

# **Compressed Sensing: Single Pixel Imaging in Short-Wave Infrared Spectrum**

**Examensarbete**

TQET33

Andreas Brorsson, Andbr981, (911023-1215)

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# 1 Introduction

The development and research of compressed sensing applied to a single pixel camera (SPC) is a relative new area in signal processing with the first functioning camera architecture in 2006. Since then numerous improvements and methods have been proposed how to capture images. In this section a introduction to the SPC architecture and the theory of compressed sensing is presented followed by the aim, research questions and thesis outline of this master's thesis.

## 1.1 Single pixel camera architecture

## 1.2 Compressive sensing

Compressive sensing is a relative new sampling strategy which reconstructs a compressible or spares signal by finding solution to undetermined linear system. The signal is encoded by a number of measurements using measurement matrices and can then be reconstructed from that encoded signal. Two constraints need to be fulfilled to apply compressed sensing sampling: the sampled signal needs to be spares in some basis e.g. Fourier, or gradient, the second condition is that the measurement matrix must be incoherent with the sparse transform.

The CS sampling model is defined as

$$\mathbf{y} = \Phi \mathbf{x} + \epsilon, \quad (1)$$

where,  $\mathbf{x}_{N \times 1}$  is the signal with  $N$  samples,  $\mathbf{y}_{M \times 1}$  is the vector with  $M$  measurements,  $\Phi_{M \times N}$  is the measurements matrix (each unique sensing matrix as a column vector  $1 \times N$ ) and  $\epsilon$  is the noise. In conventional sampling the number of measurements  $M$  needs to be at least equal to the number of samples  $N$  to recover the signal but CS states that  $M$  can be relatively small compared to  $N$  given how compressible the signal is. The signal  $\mathbf{x}$  can be represented as

$$\Psi \theta = \mathbf{x}, \quad (2)$$

where,  $\Psi_{N \times N}$  is some basis matrix and  $\theta_{N \times 1}$  is the coefficients where  $\theta$  is  $K$ -sparse.  $K$ -sparse means that the signal  $\mathbf{x}$  has  $K$  non zero elements in basis  $\Psi$ ,  $\|\theta\|_0 = K$ . Given equation 2, equation 1 can be expand to

$$\mathbf{y} = \Phi \mathbf{x} + \epsilon = \Phi \Psi \theta + \epsilon = \mathbf{A} \theta + \epsilon, \quad (3)$$

where,  $A_{M \times N} = \Phi \Psi$  is the reconstruction matrix. The last statement is what makes CS powerful, a signal which is not sparse can be sampled with measurement matrix  $\Phi$  and the reconstructed with reconstruction matrix  $A$  in a basis where  $x$  is sparse.

### **1.3 Measurement matrix**

#### **1.3.1 Random**

#### **1.3.2 Walsh Hadamard**

### **1.4 Reconstruction methods**

#### **1.4.1 $\ell_1$ minimization**

#### **1.4.2 Greedy algorithms**

#### **1.4.3 Total variation**

### **1.5 Aim**

What image quality can be achieved in natural images captured with a single pixel camera in daylight using state of the art methods?

### **1.6 Research questions**

- How can the quality of images reconstructed by CS or a SPC be evaluated?
- What is the state of the art method to capture and reconstruct images using a SPC architecture?
- What image quality is achieved using state of the art methods applied to the SPC?

### **1.7 Limitations**

- The hardware rig provided by FOI
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### **1.8 Thesis outline**

## 2 Related work

In this section important, relevant and fundamental articles to this master's thesis is presented each with a summary. The articles covers compressed sensing theory applied to compressed imaging, SPC architecture and how to evaluate the images i.e. the fundamental source of information on how to build a state of the art SPC system and how to evaluate its performance.

### 2.1 Compressed imaging

- In **article:CS·donoho1** David L. Donoho proposed the framework of compressed sensing and its application to images.
- 
- **article:SRM** Fast and Efficient Compressive Sensing Using Structurally Random Matrices. Describes that SRM works and why.

### 2.2 Evaluation

- Al Boviks book the essential guide to image processing **book:image·processing** contains the majority of fundamental image processing techniques and measurements. Two image quality metrics of interest is PSNR and SSIM which can be used when a reference image is available.
- **article:il'niqe** A Feature-Enriched Completely Blind Image Quality Evaluator describes how the no reference image quality assessment tool IL-NIQE works and compares to other NR-IQA algorithms. In the article a comparison with other state of the art NR-IQA is conducted which concludes that IL-NIQE is the best over all NR-IQA tool. This kind of QA is useful when there is no reference image available, which is true when taking photos with the SPC.

### 2.3 Analysis

### 3 Method

In order to answer the research questions stated in section 1.6 a state of the art SPC, experiments and evaluation methods needs to be set up. In this section the SPC hardware and image sensing and reconstruction scheme is described as well as the different evaluation metrics and methods.

#### 3.1 Single pixel camera architecture and hardware

FOI designed the SWIR SPC platform using a DMD, a Newtonian telescope and a single pixel detector which are further described in section 3.1.1. The system also has a reference camera in the visual spectrum which can capture images if all micro mirrors in the DMD are turned away from the single pixel sensor and towards the reference camera, it can also be used to check that the patterns are displayed correct.

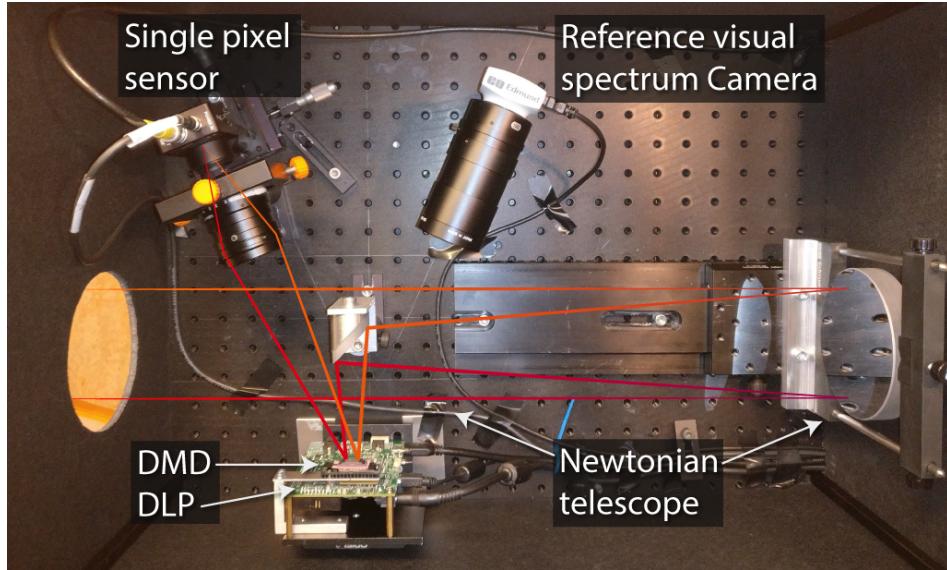


Figure 1: Single pixel imaging system (SPIS), adopted from [article:foiSPIS](#)

