

High Resolution Spectral Video Capture & Computational Photography

Xun Cao (曹汛)

School of Electronic Science & Engineering
Nanjing University

caoxun@nju.edu.cn

Dec 30th, 2015

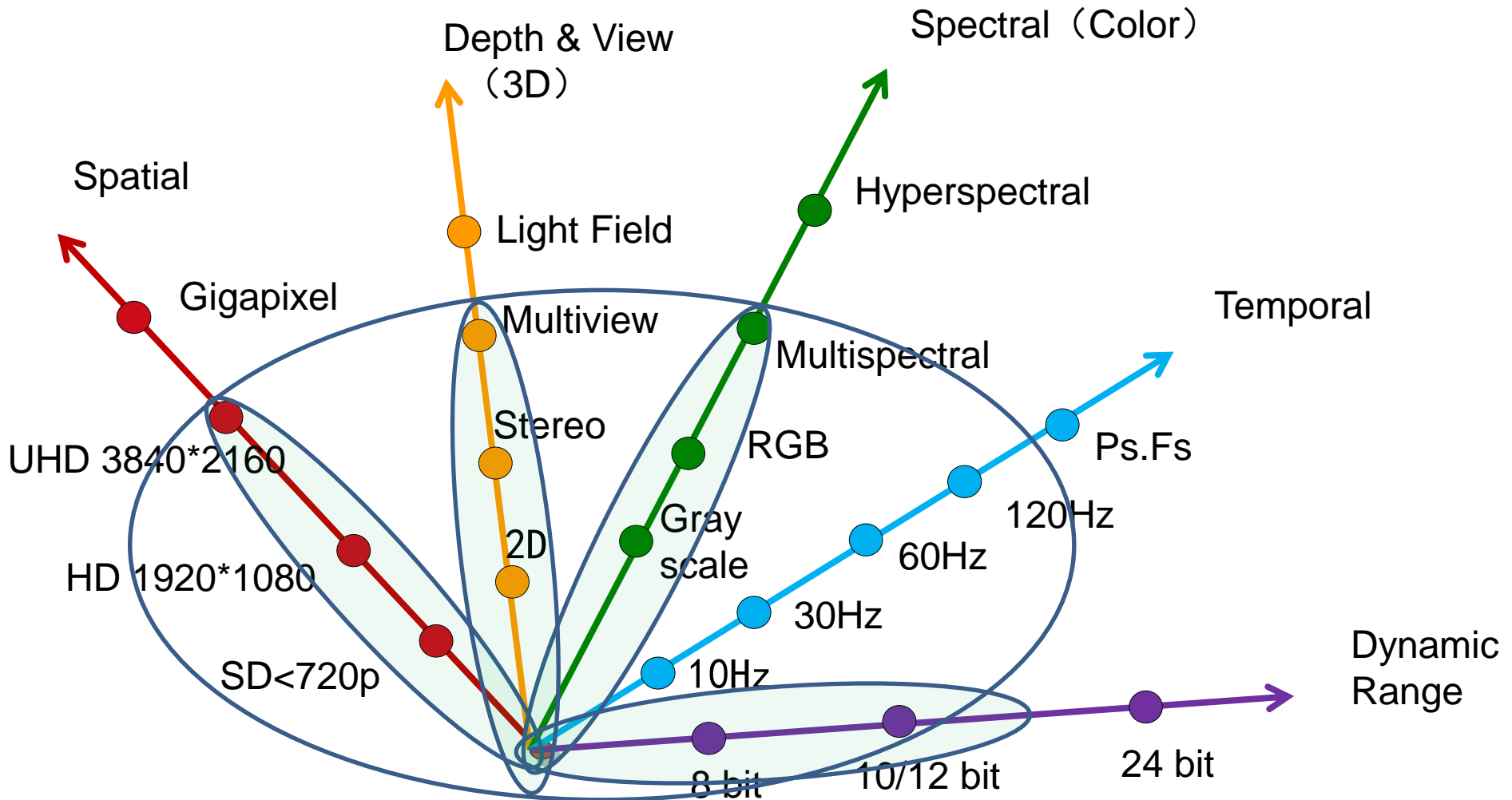
Computational Photography



Computational photography refers broadly to computational imaging techniques that enhance or extend the capabilities of digital photography. The output of these techniques is an ordinary photograph, but one that could not have been taken by a traditional camera. (Wikipedia)

Computational photography is an emerging new field created by the convergence of computer graphics, computer vision and photography. Its role is to overcome the limitations of the traditional camera by using computational techniques to produce a richer, more vivid, perhaps more perceptually meaningful representation of our visual world. (CMU Course Introduction)

CP for various imaging dimensions



The lab focuses on **3** kinds of computational cameras

- **Spectral Camera**

- High Resolution Spectral Video Camera: **PMIS**

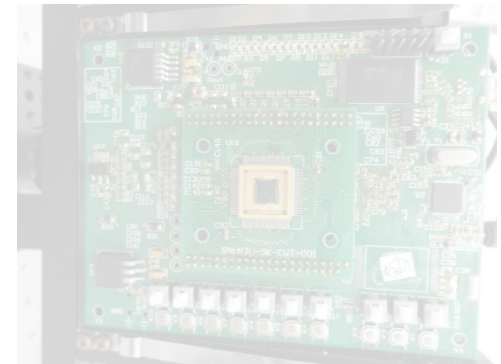
- **Multiview Stereo Camera Array**

- High Accuracy 3D Reconstruction

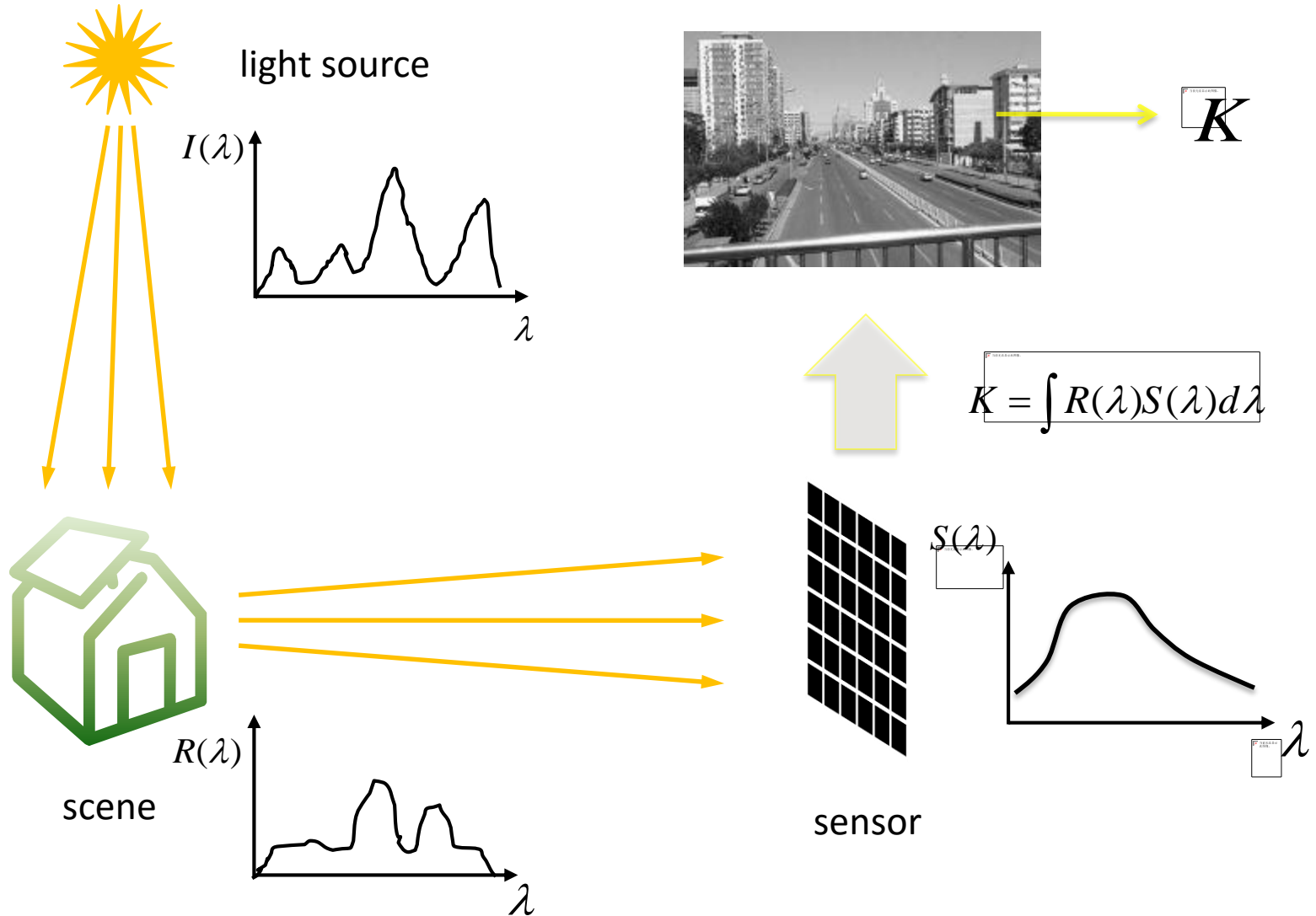
- **Super-Resolution Camera**

- Nano-Scale Pixel Camera

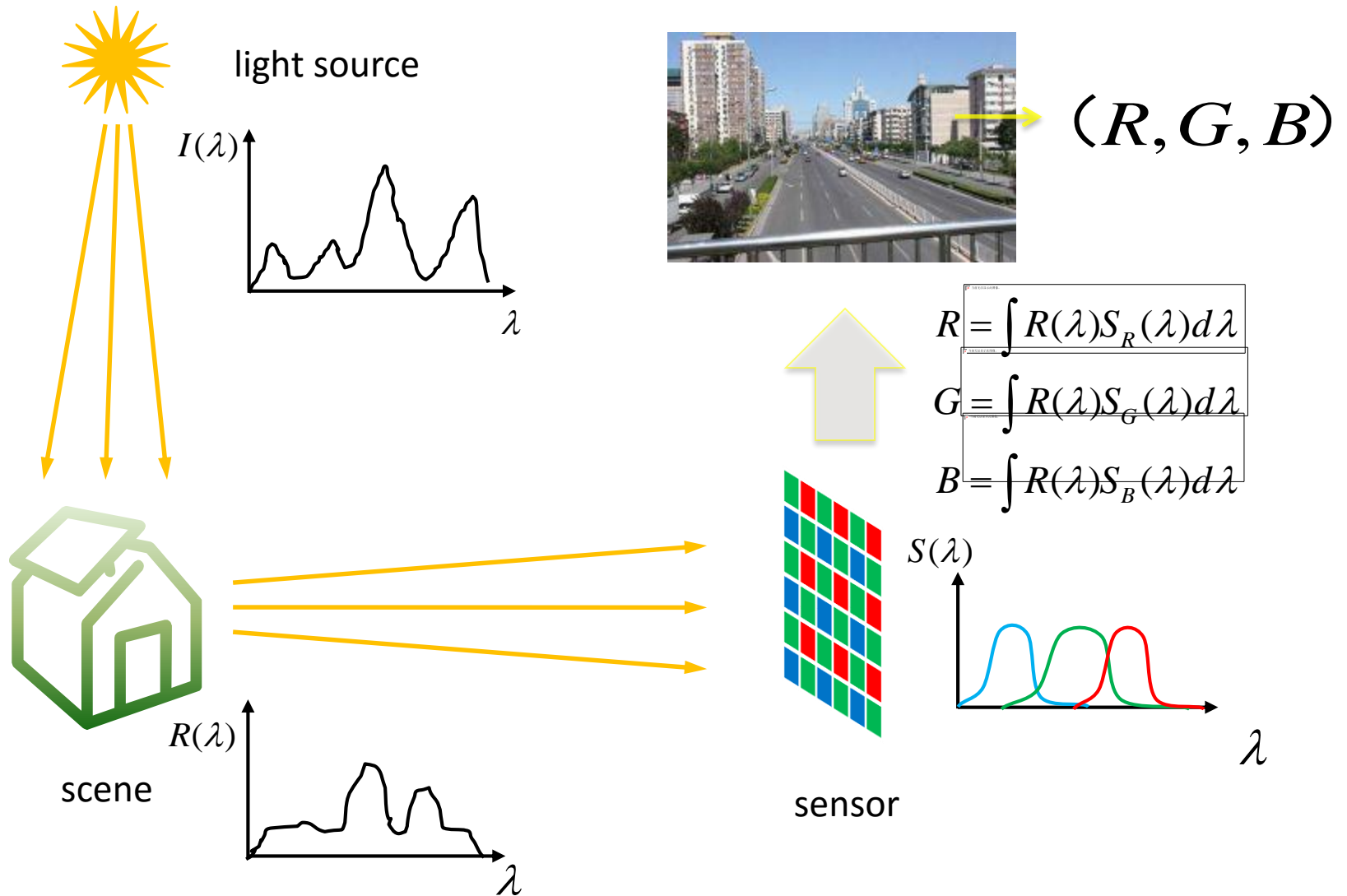
- Gigapixel on Single Chip



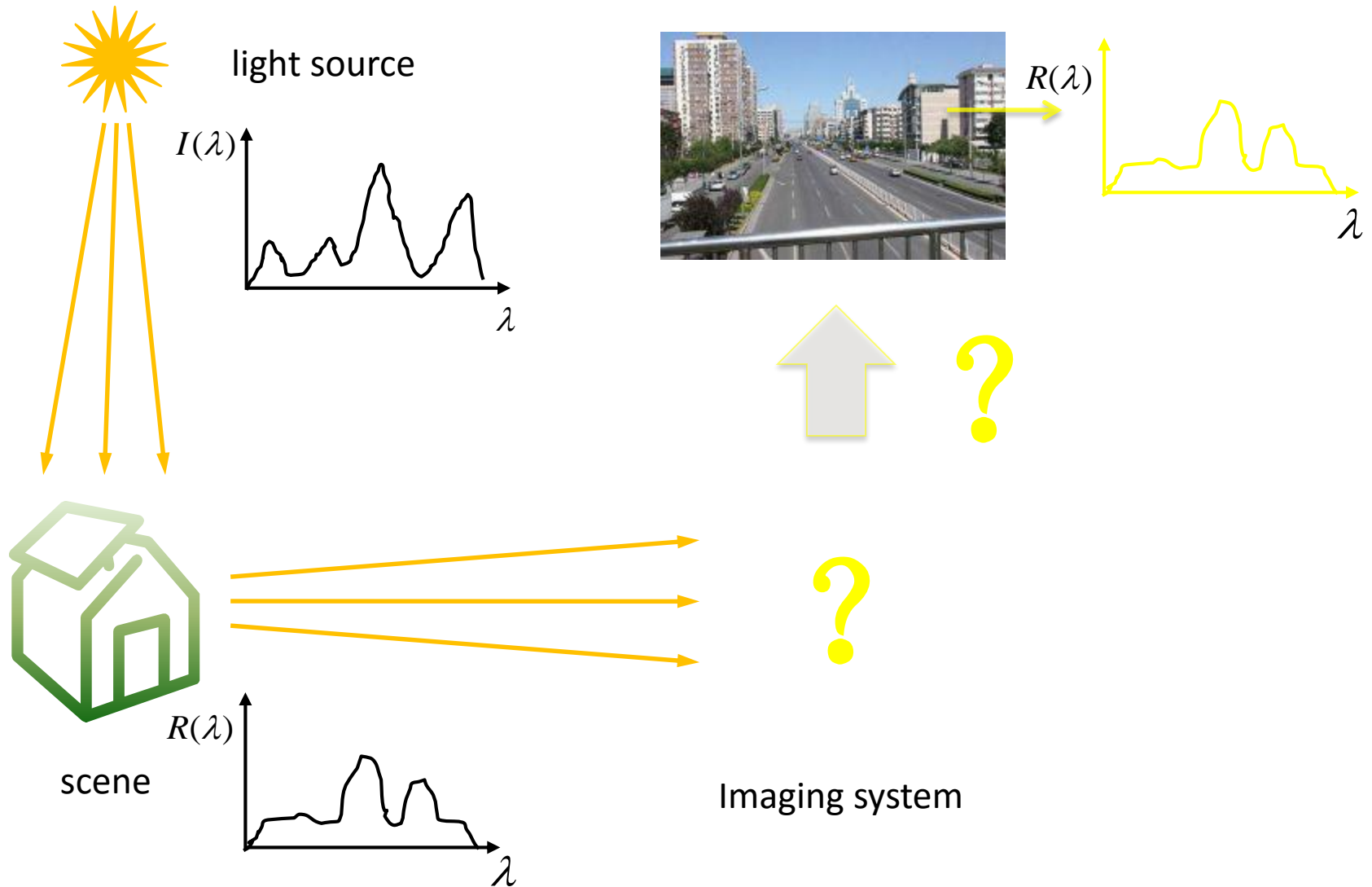
Grayscale Imaging



Color Imaging



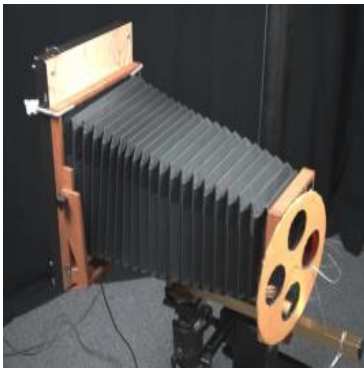
Spectral Imaging



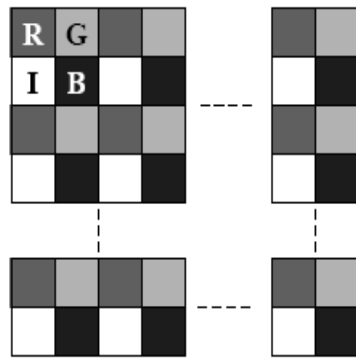
Related Work (1)

➤ Filtered Camera based Spectrum Imaging

[Kidono07] [Gat00][Yamaguchi06][Schechner02]...



Filter wheel



Color Filter Array



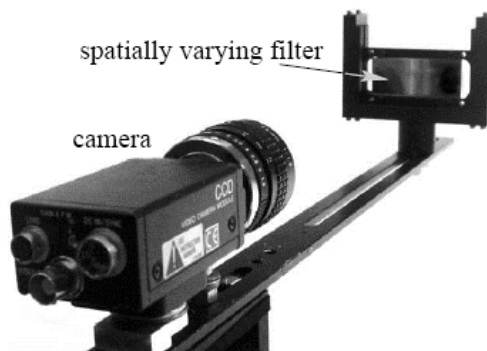
Programmable Filter



Filter Scanning



Prof. S.Nayar
Columbia



Spatially varying filter
PAMI '02

Key idea: Trade time for spectrum

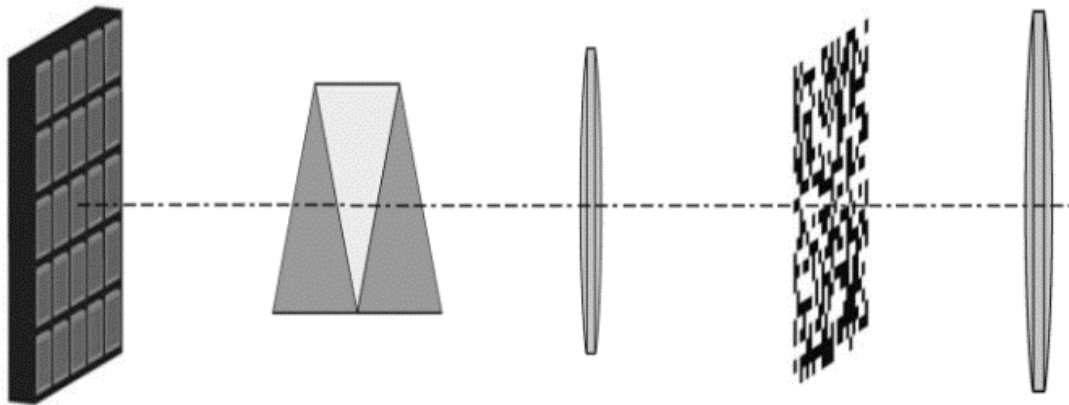
Shortcomings:

- Incapable of capturing dynamic scenes
- Low spectrum resolution

Related Work (2)

➤ Coded Aperture Snapshot Spectral Imager (**CASSI**)

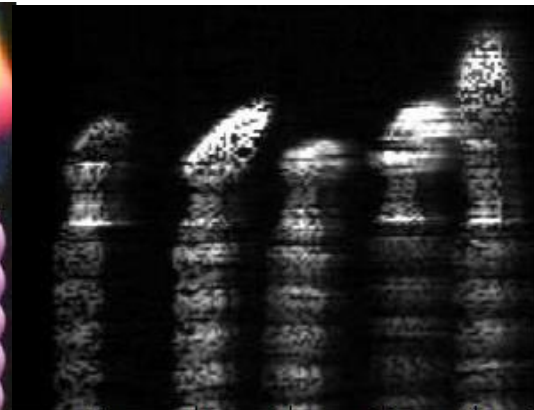
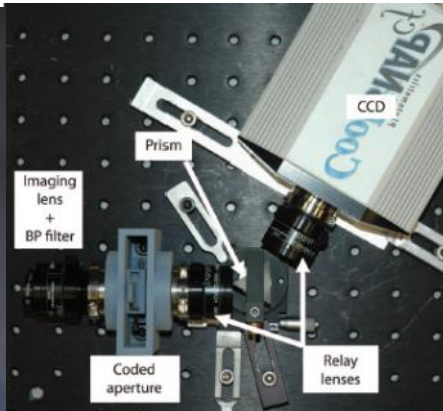
[Brady'06] [Willett'07] [Gehm'07] [Wagadarikar'08]



Key Idea: Coded Aperture

2D Imaging + reconstruction

- Spectrum resolution: 6 nm
- Spatial resolution: 256 x 248
- Limited spatial resolution
- Limited accuracy
- Time-consuming reconstructing (20min / frame)



Prof. D.Brady (Duke Univ.)

