IMAGING UNDER STRUCTURED LIGHT

Prasanna Rangarajan *prangara@smu.edu*

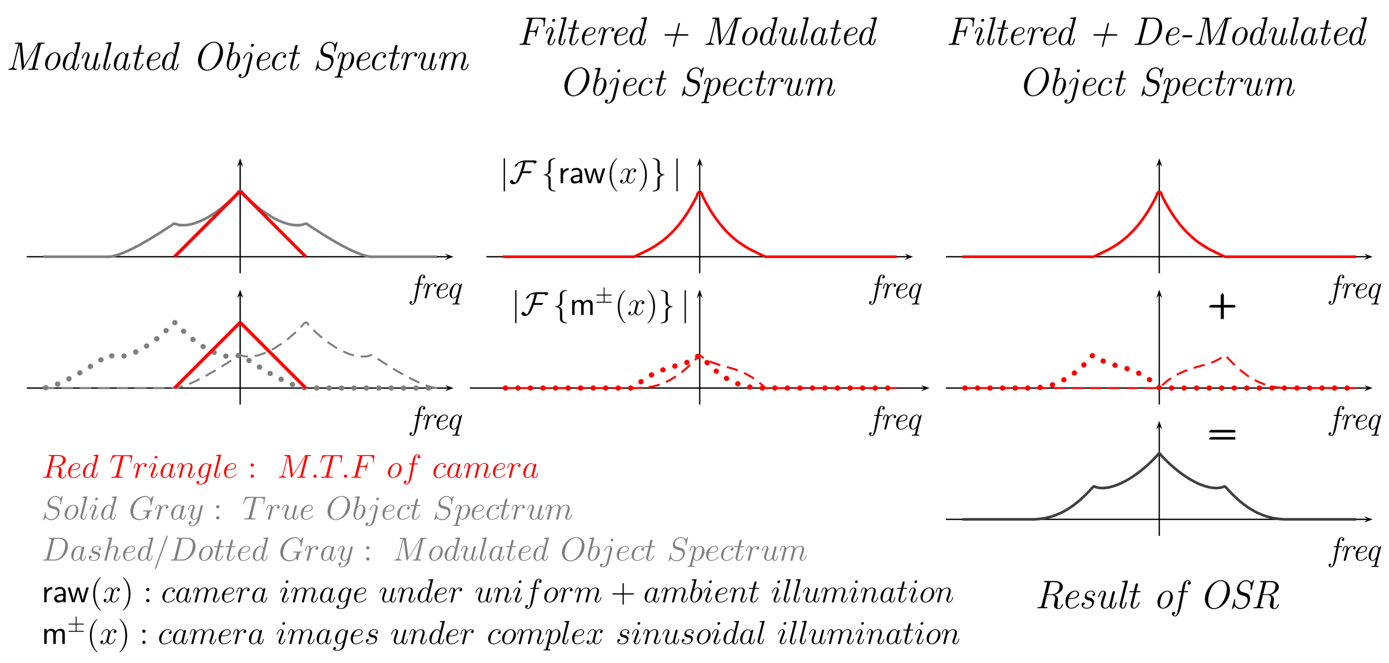
SMU | Bobby B. Lyle School of Engineering

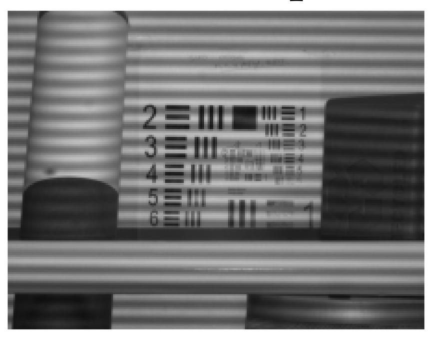
Challenge - resolve spatial detail beyond the diffraction limit of a perspective camera — Optical Super Resolution (OSR)

