Summary

Learned Skills

1. Applied calibration and preformat in experiment, fixed pile up.
2. Set up the NLOS simulation from scratch: considering noise, windowing effect, Lambertian shading, vignetting.
3. Utilized the simulation to explore the effect of FoV size, exposure time, non-confocal geometry, pulse width, depth resolution.

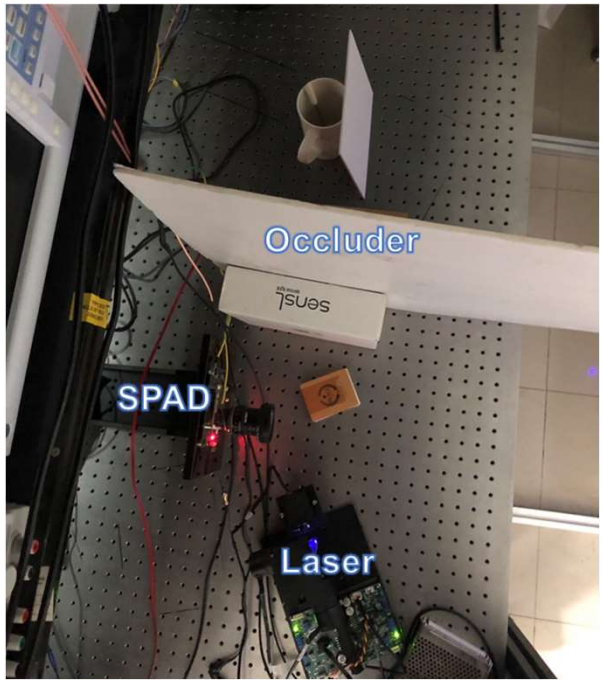
Contribution

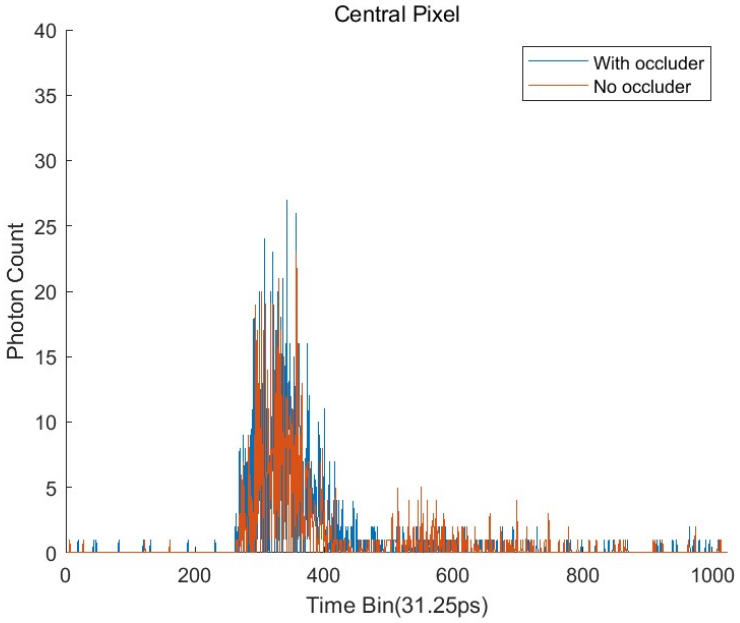
1. Developed stitch method for SPAD array FoV. (W5, W9)
2. Developed interpolation method for camera shooting from an angle. (W11)
3. Implemented 2-stage RSD for non-planar wall, added mask, shading and correct phase, and verified the algorithm on real data. (W13-21)

W0: Experiment Setup

Got SPAD and laser work;
Estimated photon count.

There was annoying first bounce, although laser point was out of FoV.





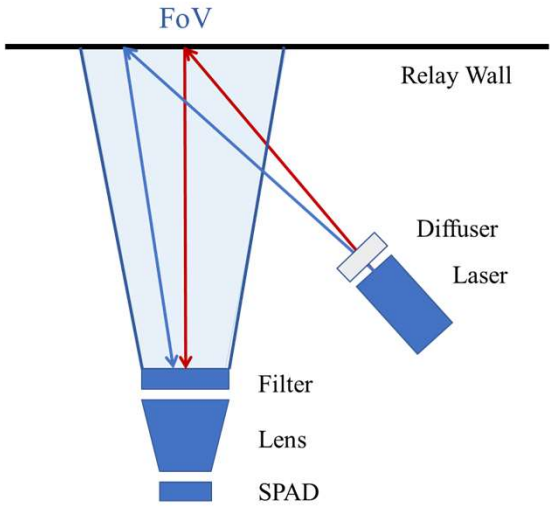
$$\frac{average\ power}{repetition\ rate} \times \frac{1}{h\nu} \times \left(\frac{20cm \times 20cm}{2\pi(1.5m)^2}\right)^2 \times \frac{80cm \times 80cm}{2\pi(1.5m)^2}$$

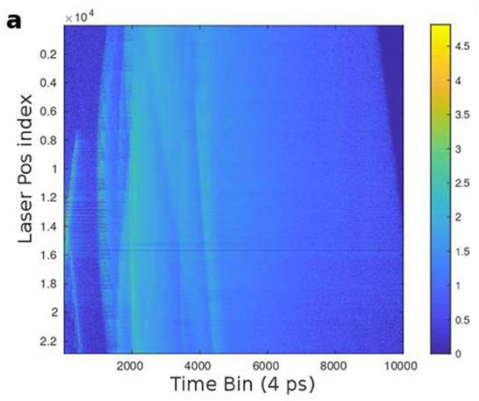
1W, 500k, 440nm | FoV size | Object size

W1: 3D Reconstruction of FoV

- Calibrated the SPAD array pixels;
- Got RSD algorithm work.

No hyperbola due to small FoV.