As seen in figure 1 light from the scene is focused by the Newtonian telescope and reflected onto the DMD. The mirrors on the DMD can turn individually either into the single pixel sensor or the reference camera. The DMD acts as a Spatial Light Modulator (SLM) and reflects different patterns which are 'summed up' in the single pixel sensor as an intensity. The reconstructed image from the system will have the same resolution as the DMD patterns. The DLP is the DMD control unit which controls which patterns that are displayed on the DMD either by reading images from memory or the video port.

##### 3.1.1 Hardware

##### 3.1.2 Newtonian telescope

A Newtonian telescope is a reflecting telescope, using a concave primary mirror and a flat diagonal secondary mirror, see figure 1. In this set-up the telescope act as a lens focusing the scene onto the DMD. The motivation to use a Newtonian telescope instead of a lens system is partly that chromatic aberration is eliminated and partly that a reflective optical system works over a greater range of wavelengths that includes SWIR, near infrared (NIR) and the visible spectrum.

### 3.1.3 DLP and DMD

The DMD (Texas Instruments DLP4500NIR) is a matrix of micro mirrors that can be individually tilted  $\pm 12^\circ$  and reflects wavelengths in the range 700-2500 nm. The DMD is controlled by the DLP (DLP LightCrafter 4500) which can be controlled either by video port (HDMI) or by the internal flash memory. The internal memory can theoretically be faster than the video port but due to constraints in both memory and memory bandwidth the fastest measurement matrix rate gets stuck at 270 – 300 Hz. The video port can be operated at 120 Hz and display one bit plane at the time, which gives a maximum measurement matrix rate at  $120 * 24 = 2880$  Hz, but in the current configuration only 60 Hz frame rate was achieved giving a measurement matrix rate at 1440 Hz. Because the diamond shape of the mirrors and how their index is defined in the DLP where one column is two mirror column arrays wide, see figure 2, the reconstructed image needs to be reshaped to a Cartesian grid. To control the DMD the software 'DLP LightCrafter 4500 Control Software' is used. **manual:DLP**

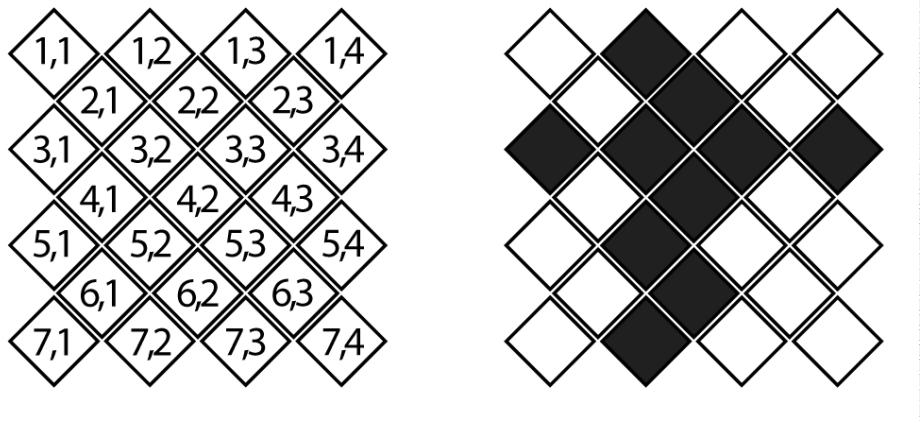


Figure 2: DMD matrix, left shows each tiles index and right shows second row and second column in black.

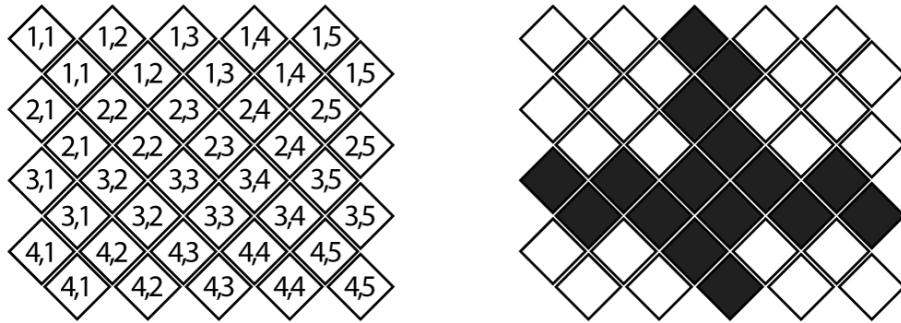


Figure 3: DMD matrix, left shows each tiles index and right shows second row and second column in black.

How does this effect the result?

### 3.1.4 Lens

The lens mounted on the single pixel sensor is an 50mm SWIR Fixed Focal Length Lens f1.4 designed for wavelengths ranging from the 800 nm in the visual spectrum to 2000 nm in the SWIR spectrum. [website:SWIR objective](#)

### 3.1.5 Single pixel sensor

The single pixel sensor is a Thorlabs PDA20C/M and is sensitive in wavelength range 800-1700 nm which is beyond the visual spectrum (390-700 nm). [manual:PDA](#)

### 3.1.6 Signal spectrum

All components characteristics assembled should capture signals in 800-1700 nm spectrum.

## 3.2 System overview

### 3.2.1 Measurement matrix

### 3.2.2 Reconstruction algorithm

## 3.3 Evaluation

The evaluation will be divided into two categories: reconstructed images from synthetic data and images reconstructed from data acquired by the SPC.

The evaluation on synthetic data is focused on evaluating the performance of the measurement matrix and reconstruction algorithm. Evaluating synthetic data gives two possibilities that can not be achieved with images reconstructed using the SPC which is that there is a reference image which the resulting image can be compared to.