CASSI: Applied Optics SPIE, JOSA'06-09

Related Work (3)

➤ Computed Tomography Imaging Spectrometer

[Descour95] [Descour01] [Vandervlugt07] [Hagen08]...



Prof. E. Dereniak
Arizona

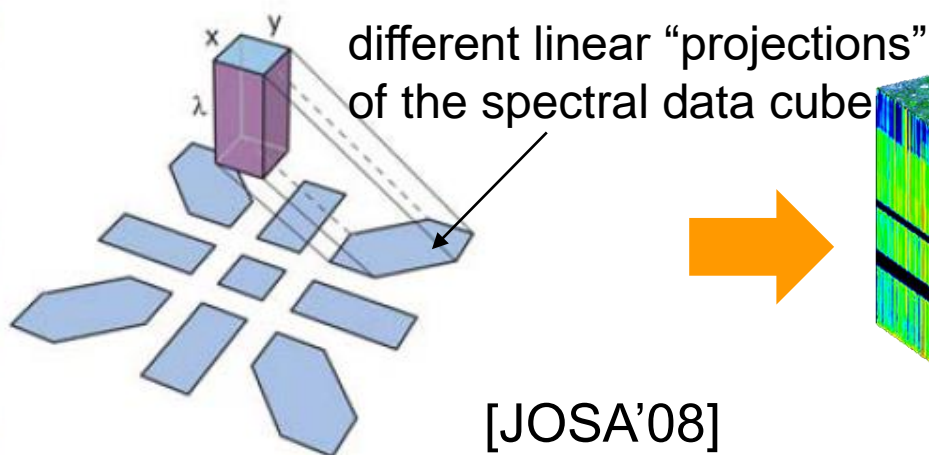
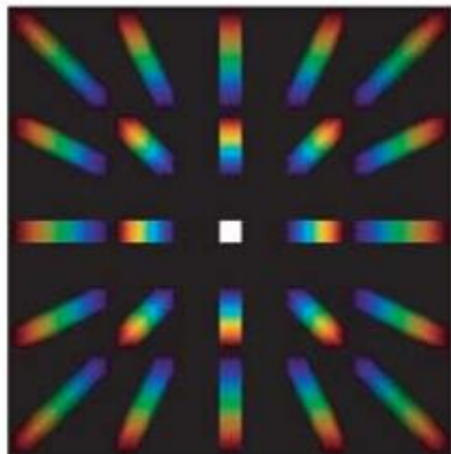


**Computed Tomographic
Imaging Spectrometer**

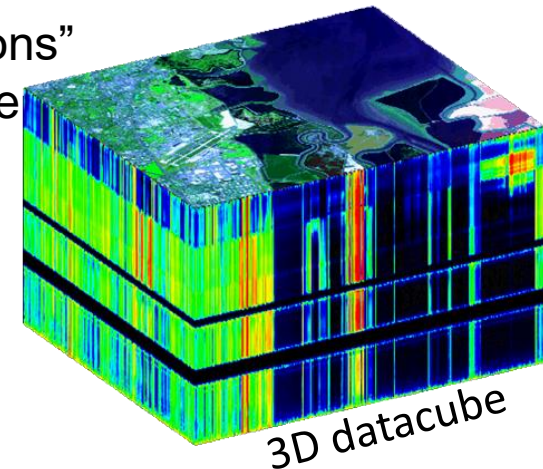
CTIS

Key Ideas:
CT Projections
+
Reconstruction

Shortcomings:
Low Resolution
Difficult to Calibrate
High Computational Cost



[JOSA'08]



Our Spectral Video Camera - PMIS

2008~2010: Prism-Mask Imaging Spectrometer (PMIS¹)

- Directly capture multispectral video
- High spectra-resolution
- Low cost
- Easy setup and calibration

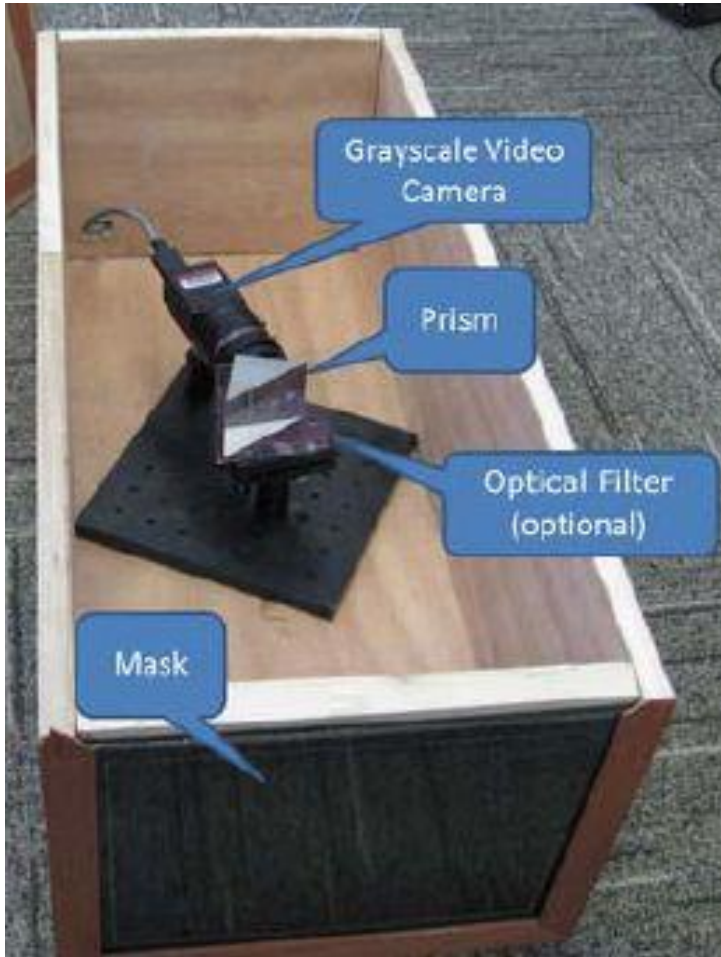
2011~2014: Hybrid-Camera PMIS²

- Both high spectral and spatial resolution
- Real-time hyperspectral video capture

2014~now Scene-Adaptive PMIS³

- Space-time coded modulation
- Spectral video capture with improved accuracy and efficiency

A glance at PMIS¹



capturing system



Pointgrey grayscale camera
2248x2048 @15fps

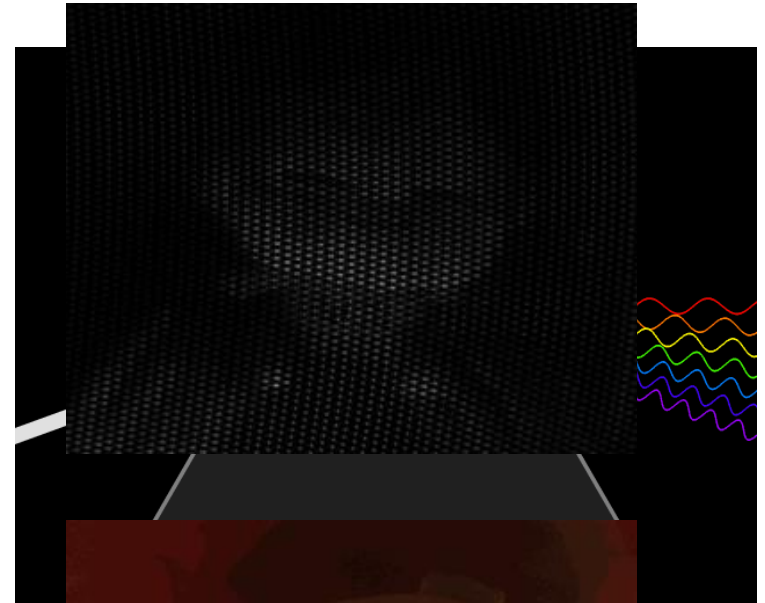
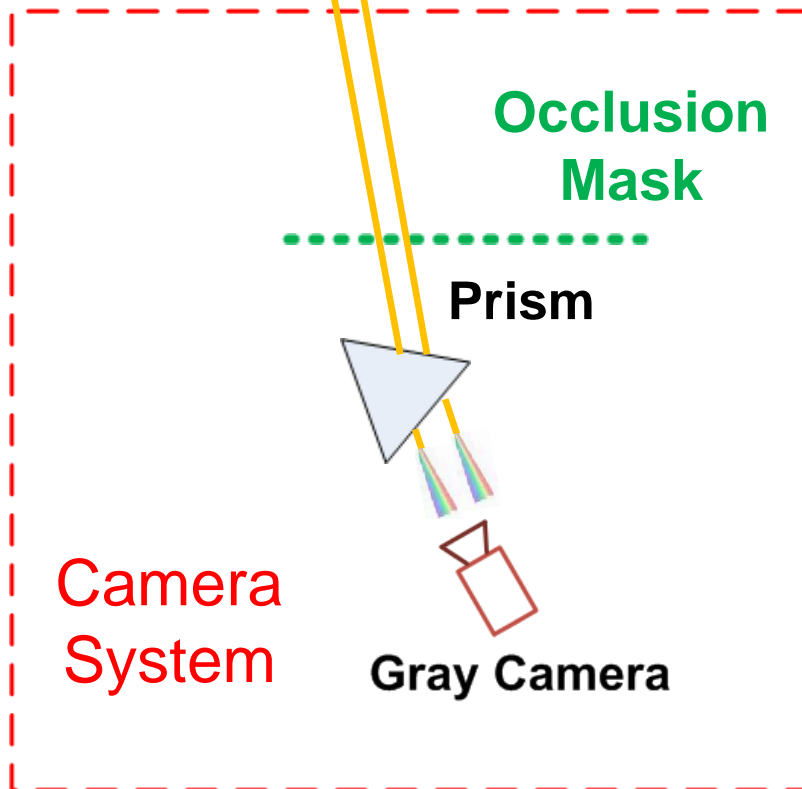


mask

System Principle



Grayscale Camera

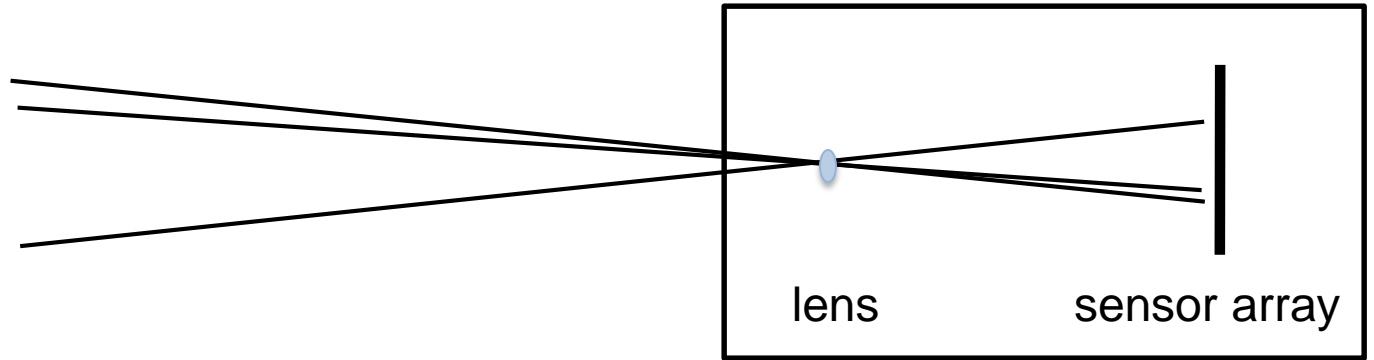


GIF source: Wiki

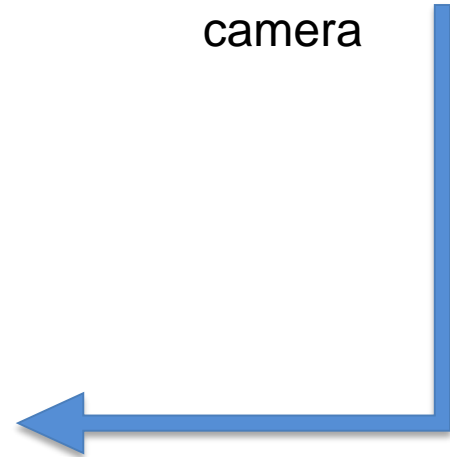
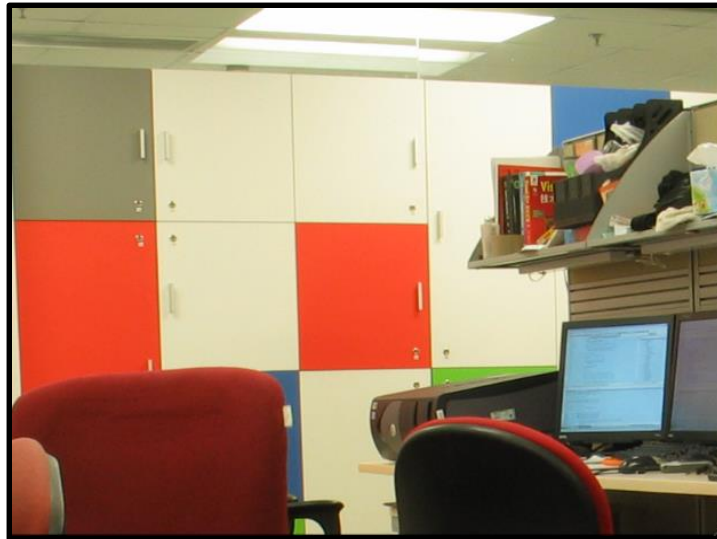


