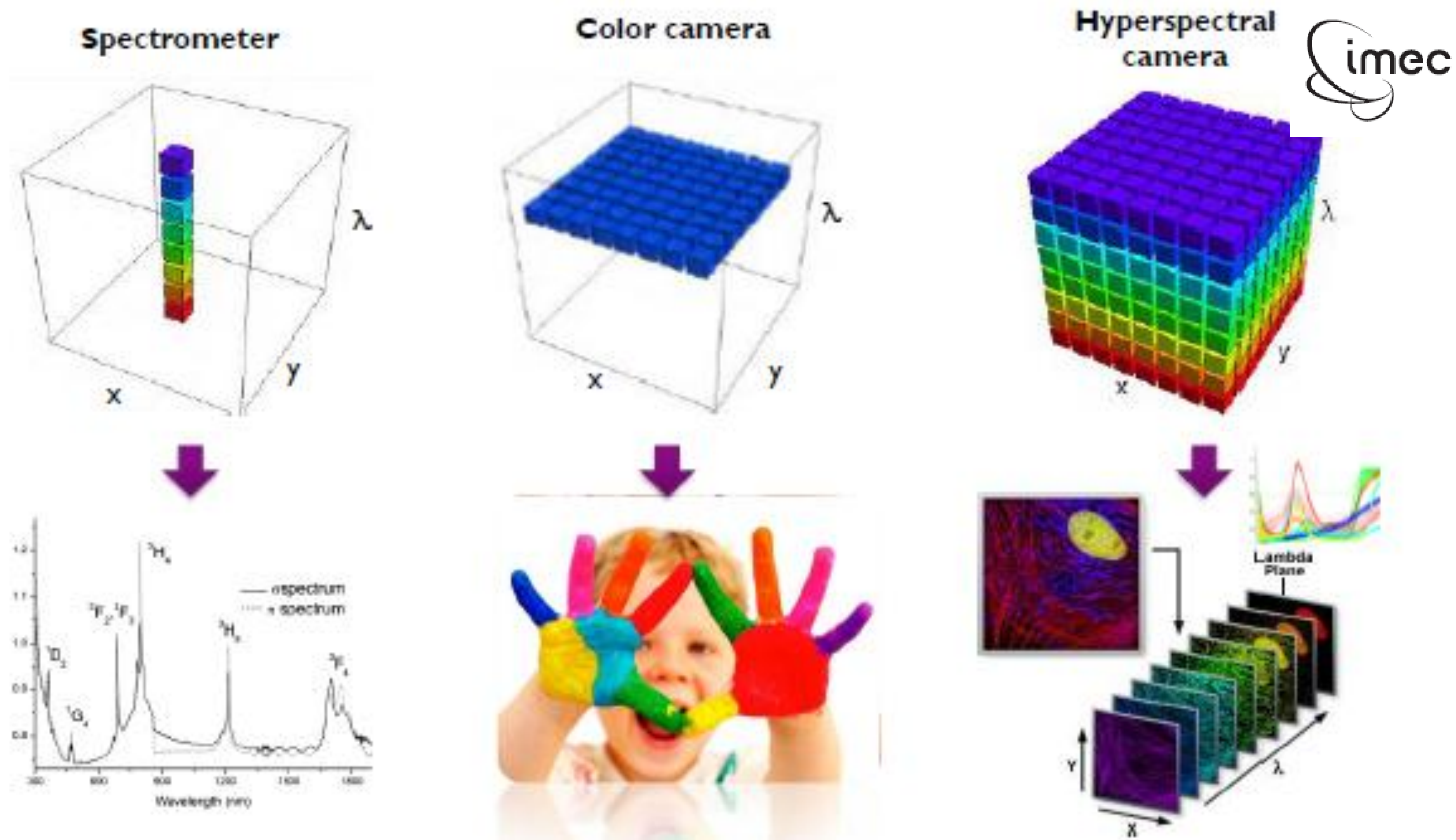


Figure 1

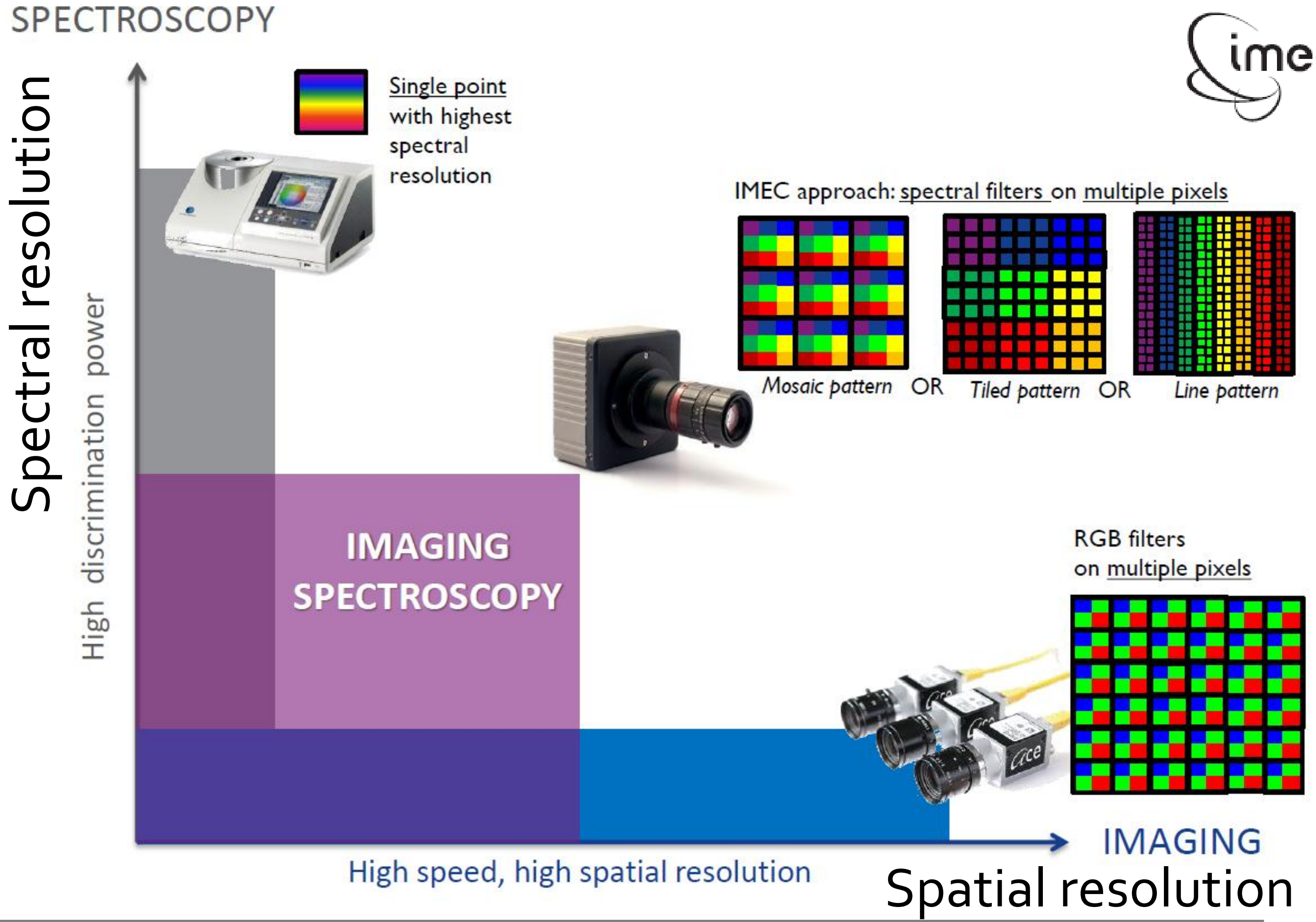


Imaging and Spectroscopy



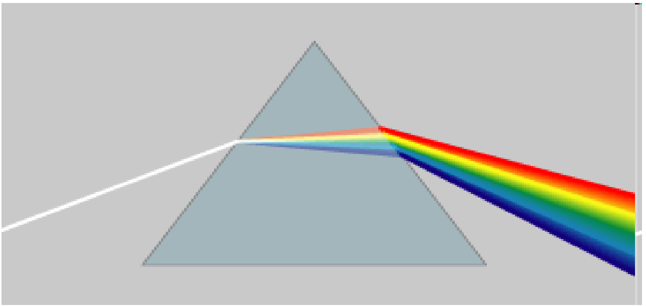
[imec]

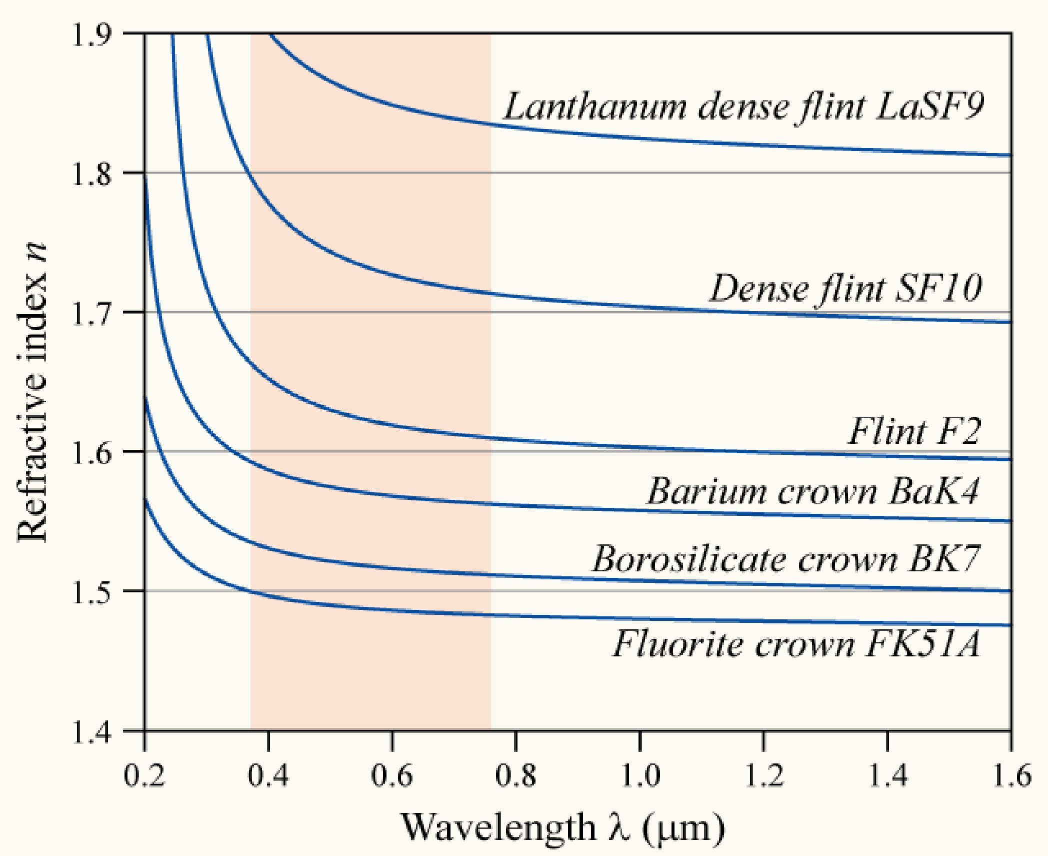
Imaging and Spectroscopy



[imec]

Principle of Operation - Dispersion





Principle of Operation - Diffraction

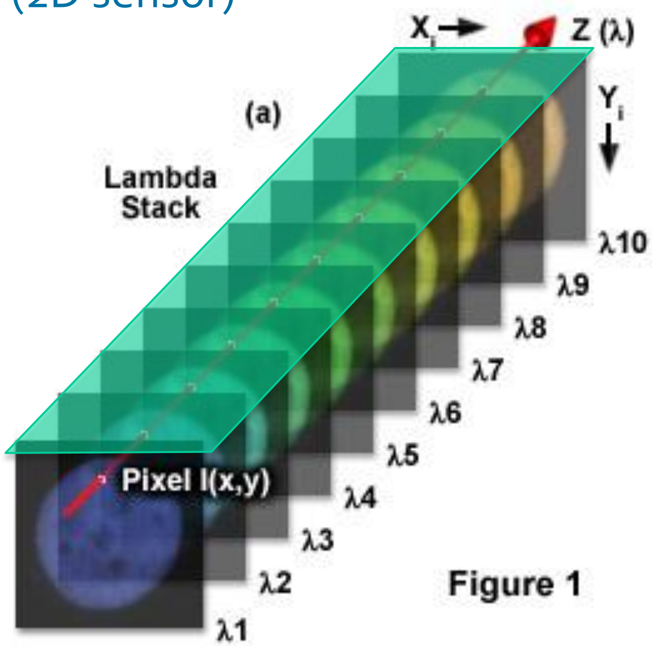
- At center, no diffraction
- For higher orders, diffraction is taking place

Diffraction Order	Percentage of transmitted Light
0	25%
1	20.26%
2	10.13%
3	2.25%
4	0 %
remainder	9.72%

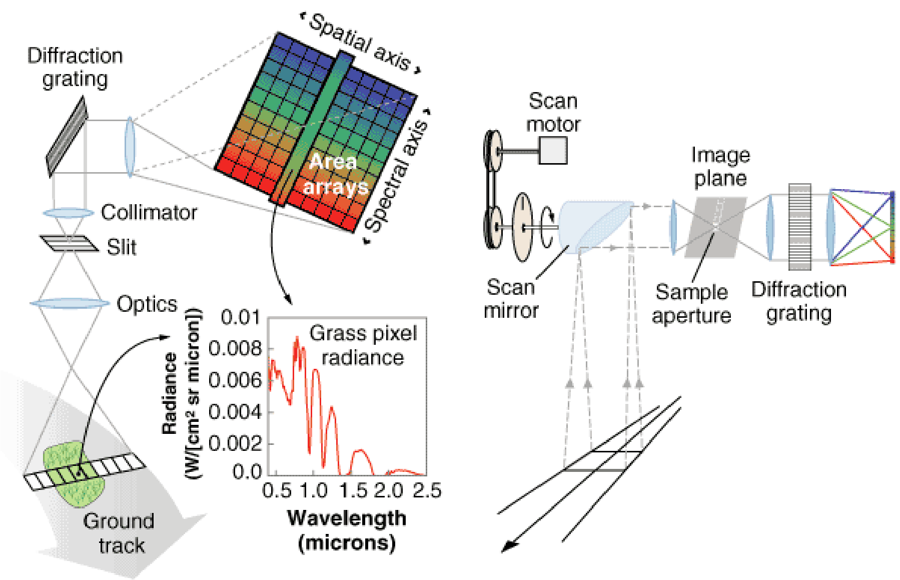
The spectral data cube

- Spatial Scanning

(2D sensor)