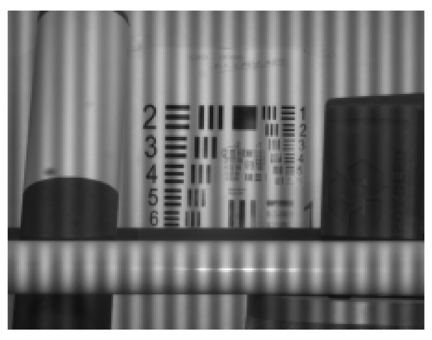
Abstract *: The present work describes a novel attempt at using Structured Light, to resolve spatial detail exceeding the optical bandwidth of a perspective camera (Optical Super-Resolution). It also identifies a family of camera+projector arrangements that can recover depth maps & realize OSR, in an un-calibrated fashion.*

Objective of OSR : overcome the fundamental limit on the resolution of an imaging system (due to diffraction), without altering its physical parameters. The idea is in stark contrast to Digital Super-Resolution which recovers spatial detail lost to aliasing, but limited to diffraction.

Principle behind OSR [1] : Shift frequencies that are outside the passband of the optics into the passband, by modulating the amplitude of a complex sinusoidal pattern with scene information. To this end, we project a series of phase-shifted sinusoidal patterns (*structured light*) onto the scene [2].







Problem The difference in viewpoint between the camera and projector, induces scene-dependent lateral displacements and frequency changes in the periodic pattern. This forms the basis for *depth estimation using Structured Light* [3].

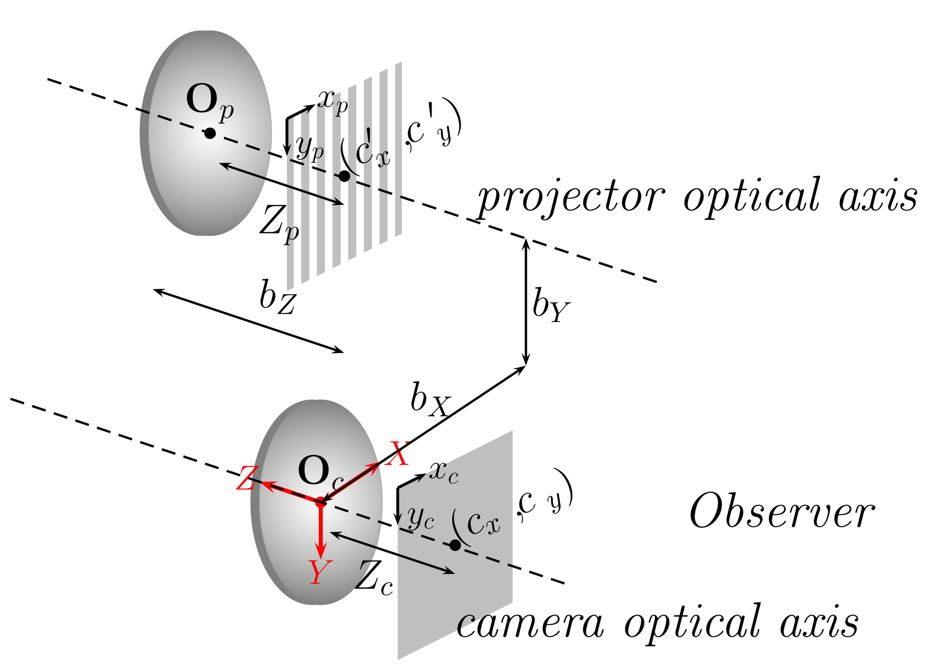
There are periodic patterns & camera+projector arrangements, for which the scene dependent-distortion in the illumination pattern disappears [4],[5]. But, *are we really shifting frequencies outside the passband, into the passband, in these cases?*

Note : *OSR for perspective cameras is an UNSOLVED problem.*

Original contributions of this work — Un-calibrated "OSR + depth estimation" for a perspective camera, with the aid of Structured Light

○ **Unified mathematical model for imaging under structured light** .... expressions shown here for a stereo setup with parallel optical axes

Suppose (x', y') projector pixel illuminates the scene point (X, Y, Z), and its corresponding camera pixel (x, y). Let $\mathsf{r}(x,y) \triangleq \frac{\text{detected intensity}}{\text{incident intensity}}$ along this path.