Re-generated RGB Video

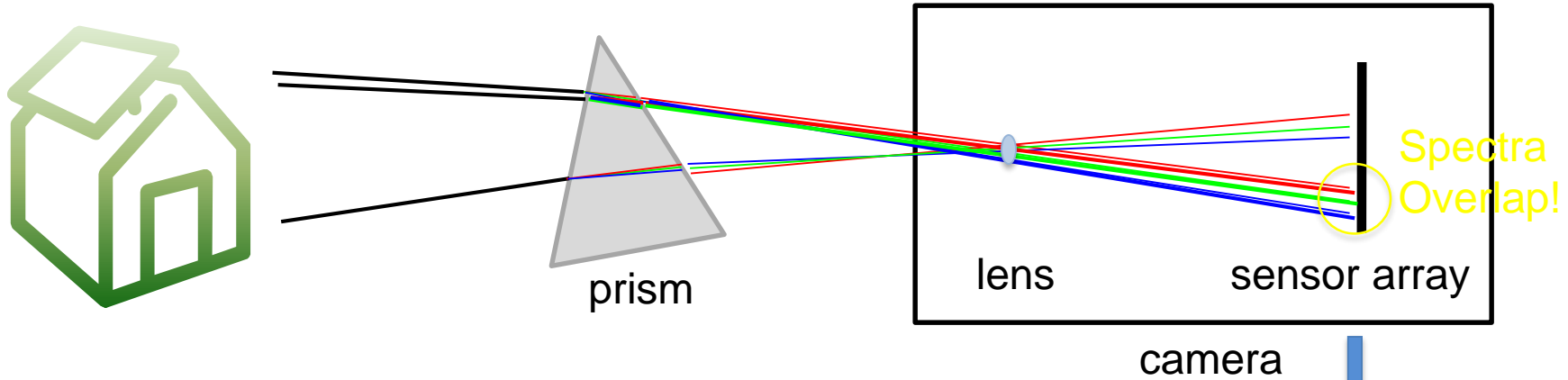
A Typical Camera



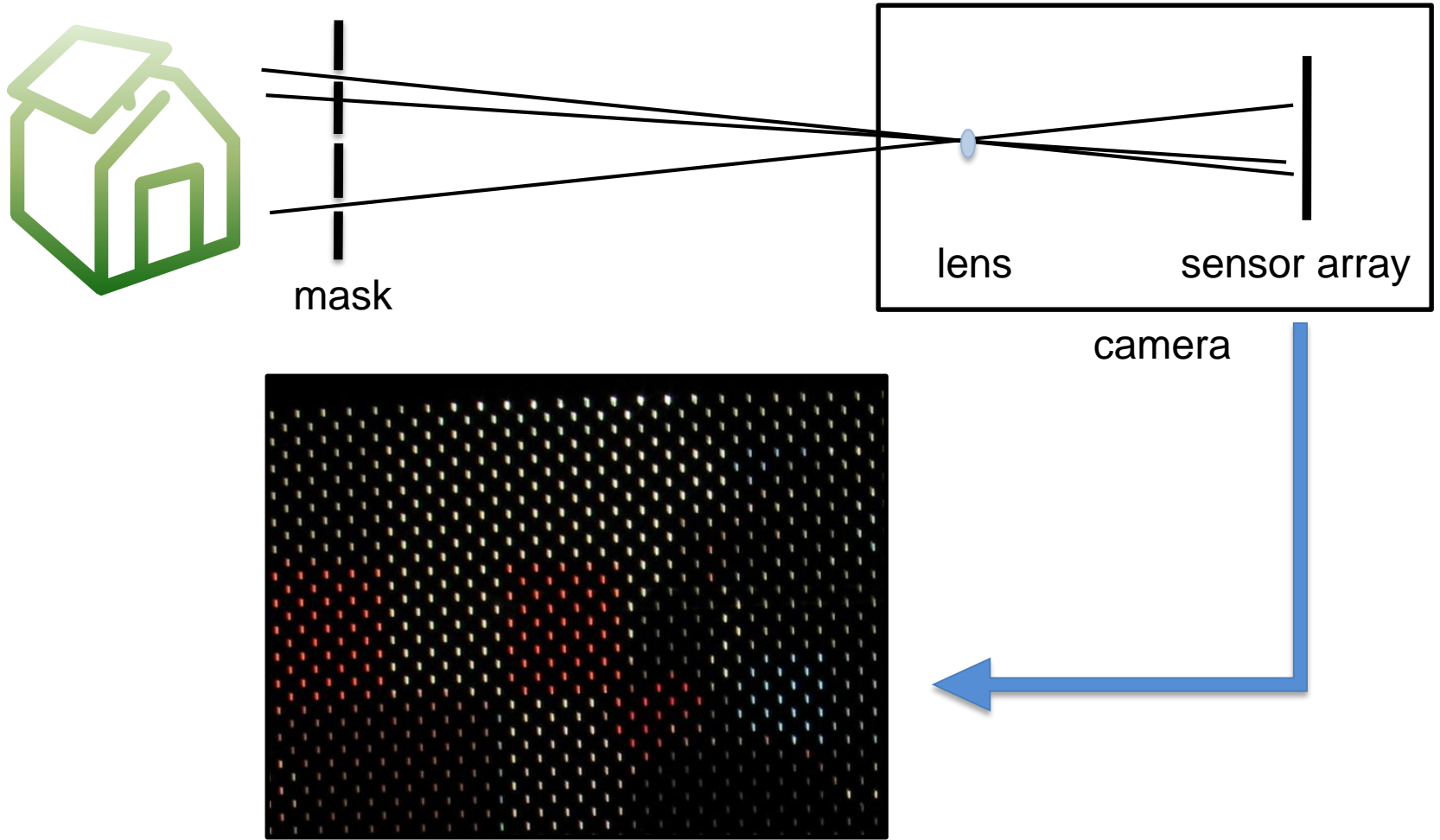
camera



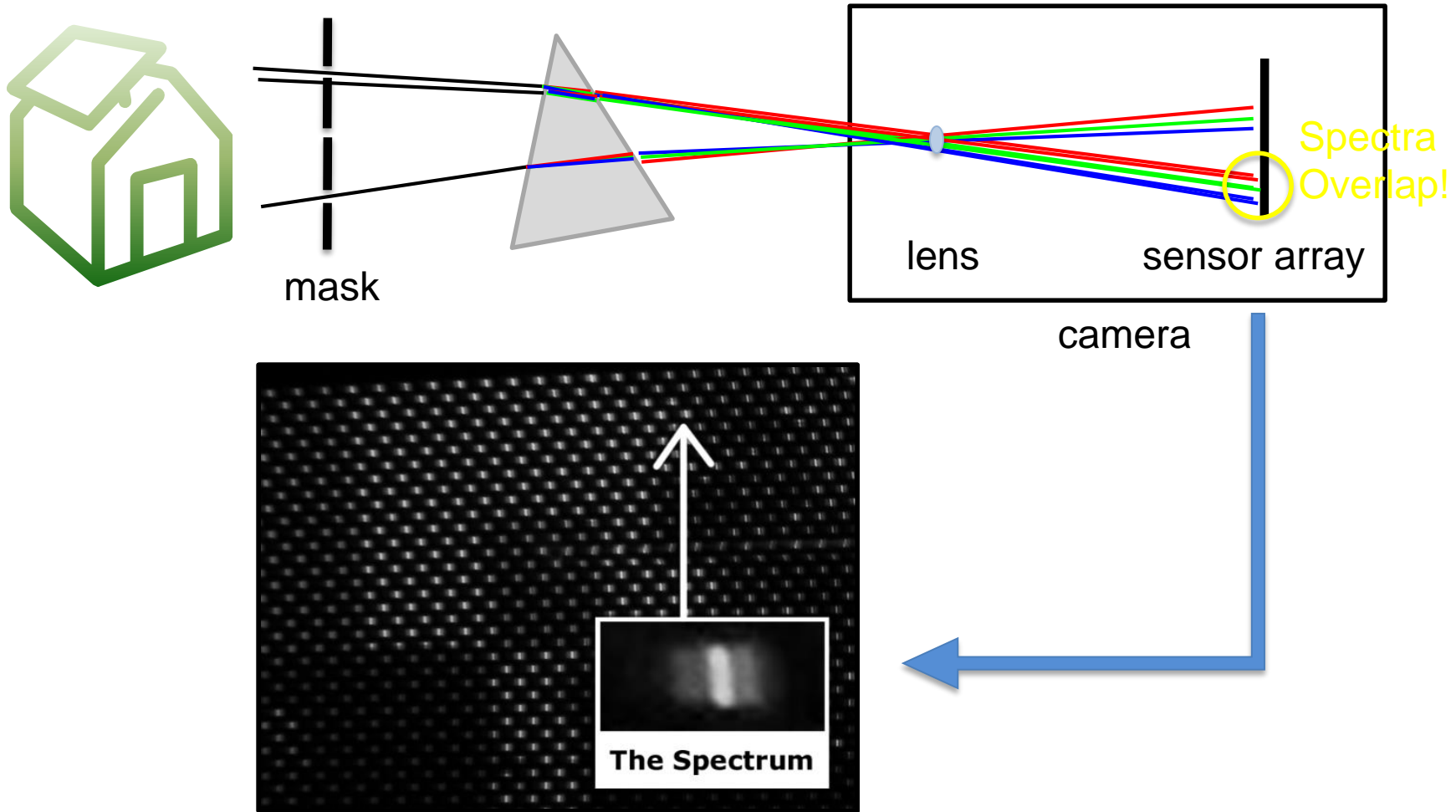
Camera & Prism



Camera & Mask



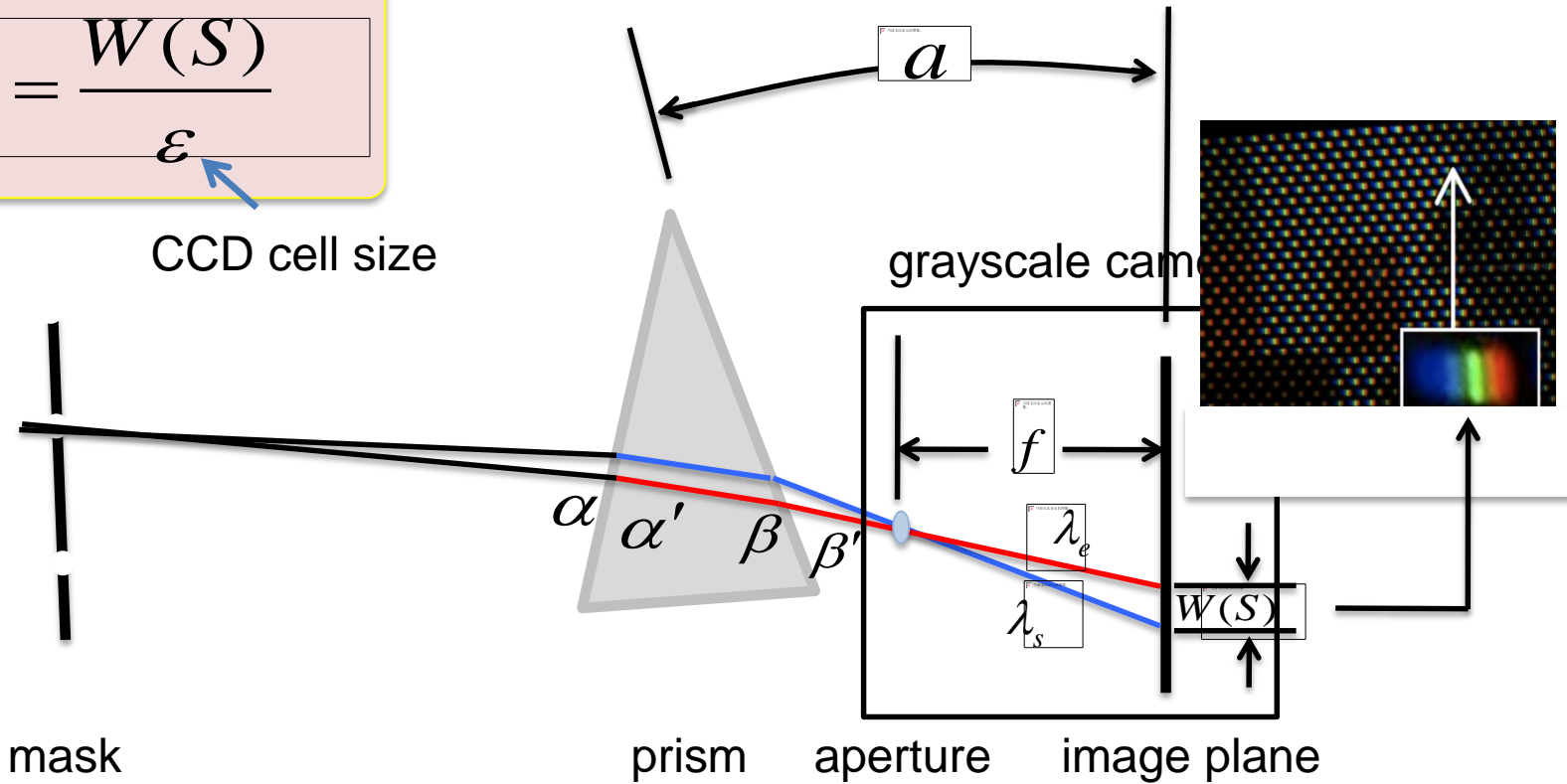
Camera & Mask & Prism



Spectral Resolution

$$R_{spec} = \frac{W(S)}{\epsilon}$$

CCD cell size

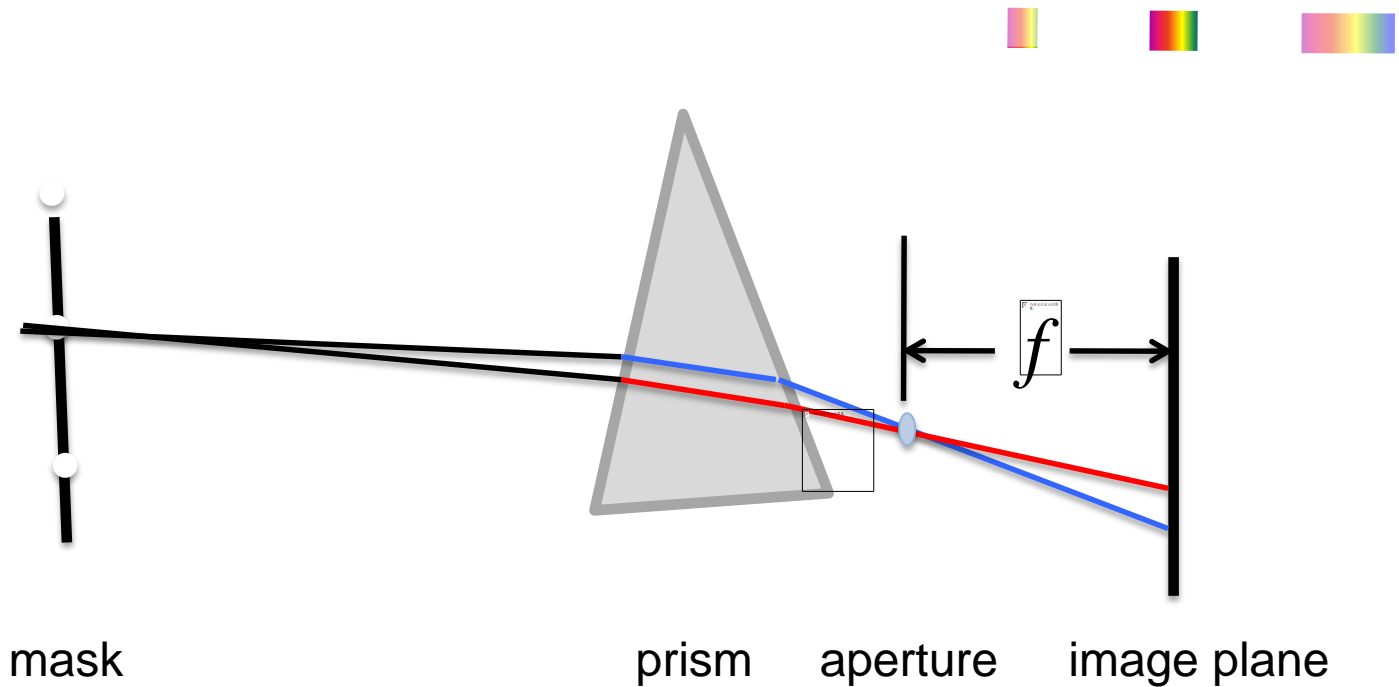


$$n_\lambda = \frac{\sin(\alpha)}{\sin(\alpha'(\lambda))} = \frac{\sin(\beta'(\lambda))}{\sin(\beta(\lambda))}$$

$$W(S) = f \left[(\tan(\beta'(\lambda_e) - a) - \tan(\beta'(\lambda_s) - a)) \right]$$

Spectral Resolution

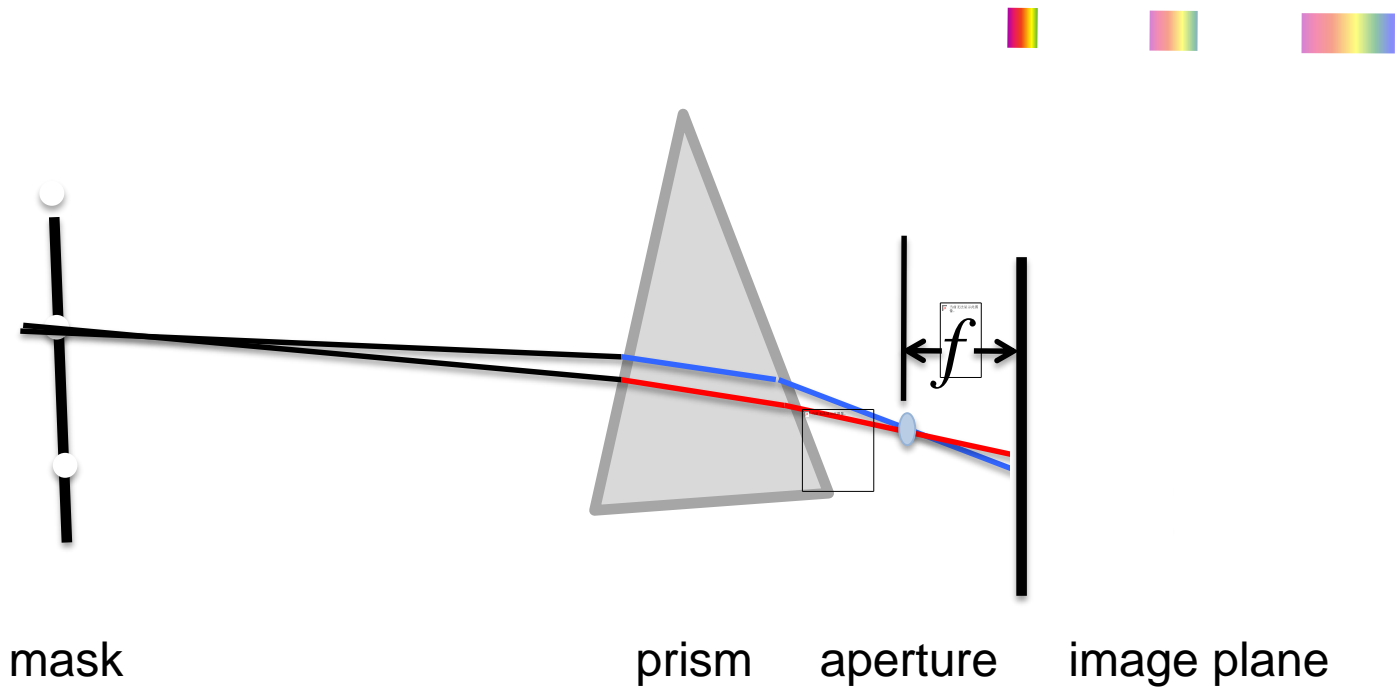
- Tradeoff Spatial/Spectral Resolution



$$W(S) = f \left(\tan(\beta'(\lambda_e) - a) - \tan(\beta'(\lambda_s) - a) \right)$$

Spectral Resolution

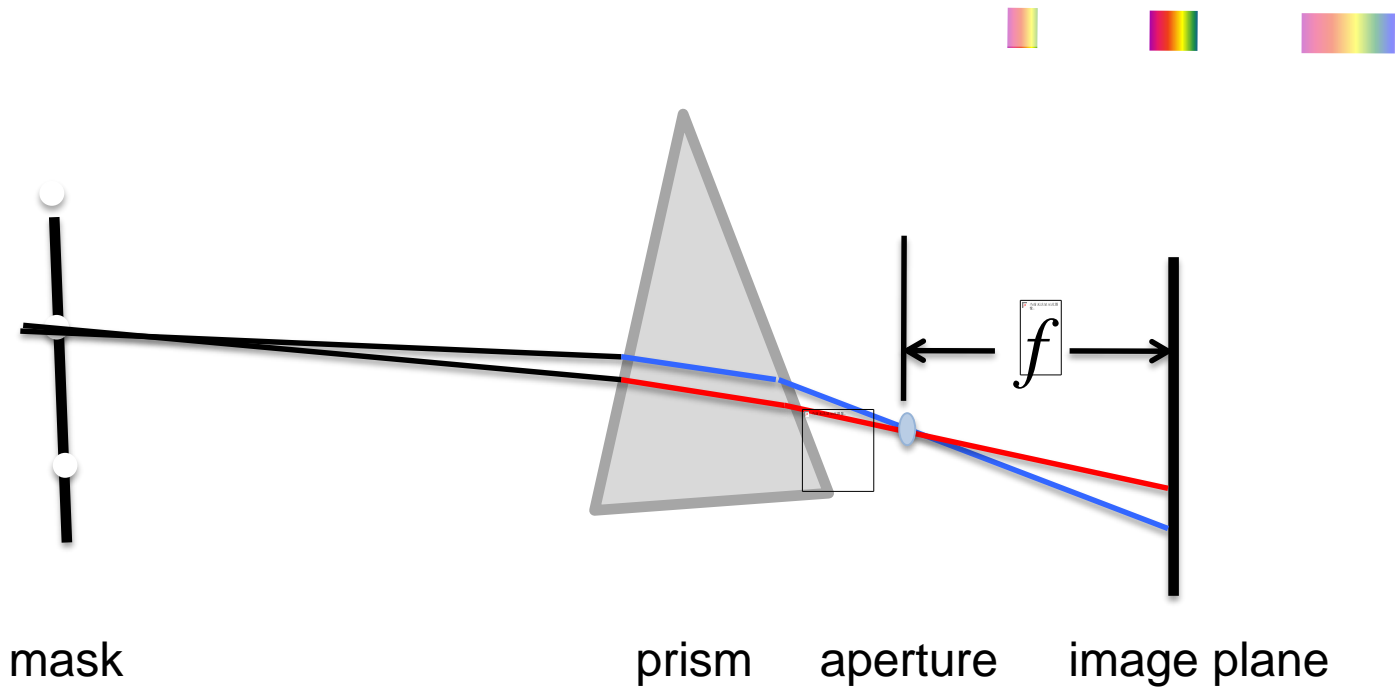
- Tradeoff Spatial/Spectral Resolution



$$R_{spec} = \frac{W(S)}{\epsilon} \quad W(S) = f \left(\tan(\beta'(\lambda_e) - a) - \tan(\beta'(\lambda_s) - a) \right)$$

Spectral Resolution

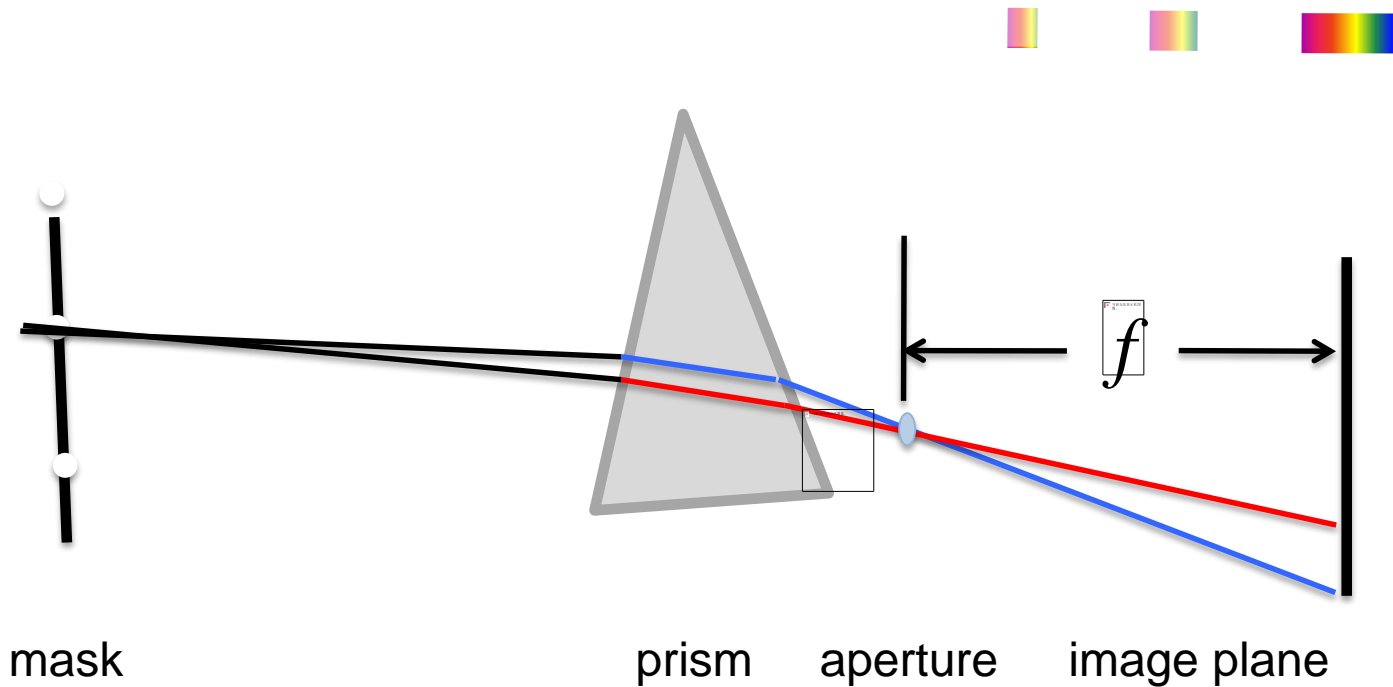
- Tradeoff Spatial/Spectral Resolution



$$R_{spec} = \frac{W(S)}{\varepsilon} \quad W(S) = f \left(\tan(\beta'(\lambda_e) - a) - \tan(\beta'(\lambda_s) - a) \right)$$