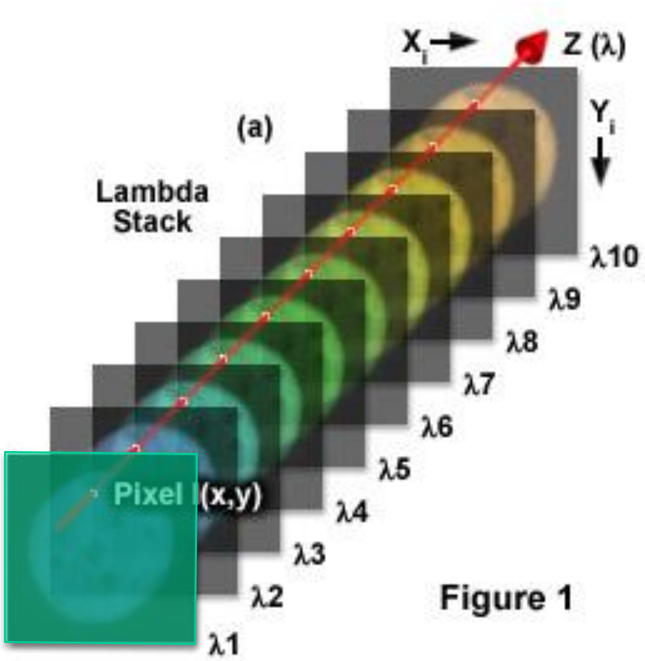


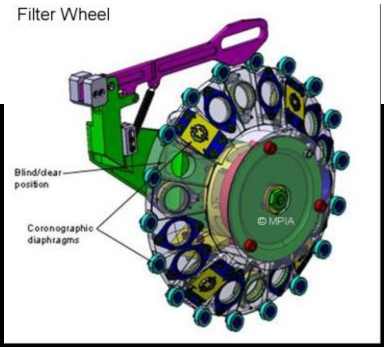
- E.g. in satellite imaging
  - Pushbroom scanning



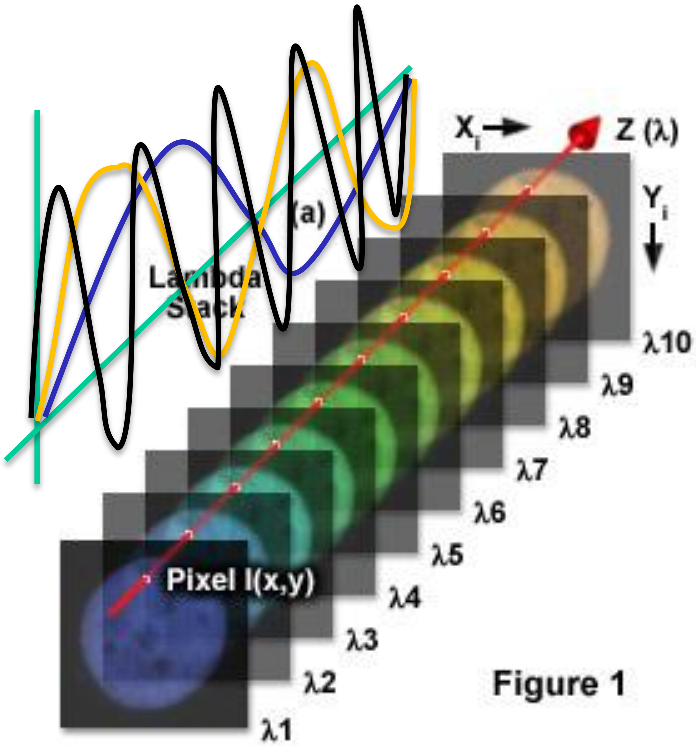
The spectral data cube

- Spectral scanning

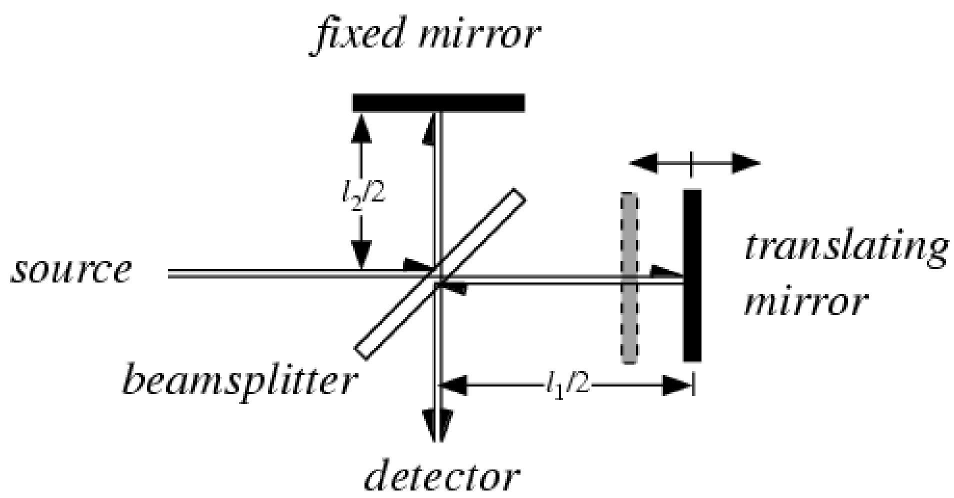




Frequency Scanning



- Michelson Interferometer with moving mirror - Fourier Transform Imaging Spectroscopy (FTIS)

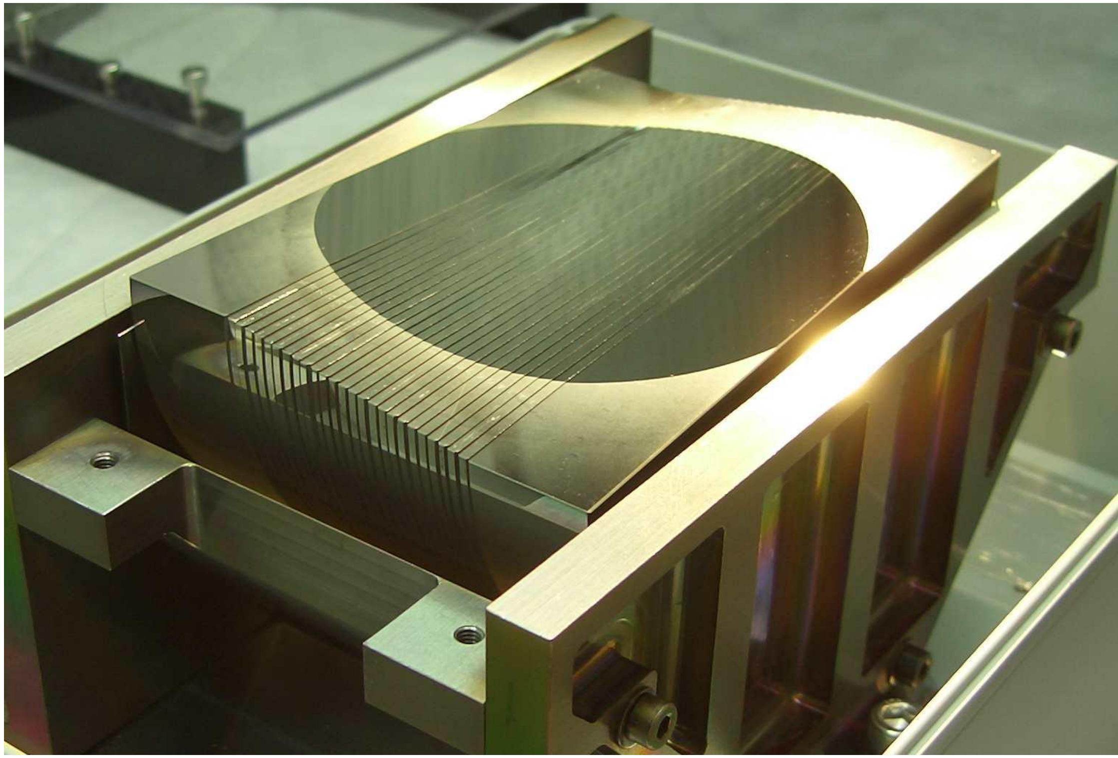


$$I(\tilde{\nu}) = 4\int_0^{\infty} \left[I(p) - \tfrac{1}{2}I(p=0)\right] \boxed{\cos(2\pi\tilde{\nu}p)}\, dp.$$

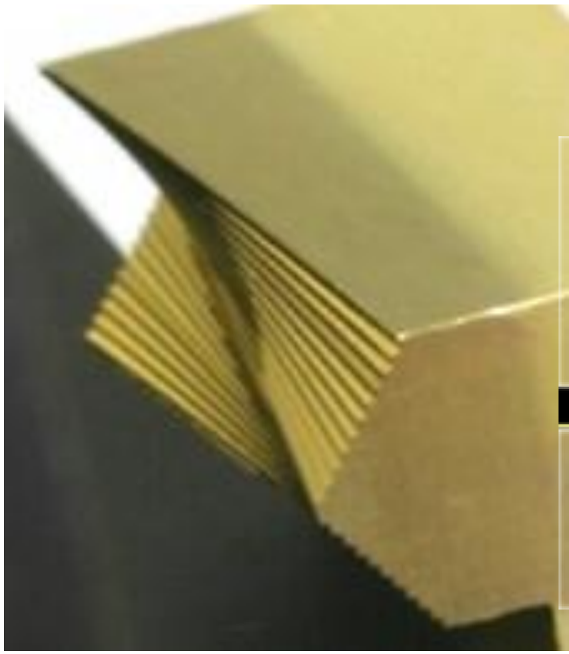
Imaging Spectrometers

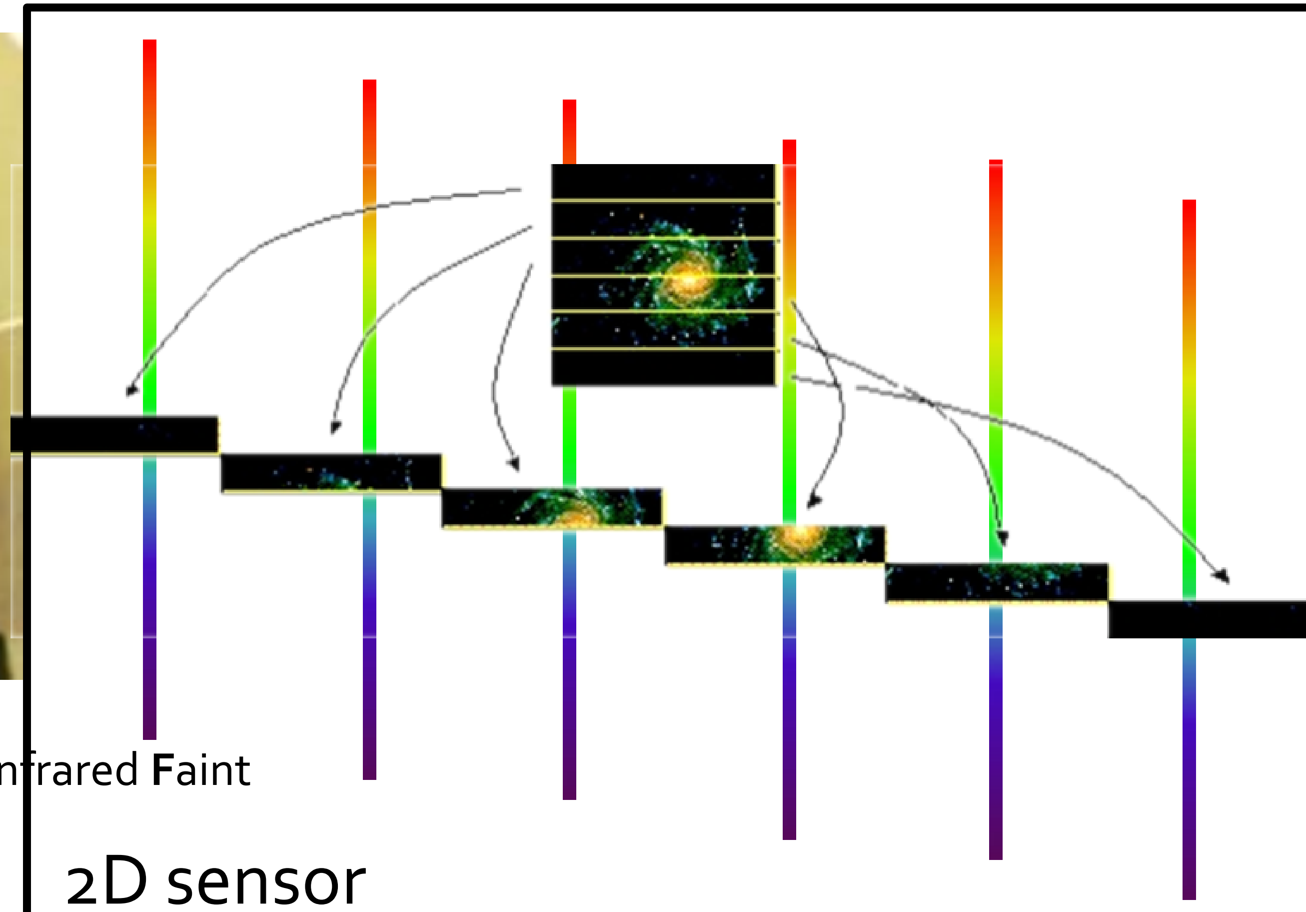
Multiplexing – Image Slicers

[WiFeS – Wide Field Spectrometer]