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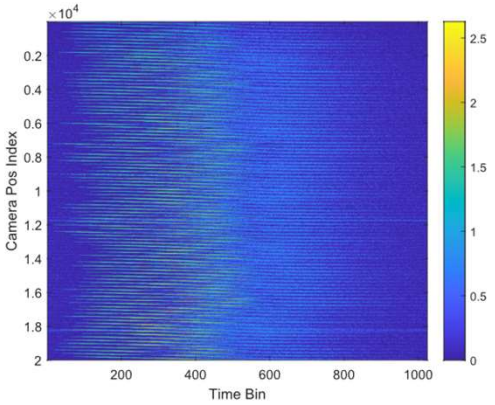
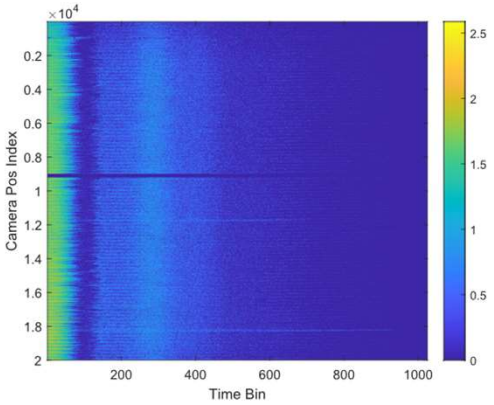


Raw

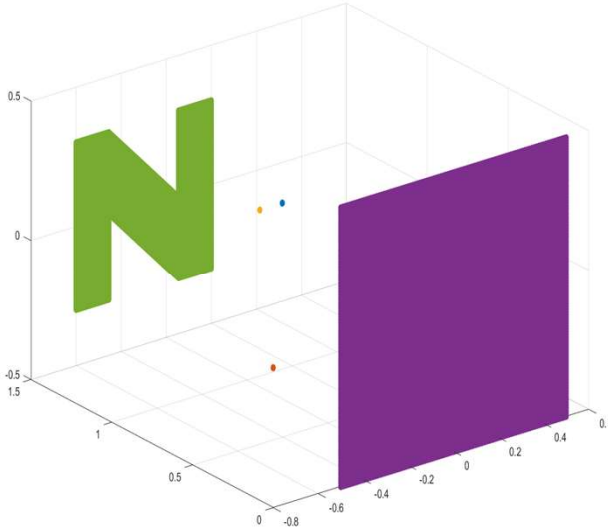


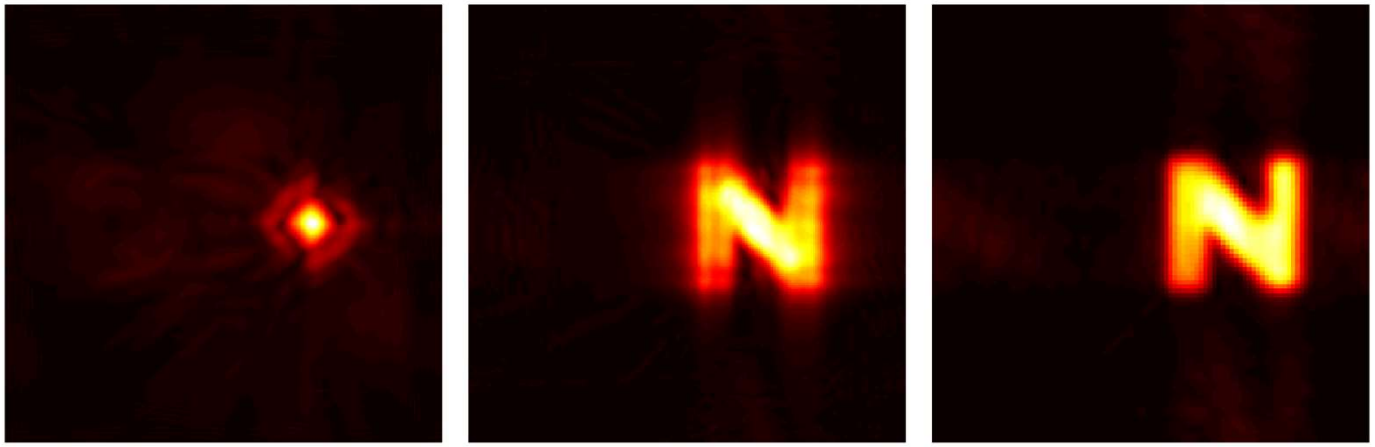
Calibrated

W2: FoV Simulation

- Set up simulation from scratch;
- Decided how large the FoV should be.

Ignored the noise.





FoV 0.5m*0.5m

FoV 1m*1m

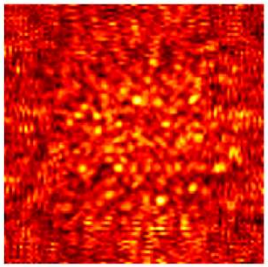
FoV 2m*2m

W3: Exposure Time Simulation

- Added Poisson & Gaussian noise in simulation to decide exposure time;
- Tried LPF to compensate.

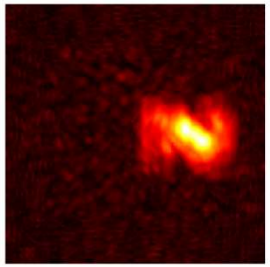
Back projection method messed up.

Exposure Time: 0.1ms
Peak: 263

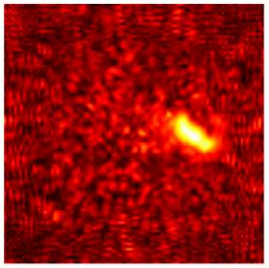


About 1.6s per pixel in our experiment setup (detection rate etc,), 40 readouts add up, it can take several hours labor ☹