Spectral Resolution

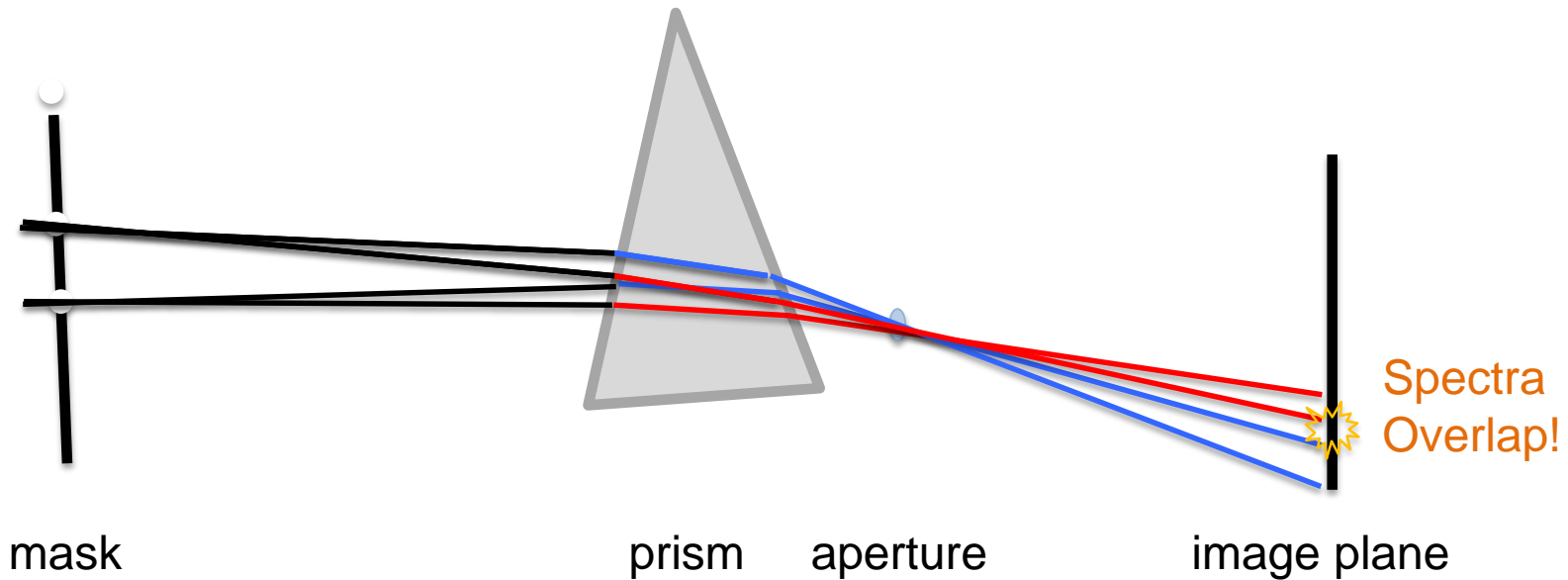
- Tradeoff Spatial/Spectral Resolution



$$R_{spec} = \frac{W(S)}{\varepsilon} \quad W(S) = f \left(\tan(\beta'(\lambda_e) - a) - \tan(\beta'(\lambda_s) - a) \right)$$

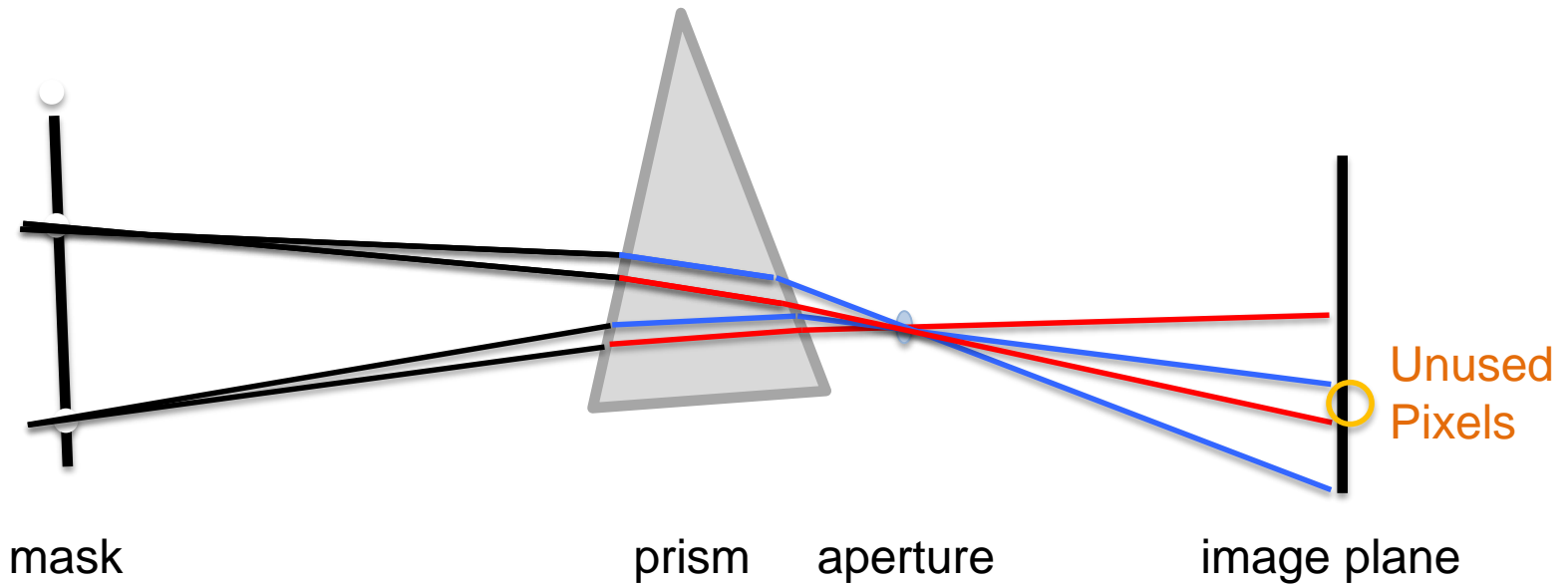
Spatial Resolution

- Small Mask Hole Distance



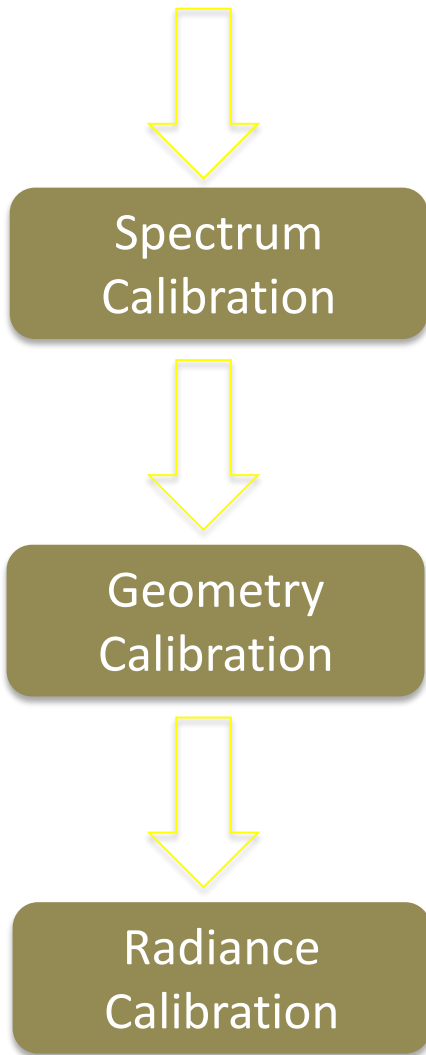
Spatial Resolution

- Large Mask Hole Distance

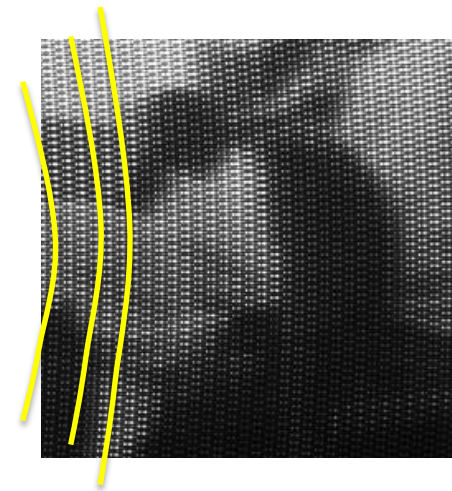


Device Calibration

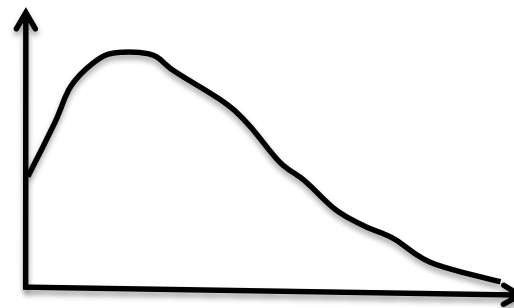
Calibration Overview



Mapping Position to Wavelength

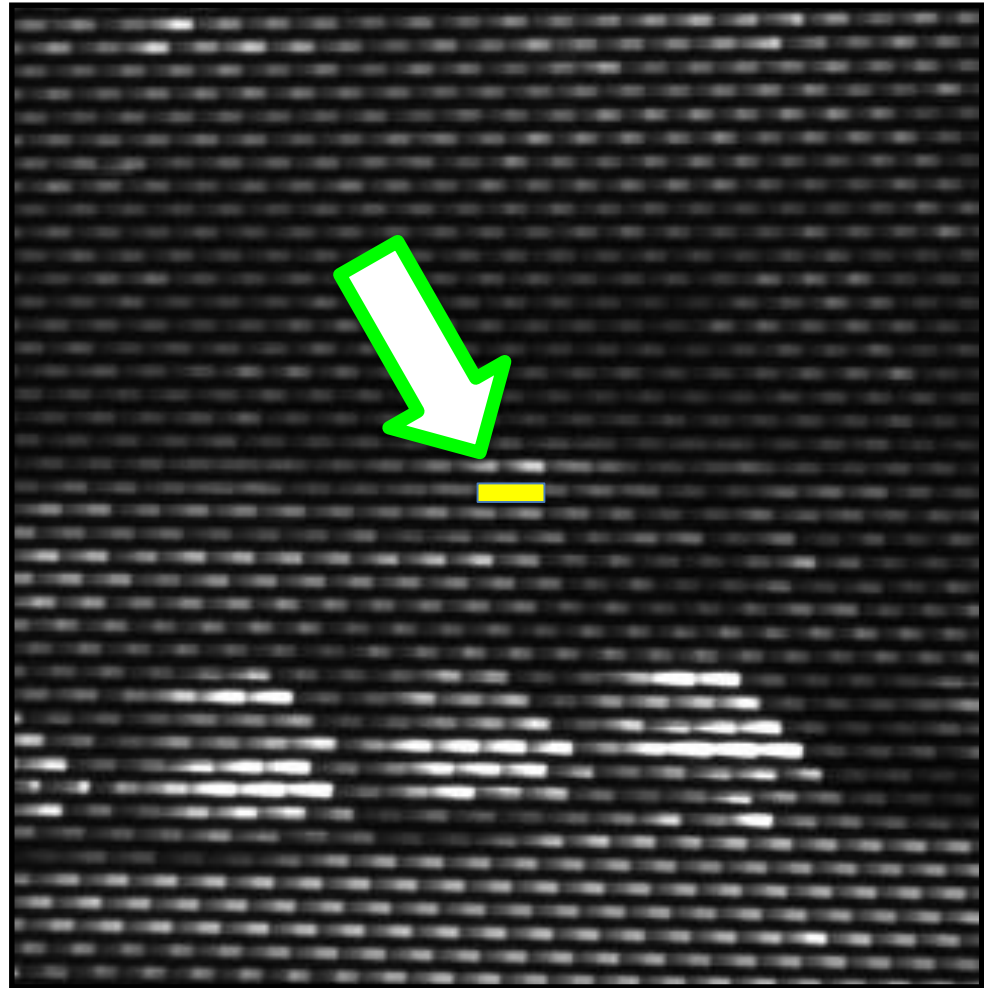
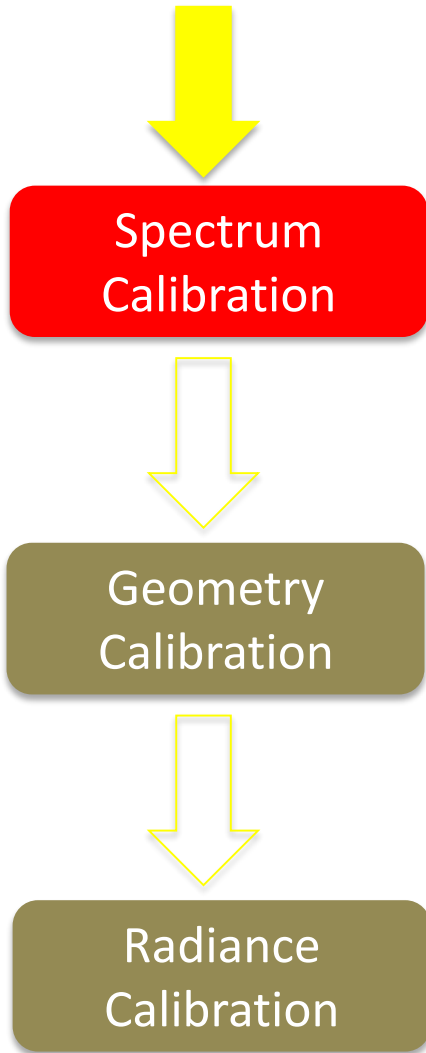


Geometry Distortion caused by the prism (Smile Distortion)

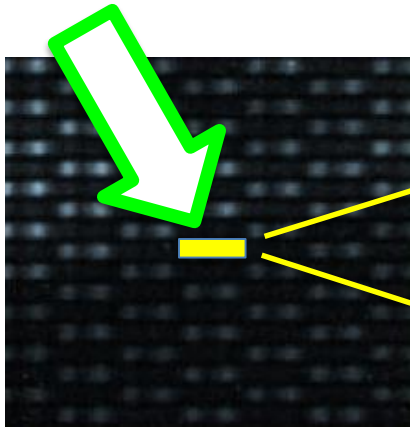


Non-constant
CCDSensitivity

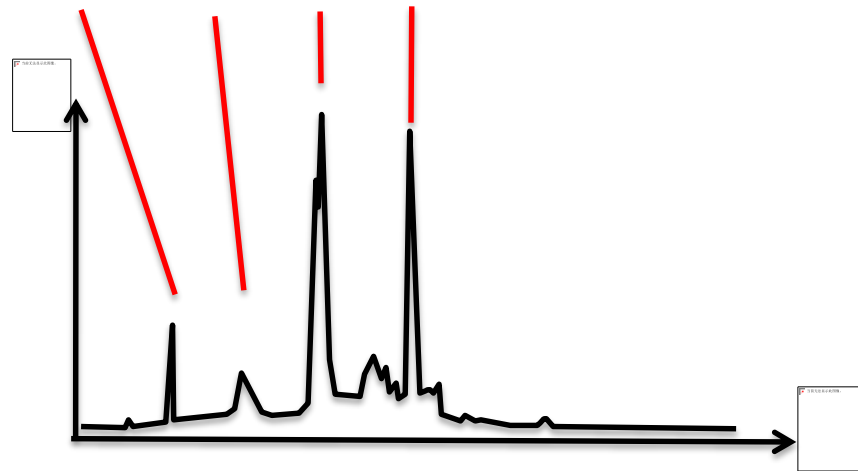
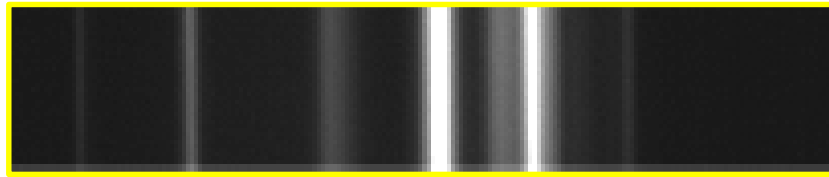
Spectrum Calibration



Spectrum Calibration

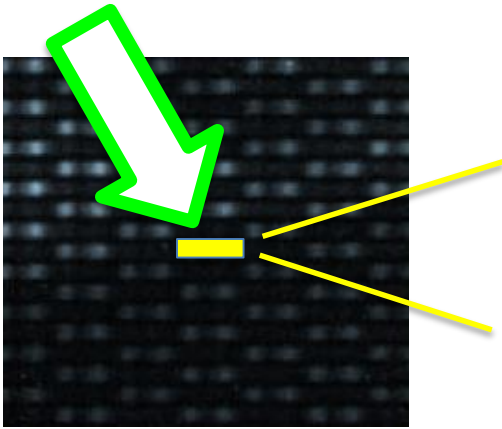


captured spectra

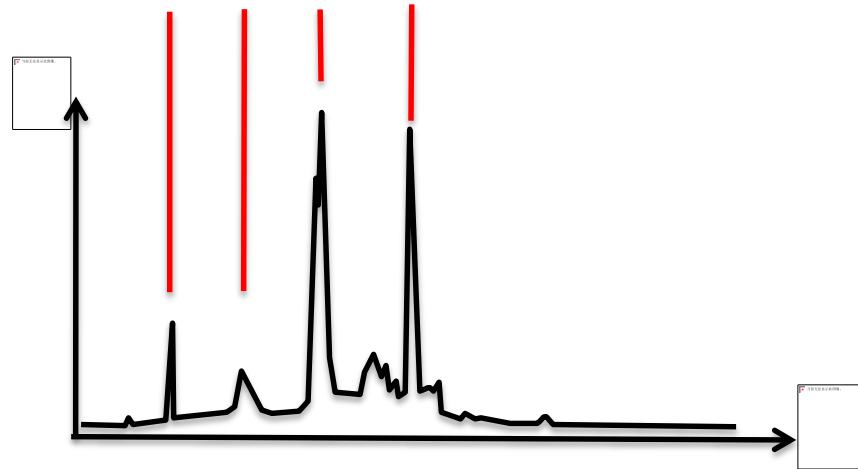
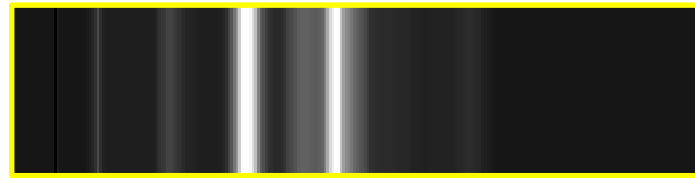