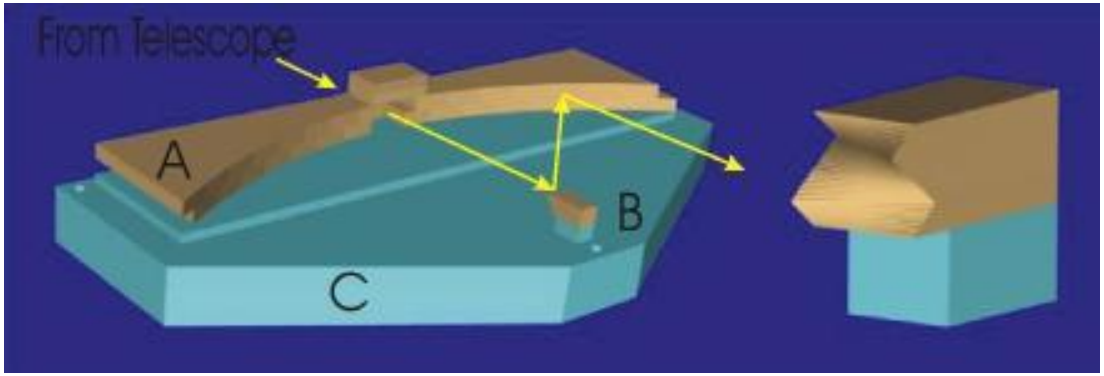
Multiplexing – Image Slicers

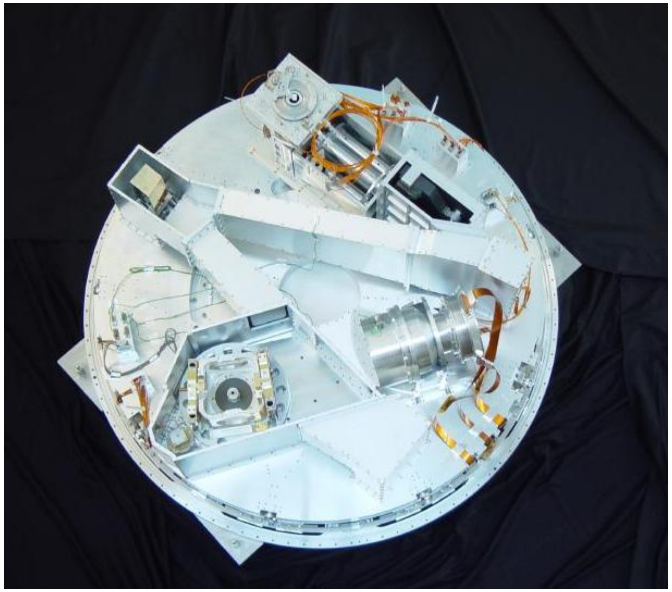




[SPIFFI - SPectrometer for **I**nfrared **F**aint **F**ield **I**maging]

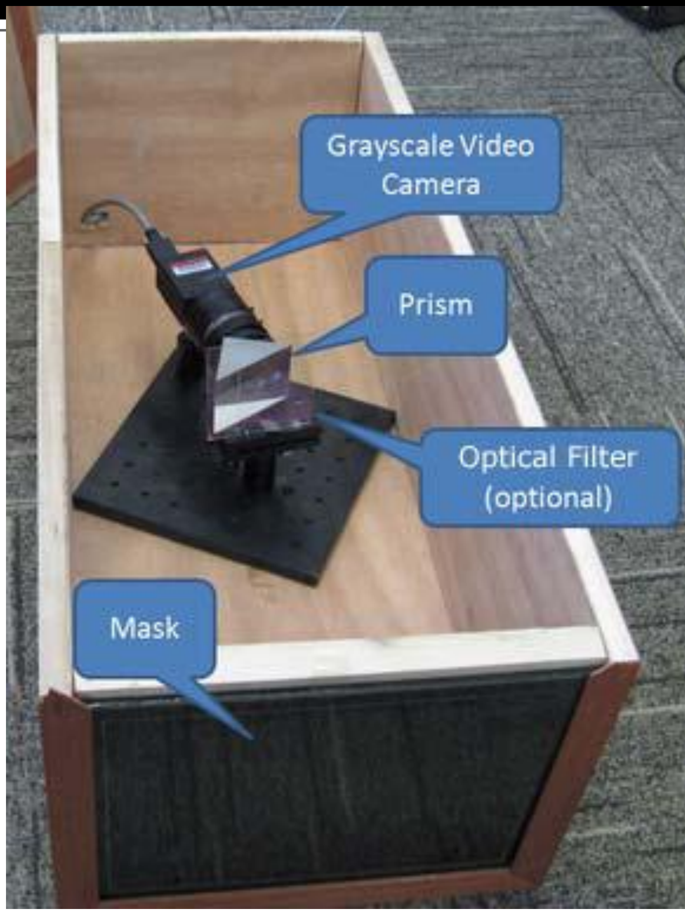
Multiplexing – Image Slicers

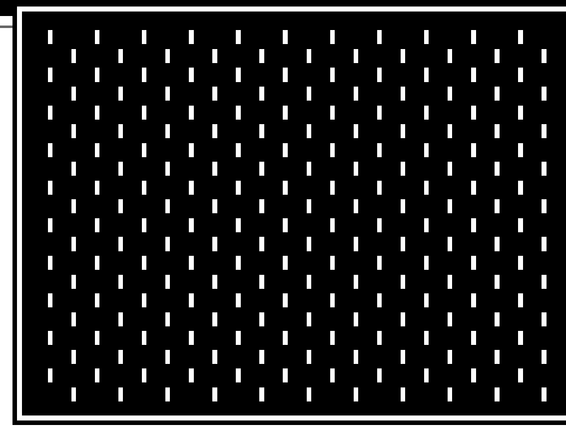


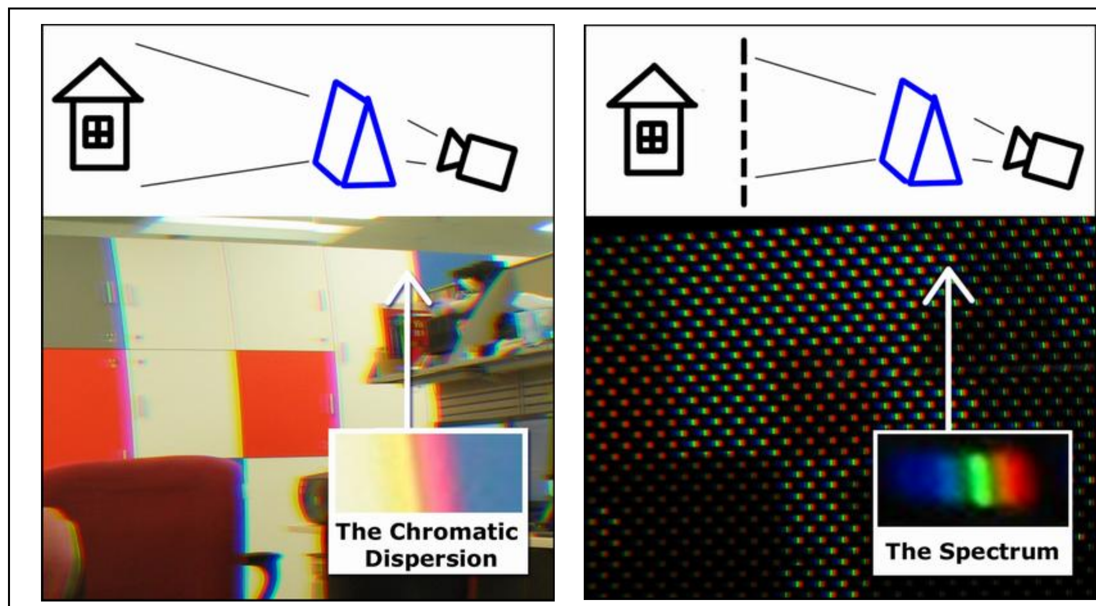


[**SPIFFI - SP**ectrometer for **I**nfrared **F**aint
Field **I**maging]

Spatial Multiplexing: Prism-Mask Based System

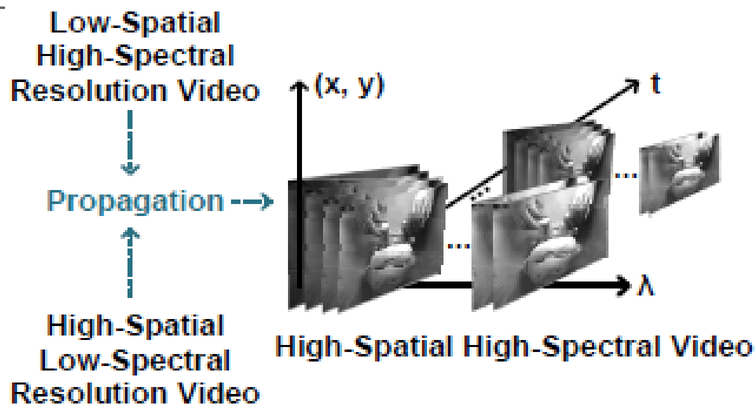




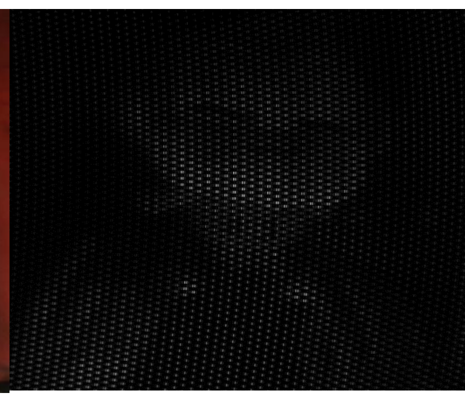


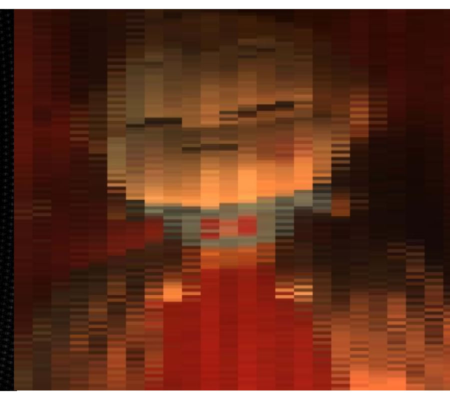
Du et al.: "*A prism-based system for multispectral video acquisition*", CVPR, 2009.

Spatial Upsampling of Spectra




RGB image

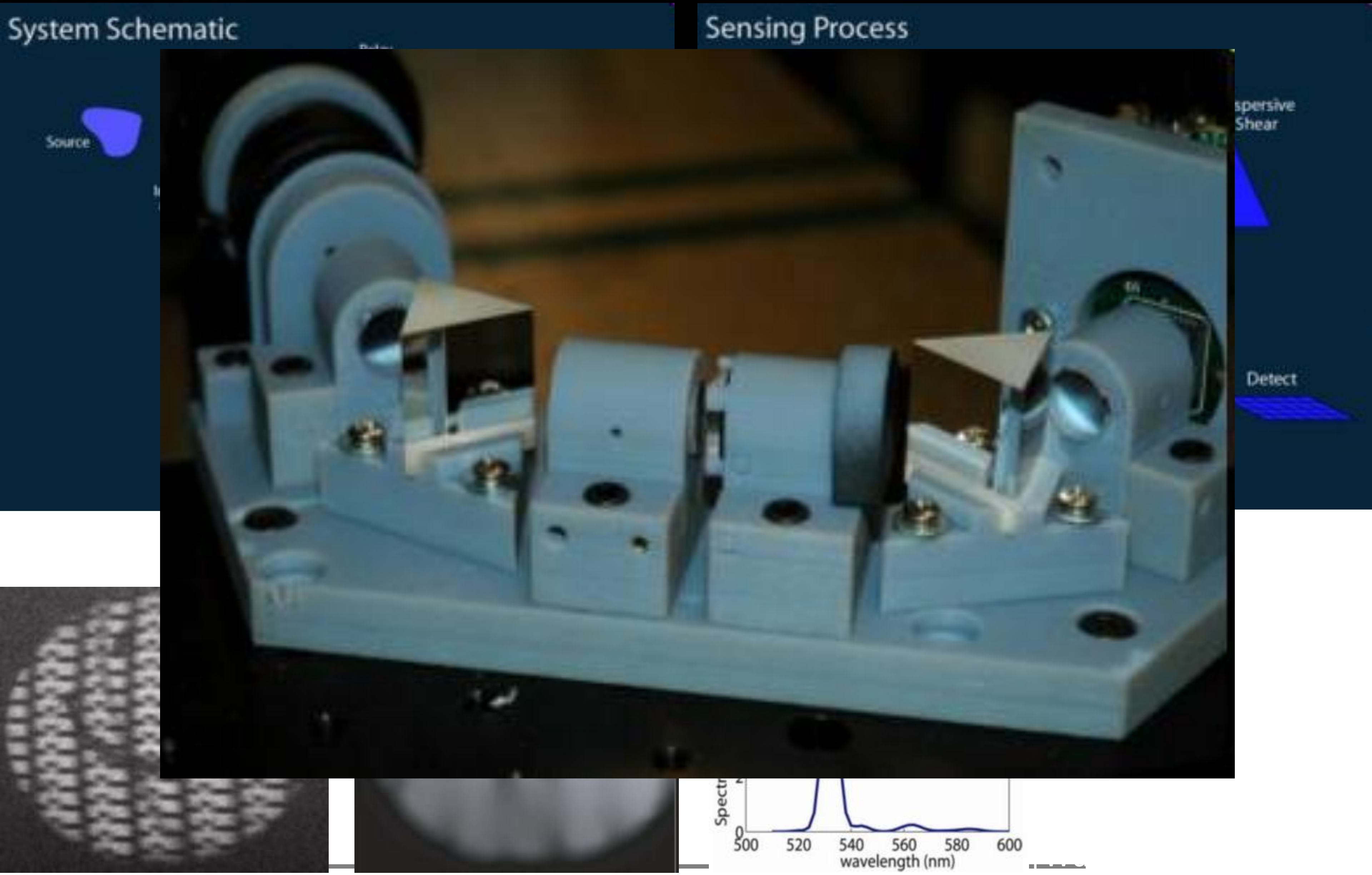

multispectral image


multispectral image converted to RGB


ùpsampled image high res – full spectra

Cao et al.: "*A prism-mask system for multispectral video acquisition*",*PAMI*,*2011*.