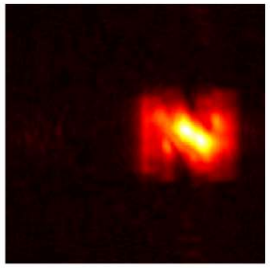
Exposure Time: 10ms
Peak: 2.2e4

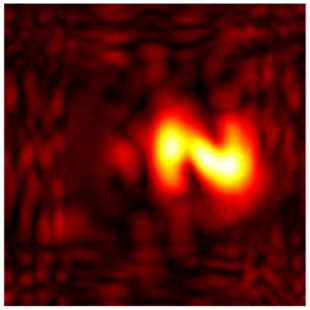


Exposure Time: 1ms
Peak: 2288



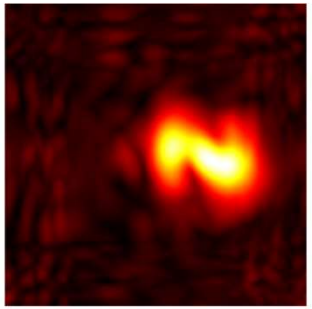
Exposure Time: 100ms
Peak: 2.1e5





Lambda =

12 * sampling_spacing

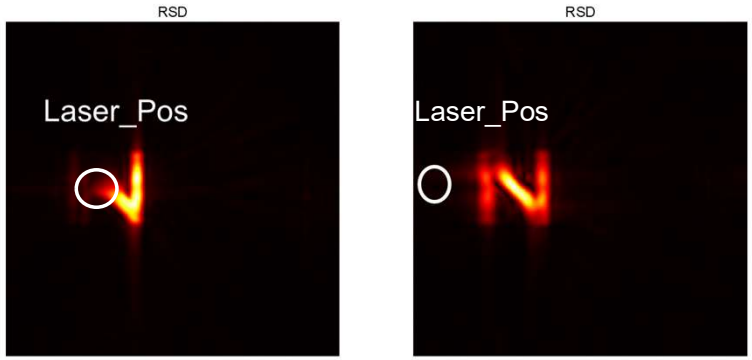


Add LPF

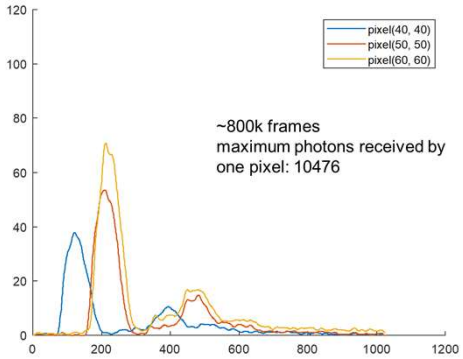
W4: Non-confocal Geometry

- Explored about the geometry;
- Figured out problem of BP: Laplacian filter;
- Preformatted the experimental data.

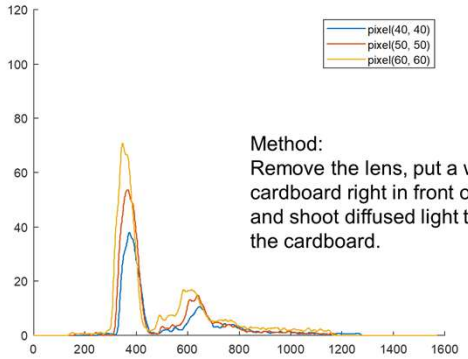
How to choose the laser position is tricky is this experimental setup.



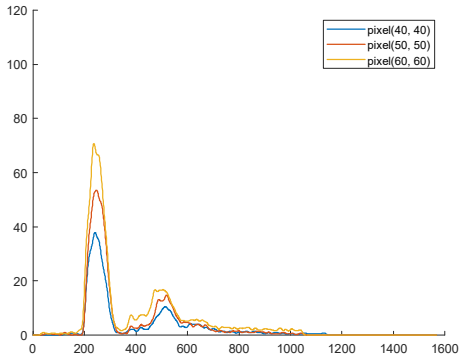
Can’t block first bounce, pile up effect.



Raw



Calibrated



Preformetted

W5: Stitch Method for FoV

- Did theoretical analysis;
- Stitched FoV: edge detection + superposition.

Detected artifact for close objects.

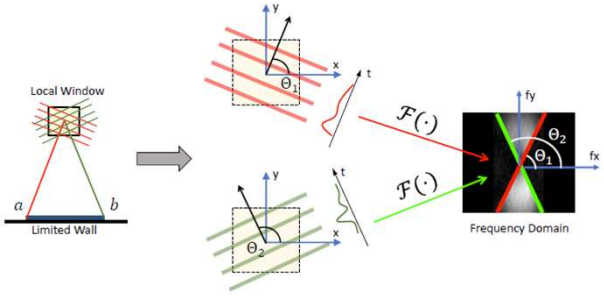
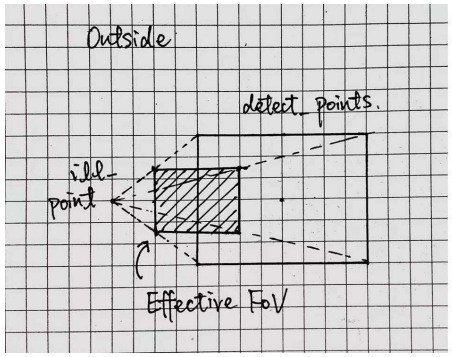
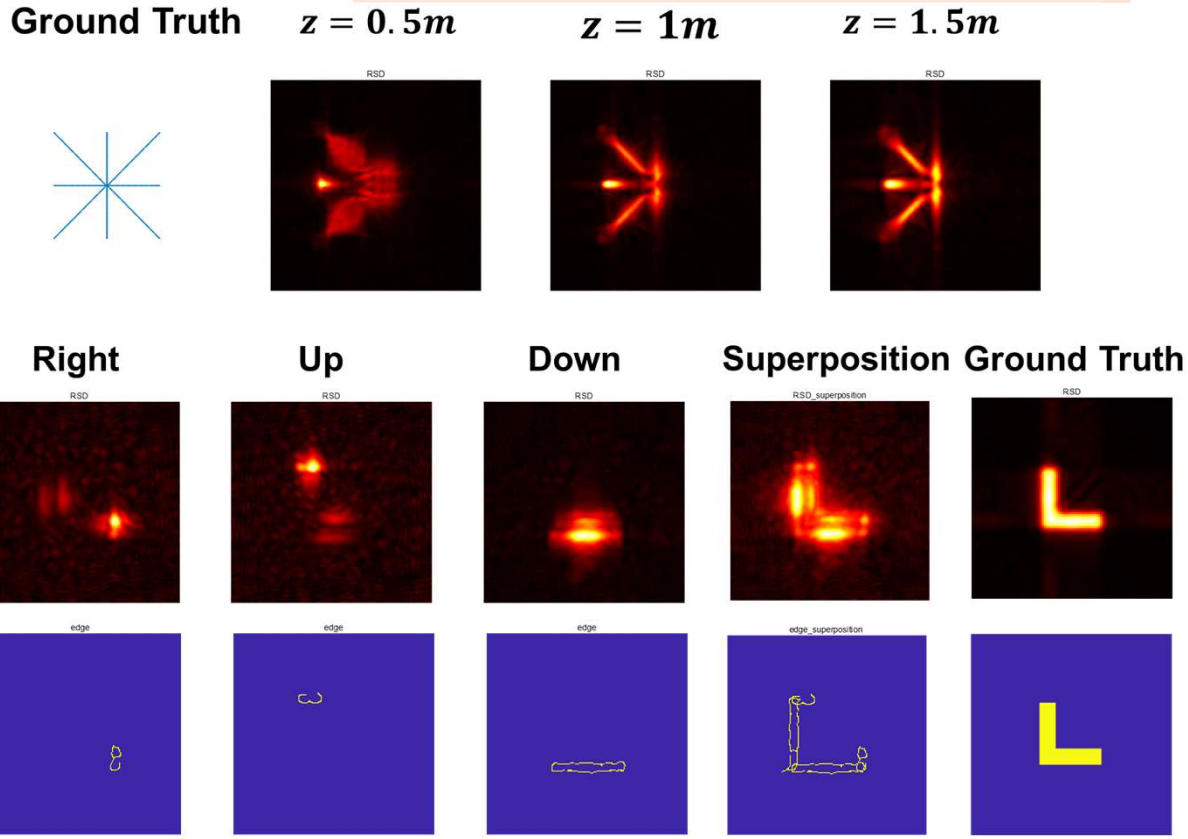


Figure 5. Fourier slice theorem and cone generation.