Reconstructed image from synthetic data is acquired by creating a signal  $\mathbf{y}_{M \times 1}$  taking the inner product of  $\mathbf{y} = \Phi\mathbf{x} + \epsilon$  where,  $\mathbf{x}$  is the synthetic image reshaped to a vector,  $\Phi$  is the measurement matrix with the desired amount of measurements  $M$  and synthetic noise  $\epsilon$  which can be regulated to simulate different conditions, then using the reconstruction algorithm on the signal  $\mathbf{y}$  to obtain the reconstructed image  $\hat{\mathbf{x}}$ . Because the measurement matrix and reconstruction algorithm is independent of the SPC hardware the subsystem can be evaluated independently. Two advantages of evaluation the sensing and reconstruction independently of the SPC is that parameters such as number of measurements and noise can be regulated easily and the second advantage is that a reference image is available for comparison.

With a reference image available two image quality assessments are performed on the result from the simulation: Peak signal-to-noise ratio (PSNR) and SSIM. PSNR is defined as

$$\text{PSNR}[f(x, y), g(x, y)] = 10 \log_{10} \frac{E^2}{\text{MSE}[f(x, y), g(x, y)]} \quad (4)$$

where,  $f(x, y)$  and  $g(x, y)$  is intensity in pixel  $(x, y)...$

## 3.4 Method criticism

- No Reference Image Quality Assessment is not designed for SWIR images or SPC:s characteristics noise therefore the results may not reflect how the QA would answer to visual wavelength cameras.

## 4 Evaluation

This section is structured as, for each experiment and setup a detailed explanation and motivation on how and why the experiment is needed followed by the results of that experiment. The experiments are motivated by gathering as much information and results as possible to answer the research questions. The first subsection 4.1 will present the results from experiments with synthetic data where a reference image is available. The second subsection 4.2 will present the result from images reconstructed from the SPC. No perfect reference image is available in those experiments therefore the images will be evaluated against near optimal image, no reference QA and against a state of the art SWIR camera.

### 4.1 Synthetic data

#### 4.1.1 PSNR, SNR, SSIM

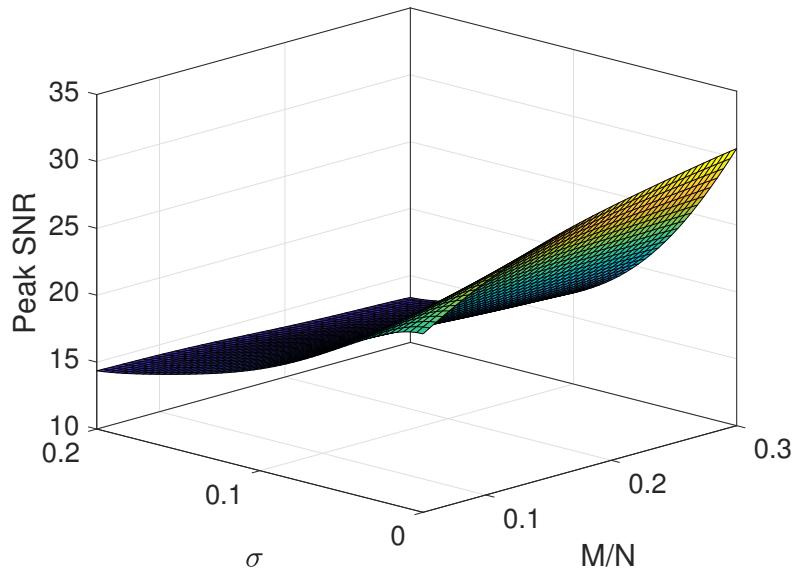


Figure 4: Peak SNR result depending on number of measurements and simulated noise level.

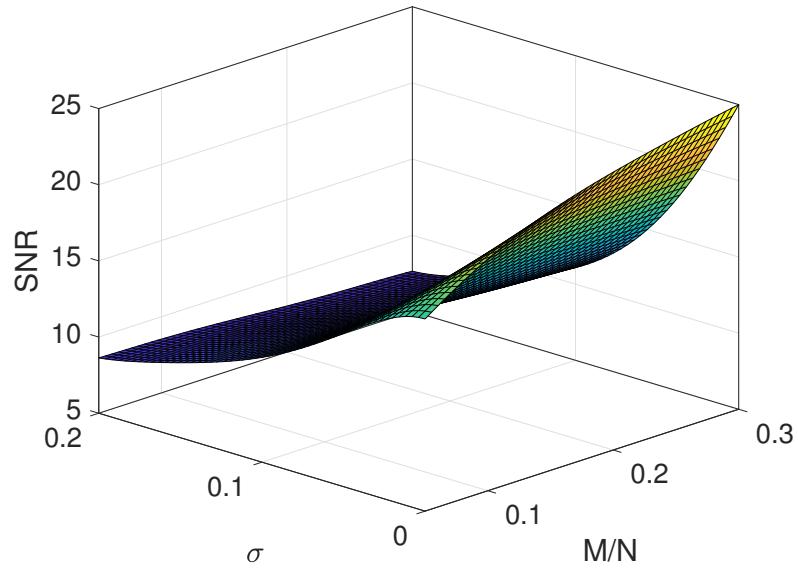


Figure 5: SNR result depending on number of measurements and simulated noise level.

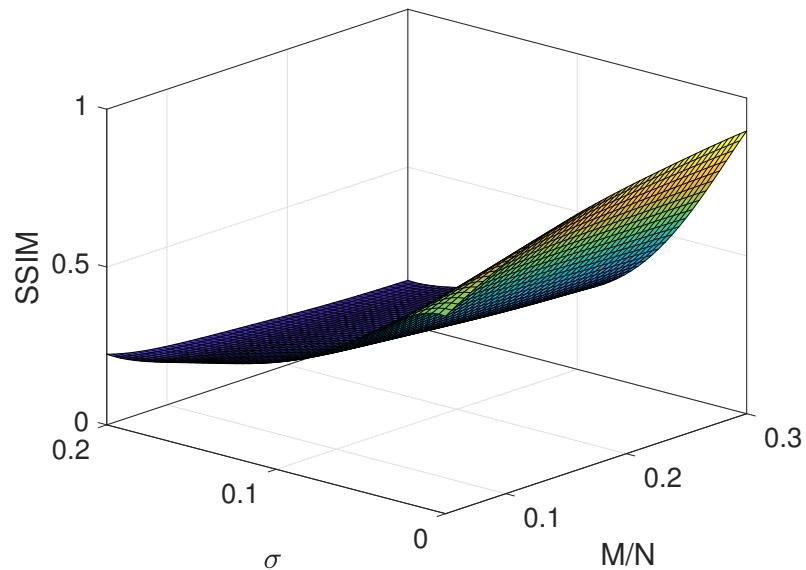


Figure 6: SSIM result depending on number of measurements and simulated noise level.