Coded Aperture Snapshot Spectral Imaging



Computed Tomography Imaging Spectrometer CTIS

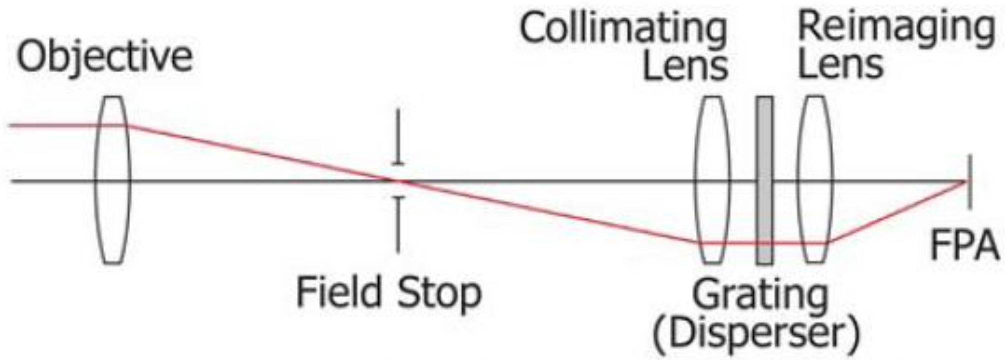
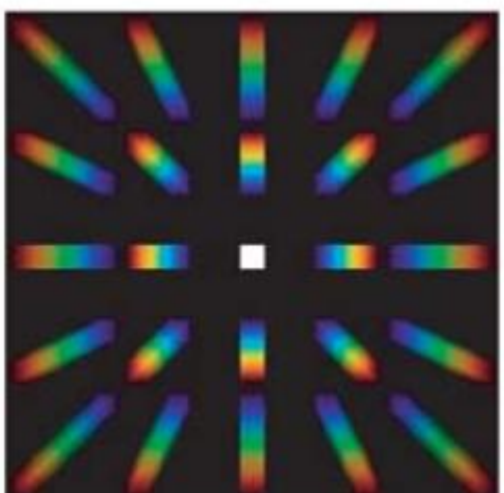
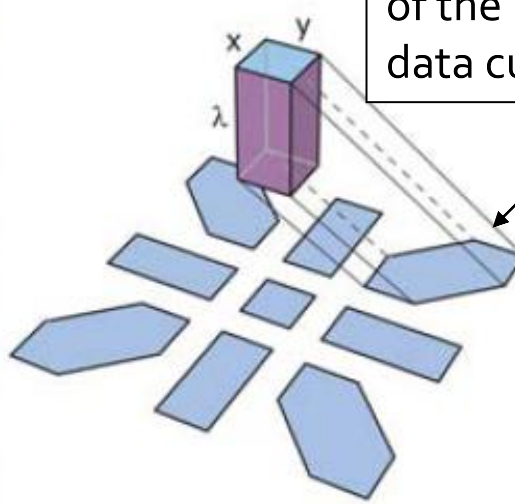


Fig. 1. (Color online) CTIS instrument views the target scene through a 2D grating. The field stop limits the field of view, such that the dispersed diffraction orders are spatially separated.

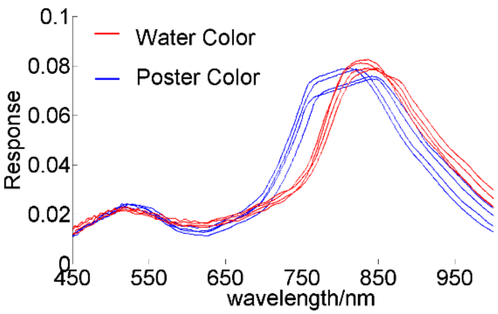
different linear "projections" of the multispectral data cube



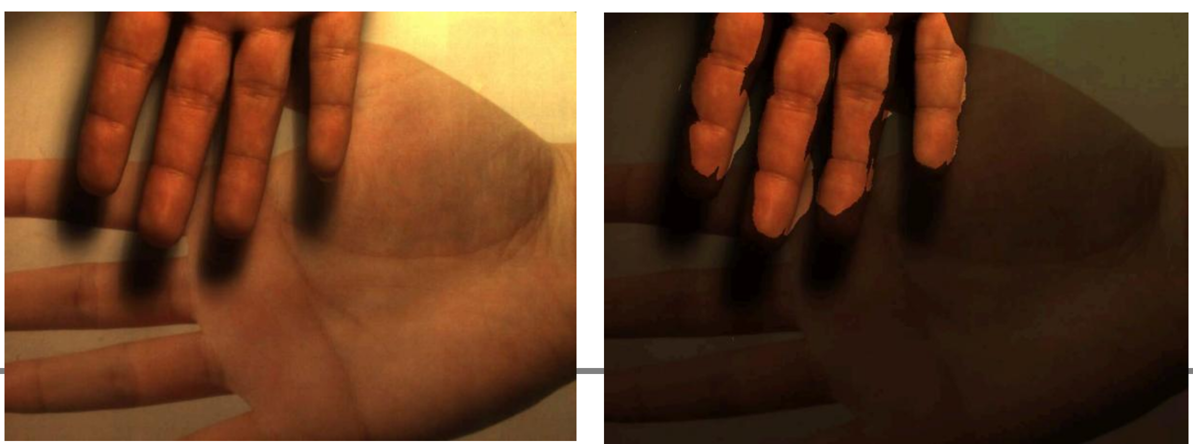


Example Applications

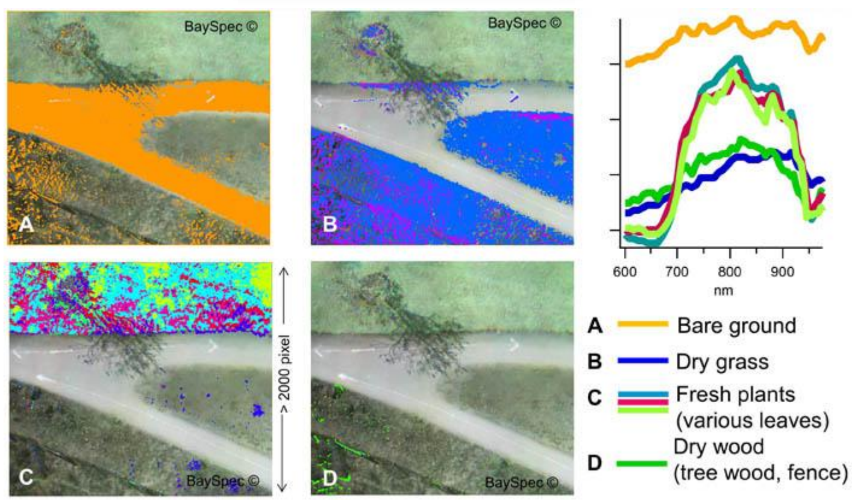
- improved tracking



- real and fake skin detection



Commercial Snapshot Systems



BaySpec

180g with optics
Ca. 400 x 300 pixels
16-25 spectral bands

Ximea

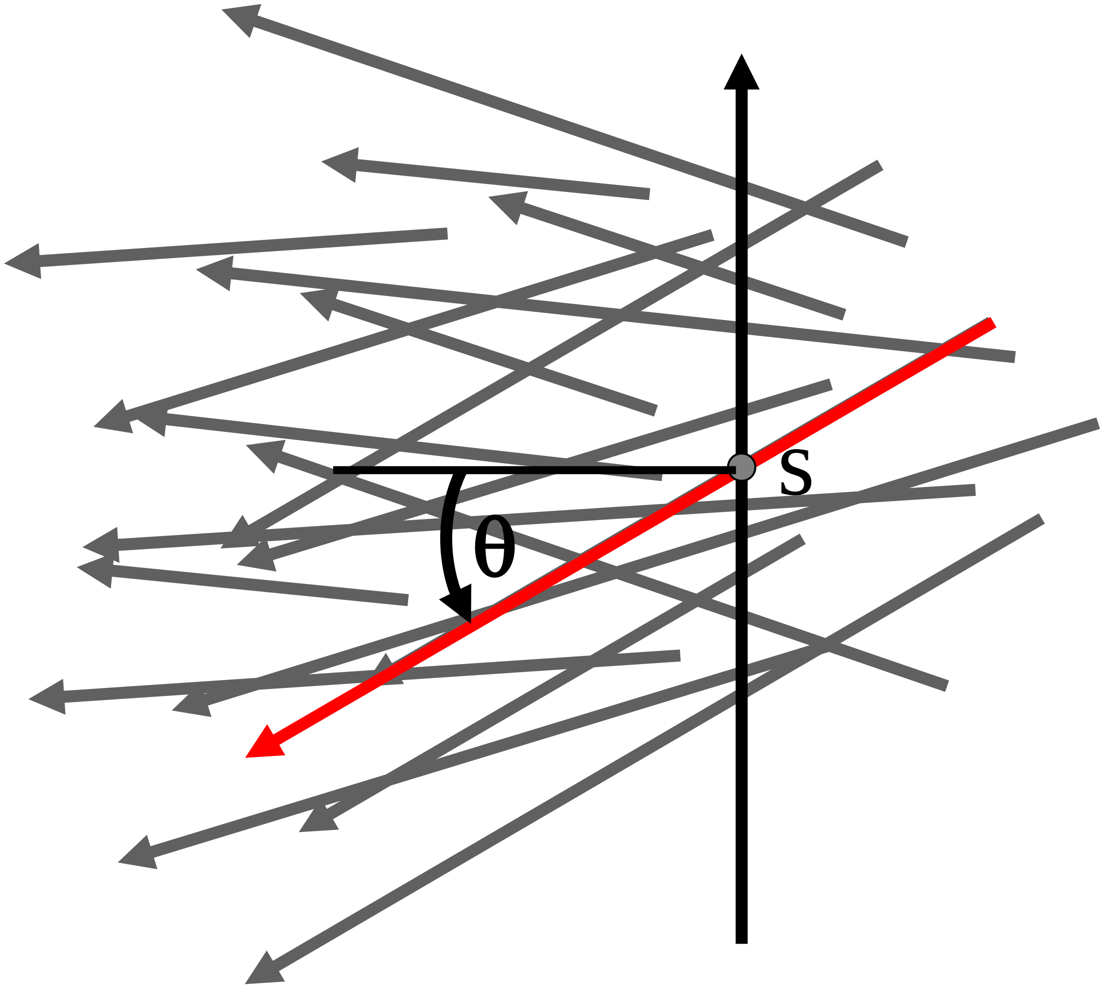
27g w/o optics
Ca. 400 x 300 pixels
16-25 spectral bands