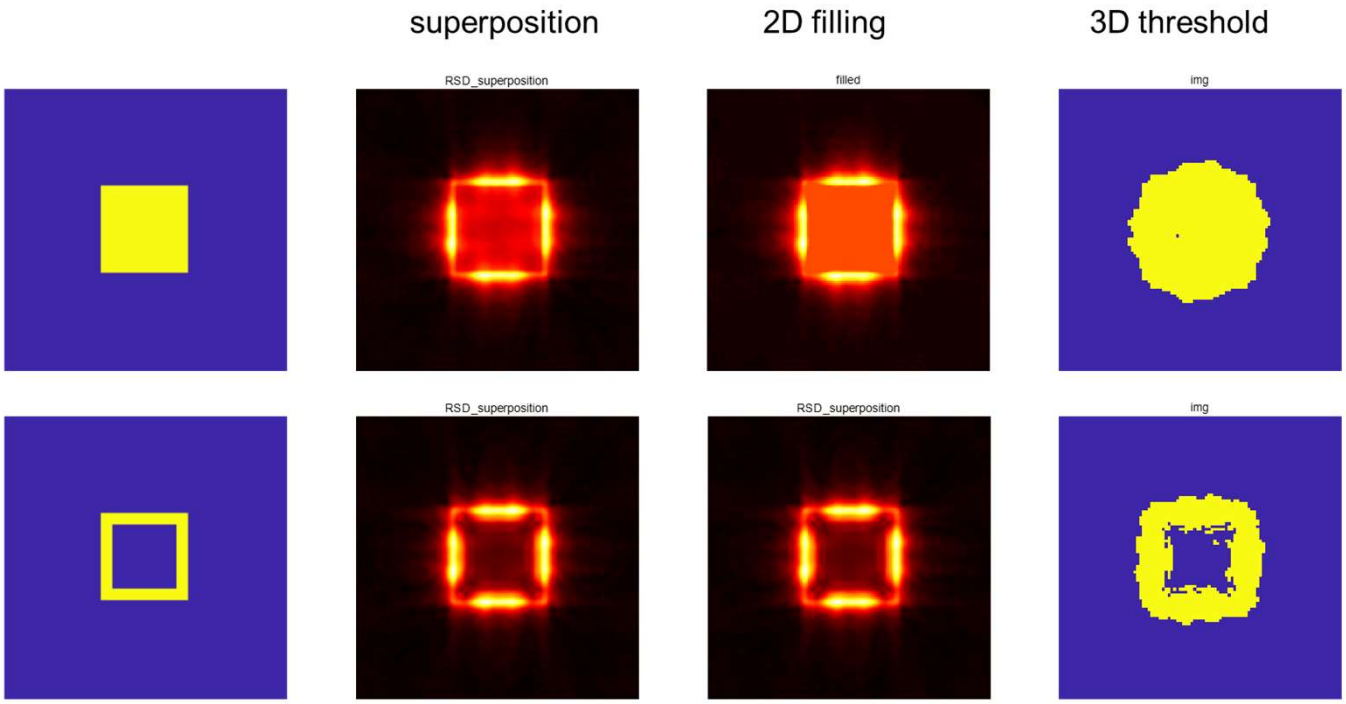


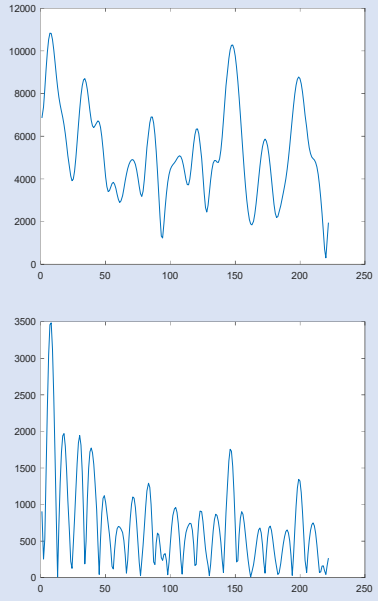


W6: Fill-in for Stitch Method

Worked out the difference between box and frame.

Simulation went wrong: windowing effect detected.





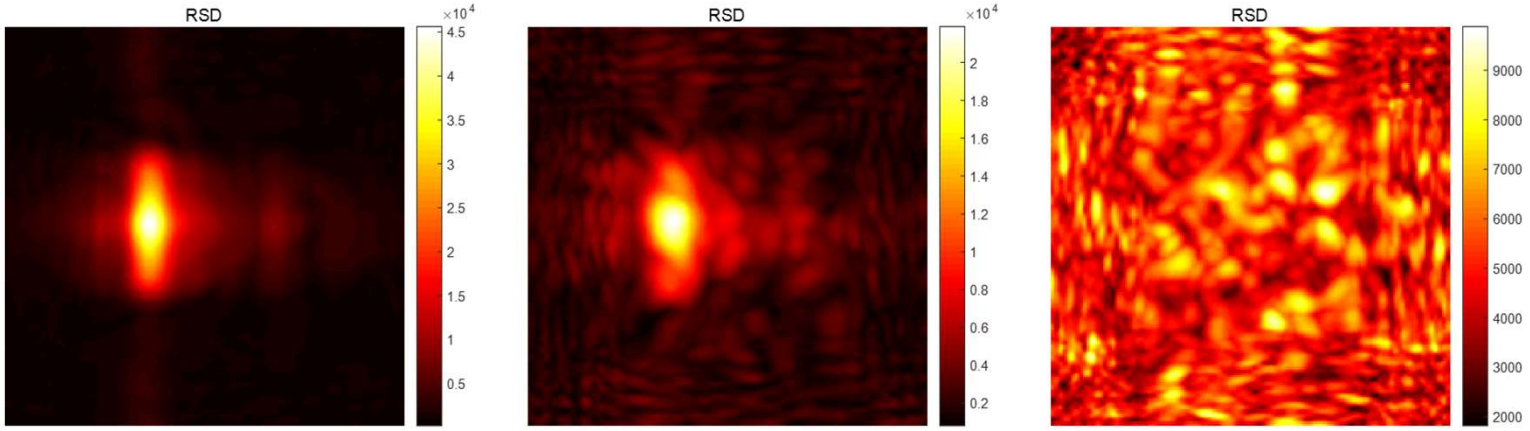
Windowing effect

W7: Pulse Width Simulation

Fixed windowing effect.