#### 4.1.2 No Reference quality assessment

BRISQUE lower score is better.

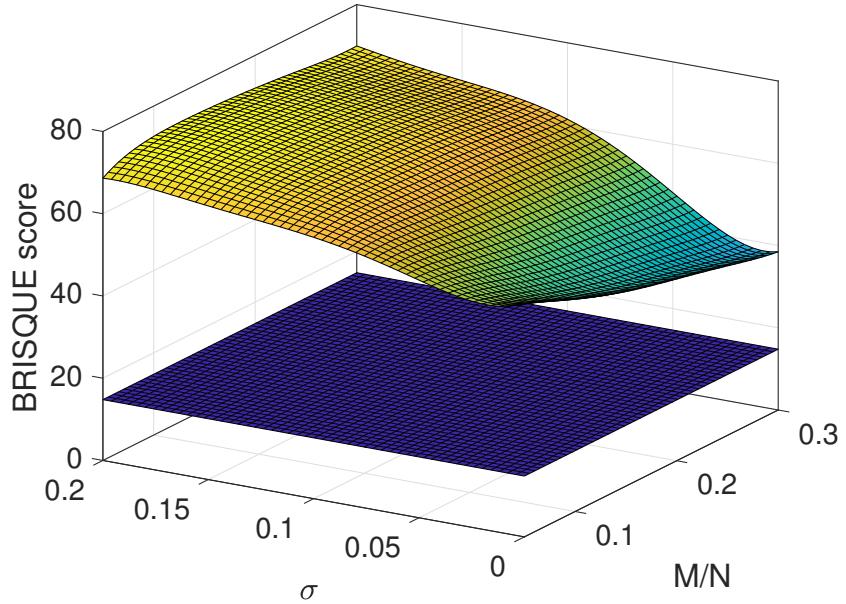


Figure 7: BRISQUE result depending on number of measurements and simulated noise level. Lower surface is reference image score.

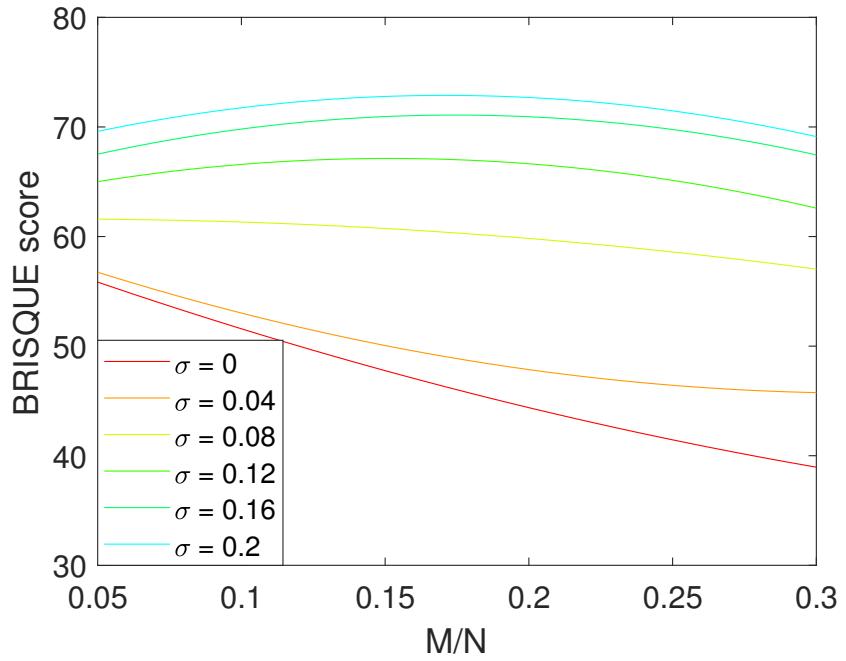


Figure 8: BRISQUE result depending on number of measurements for different simulated noise levels.

#### 4.1.3 Dynamics in scene

Dynamics in the scene can roughly be divided into three separate scenarios, in this section each of them will be tested in a controlled environment with each scenario isolated to show how the signal and the reconstructed image is effected.

In the first scenario a object will be placed in an image but for each measurement matrix the location of the object will be moved in a bounded area of the image. This will model as a scene where the background is static but a person is standing in the same spot but moving around.



(a) Original reference image

(b) Reconstructed 30% image from reference image without movement

(c) Reconstructed 30% image with local movement

Figure 9: Local movement

The difference between figure 9b and 9c is visible with the naked eye, not only does the object moving around get blurry and noisy but the whole image globally. In table 1...

Peak SNR	SNR	SSIM
29	25	91

Table 1: Effects comparing non perturbed reconstructed image against reconstructed image with local movement

Commenting the result from the table... In figure ?? the effects of the movement is shown plotted against the non perturbed signal.