Light Fields

Position-Angle Parameterization

2D position

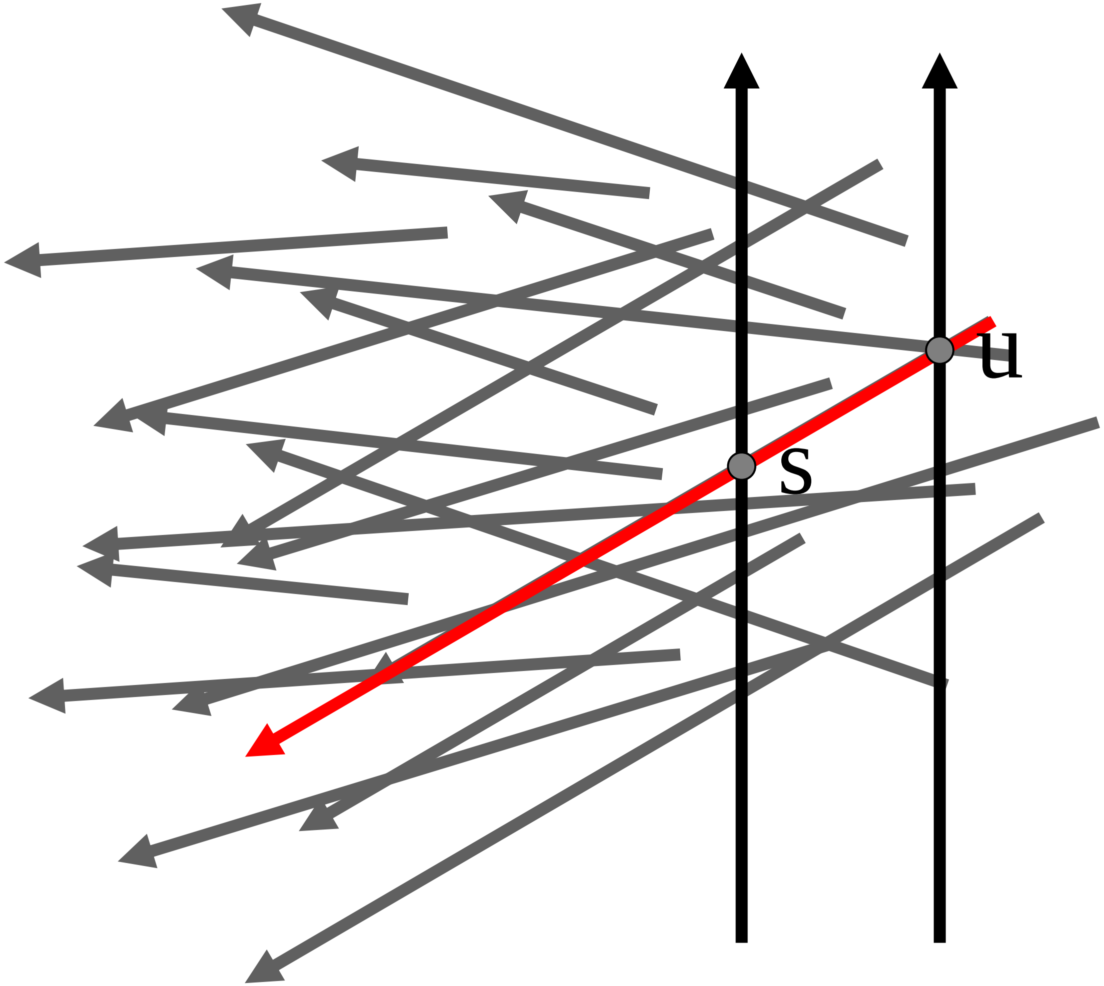
2D direction



Two-Plane Parameterization

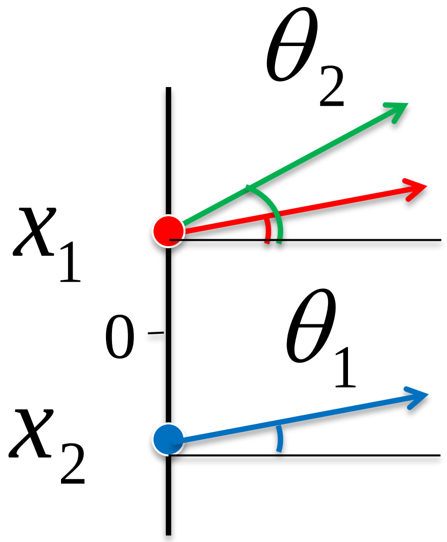
2D position

2D position

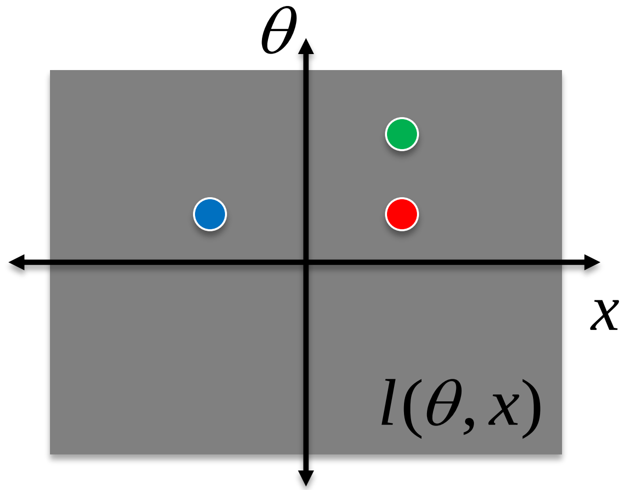


Position-Angle vs. Phase Space

pos.-angle space

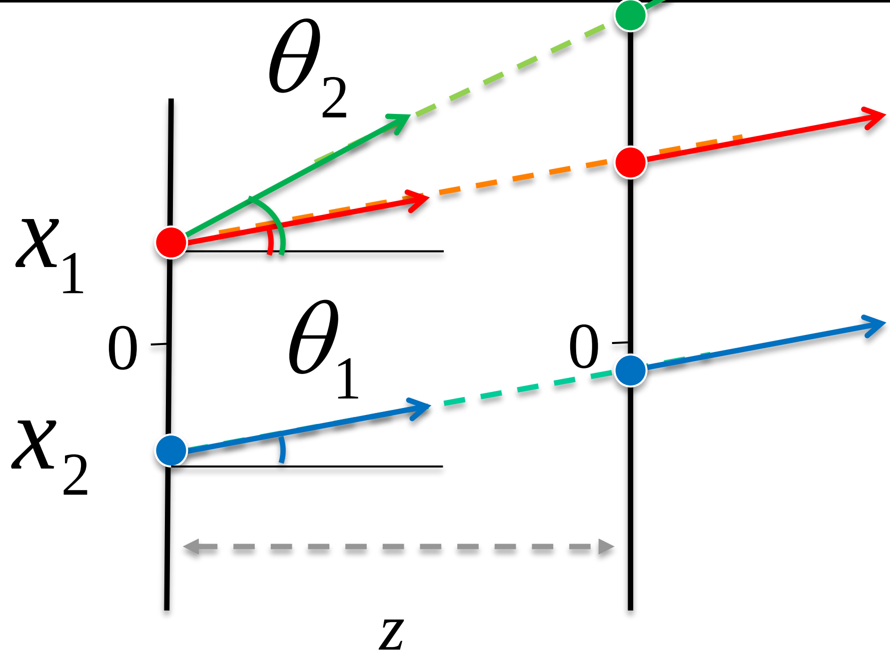


phase space



Pos.-angle vs. phase space – free space transport

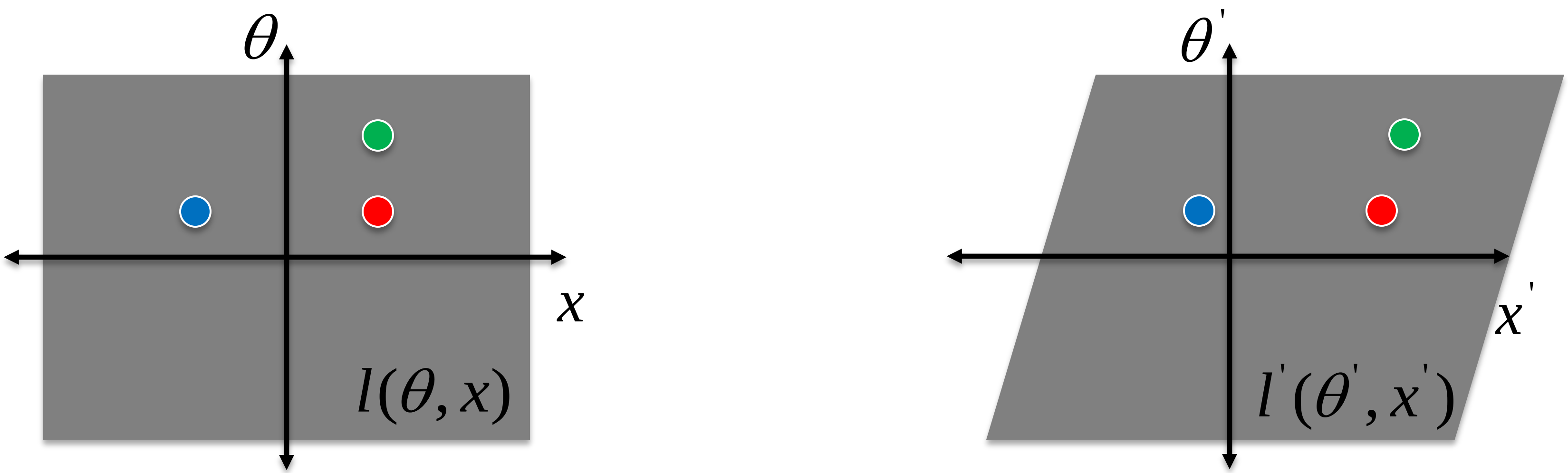
pos.-angle space



$$x_1' = x_1 + \theta_1 \cdot z$$

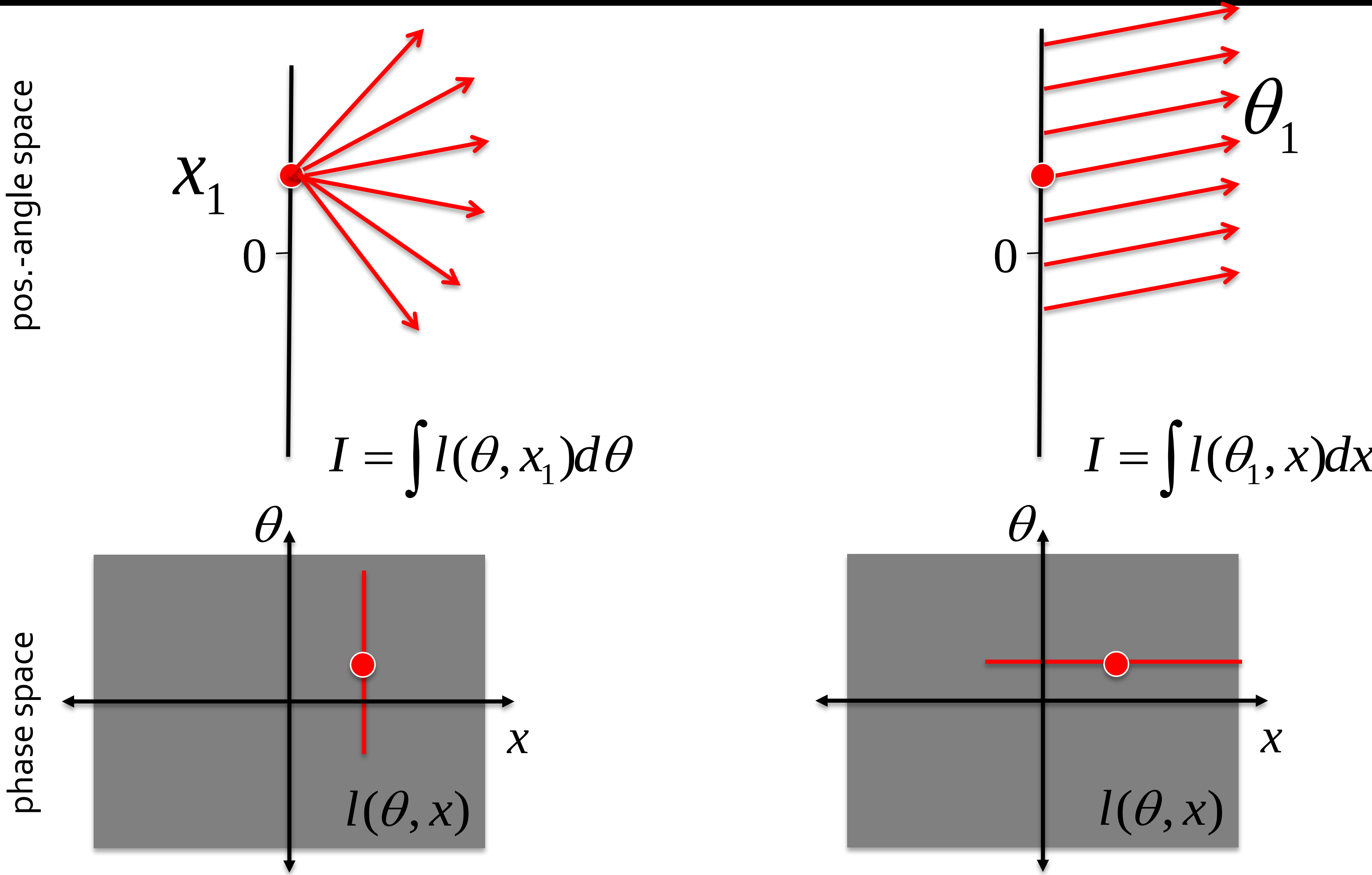
$$\theta_1' = \theta_1$$

phase space



$$l'(\theta', x') = l(\theta, x)$$

Pos.-angle vs. phase space – integration surfaces



Light Fields – Acquisition & Applications

- Multi-Camera Array
  - 128 cameras (Stanford)
- Application:
  - dynamic light field acquisition
  - synthetic aperture imaging
  - spatio-temporal interpolation
  - HDR light field imaging

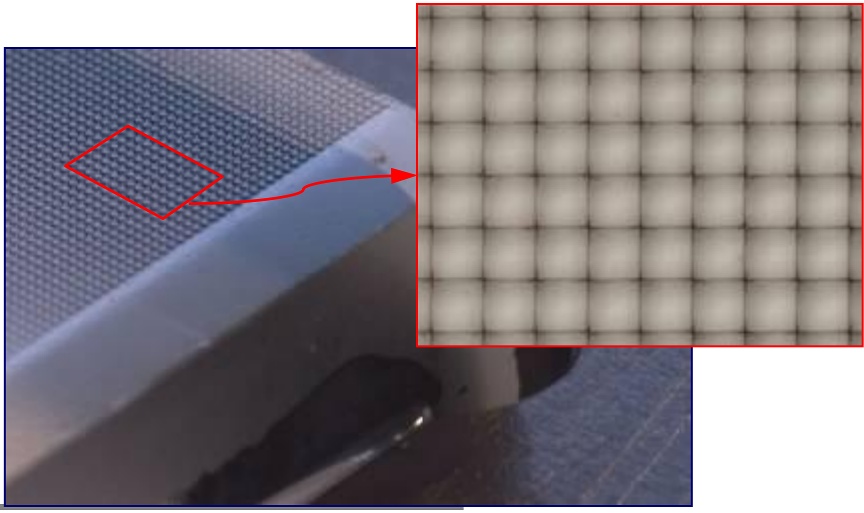
Wilburn et al.: "*High performance imaging using large camera arrays*", *Siggraph, 2005*

Light Fields – Acquisition & Applications

- Plenoptic Camera
- conventional lens + microlens array
  - 4000x4000 pixels
  - 129x129 microlenses
  - =14x14 pixels per microlens
- Applications:
  - viewpoint shifts
  - perspective changes
  - digital refocusing

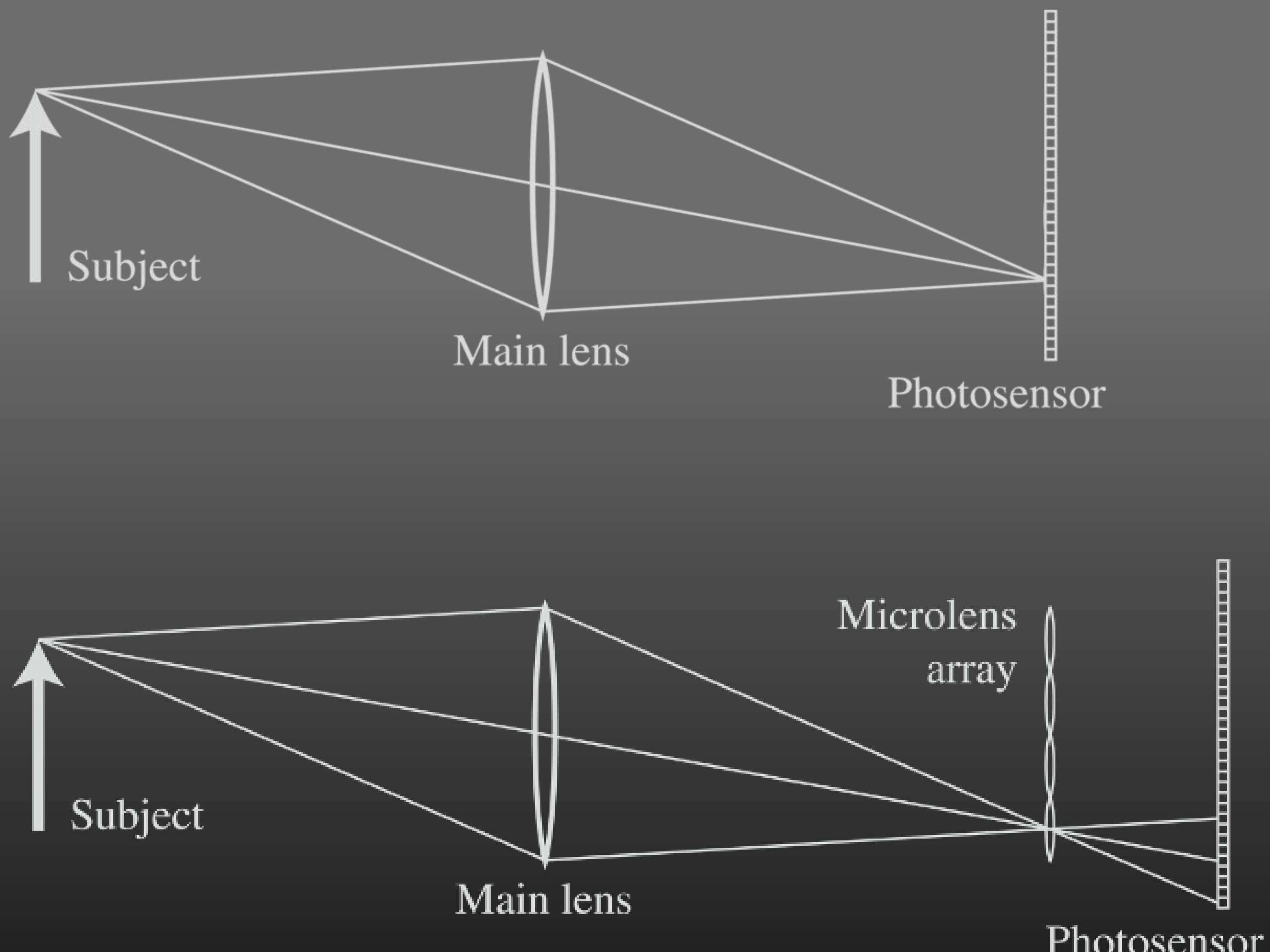
Ng et al.: "*Light field photography with a hand-held plenoptic camera*", *Stanford TechReport, 2005*