Ground truth fluorescent spectra

Spectrum Calibration



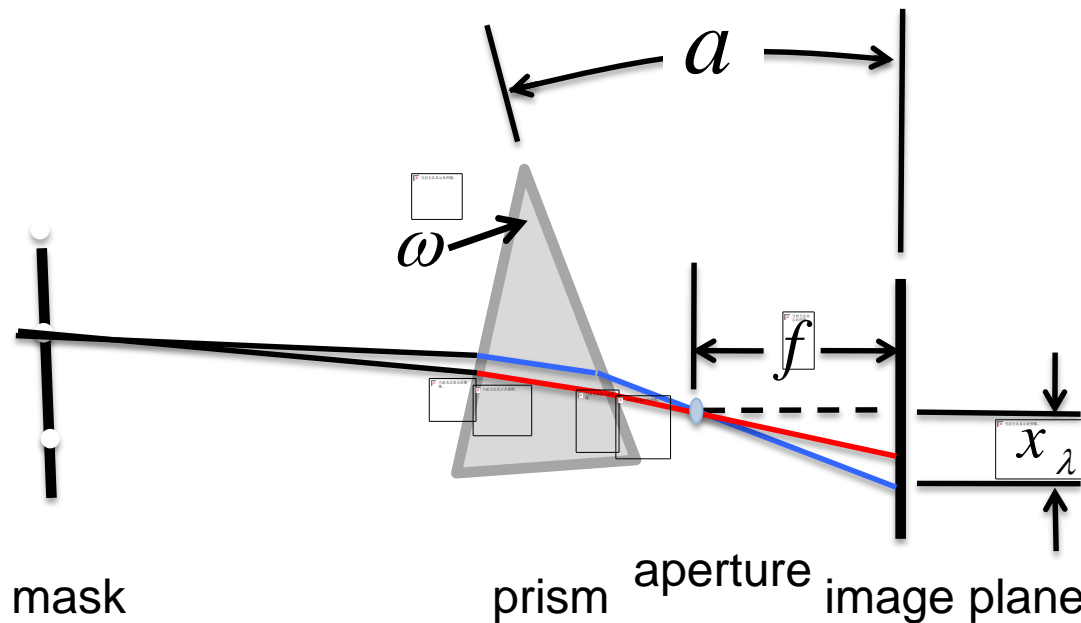
target spectra



Ground truth fluorescent spectra

Spectrum Calibration

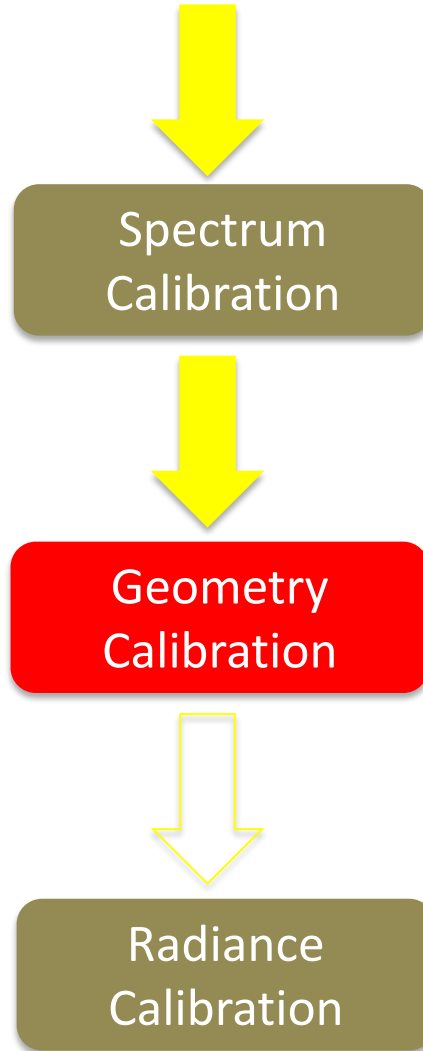
- Mapping Function : Wavelength \leftrightarrow Position



$$x(\lambda) = f \tan \left\{ a + \arcsin \left(n_\lambda \sin \left(\omega - \arcsin \left(\frac{\sin \alpha}{n_\lambda} \right) \right) \right) \right\}$$

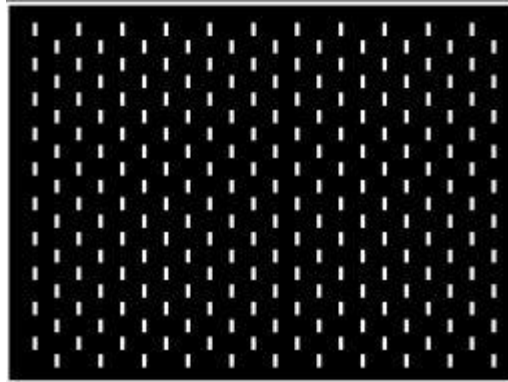
Non linear , but
smooth curve !

Geometry Calibration

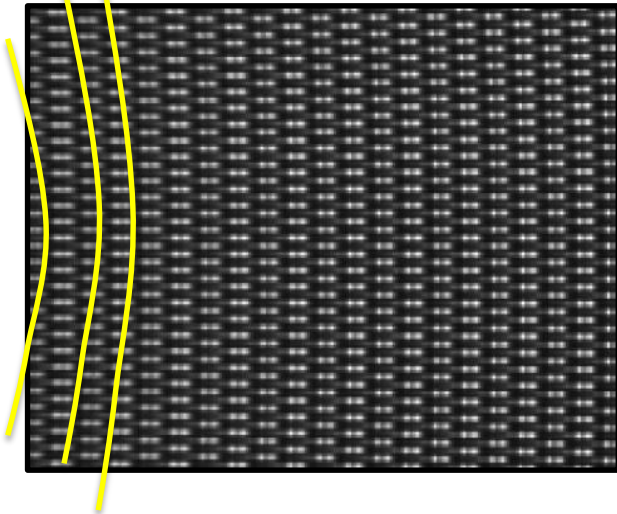


Geometry Calibration

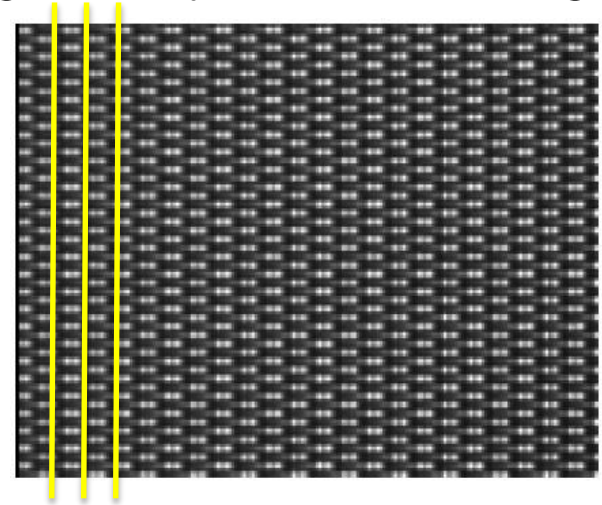
Predefined mask pattern



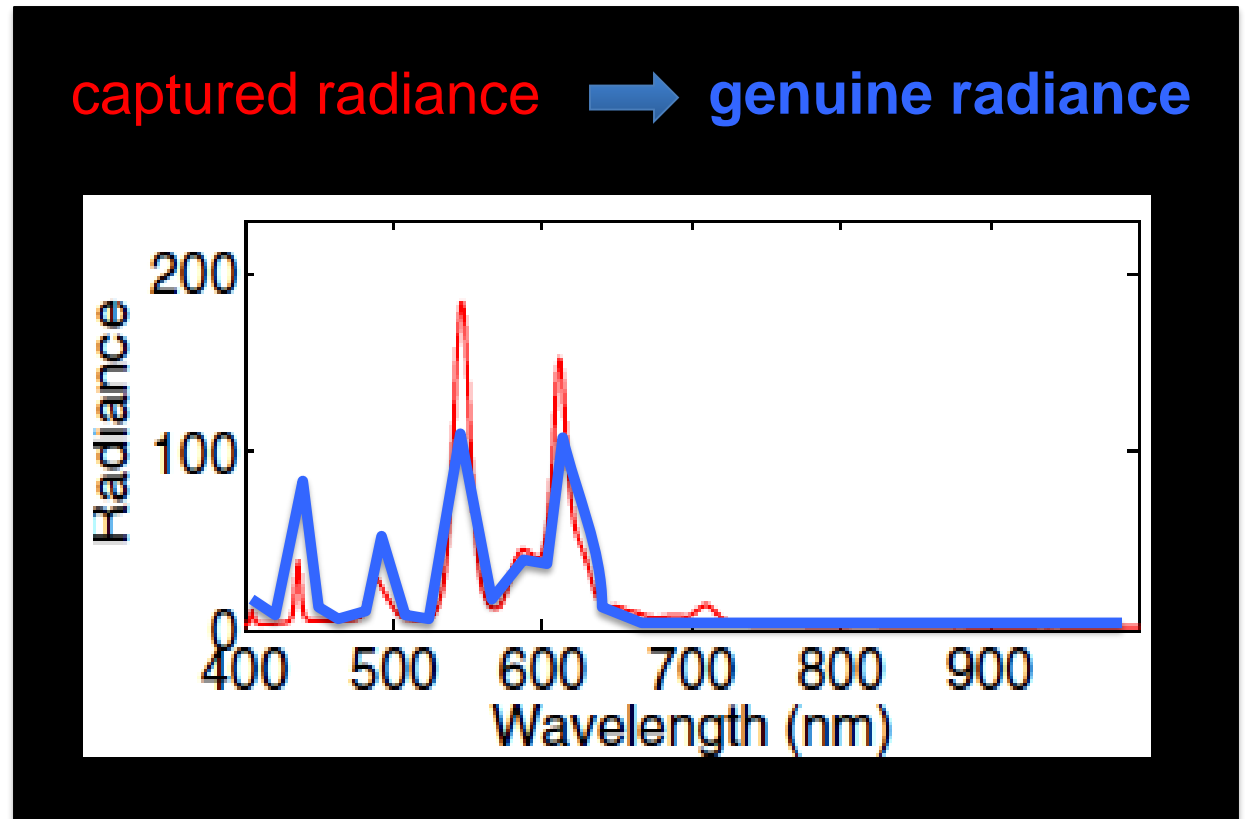
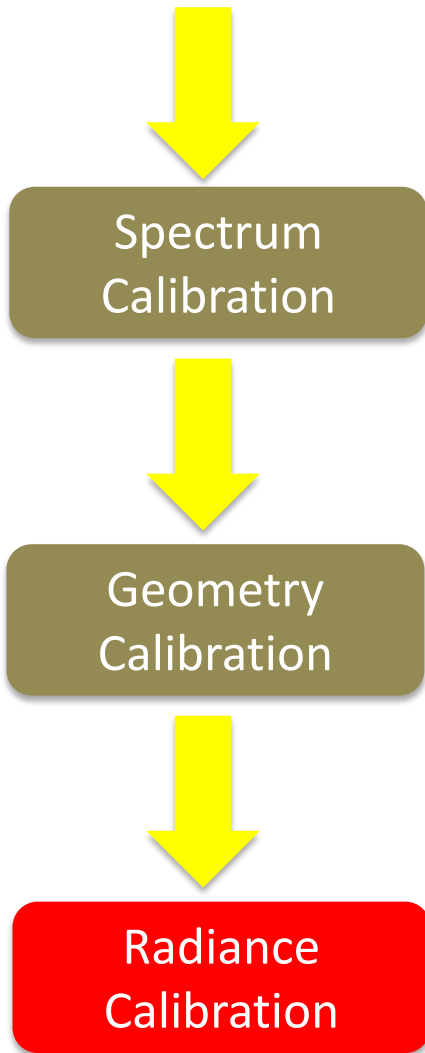
captured image



geometry calibrated image



Radiance Calibration



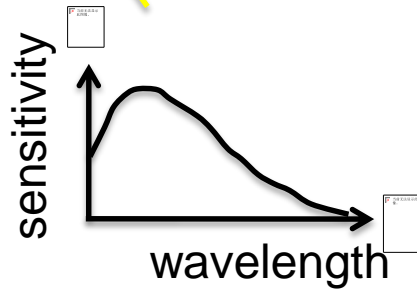
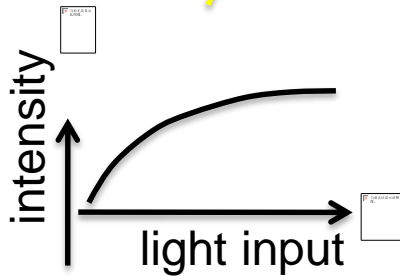
Radiance Calibration

captured radiance

genuine radiance

$$I(z) = g\left(\int_{z(\lambda_a)}^{z(\lambda_b)} c(\lambda)l(\lambda)d\lambda\right)$$

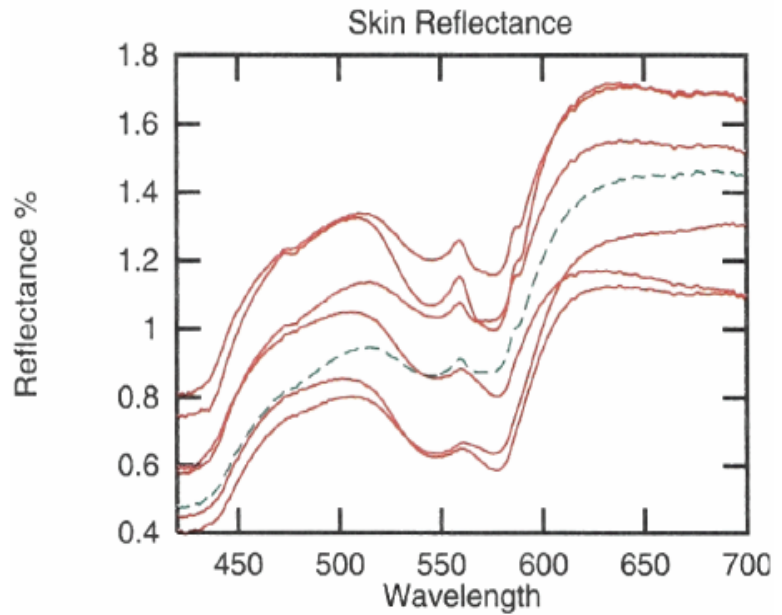
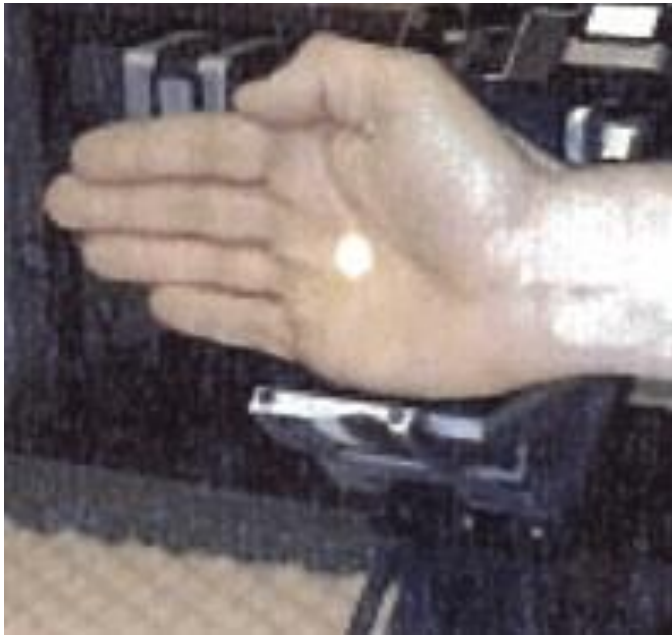
assuming $c(\lambda)$, $l(\lambda)$
locally constant



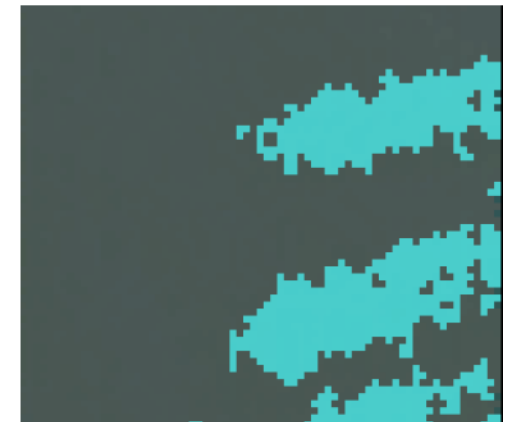
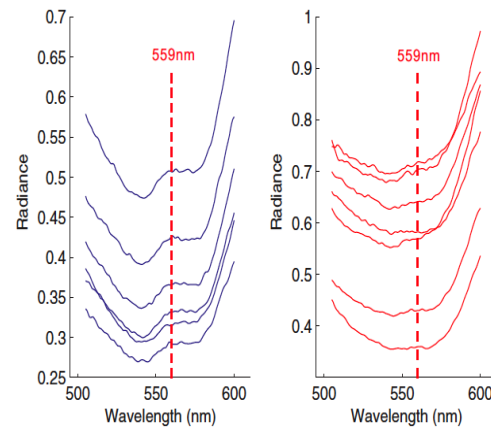
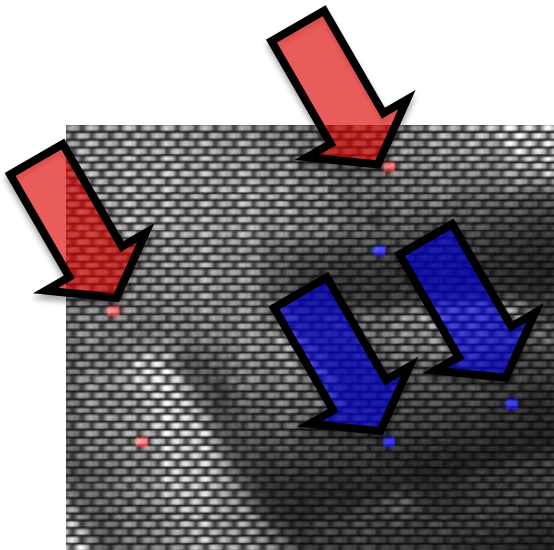
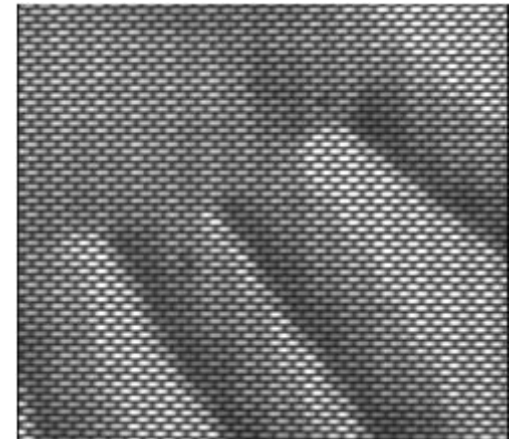
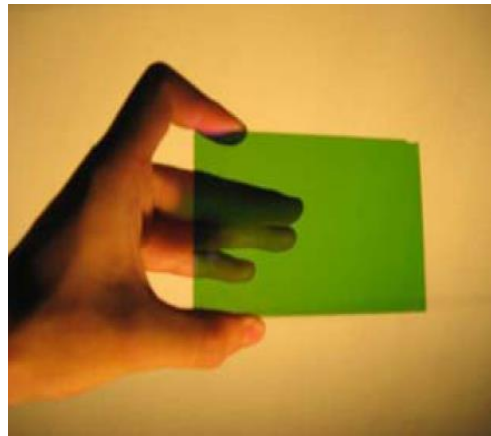
$$l(\lambda) \approx \frac{g^{-1}(I(z))}{c(\lambda)(\lambda_b - \lambda_a)}$$

Application 1: Human Skin Detection

- The 'W' pattern in human skin reflectance
 - [Angelopoulou01]