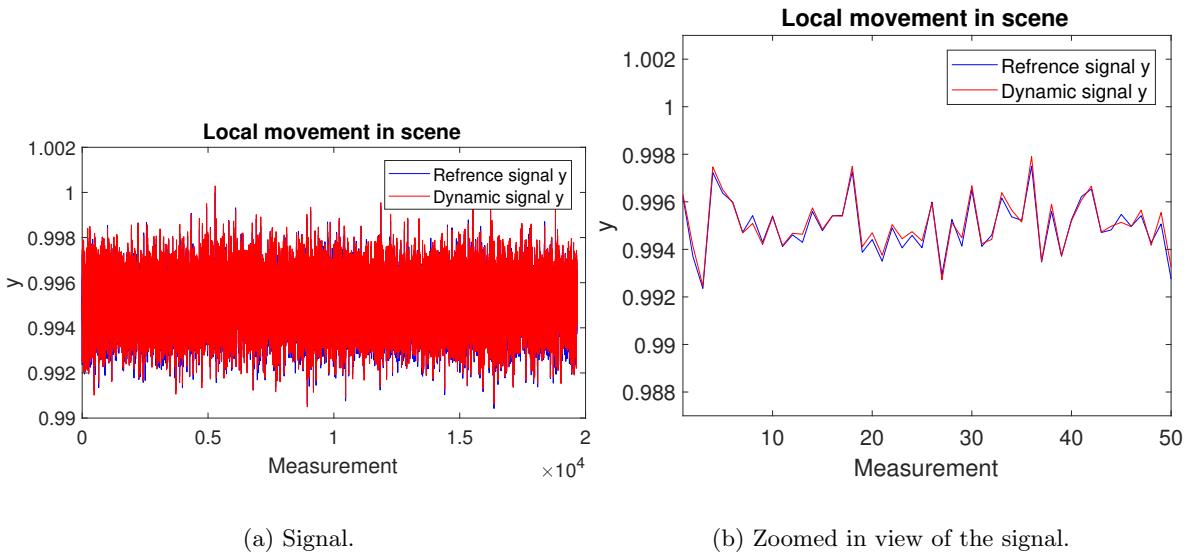


Figure 10: Local movement, acquired signal

As seen in figure 12a there is no obvious difference between the non perturbed reference signal and the distorted signal. In figure 9b where some of the samples is displayed no large difference can be seen ether, the conclusion of this test implies that local movement in a scene will cause noise in the image globally and especially locally where the movement occurred. It also implies that local movement is very hard to detect on the signal even if a reference signal is available.

The second scenario is an object is passing through, moves out or moves to an other place in the scene far from the original place. In other words, large global movement in the scene. The problem is modeled with a static background then as the simulated measurement is acquired the same object as in the first experiment will cross the scene, like a car, human or animal might do when using the SPC. The object will cross the scene in 1000 measurements of approximately 19000, corresponding to approximately 0.7 seconds when capturing with the SPC in its current setup.



(a) Original reference image      (b) Reconstructed 30% image from reference image without movement  
 (c) Reconstructed 30% image with object passing through

Figure 11: Object passing through scene.

The difference between figure 11b and 11c is visible with the naked eye, A global noise arises in the

image and the object cant be seen. In table 2...

Peak SNR	SNR	SSIM
23	18	58

Table 2: Effects comparing non perturbed reconstructed image against reconstructed image with local movement

Commenting the result from the table... In figure ?? the effects of the movement is shown plotted against the non perturbed signal.

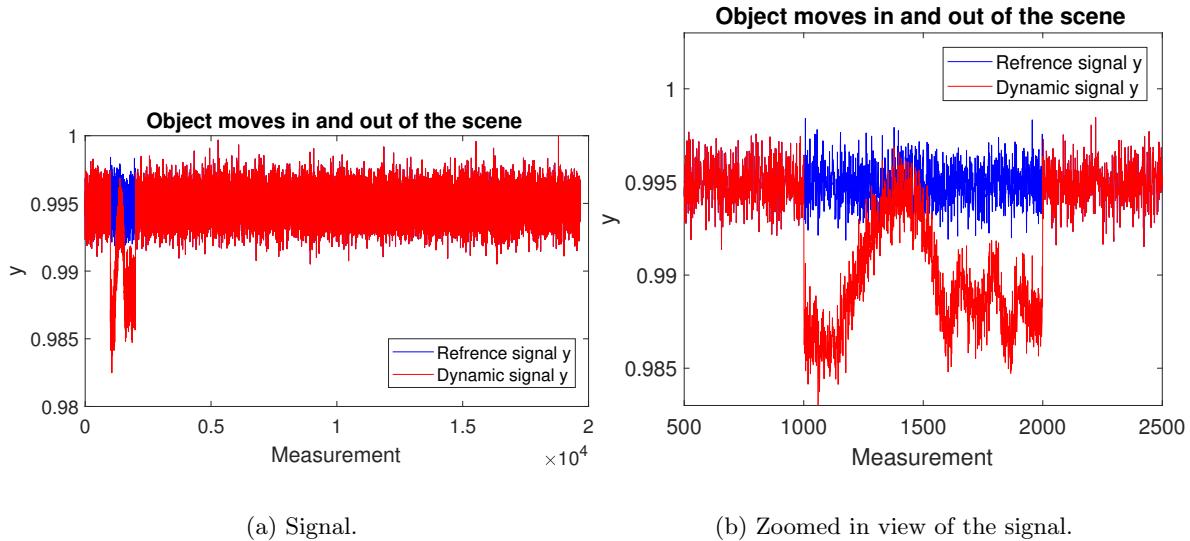


Figure 12: Global movement, acquired signal

- Large changes in the scene can be detected
- Remove the identified measurements to get a good signal

The third scenario is luminance change in the scene caused by clouds occludes the sun or the light intensity from the lights is not constant. This scenario is modeled by adding or subtracting the global intensity in the image over the measurements.



(a) Original reference image  
(b) Reconstructed 30% image from reference image without movement  
(c) Reconstructed 30% image with global luminance change  
(d) Reconstructed 30% image with mean subtraction

Figure 13: Global luminance change in scene.

The difference between figure 13b and 13c is visible with the naked eye, A global noise arises in the image, but as seen in figure 13d the effect can be suppressed explained under figure 14. In table 2...

	Peak SNR	SNR	SSIM
Perturbed signal	19	14	38
Mean subtracted signal	33	29	93

Table 3: Effects comparing non perturbed reconstructed image against reconstructed image with global luminance change

Commenting the result from the table... In figure ?? the effects of global luminance is shown plotted against the non perturbed signal.