Kodak 16-megapixel sensor



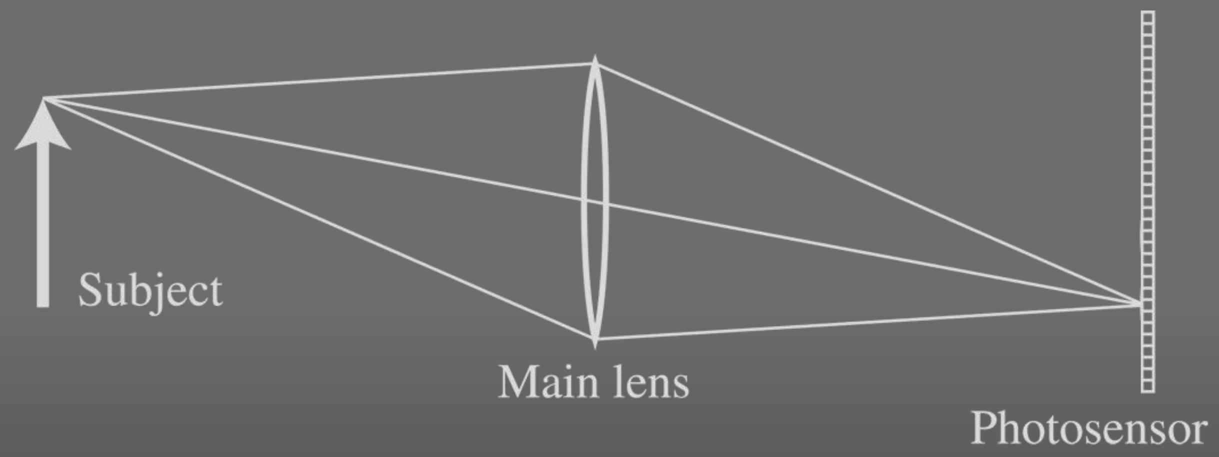
125μ square-sided microlenses

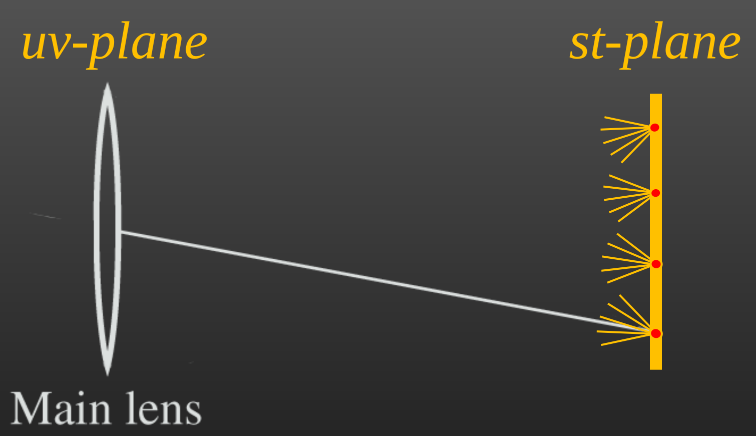
Conventional vs. light field camera



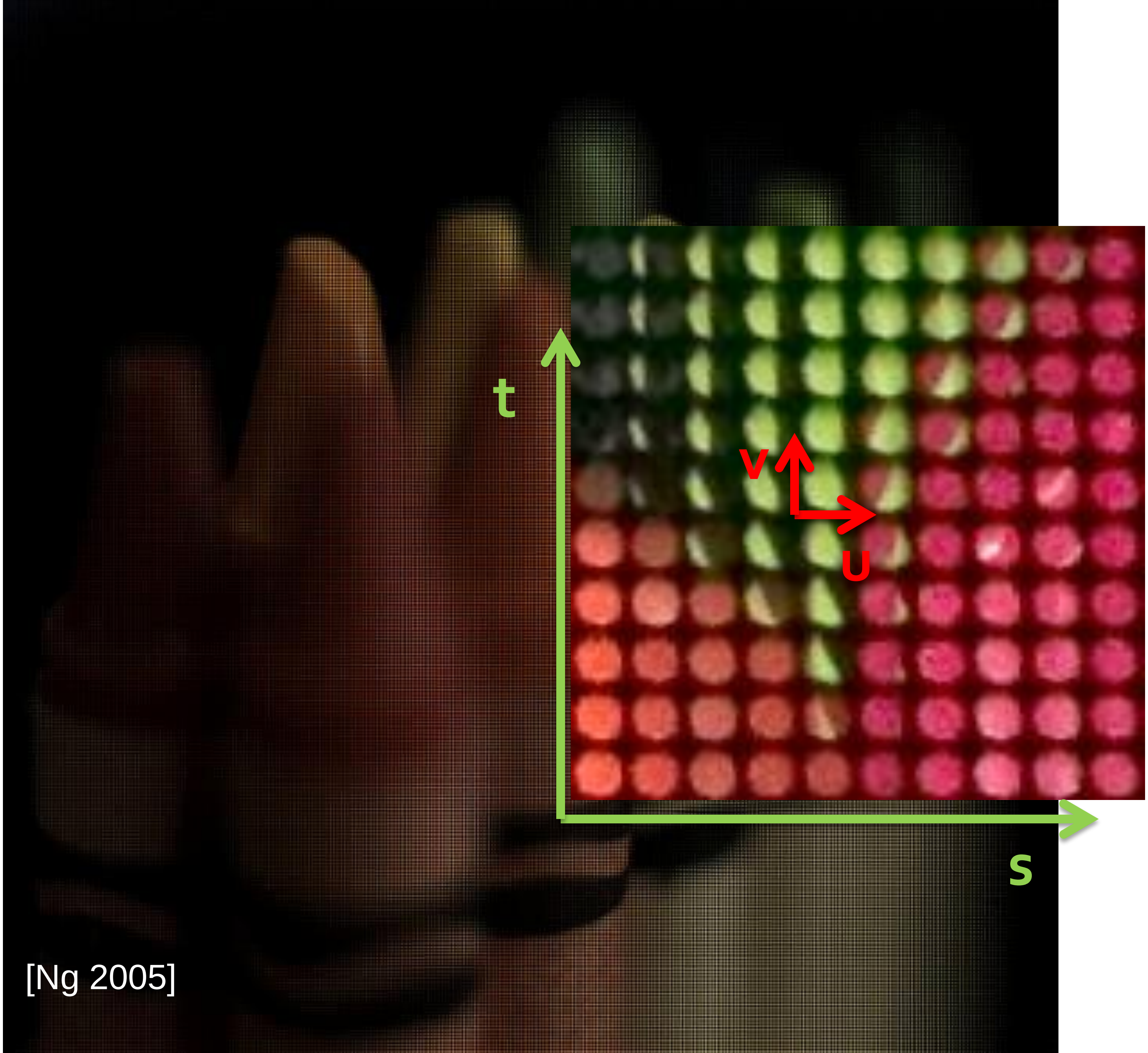
[Ng 2005]

Conventional vs. light field camera



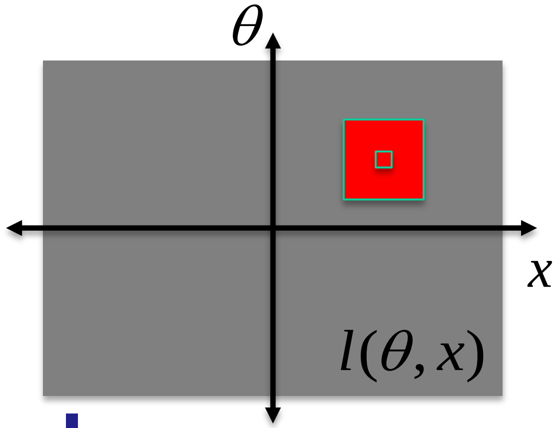


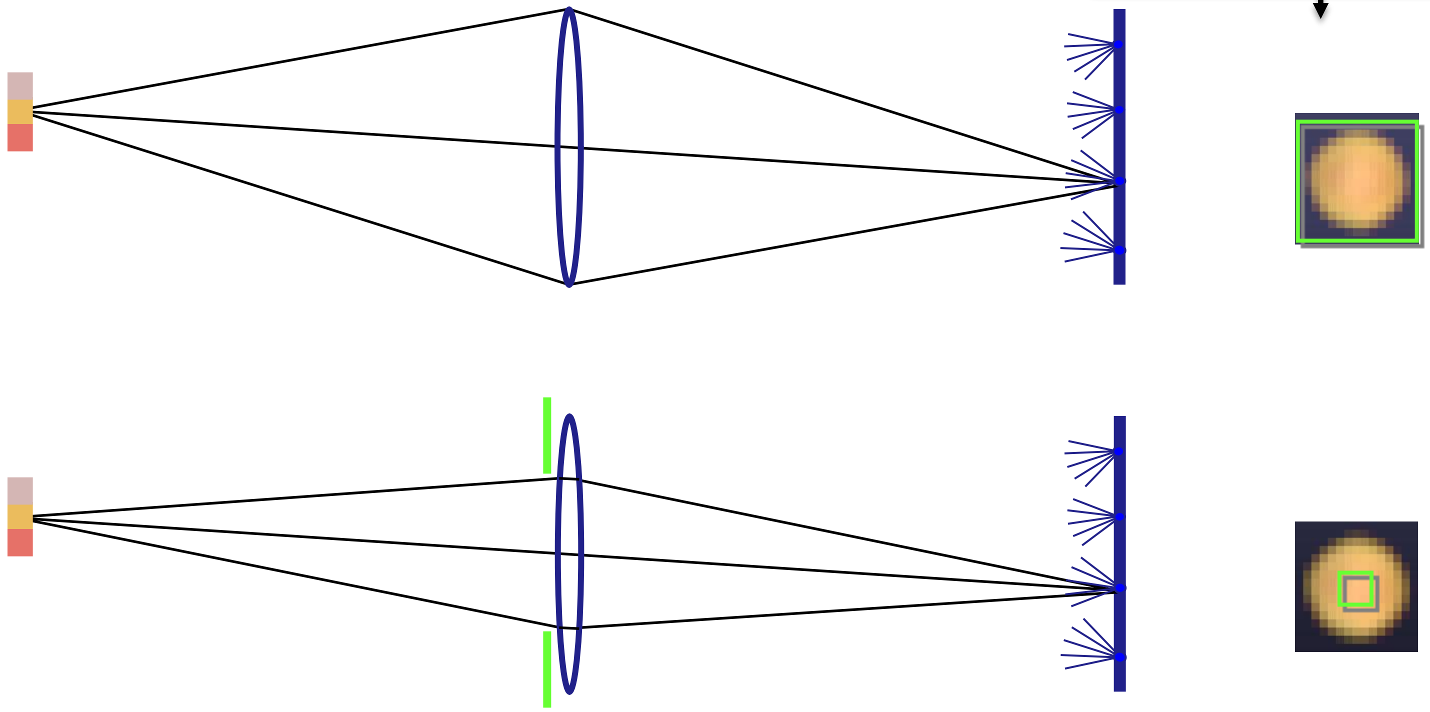
[Ng 2005]



[Ng 2005]