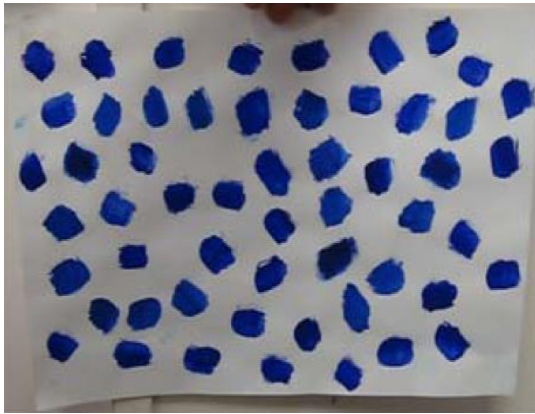


Application 1: Human Skin Detection

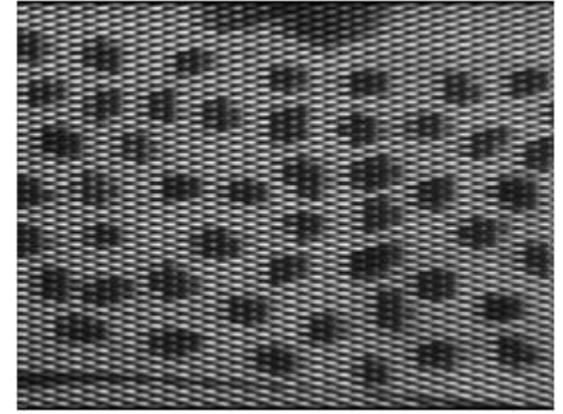
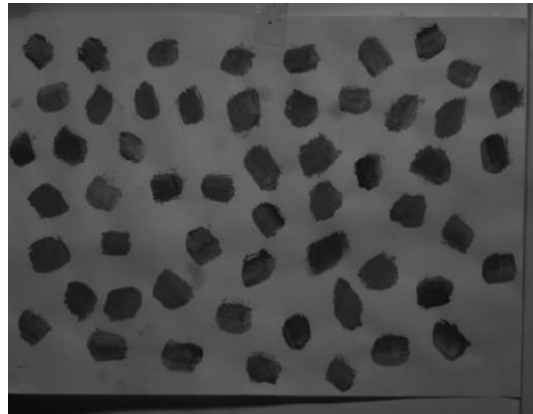


Application 2: Material Discrimination

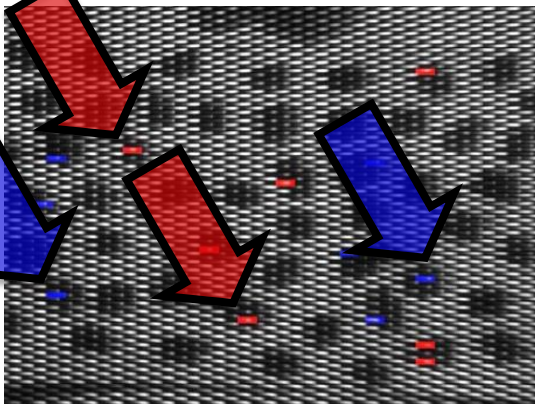
RGB Image



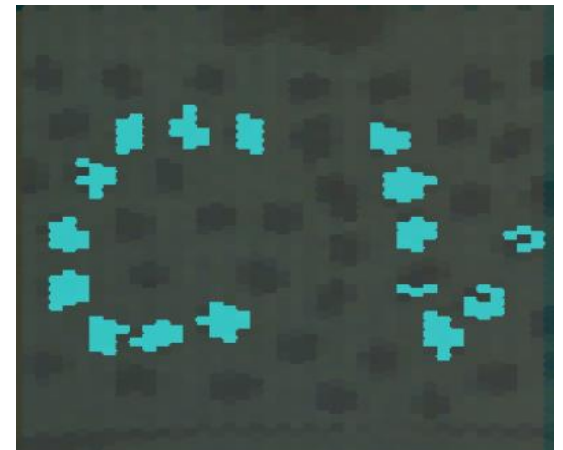
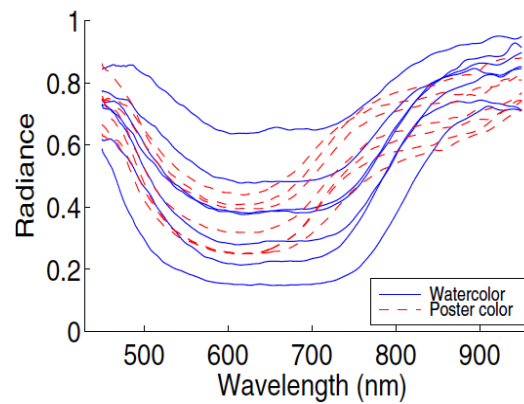
IR Image



Our measurement

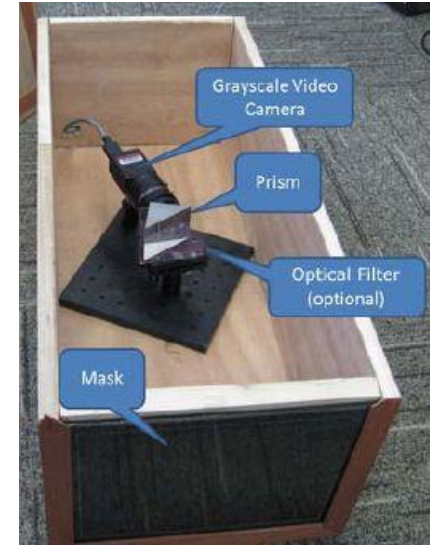


The differences in IR



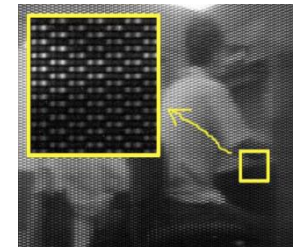
PMIS¹ Conclusions

- Compared to Traditional Spectrometers
 - Passive Multispectral **Video Capture**
 - High spectral resolution
 - Tradeoff spectral and spatial resolution
 - Easy setup and calibration



- Applications

- Skin Detection
- Material Recognition
- Illumination Identification

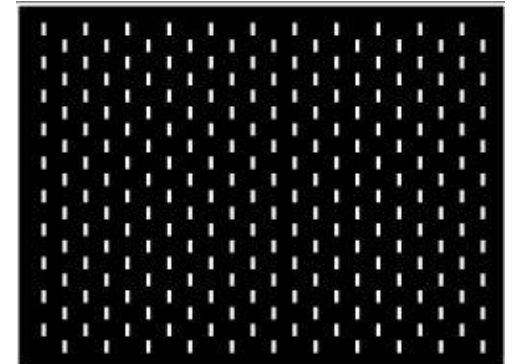
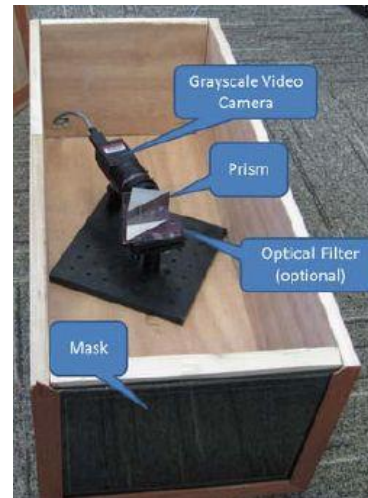


PMIS¹: A Prism-Mask System for Multispectral Video Acquisition,
IEEE Intl' Conf. Computer Vision (ICCV), 2009 , Oral
IEEE Trans. Pattern Anal. Mach. Intell. (PAMI), 2011

High Resolution Multispectral Image Capture, *US Patent.20140085502*

PMIS¹: limitations

- Light throughput is limited by
 - occlusion mask
 - relatively small aperture



- Can NOT achieve both high spatial and spectral resolution
 - Limited CCD resolution
 - Spatial resolution (1000 pixels)

Scene or Object

Hybrid Camera System

Occlusion Mask

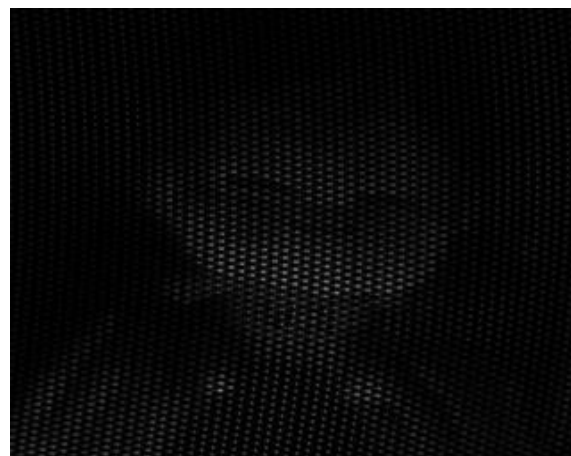
Prism

Gray Camera



Gray Camera

**Low-Spatial
High-Spectral
Resolution Video**

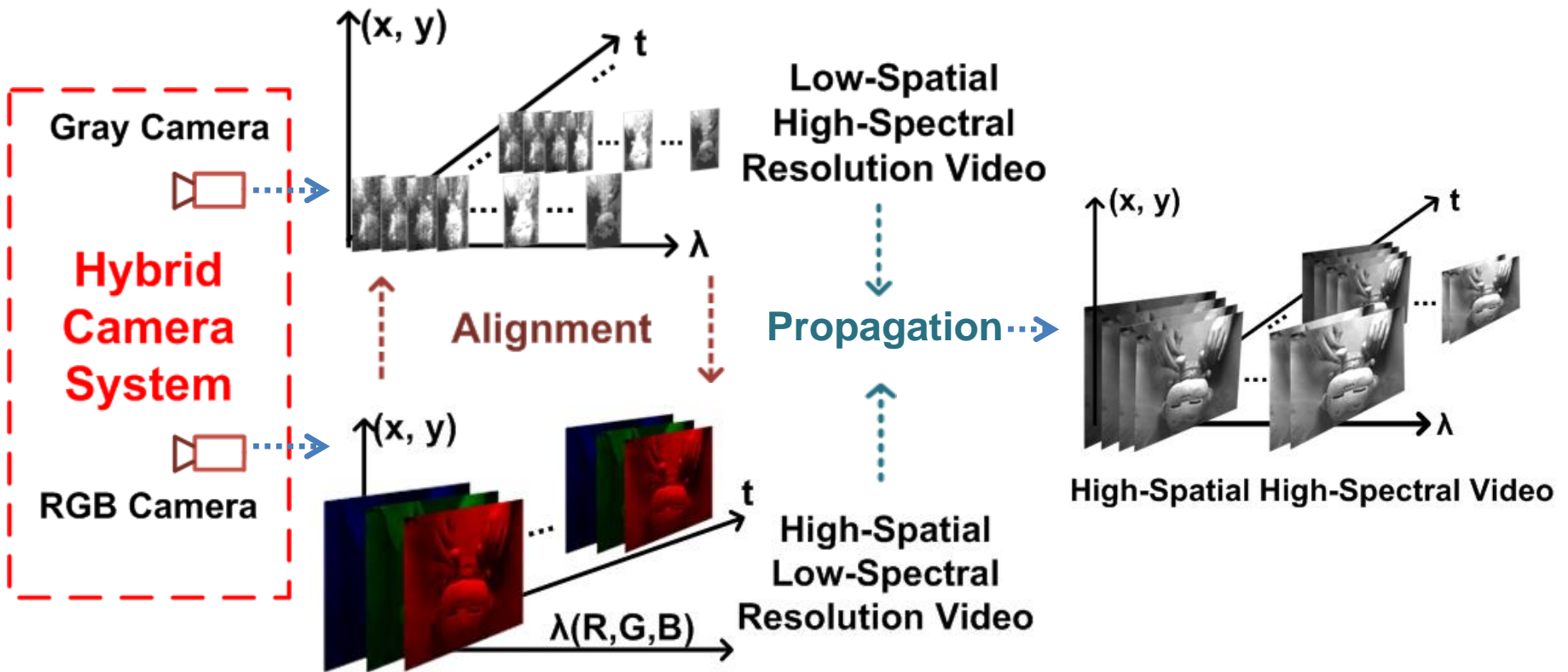


RGB Camera

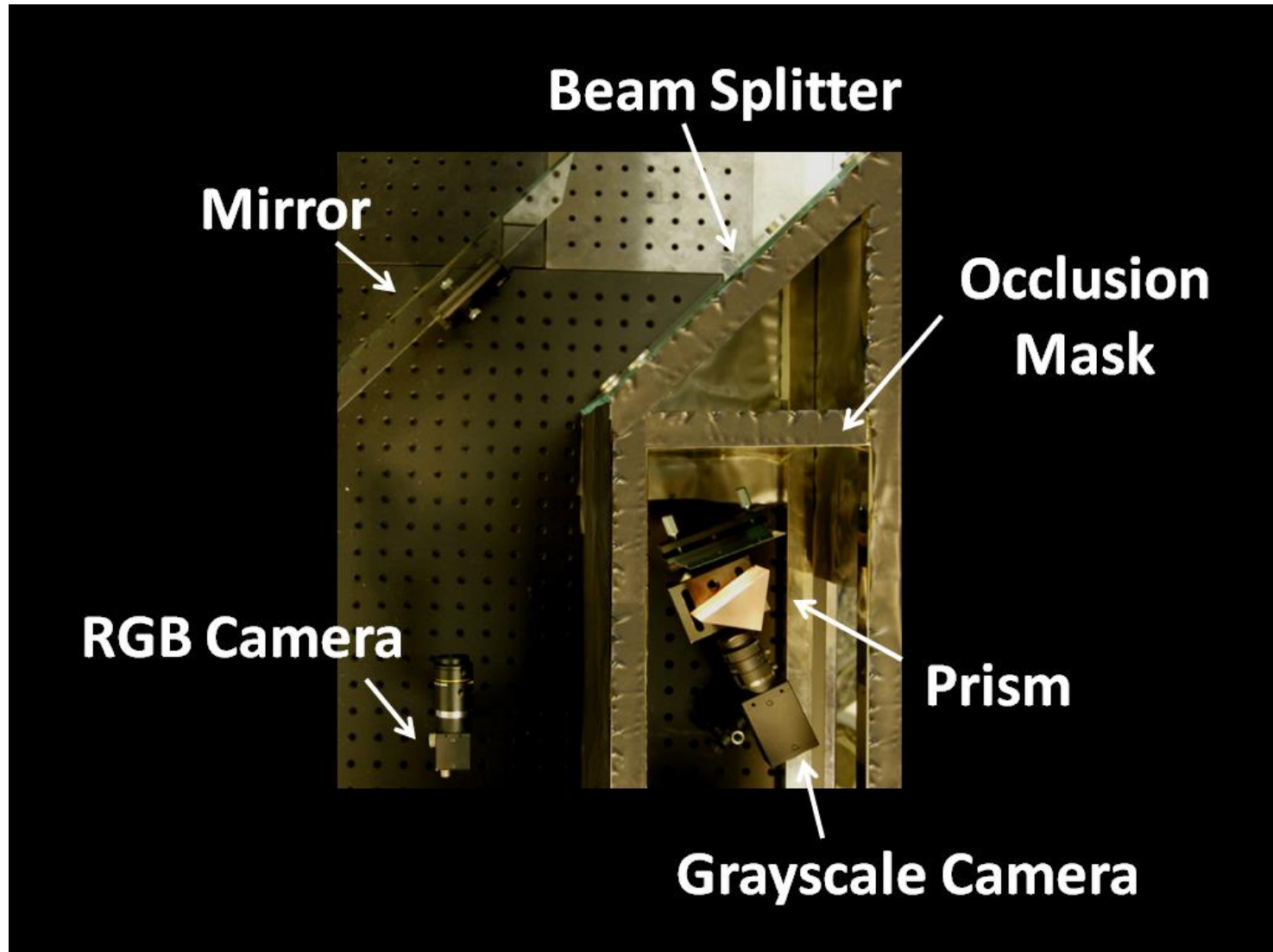
**High-Spatial
Low-Spectral
Resolution Video**

PMIS²: Hybrid Camera System

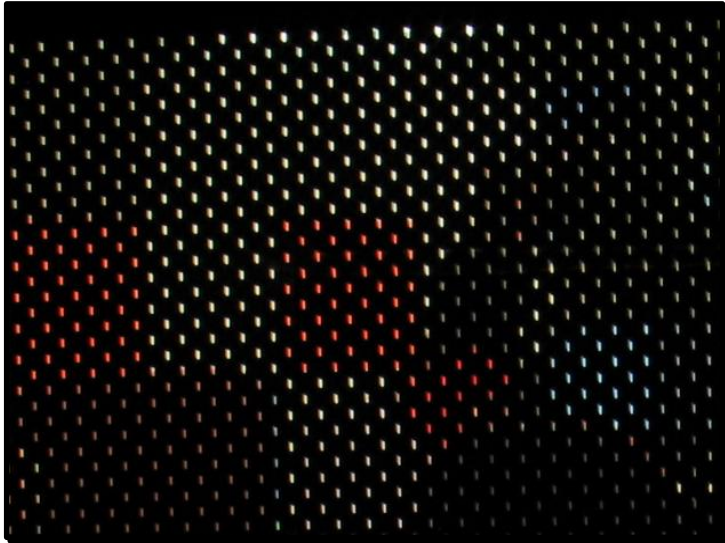
PMIS²: System Pipeline



PMIS²: System Implementation

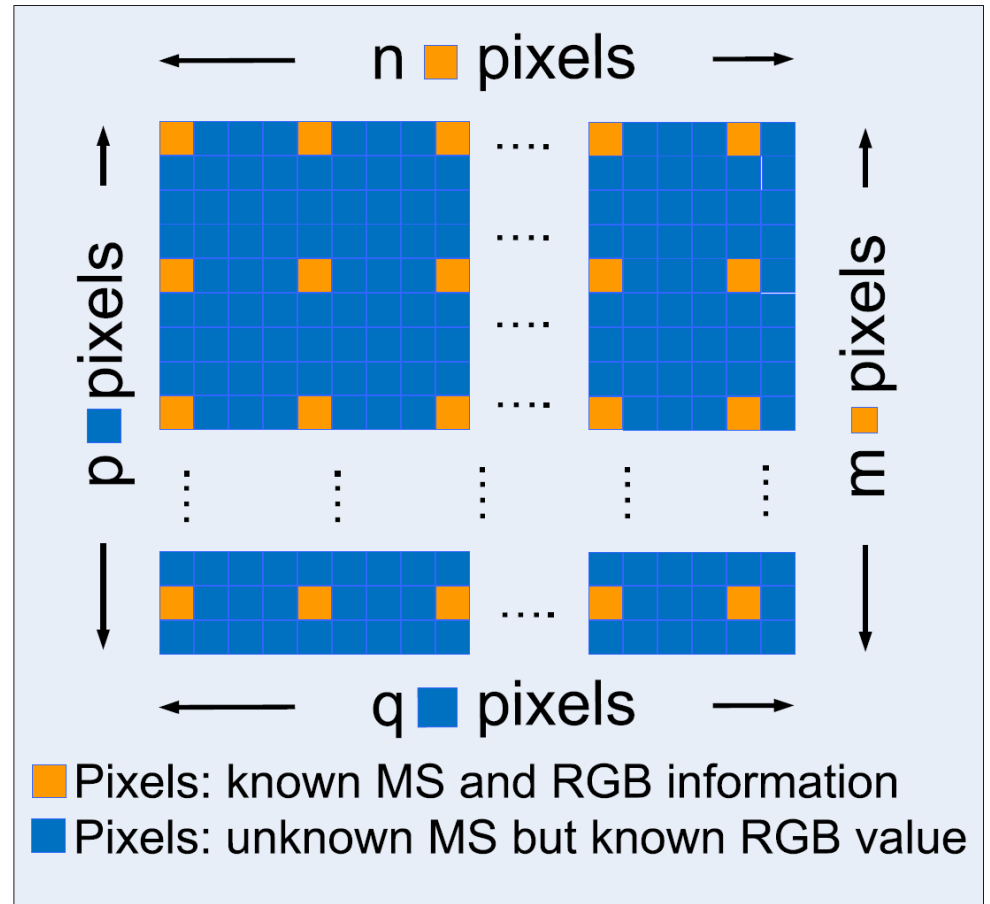


Propagation Algorithm

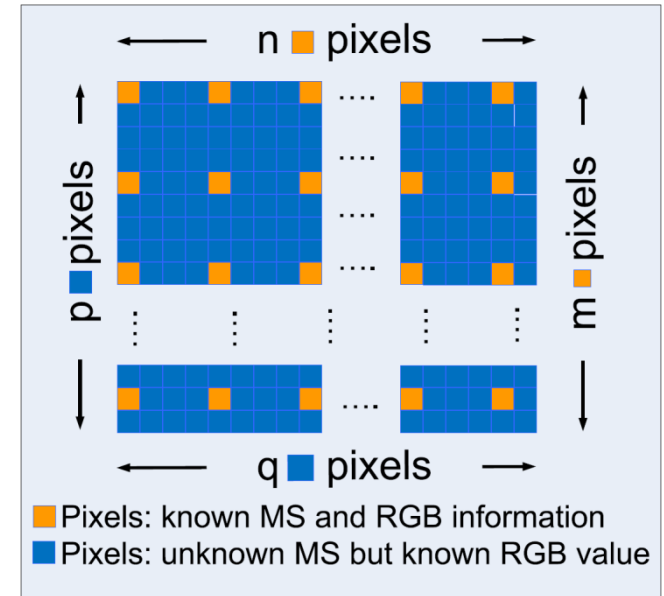
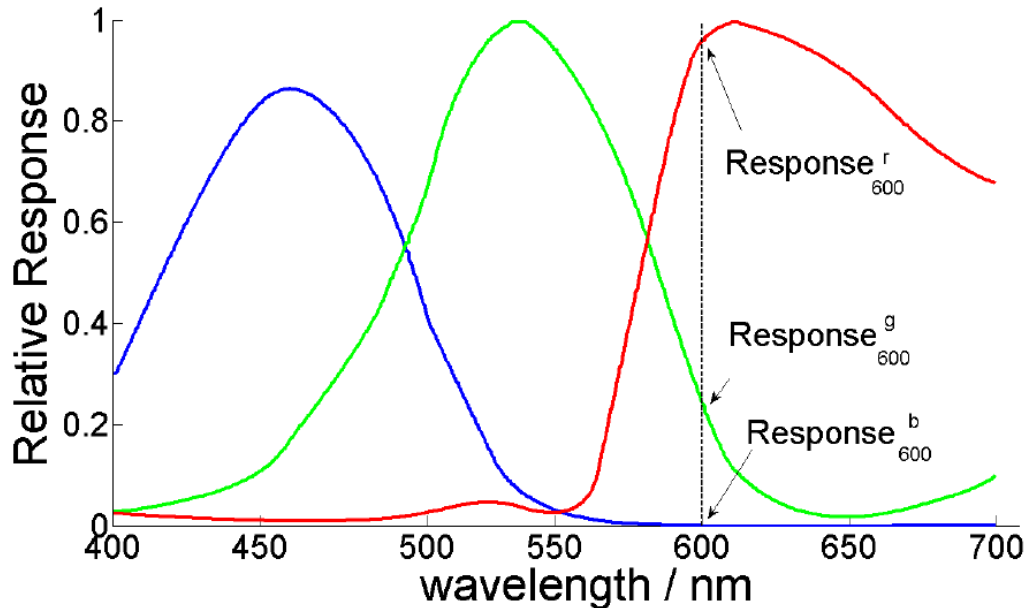