Illumination $\mathsf{s}_\theta(x', y') = \frac{A}{2} + \frac{A}{2} sin\left(2\pi\left(\frac{\xi_0}{N_p}x' + \frac{\eta_0}{M_p}y'\right) + \theta\right)$ | M_p, N_p *#rows, columns in projected image*; (ξ_0, η_0) *spatial frequency of pattern*

camera image of size $N_c \times M_c$

$$\mathsf{i}_\theta(x,y) = \left\{\mathsf{r}(x,y)\, \alpha_Z A_{Z,\xi_0,\eta_0}\, sin\left(\varphi(x,y) + \theta\right)\right\} \otimes \mathsf{h}(x,y) + \{\textit{image under uniform \& ambient illumination}\}$$

$$\varphi(x,y) \triangleq 2\pi\mu_Z\left(\mu_h\frac{\xi_0}{N_c}(x - c_x) + \mu_v\frac{\eta_0}{M_c}(y - c_y)\right) + 2\pi\frac{\xi_0}{N_p}c'_x + 2\pi\frac{\eta_0}{M_p}c'_y + \psi_Z \quad , \quad \mathsf{h}(x,y) : \textit{optical blur}$$

$A_{Z,\xi,\eta}$	*projector defocus MTF at depth* Z*, and spatial frequency* (ξ, η)
$\mu_Z = \frac{Z}{Z - b_Z}$	*depth dependent magnification*
$\psi_Z = 2\pi\frac{Z_p}{s_p}\left(\frac{\xi_0}{N_p}\frac{b_X}{Z - b_Z} + \frac{\eta_0}{M_p}\frac{b_Y}{Z - b_Z}\right)$	*phase due to relative displacement between camera & projector COP*
$\alpha_Z = \mu_Z^2\, \mu_h\, \mu_v\, \frac{D_c^2}{D_p^2}$	*digital throughput*

When $b_Z = 0$, $\frac{\xi_0}{N_p}b_X + \frac{\eta_0}{M_p}b_Y = 0$, the illumination pattern appears undistorted to the camera, and $\mathsf{i}_\theta(x,y)$ contains spatial detail $\notin$ passband of $\mathsf{h}(x,y)$.
Moreover, qualitative depth information can be recovered from the phase term ψ_Z in $\mathsf{i}_\theta(x,y)$, in a collocated parallel stereo setup ($b_Z = 0$), .