Digitally stopping-down

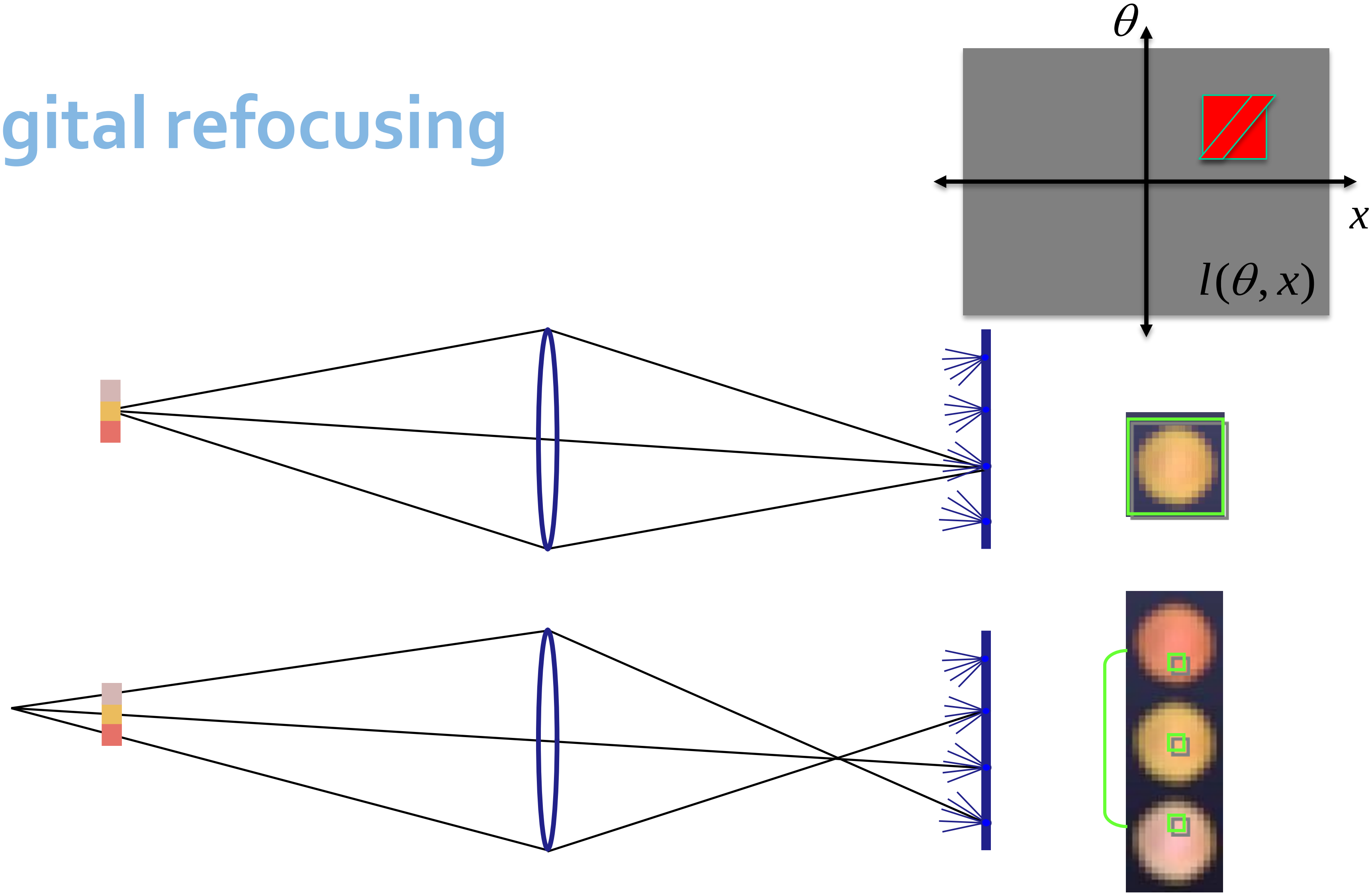




- stopping down = summing only the central portion of each microlens

[Ng 2005]

Digital refocusing



- refocusing = summing windows extracted from several microlenses

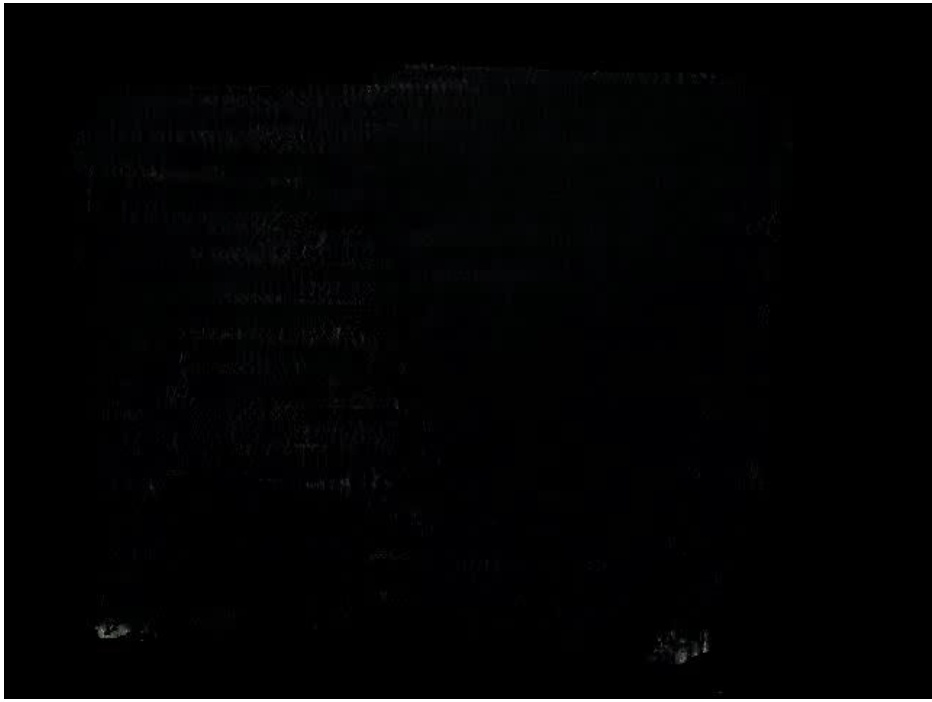
[Ng 2005]

Example of digital refocusing

[Ng 2005]

Extreme Refocussing

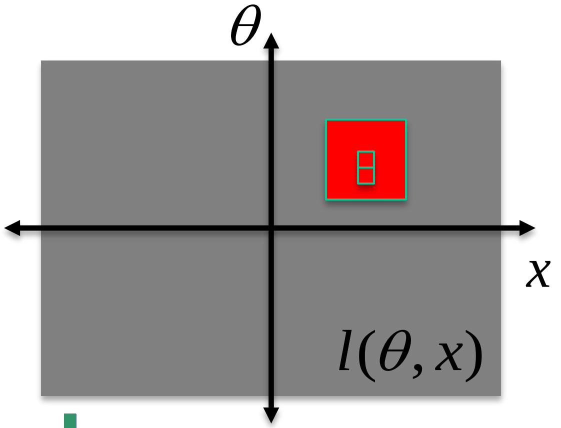
Standard Video

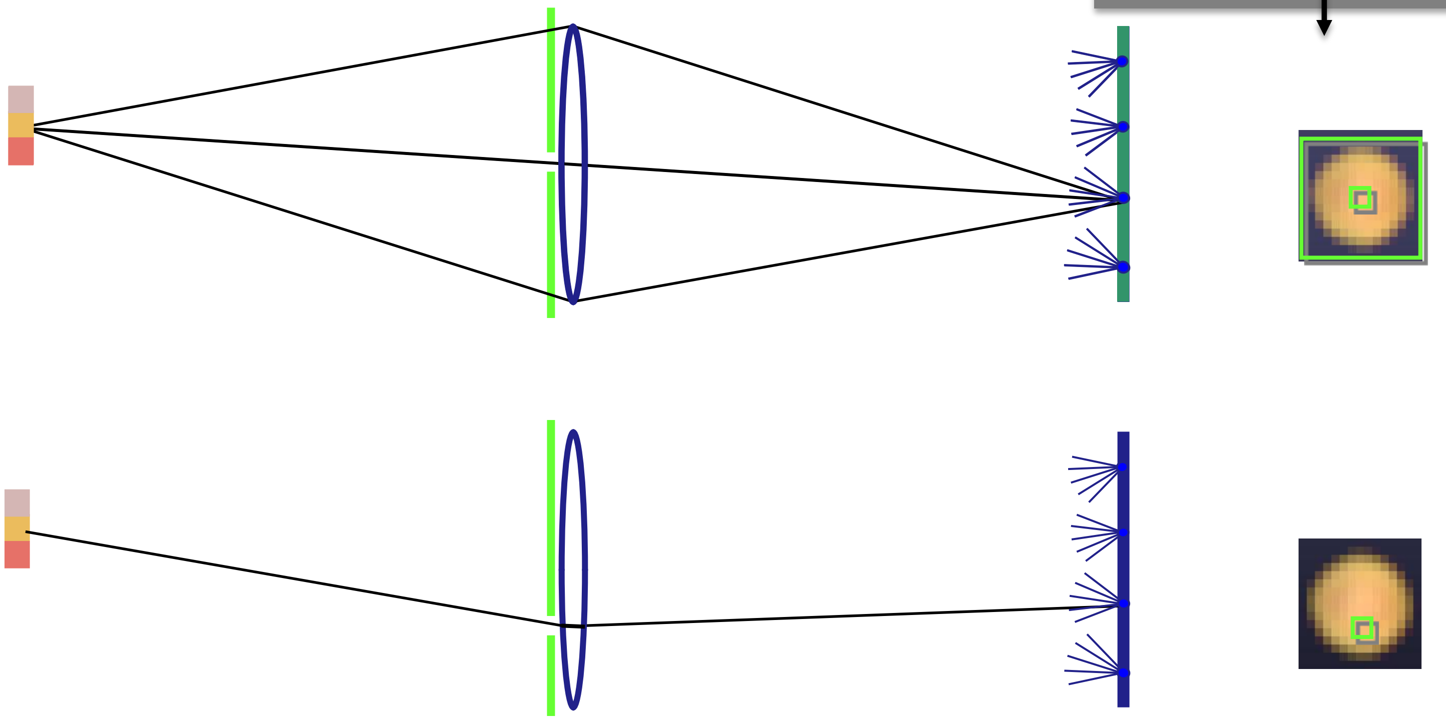


Refocussed Video +
Light Field Filtering

Wilburn et al.: "*High performance imaging using large camera arrays*", *Siggraph, 2005*

Digitally moving the observer

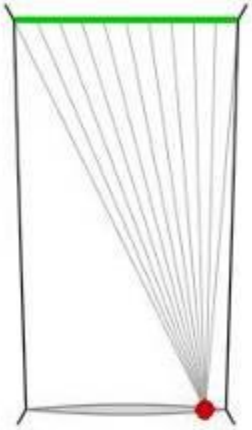




- moving the observer = moving the window we extract from the microlenses

[Ng 2005]

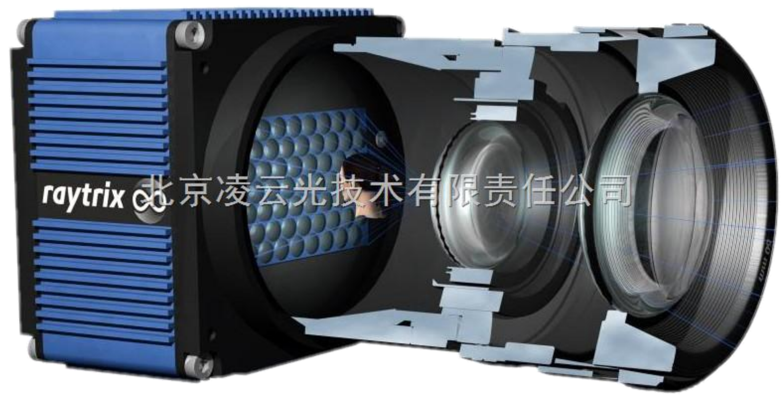
Example of moving the observer



[Ng 2005]

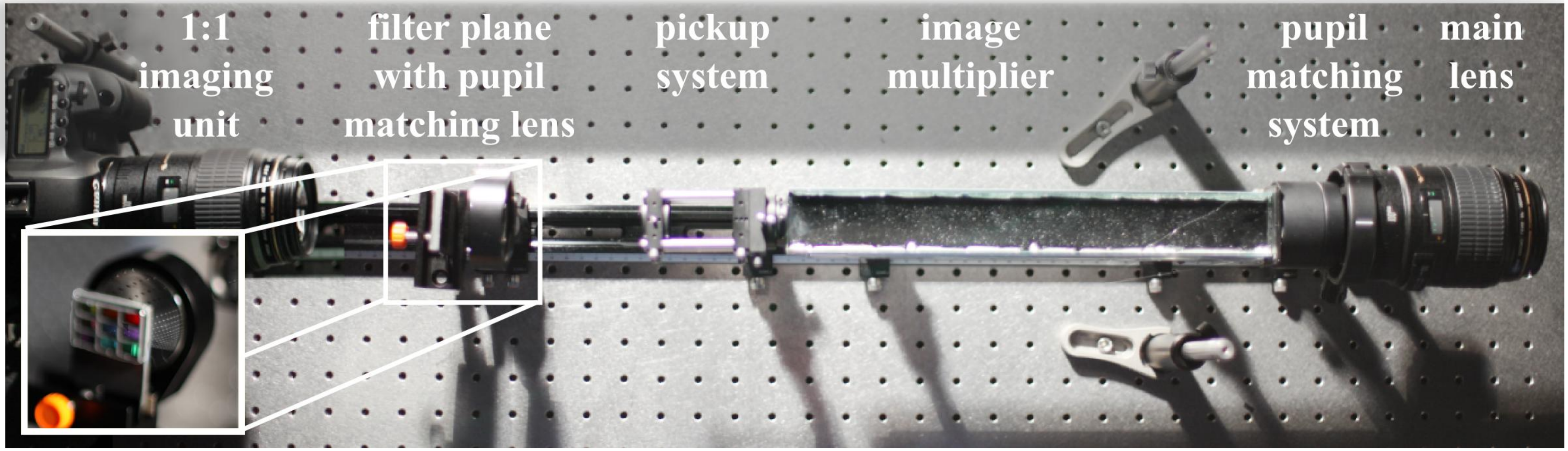
Commercial Systems:

Lytro



Raytrix

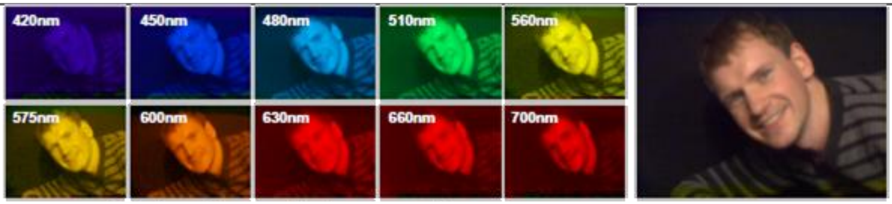
KaleidoCam



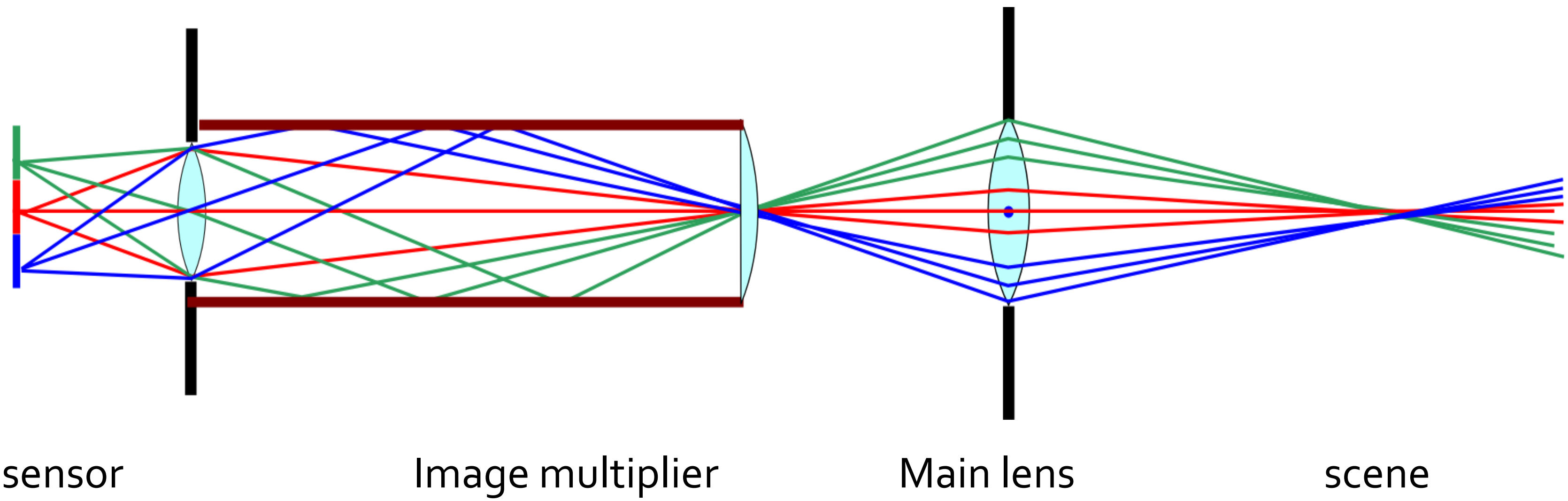
Manakov, Restrepo, Klehm, Hegedues, Eisemann, Ihrke.:
"A Reconfigurable Camera Add-On for HDR, Multi-Spectral, Polarization, and Light Field Imaging", Siggraph, 2013