Compensation & deconvolution for long pulse width failed.

Gaussian Function, width = FWHM = 2.355σ
Fix $\lambda = 8cm$



width = 30ps | width = 300ps | width = 3ns

Phasor Freq_cutoff ∝ 1/length ∝ 1/wavelength

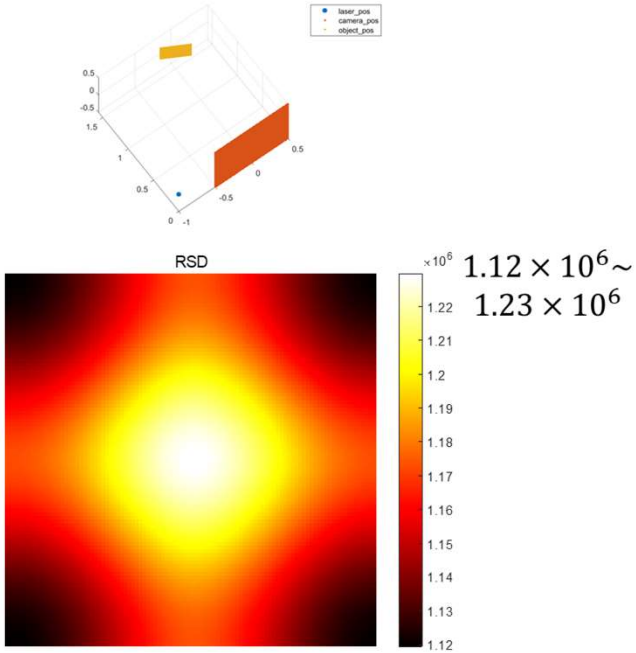
⇒ **wavelength > α(constant) * width**

W8: Tilted Object Simulation

- Tested more scenes using 3ns laser;
- Figured out the reason for sharp edges in reconstruction: padding of aperture.

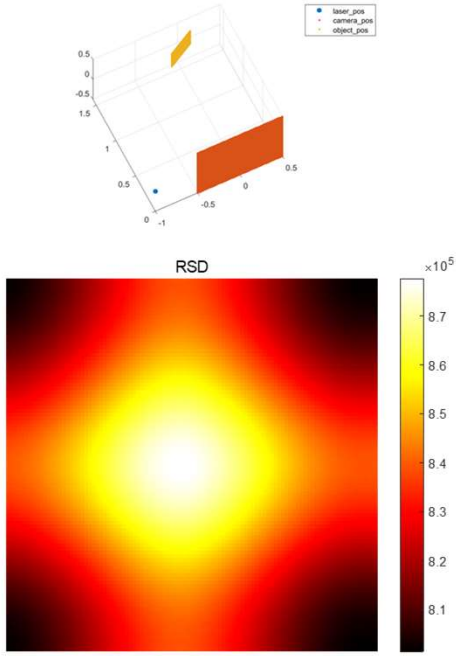
Confirmed that there's hardly any shape can be reconstructed with 3ns laser.

Raw



$1.12 \times 10^6 \sim 1.23 \times 10^6$

Tilted

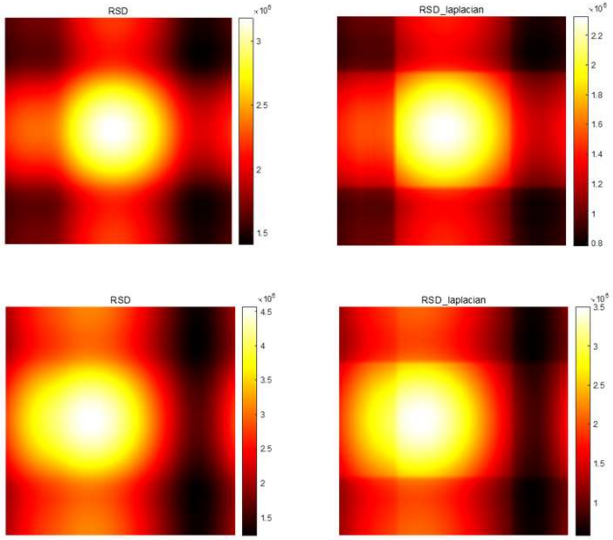


$0.80 \times 10^6 \sim 0.88 \times 10^6$

Same shape, just dimmer.