Proposed OSR Workflow

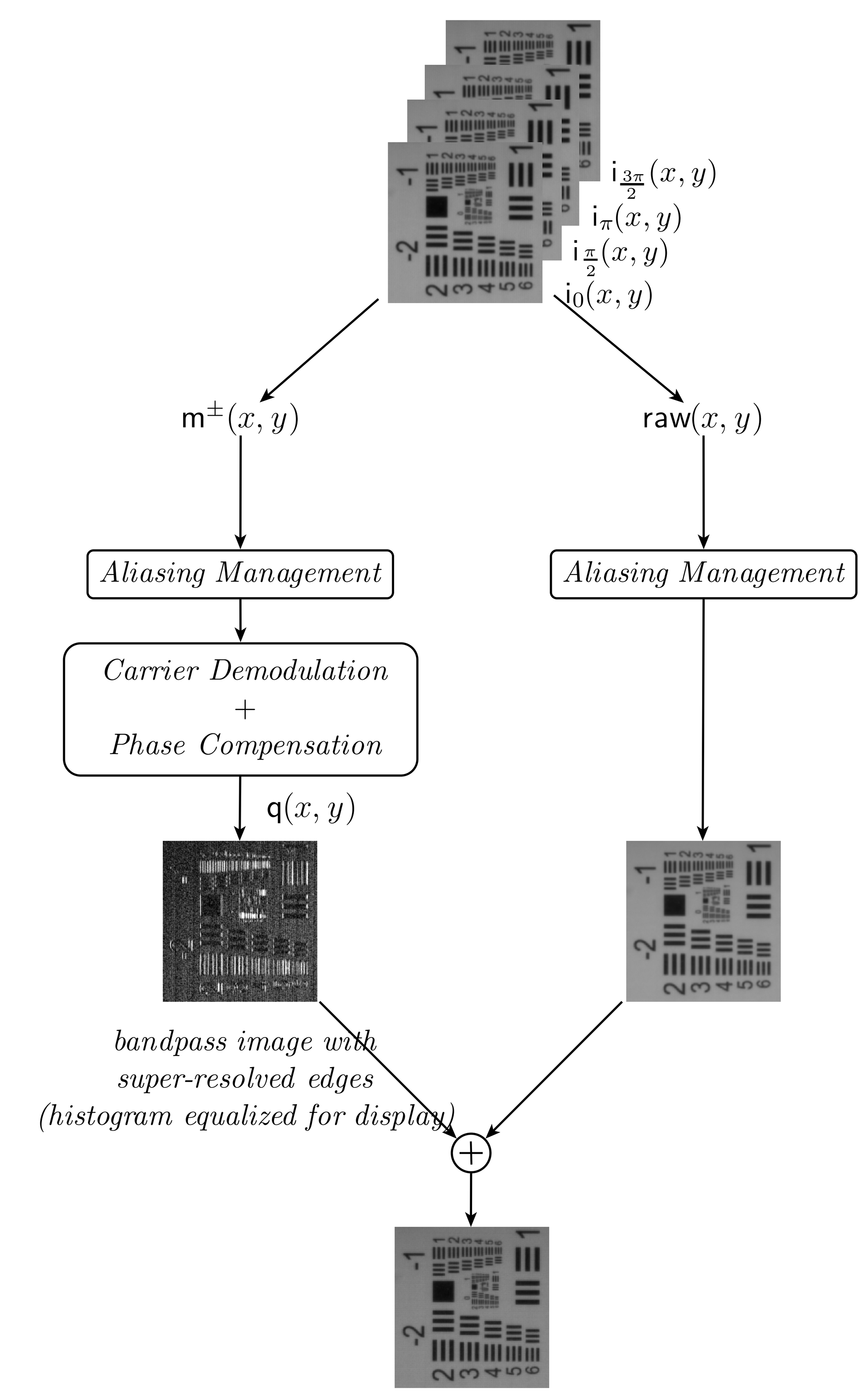


image of the scene under complex sinusoidal illumination

$\mathsf{m}^{\pm}(x,y) = \frac{1}{2}\left(\mathsf{i}_{\frac{\pi}{2}}(x,y) - \mathsf{i}_{\frac{3\pi}{2}}(x,y)\right) \pm \frac{\sqrt{-1}}{2}\left(\mathsf{i}_0(x,y) - \mathsf{i}_\pi(x,y)\right)$

image of the scene under uniform + ambient illumination

$\mathsf{raw}^{\pm}(x,y) = \frac{1}{4}\left(\mathsf{i}_{\frac{\pi}{2}}(x,y) + \mathsf{i}_{\frac{3\pi}{2}}(x,y) + \mathsf{i}_0(x,y) + \mathsf{i}_\pi(x,y)\right)$