 RGB Camera

High Spatial Resolution
Multi-spectral RGB Video



Propagation Algorithm



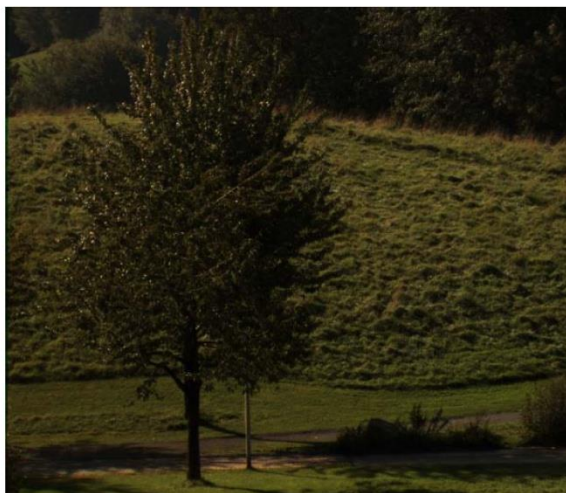
$$\mathbf{ms}_{ij} = \sum_{c \in R, G, B} \frac{\sum_{k \in \Omega} G_{\sigma_r}(d_k^{RGB}) G_{\sigma_s}(d_k^{xy}) \rho_k \mathbf{ms}_k^c}{\sum_{k \in \Omega} G_{\sigma_r}(d_k^{RGB}) G_{\sigma_s}(d_k^{xy})}$$

e.g. $\rho_k = R_{ij} / R_k$, for red channel

Propagation Algorithm

Ground Truth Data Evaluation (11 datasets, .aix, .mat)

- Spectral Database, University of Joensuu Color Group



σ_r	$Acc/\%(\sigma_s = 8)$			$Acc/\%(\sigma_s = 16)$			$Acc/\%(\sigma_s = 32)$		
	min	med	max	min	med	max	min	med	max
4	83.2	93.3	97.5	83.7	93.4	97.8	85.2	93.6	97.8
8	81.7	93.6	97.6	82.7	93.6	97.9	83.3	93.6	97.9
16	81.0	93.7	97.6	82.6	93.8	98.0	82.7	93.5	98.1
32	80.3	93.7	97.6	82.0	93.6	97.9	82.2	93.2	98.0

Table 1. Algorithm evaluation on groundtruth datasets with different propagation parameters, Acc means accuracy

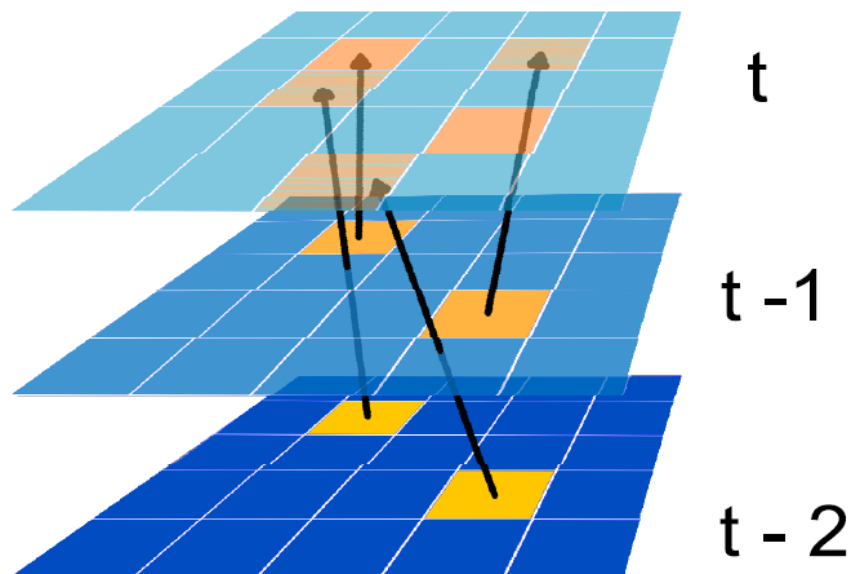
Propagation Algorithm

Temporal Enhancement

→ Optical Flow

■ Pixels: known MS and RGB information

■ Pixels: unknown MS but known RGB value



Error

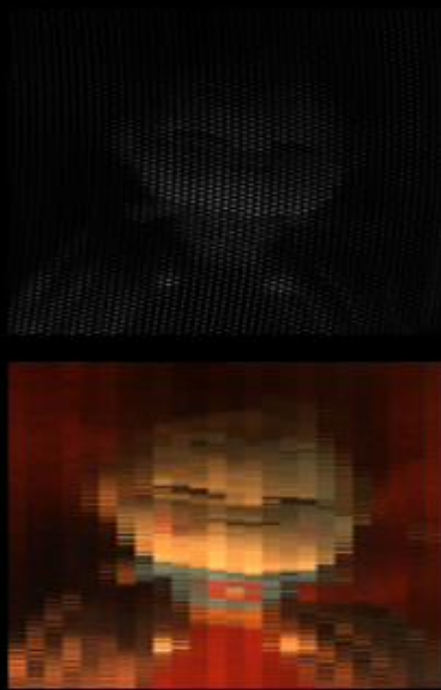
7.8%



4.3%

PMIS²: Results & Applications

Spatial Comparison



**Single Camera
(PMVIS)**

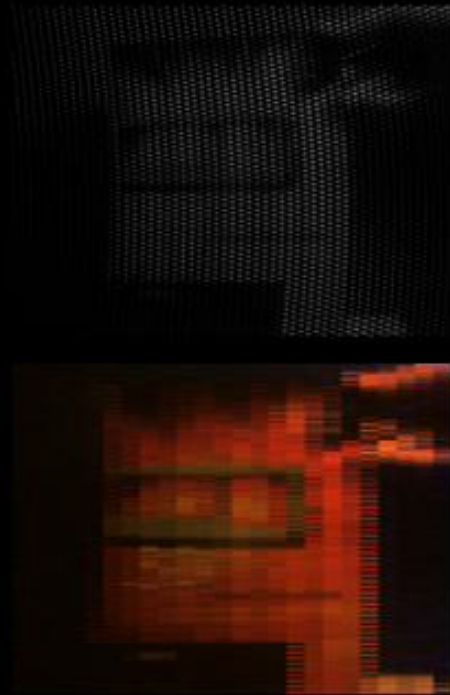


**Hybrid Camera
(HMVIS)**

PMIS¹: Prism-Mask Multispectral-Video Imaging System (ICCV'09, PAMI'2011)

PMIS²: Hybrid Camera Multispectral Video Imaging System (CVPR'2011, IJCV'2014)

Spatial Comparison



**Single Camera
(PMVIS)**

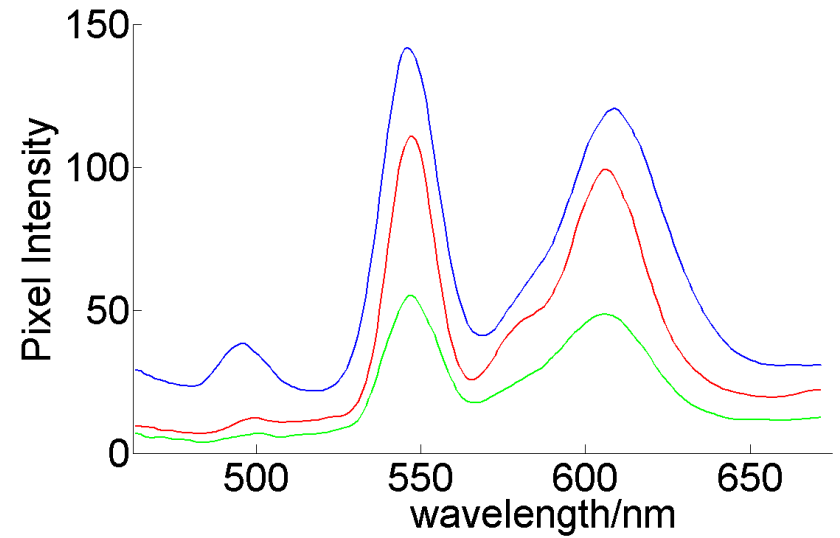
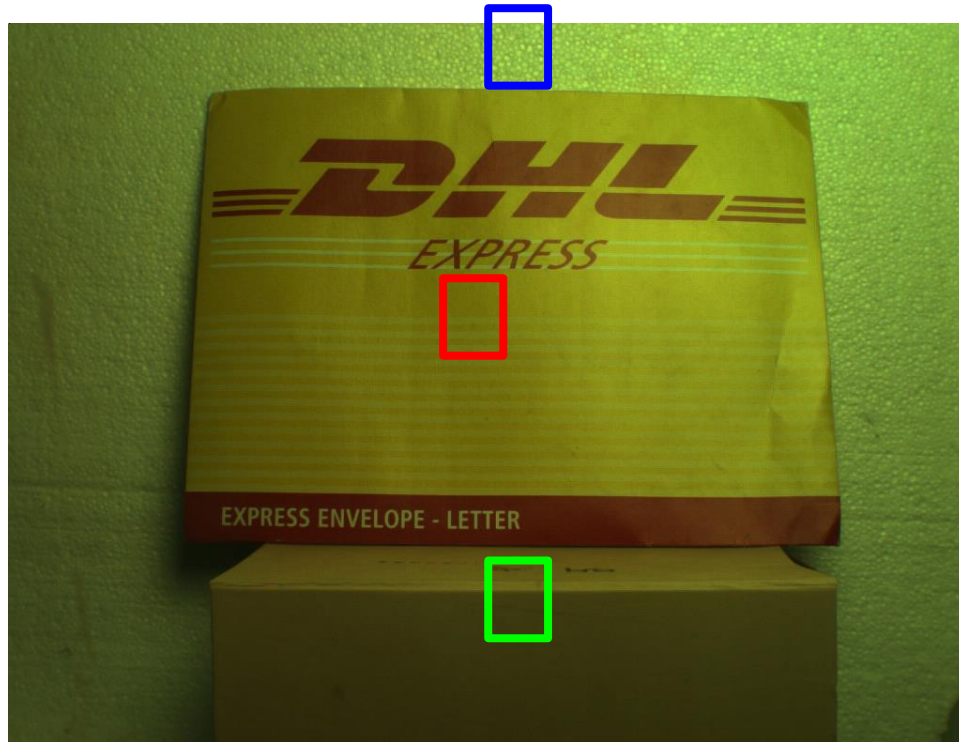


**Hybrid Camera
(HMVIS)**

PMIS¹: Prism-Mask Multispectral-Video Imaging System (ICCV'09, PAMI'2011)

PMIS²: Hybrid Camera Multispectral Video Imaging System (CVPR'2011, IJCV'2014)

Application 3: illumination recognition



(a)



(b)



(c)

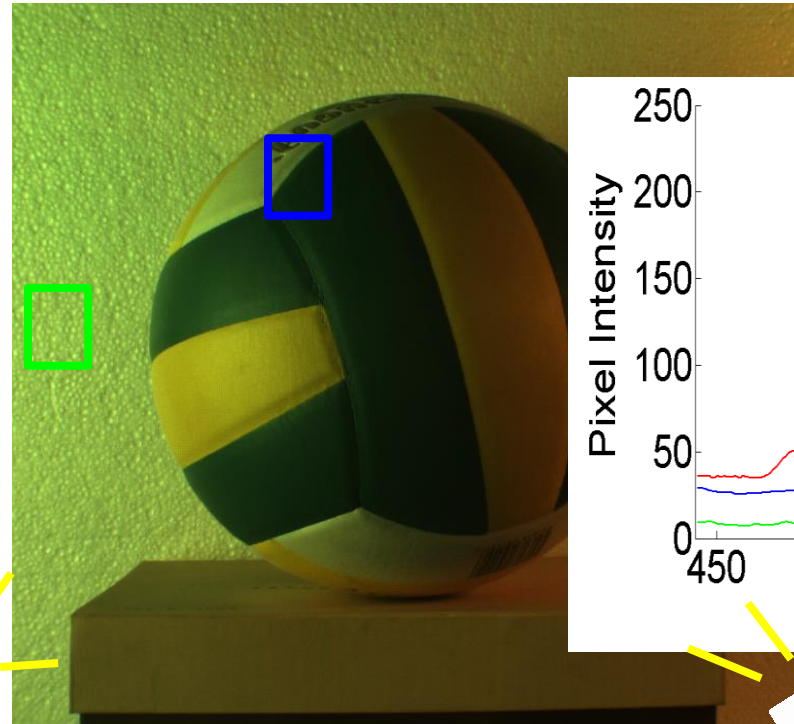


(d)

Application 3: Automatic White Balance

Temporally Varying Illumination

Application 3: mixed illumination



Fluorescent light



Tungsten light

Application 3: mixed illumination



Original Frame



Fluorescent Light

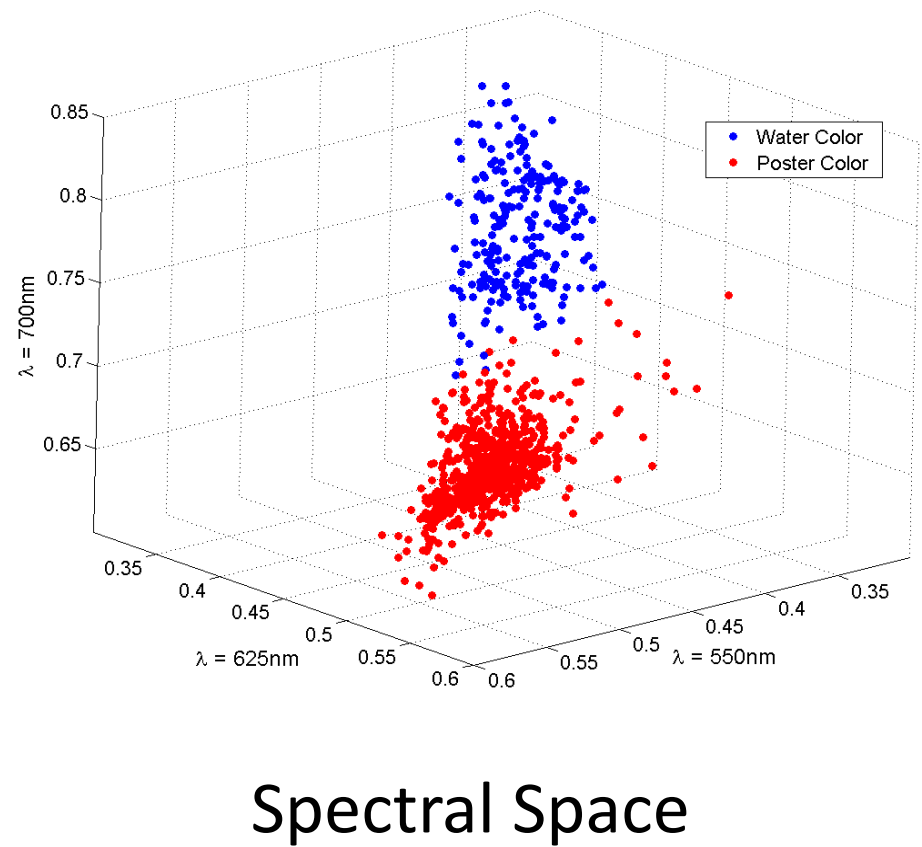
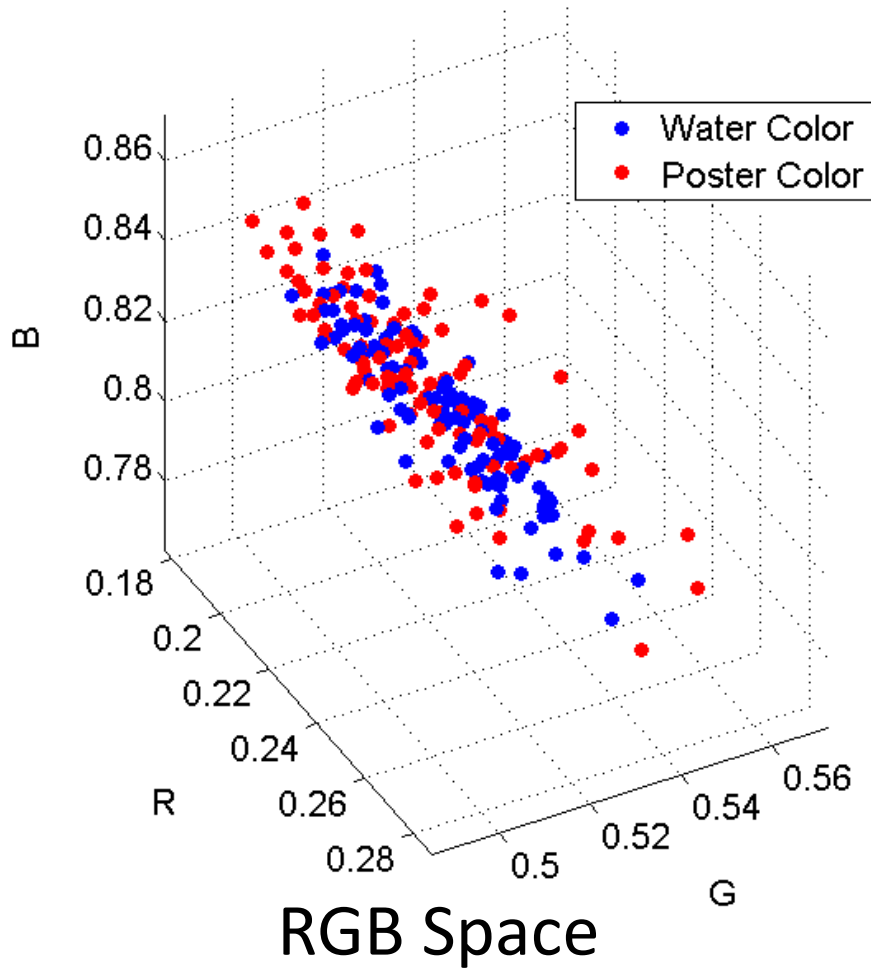