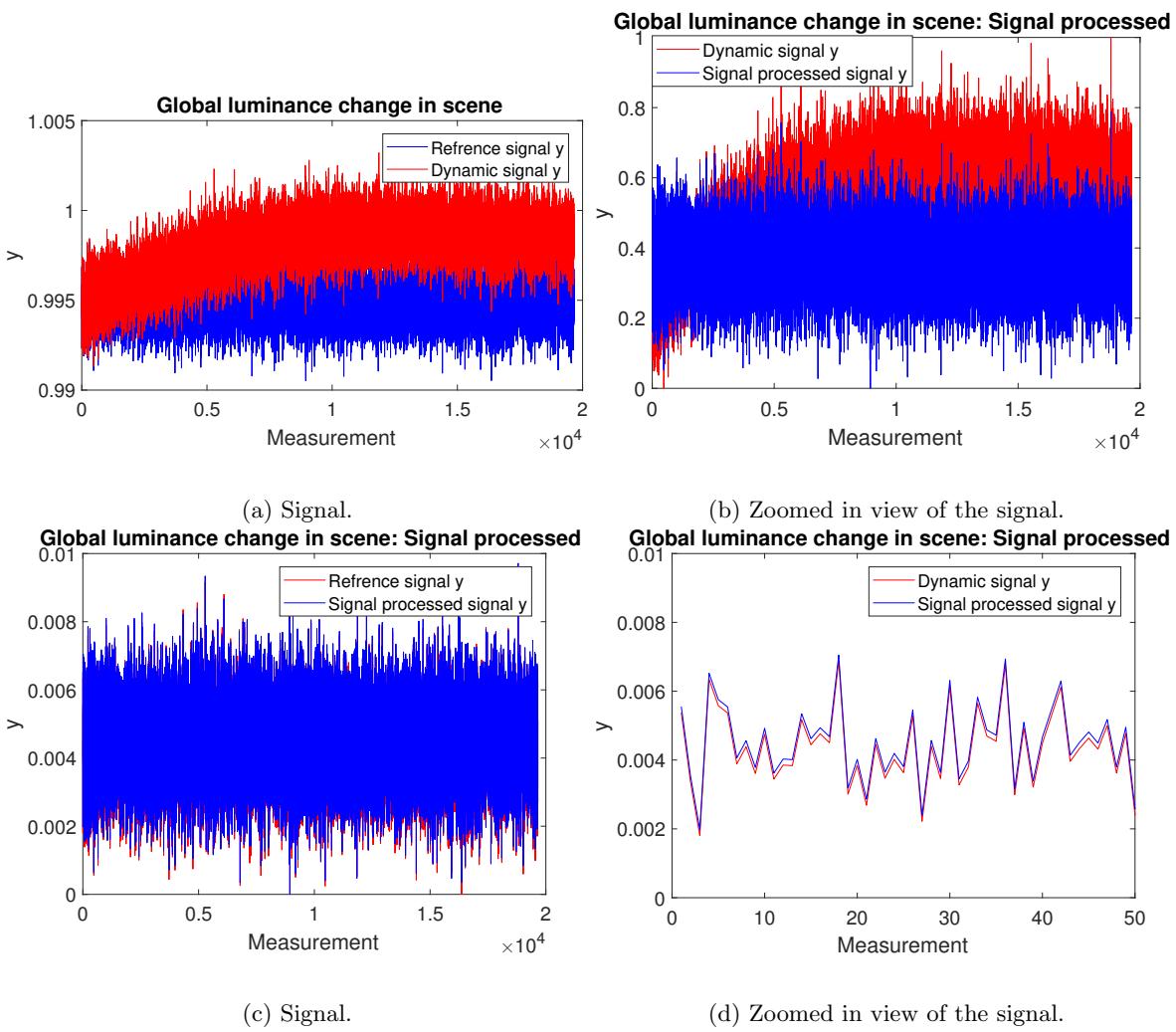


Figure 14: Global movement, acquired signal

- Dynamic signal v. Reference signal
- Dynamic signal v. Mean subtracted signal
- Reference signal v. Mean subtracted signal
- Comment on the window, pretty good.
- Can be detected with the knowledge that the signal should be stationary. Signal process the signal to look like a stationary signal.

## 4.2 SPC evaluation

### 4.2.1 Soft chessboard

Todo: Skapa rekonstruerade bilder från homographin och jämför de rekonstruerade med referensbilden

This evaluation is designed to confirm that the images reconstructed by the SPC follows the same characteristics as the reconstruction of the synthetic data.

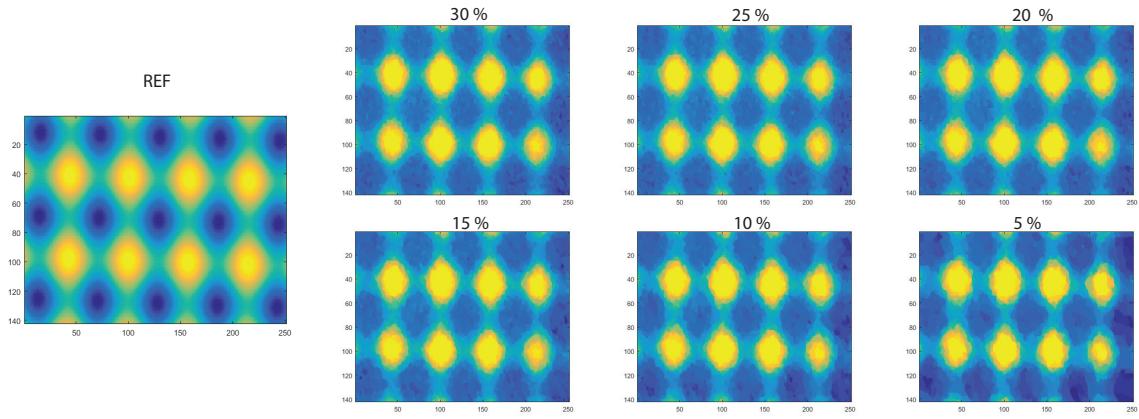
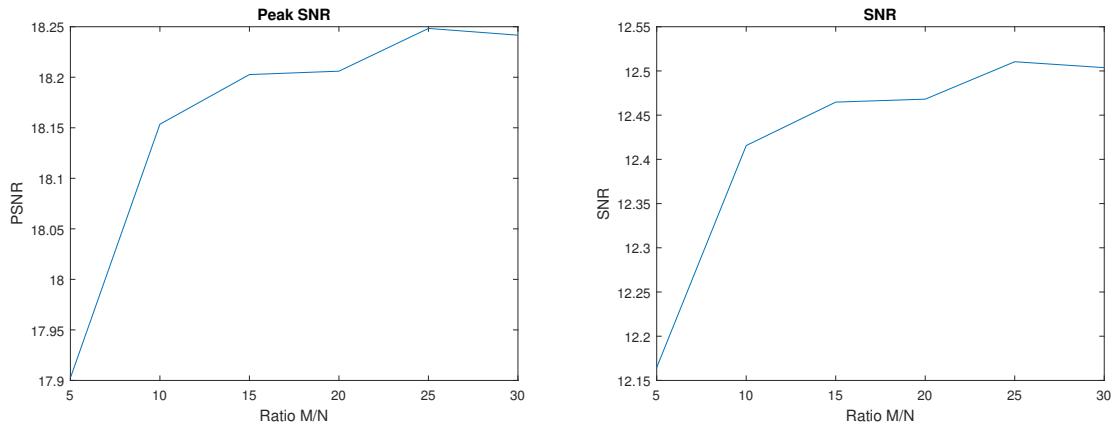
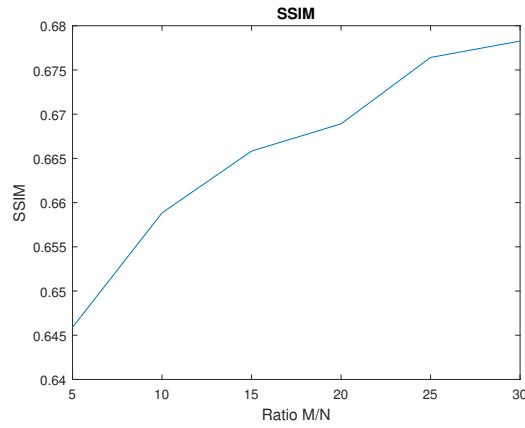


Figure 15: The reconstructed images with different number of measurements and the reference image transformed to fit the SPC images using homography.