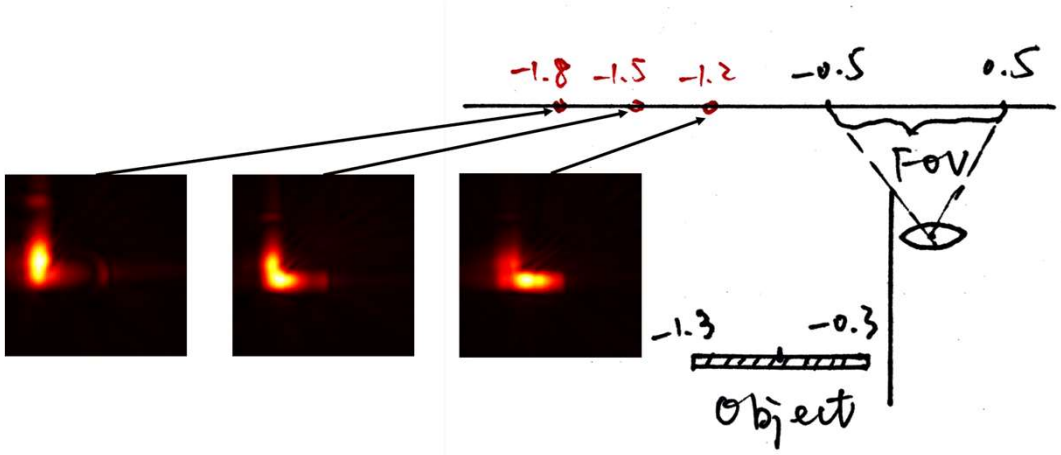
Original

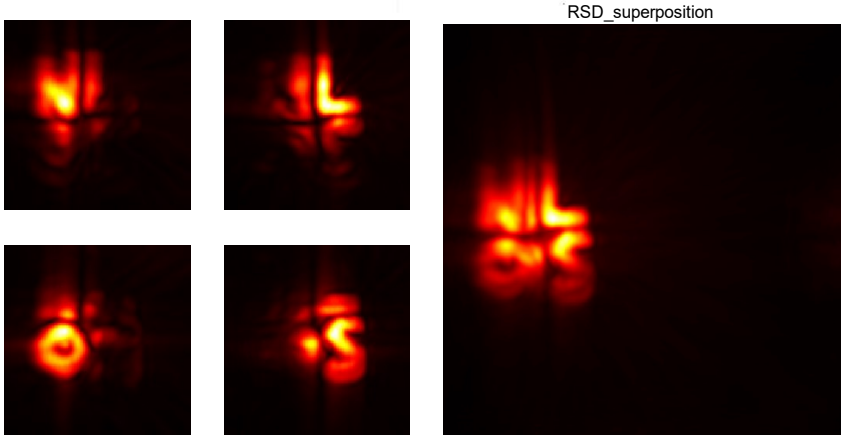
Shifted



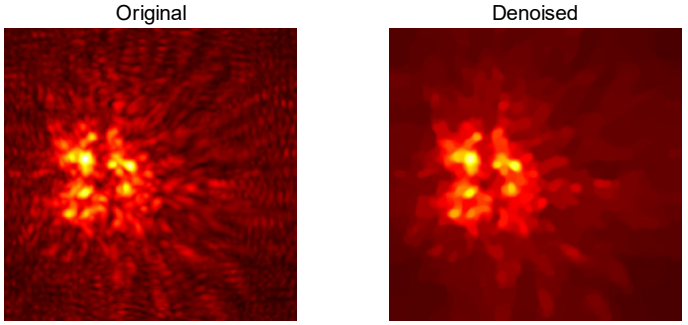
Sharp edges in RSD Laplacian due to padding

W9: Stitch Method for FoV

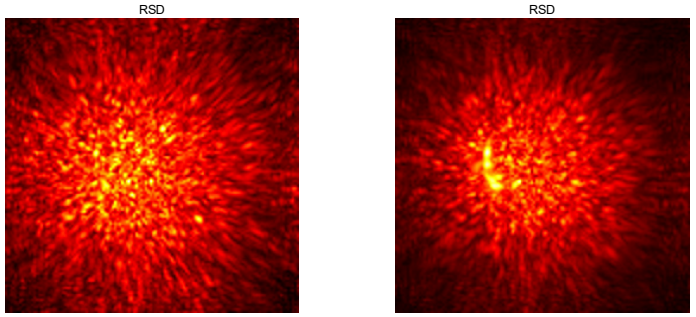




- Added Lambertian shading to simulation;
- Stitched the reconstruction of different laser points;
- Tried different denoise method.



Total Variation Denoise

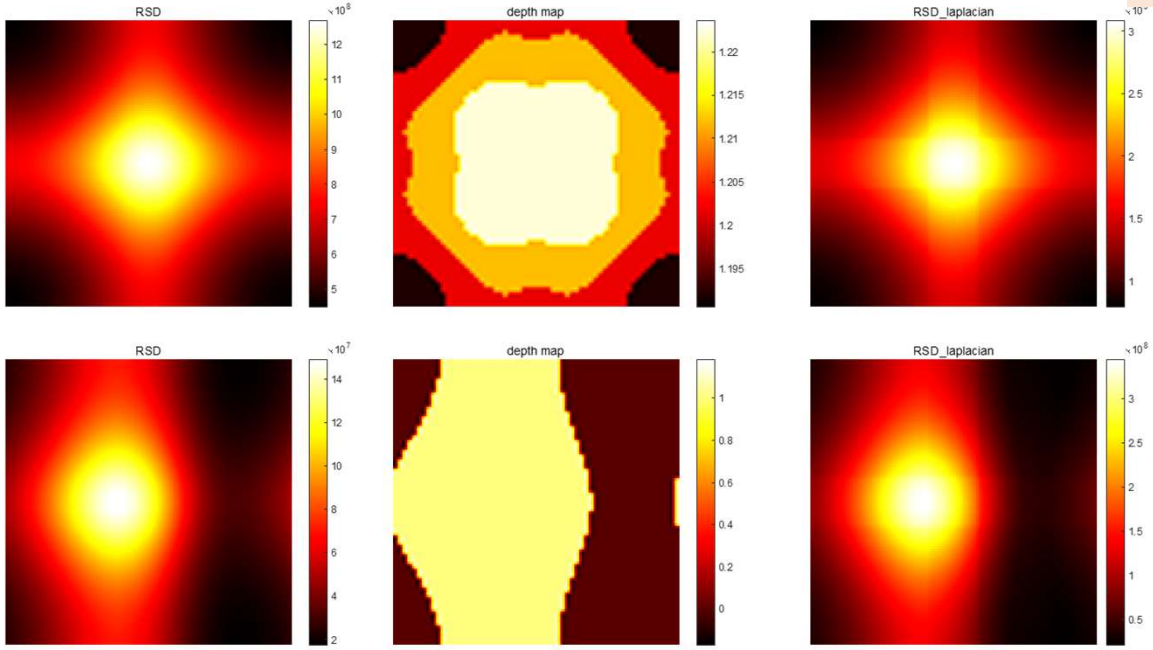


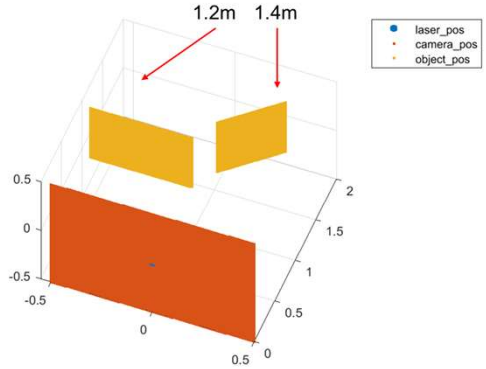
Deconvolution Denoise

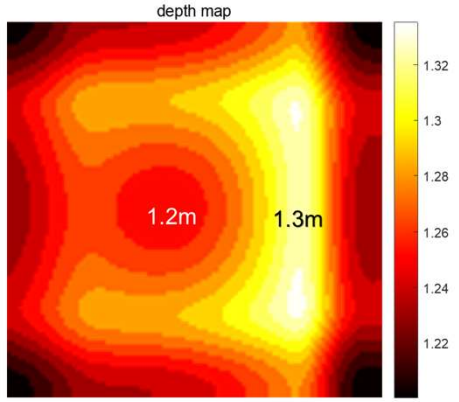
W10: Depth Map Reconstruction

Explored the depth resolution.

Better than axial resolution but distorted too.