Depth Estimation Workflow

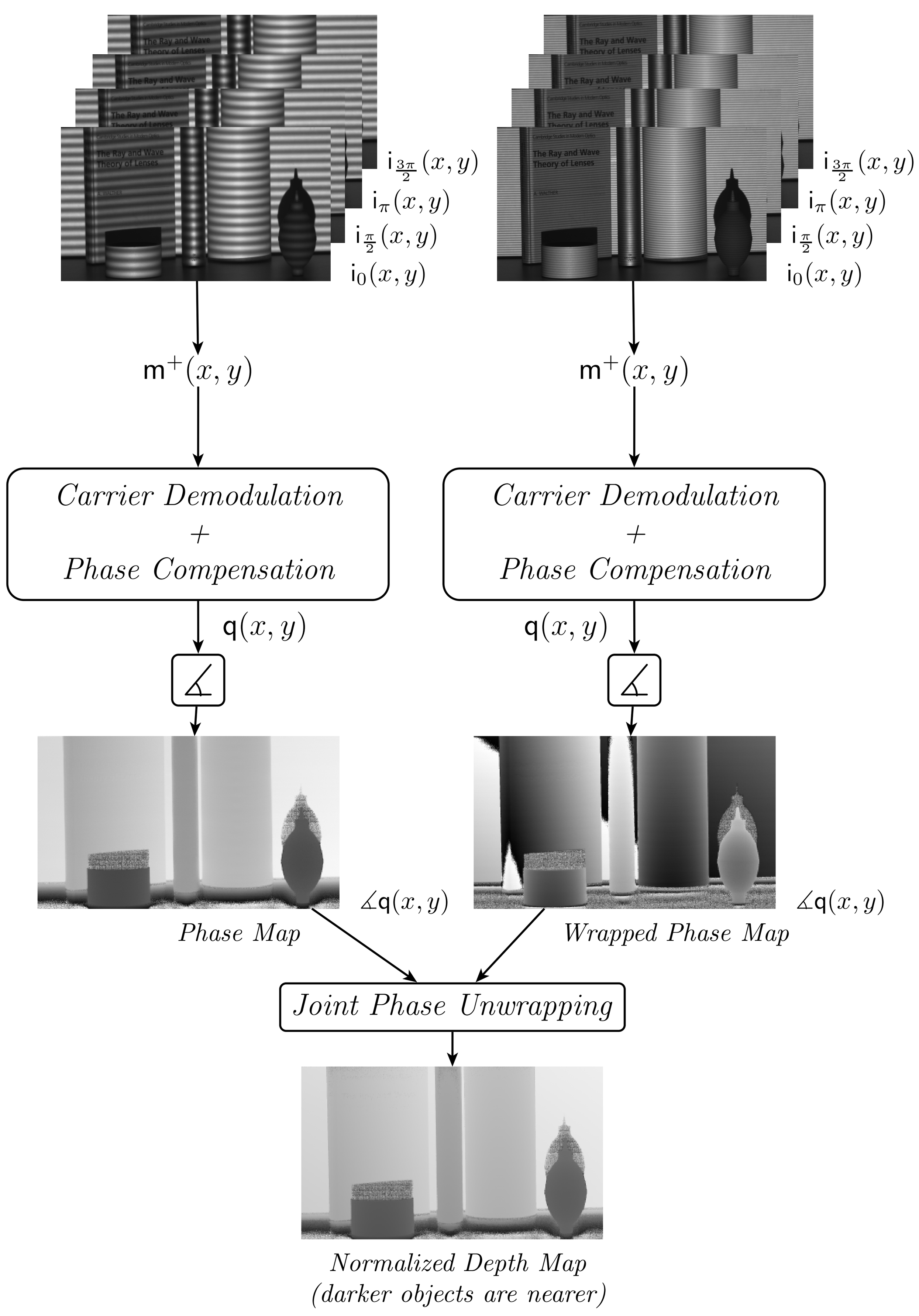


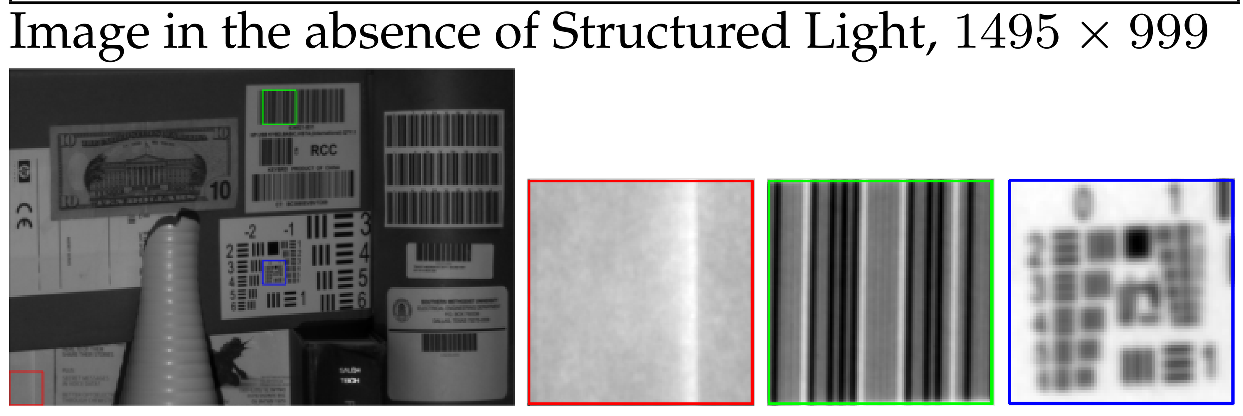
image of the scene under complex sinusoidal illumination