(a) Peak SNR for reconstructed images against reference image. (b) SNR for reconstructed images against reference image.



(c) SSIM score for reconstructed images against reference image.

Figure 16: Signal quality of SPC images compared to reference image

#### 4.2.2 No reference quality assessment

Using the no reference quality assessment measurement BRISQUE to evaluate the SPC images. Each image is evaluated at reconstruction rate 5% to 30%.

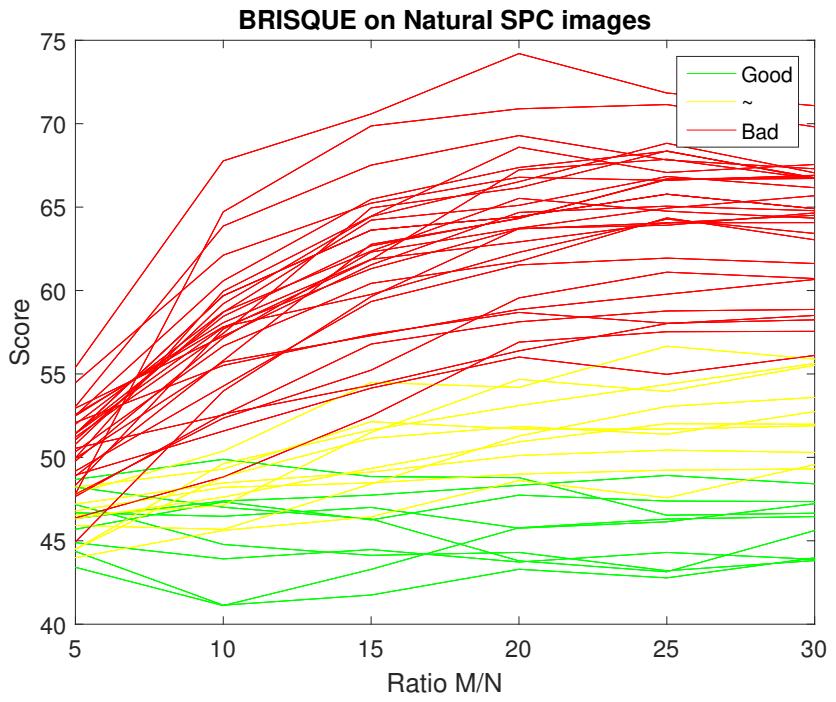


Figure 17: BRISQUE result.



Figure 18: Example of 'good' images corresponding to the green lines in figure 17.

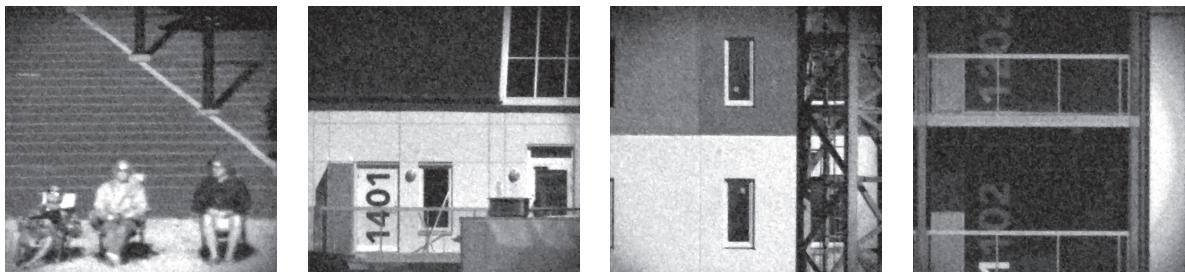


Figure 19: Example of 'medium good' images corresponding to the yellow lines in figure 17.

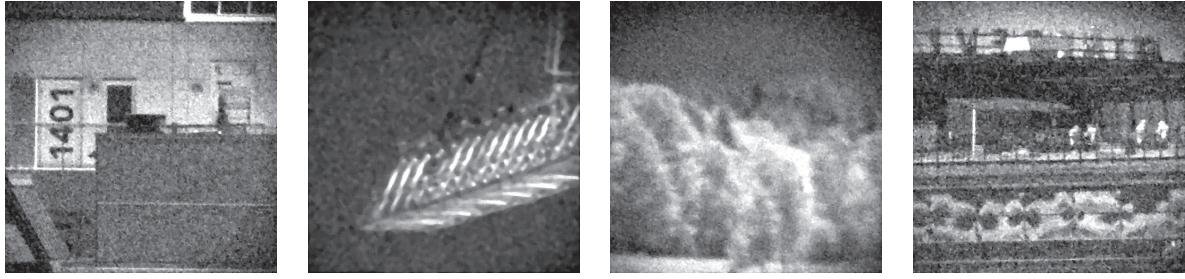


Figure 20: Example of 'bad' images corresponding to the red lines in figure 17.

- Good images are:
- Medium good images are:
- Bad images are:

#### 4.2.3 Modulation Transfer Function

The MTF is used to comparing the sharpness of cameras and lenses.

The MTF from the SPC is compared to a state of the art SWIR camera. Two scenes was captured by the SPC and a conventional SWIR camera containing printed sheath of paper with simple tilted shapes on them, see figure 21.