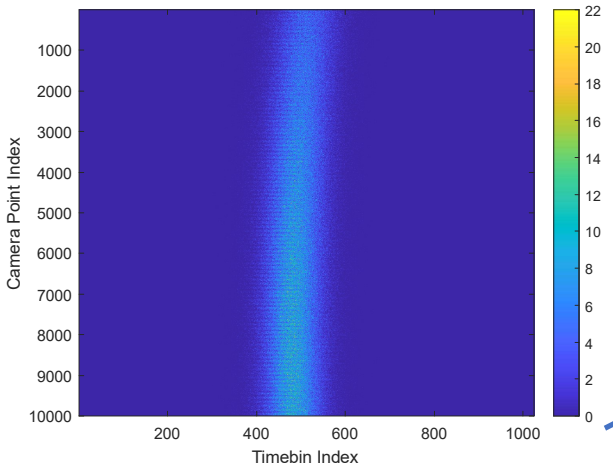
Depth Map Features

1. Very Uniform – **Good Resolution**
2. The edges depend on denoise threshold (intensity map) – **Can't help reconstruct shape (axial resolution)**

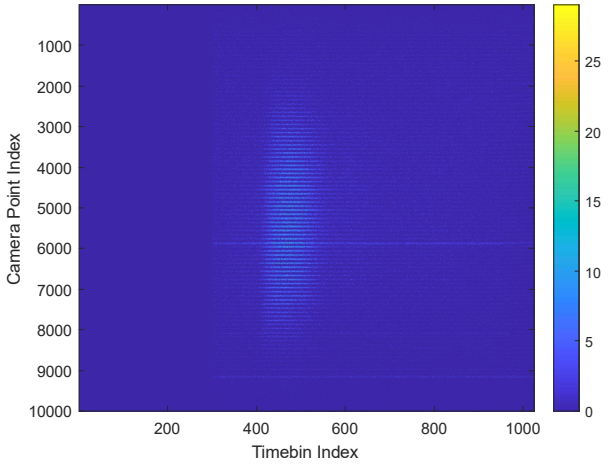
W11: Fix pile up & Interpolation

- Fixed the pile up in experiment calibration;
- Verified interpolation method for camera seeing from an angle.

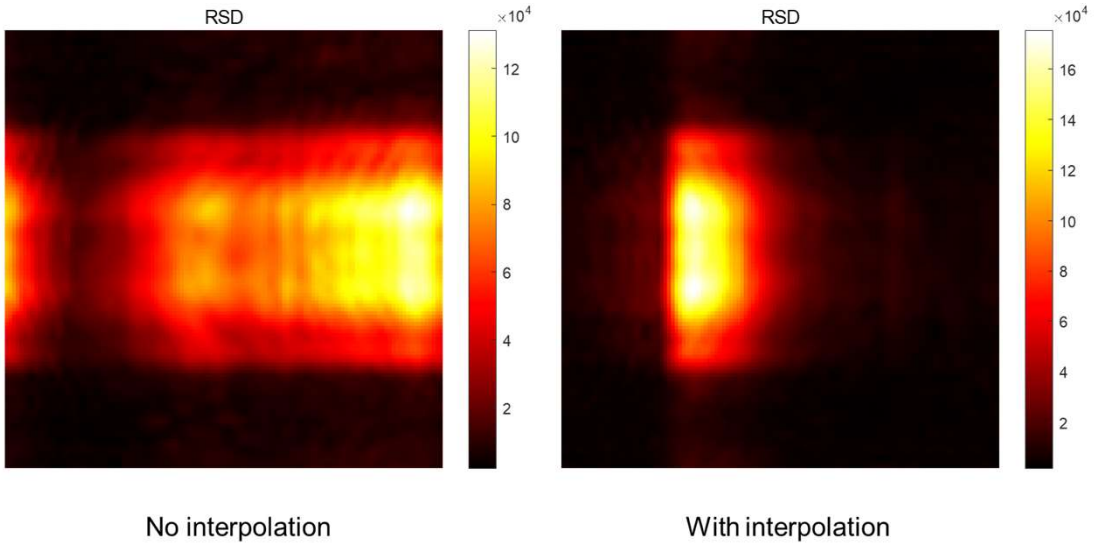
Simulation



Experiment



Strong vignetting



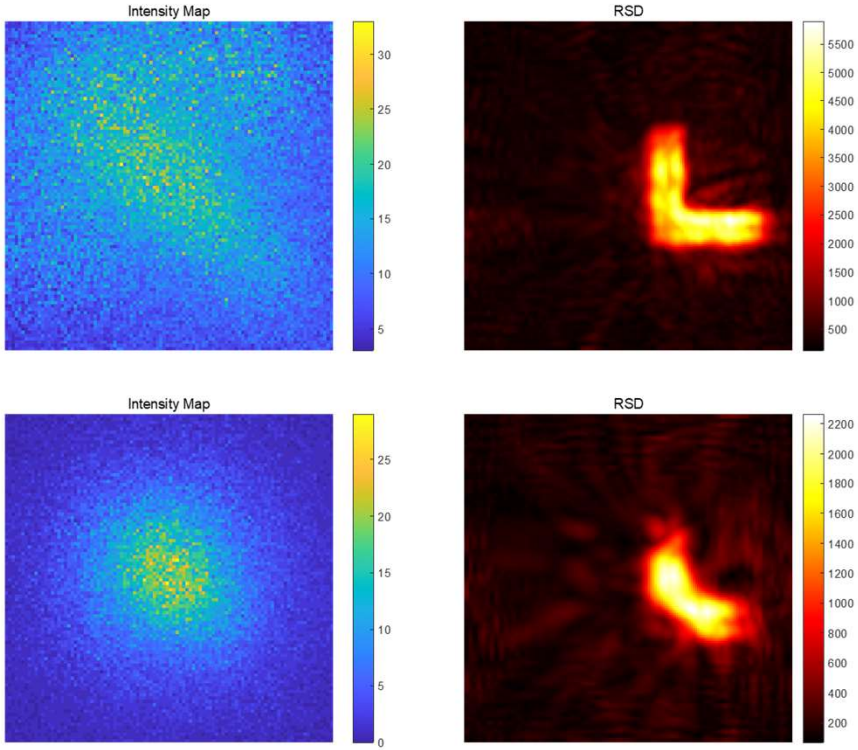
No interpolation

With interpolation

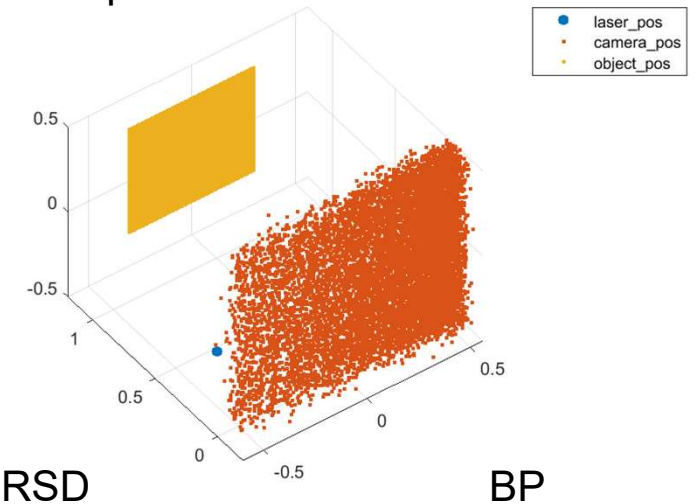
W12: Vignetting Simulation

- Added vignetting to simulation;
- Tested non-planar scene.