$\mathsf{m}^{+}(x,y) = \frac{1}{2}\left(\mathsf{i}_{\frac{\pi}{2}}(x,y) - \mathsf{i}_{\frac{3\pi}{2}}(x,y)\right) + \frac{\sqrt{-1}}{2}\left(\mathsf{i}_0(x,y) - \mathsf{i}_\pi(x,y)\right)$

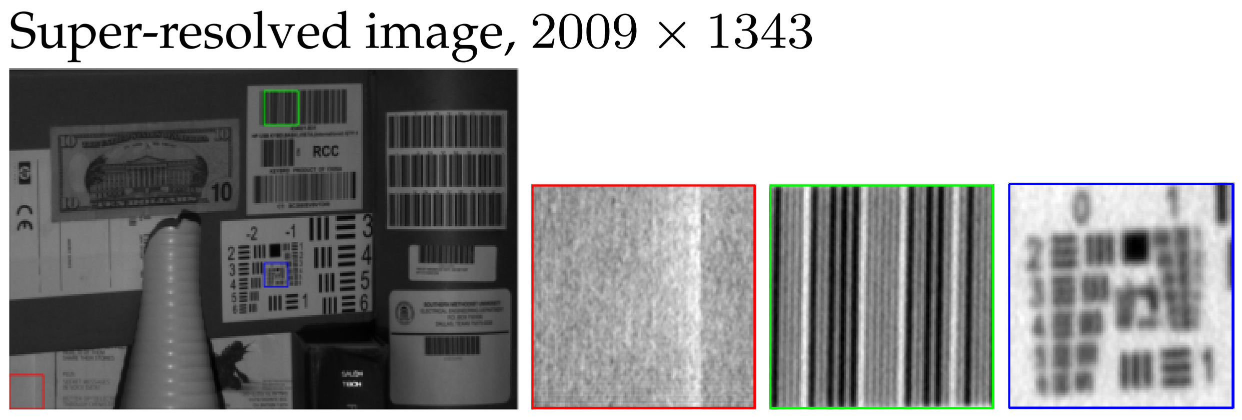
Experimental Results

Illumination Panasonic AE-3000 LCD projector
image size = 1400×1050, $\gamma = 1$ focused on plane at distance 1.905m $(\xi_0, \eta_0) = (350, 0)\frac{\text{cycles}}{\text{image}}$ for OSR $(\xi_0, \eta_0) = (0, 6)\&(0, 105)\frac{\text{cycles}}{\text{image}}$ for depth est.
Imaging SMX-115M CMOS sensor + 16mm lens
pixel pitch = 2.2μm, $\gamma = 1$,integration time= 125ms aperture stopped down to < 2mm
The camera and projector constitute a vertically collocated canonical stereo setup.

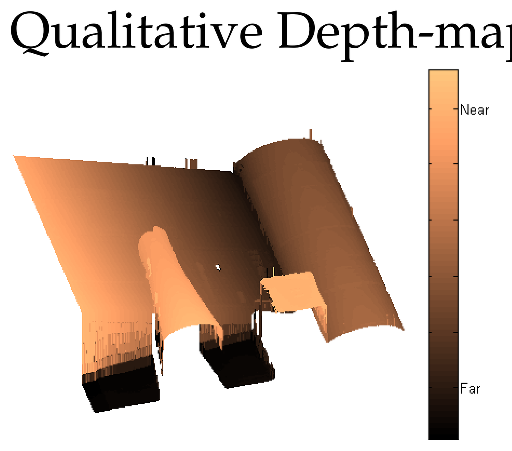
Image in the absence of Structured Light, 1495×999



Super-resolved image, 2009×1343



Qualitative Depth-map



References

[redacted] Optischen Abbildung unter Überschreitung der beugungsbedingten Auflösungsgrenze
[redacted] Surpassing the Diffraction Limit of Digital Imaging Systems Using Sinusoidal Illumination Patterns
[redacted] High-Accuracy Stereo Depth Maps Using Structured Light
[redacted] A Projector-Camera Setup for Geometry-Invariant Frequency Demultiplexing
[redacted] Projection defocus analysis for scene capture and image display