Tungsten Light



Our Result

Spectral Comparison Poster vs. Water Color



Application 4: Tracking

Tracking Results

PMIS² Conclusions



High
Resolution



- Spectral Resolution
 - (1~6nm, adjustable)
- Spatial Resolution
 - (1024 × 1024)
- Temporal Resolution
 - (15fps, Real-Time Capture)

• Additional Applications by PMIS²

- Automatic White balance

- Object Tracking

PMIS²: Acquisition of High Spatial & Spectral Resolution Video with a Hybrid Camera System,

IEEE Intl' Conf. Computer Vision & Pattern Recognition. (CVPR), 2011

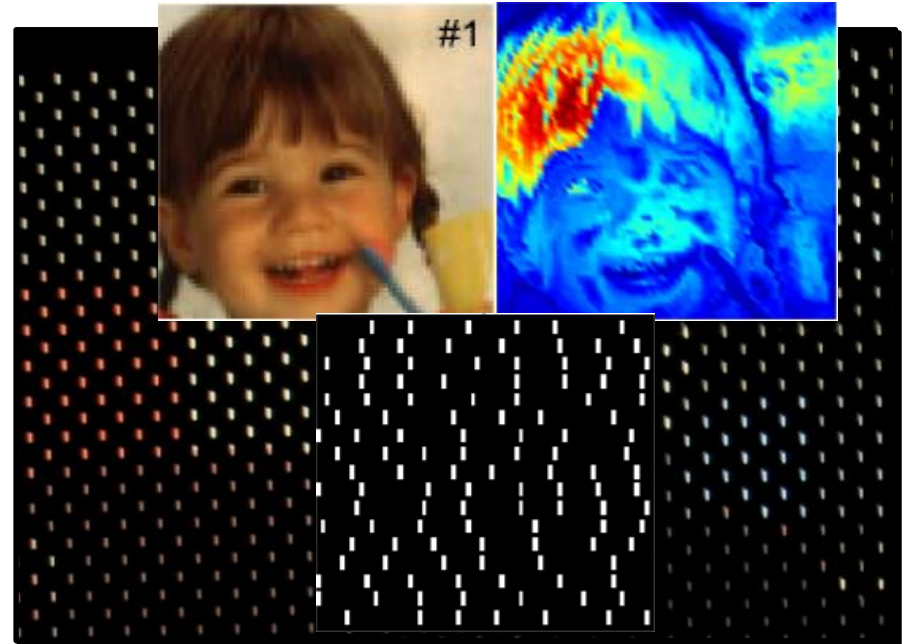
International Journal of Computer Vision (IJCV), 2014

A Computational Spectral Video Capture Device, China Patent. ZL201110212923.X

PMIS³ Basic Idea

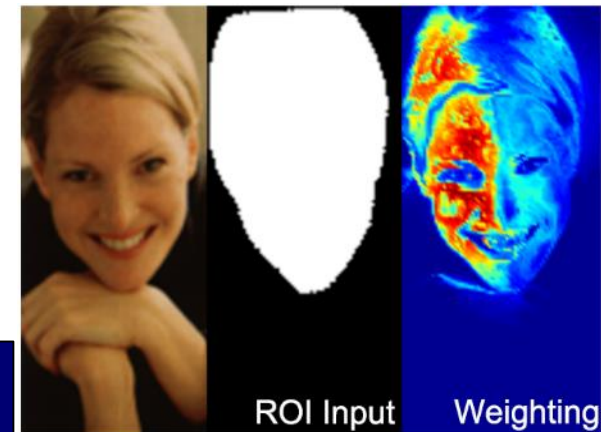
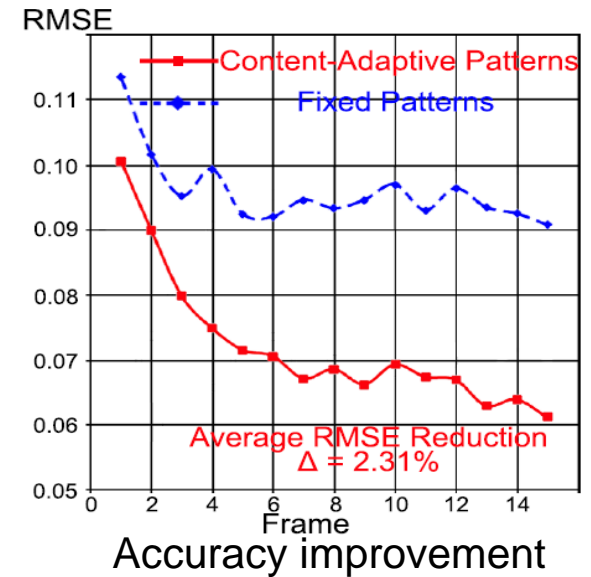
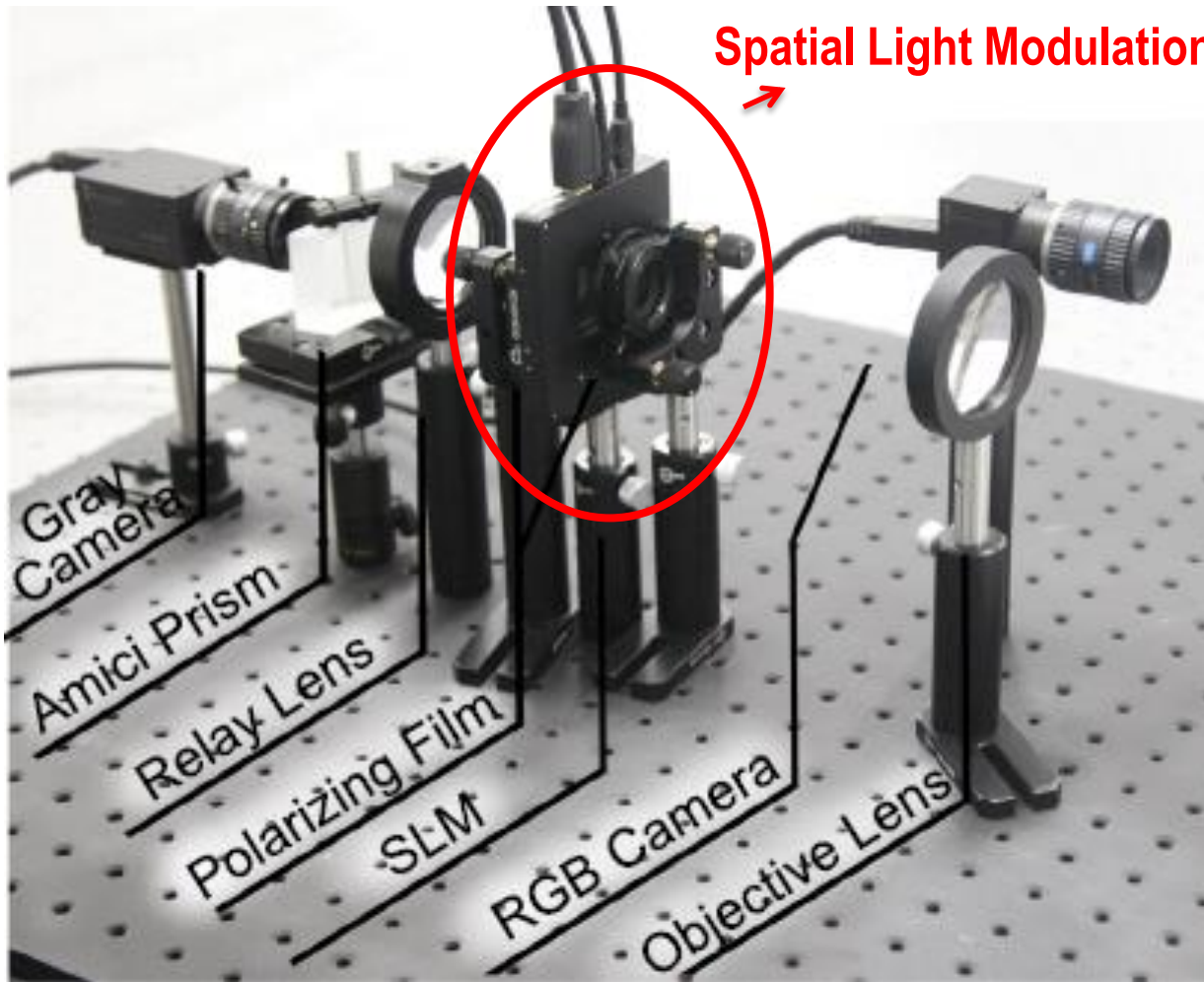
PMIS¹ & PMIS²

Fixed-Pattern Mask



Can we **dynamically** change the mask adaptive to the scene content ?

PMIS³ Prototype and Capturing Results



Targeted spectral acquisition by annotating regions of interest

PMIS³: Content-Adaptive High-resolution Spectral Video Acquisition

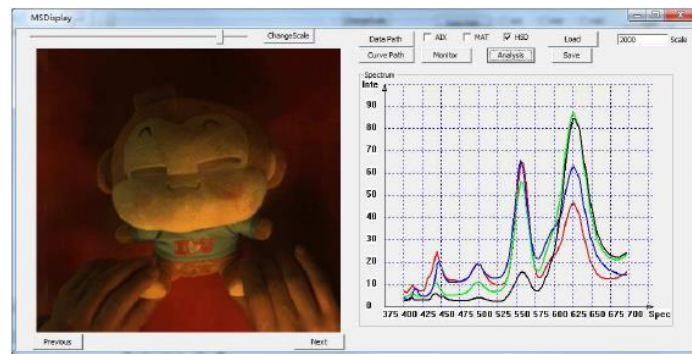
Optics Letters, 39(15), pp.1464-1466, 2014

Optics Express, 22(16), pp.19348-19356, 2014

IEEE CVPR, pp. 1684-1692, 2015

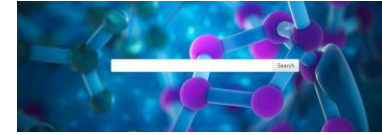
Summary

- **PMIS**: High Resolution Spectral Video Camera
 - vs Traditional Spectrometer: Snapshot Capability (Video)
 - vs CTIS / CASSI:
 - Real-Time Video Output
 - Low Reconstruction Error
 - Improved Resolution \leftrightarrow Low Cost
- **PMIS** Hyperspectral Video Datasets Available :



Spectra Viewing Software

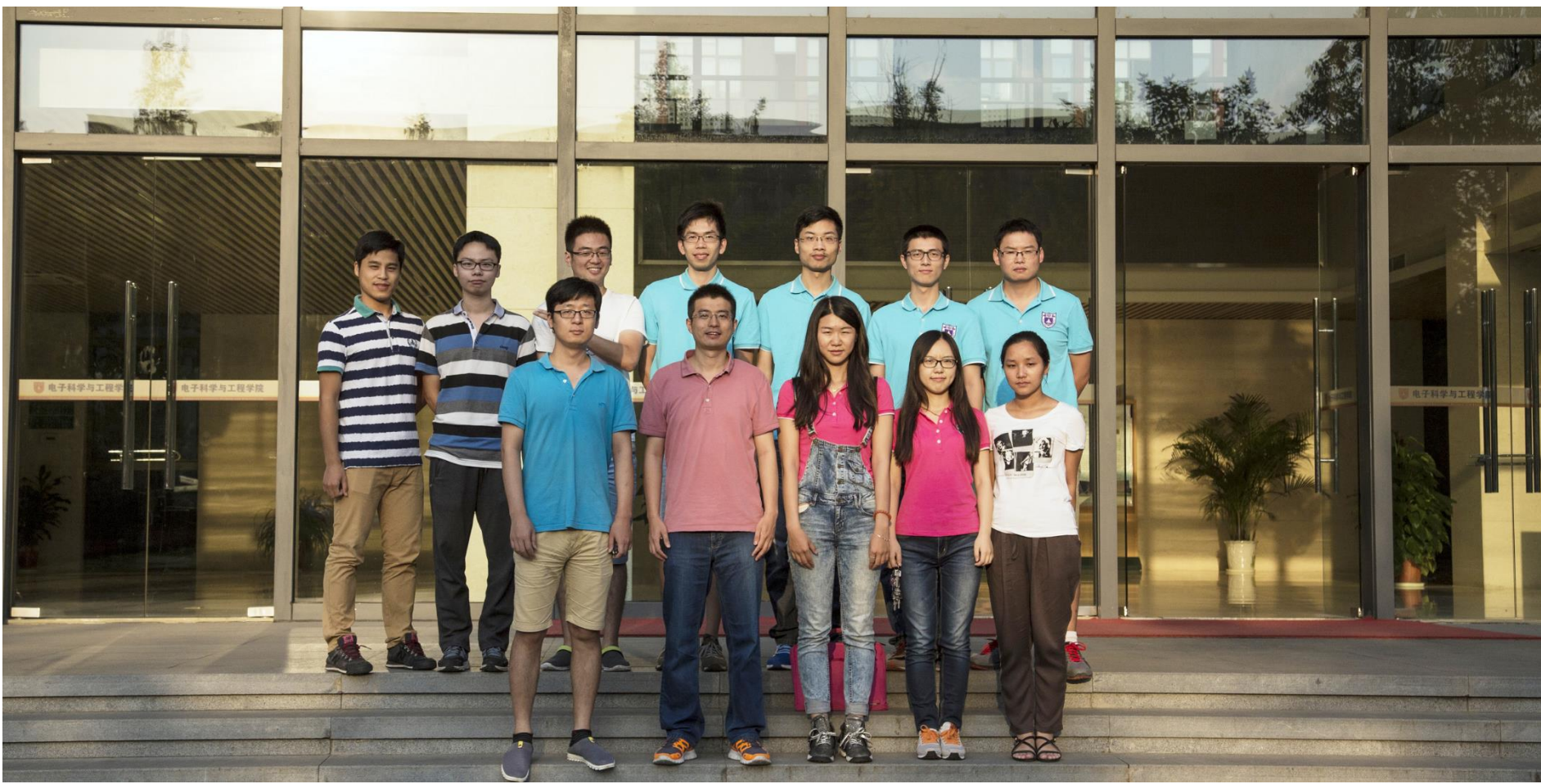
Commercial Spectral Video Cameras



Camera	Wavelength Range	Spectral Resolution	Temporal Resolution	Spatial Resolution
BaySpec	600–1000 nm	10 nm	8 fps	256*256
SoC	270–550 nm	18 nm	60 fps	320*256
PMIS	400–1000 nm	6 nm	15 fps	1024*1024 (1M)

Acknowledgements

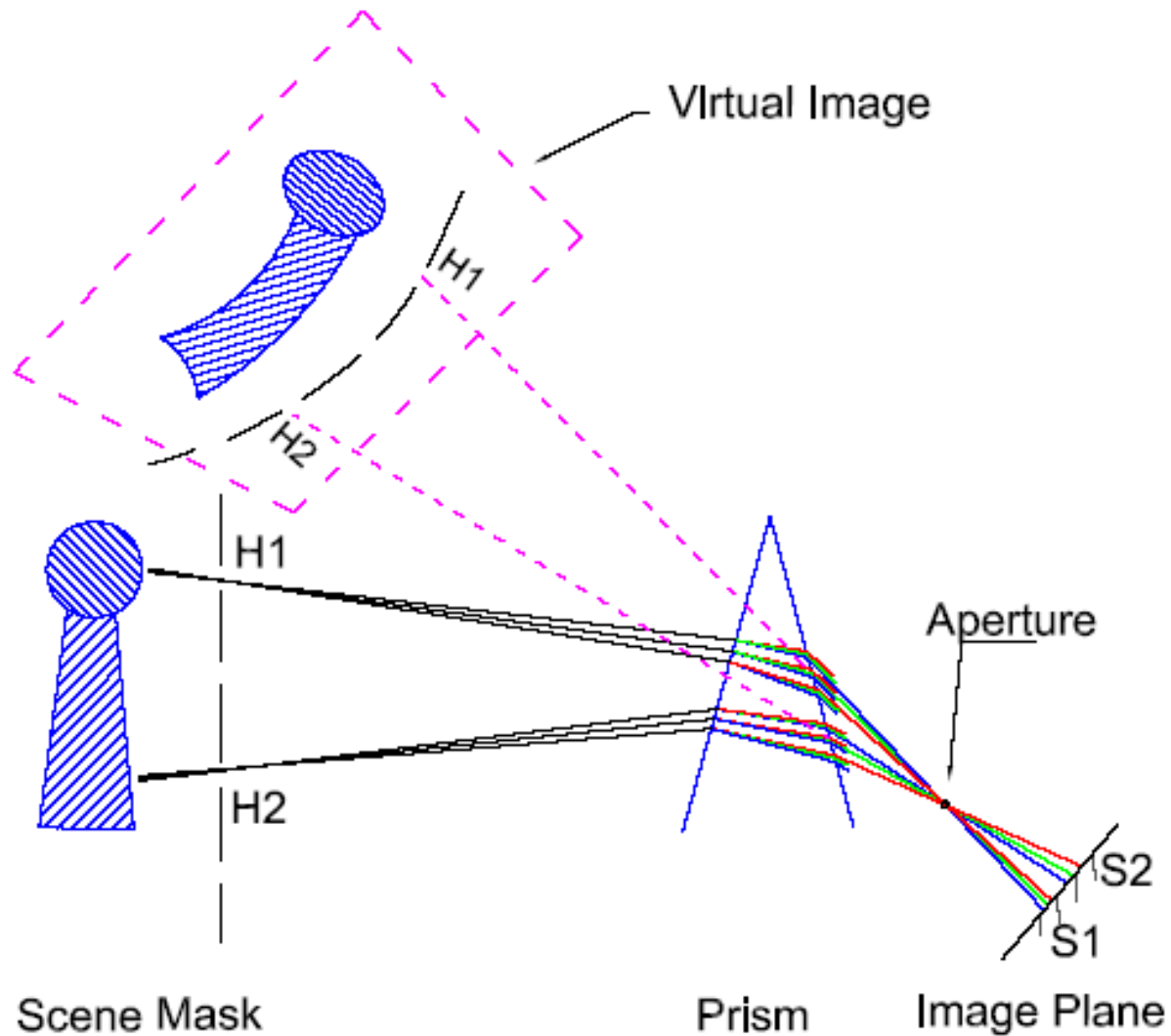
- NSF China
- Prof. Qionghai Dai, Dr. Steve Lin, Dr. Xin
- Dr. Yue Tao, Dr. Chenguang Ma
 - Assistance in experimentation
- Moshe Ben-Ezra, Yanxiang Lan
 - Helpful discussions on implementation issues



Welcome to visit CITE Lab @ Nanjing Univ.

<http://cite.nju.edu.cn>

The Optical Path



Spectra of Illuminations

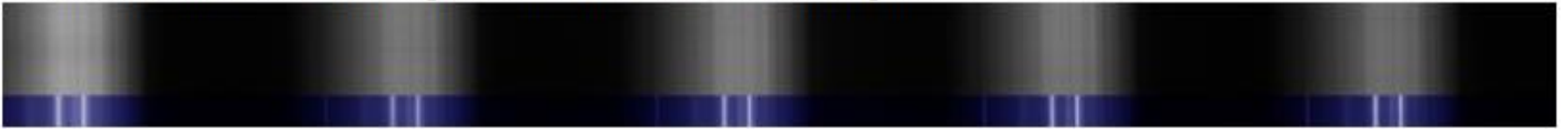
- Fluorescent Illumination



- Tungsten Illumination (the bottom blue part shows a fluorescent calibration pattern)



- Sun Illumination (the bottom blue part shows a fluorescent calibration pattern)



- Fluorescent Illumination with a 650nm red laser beam