Motivation

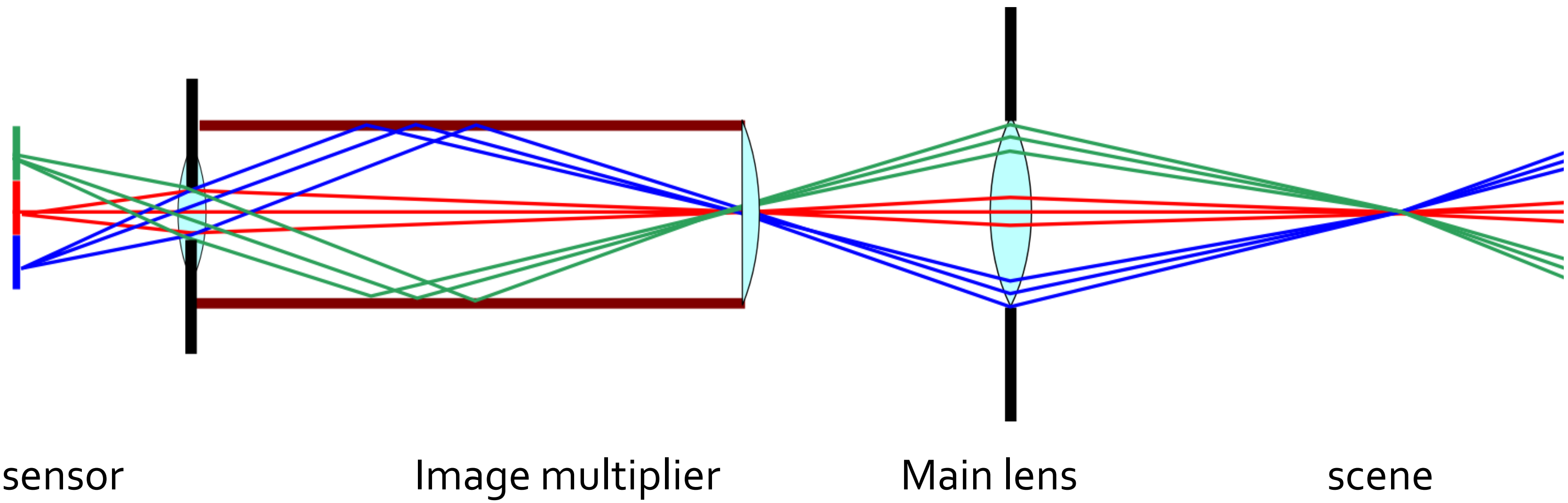
- Post-capture control
  - Exposure
  - White balance
  - Polarization
  - Focus
- Single snapshot
- Add-on architecture



KaleidoCam: Photographic Control (Aperture)

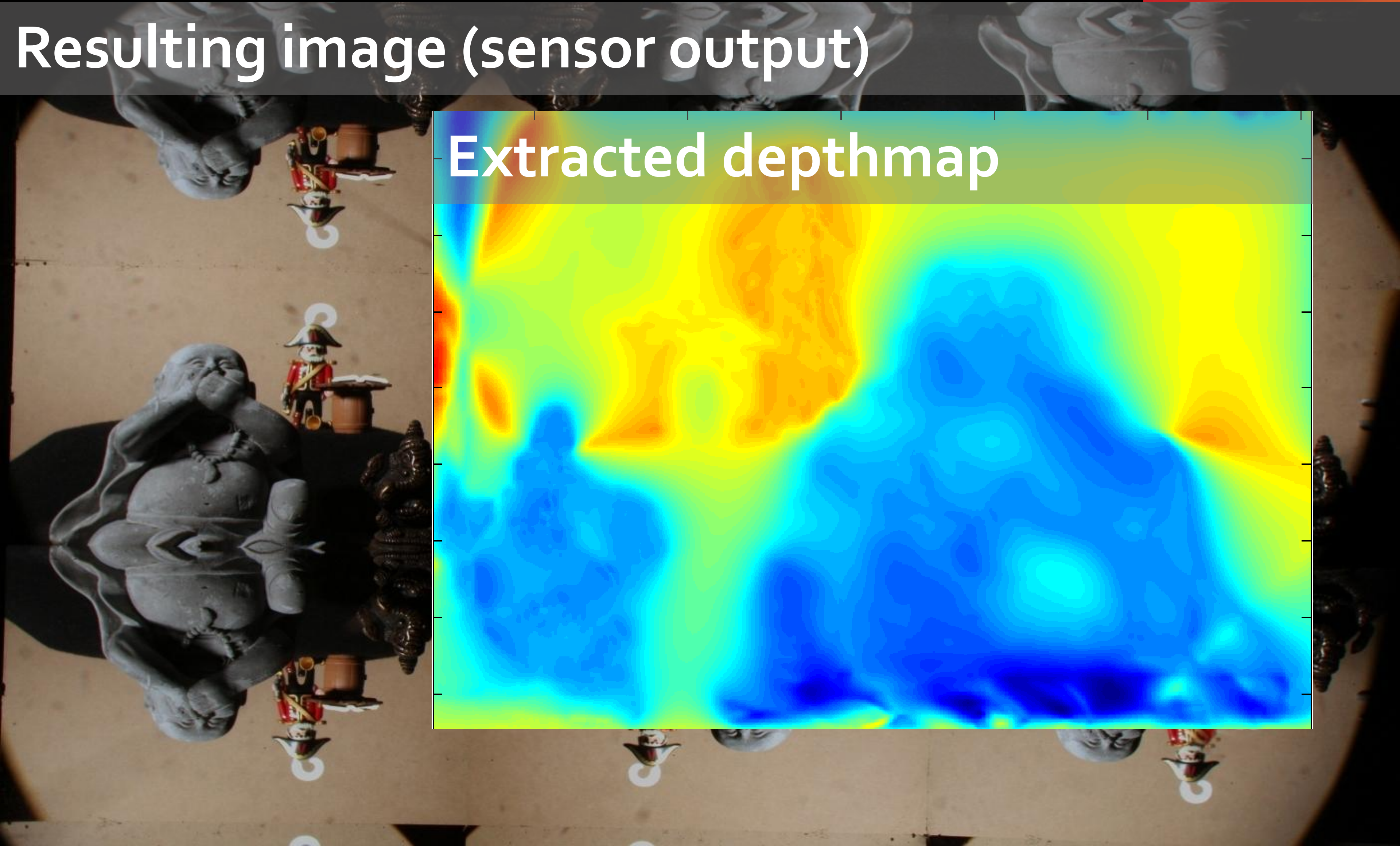


KaleidoCam: Photographic Control (Aperture)

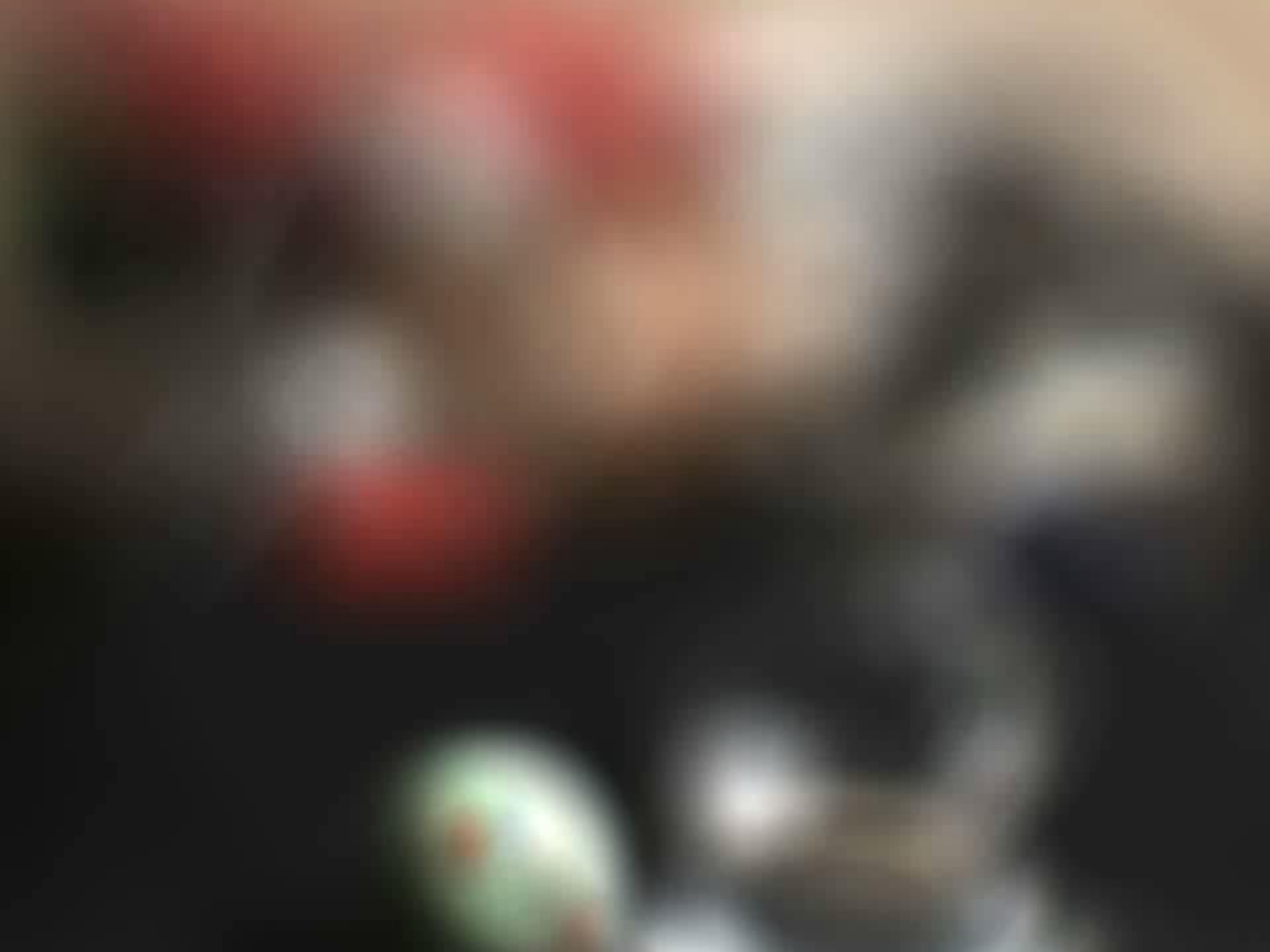


Sub-Aperture Imaging aka Light Field Capture

Resulting image (sensor output)

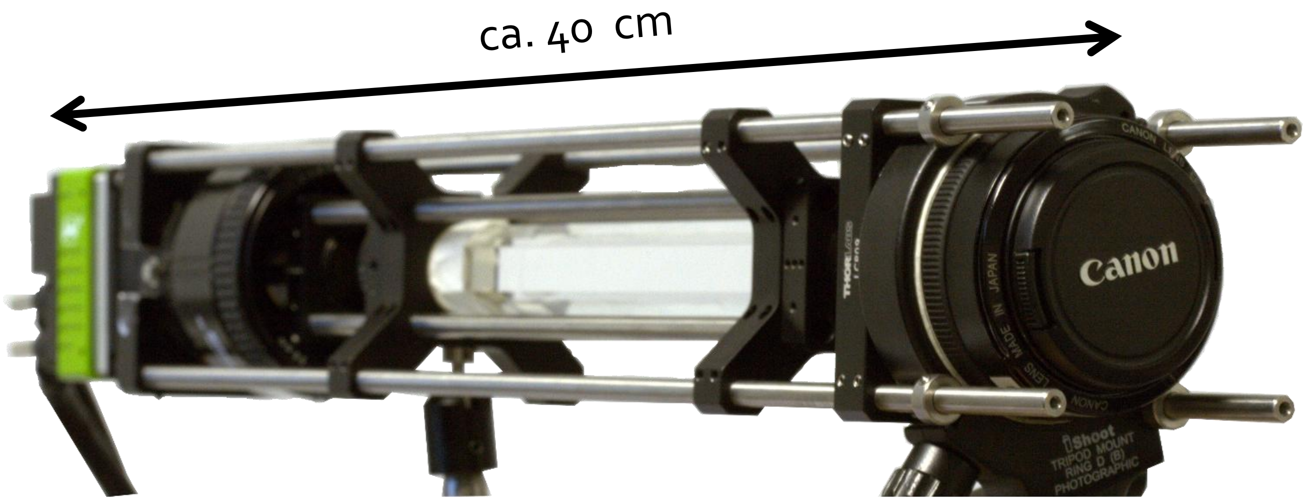


Extracted depthmap



Current System

- Video-capable version (30fps)
- Native spatial resolution ca. 1.5 Mpixel (7 views)
- Start-up incubation period on-going



Fin.

http://manao.inria.fr/