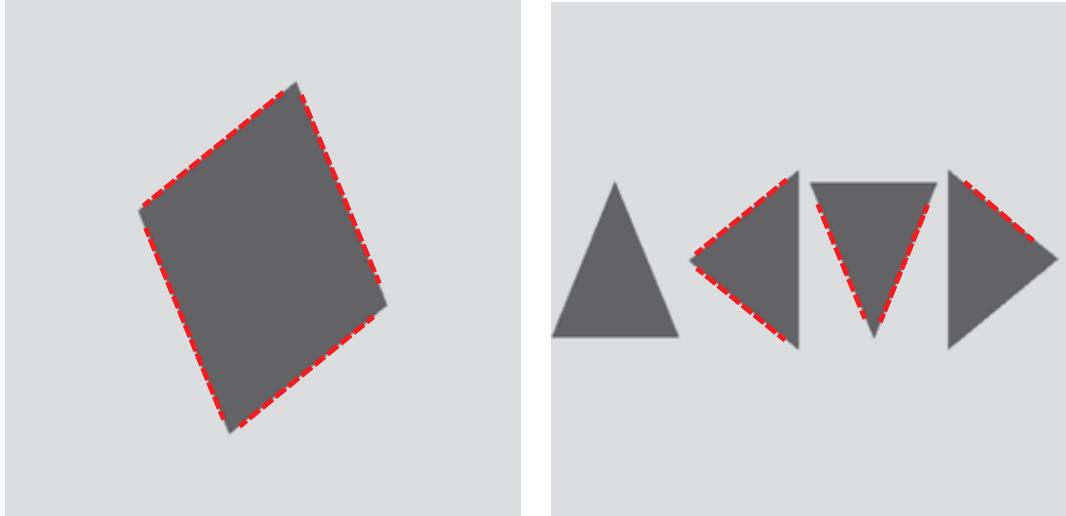


Figure 21: Printed targets with markings where the MTF measurements was performed

In the resulting images MTF measurements was performed on the specified edges to gather a mean and standard deviation for each camera. For the SPC, images reconstructed from 5% to 30% was tested in order to see if the number of measurements effected the MTF result. In figure 22 the images from the SWIR camera and SPC are presented.

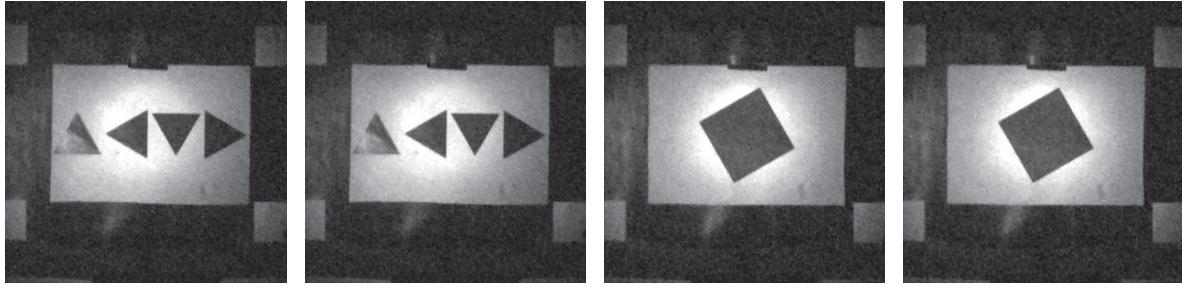
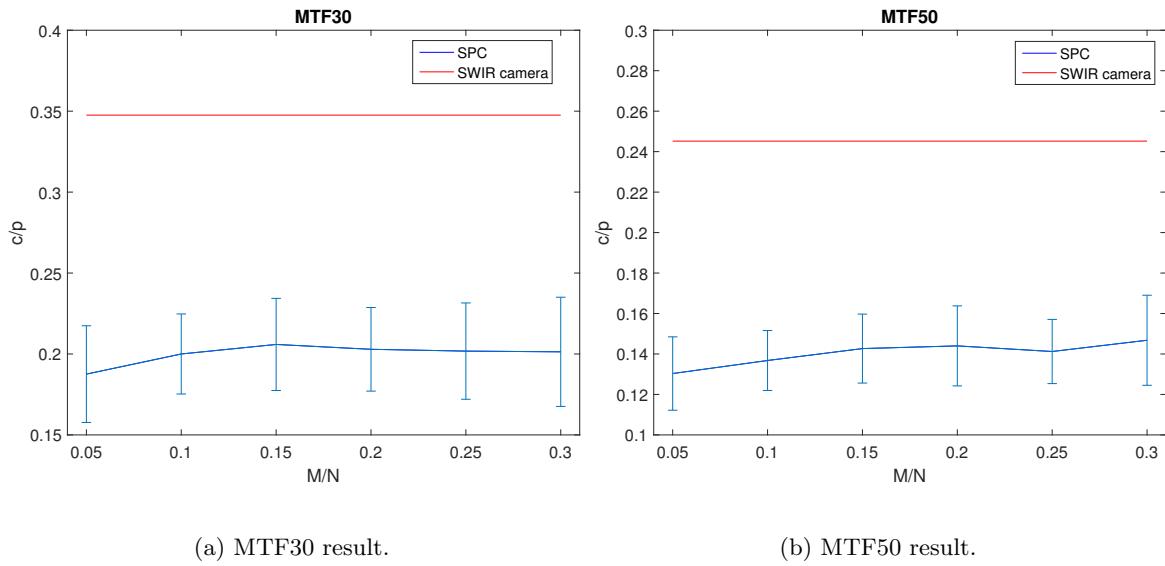


Figure 22: SPC and state of the art SWIR camera output images. (OBS! Bilder från Raptorn ska läggas till)

### 4.3 MTF



(a) MTF30 result.

(b) MTF50 result.

Figure 23: MTF results. (OBS! inte rätt figurer)

### 4.4 Edge response

The edge response is measured in the distance (pixels) required for the edge to rise from 10% to 90%. In figure 24 the result from the experiment is presented.

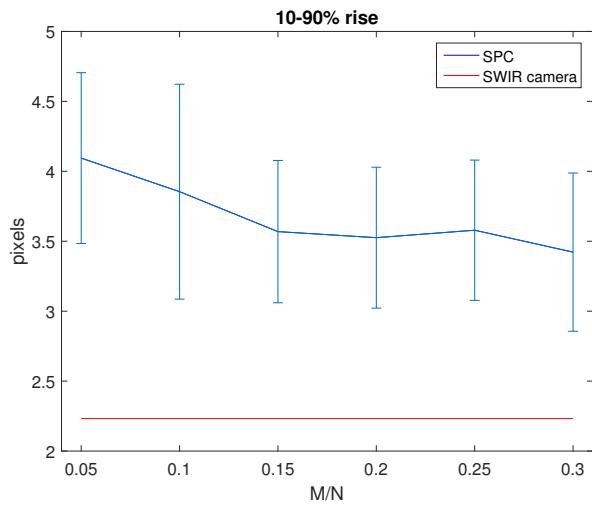


Figure 24: 10-90% rise in pixels. (OBS! inte rätt figur)