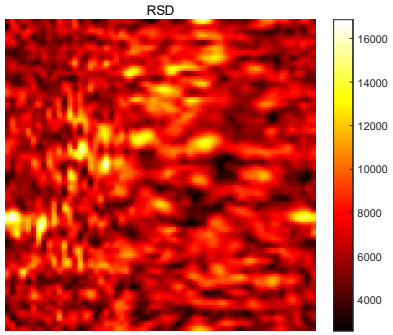
First Row: without vignetting
Second Row: with vignetting



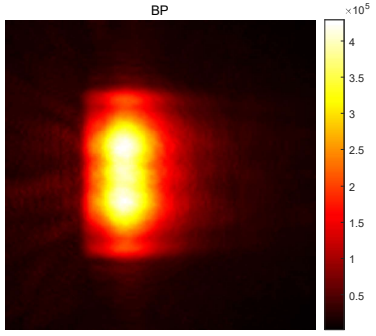
Non-planar scene



RSD



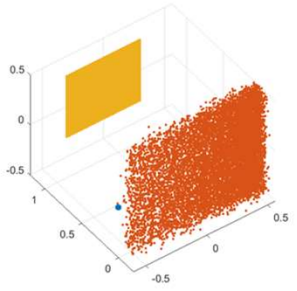
BP

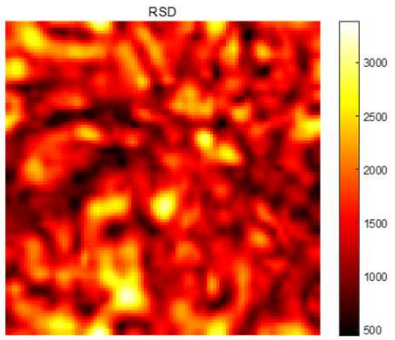


W13: 2-stage RSD Simulation

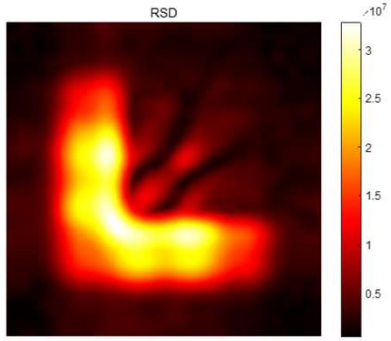
- Implemented 2-stage RSD in simulation;
- Tested the effect of mask size.

Non-planar

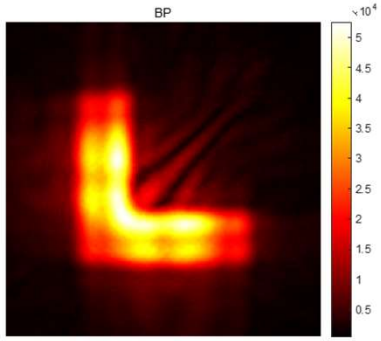




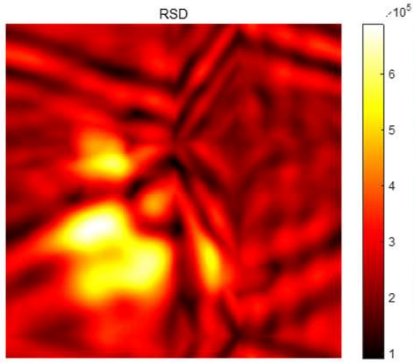
RSD: 8s



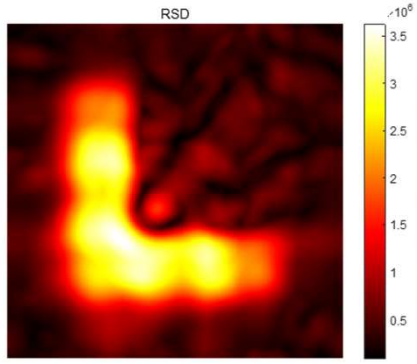
2-step RSD: 411s



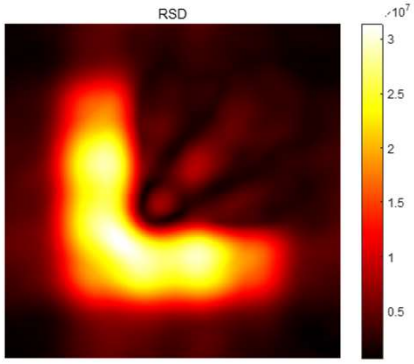
BP: 208s



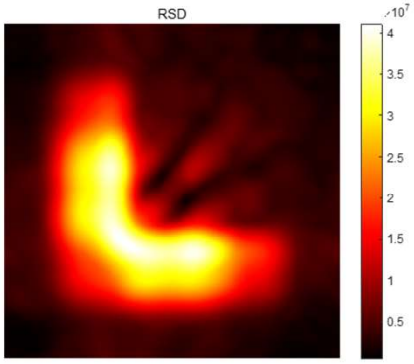
14s
Mask_size: 1



29s
Mask_size: 3



47s
Mask_size: 11



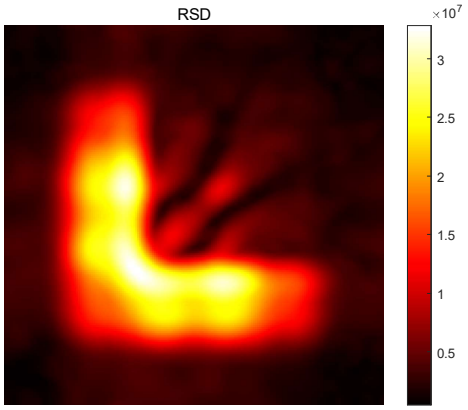
104s
Mask_size: 21

W14: Padding in 2-stage RSD

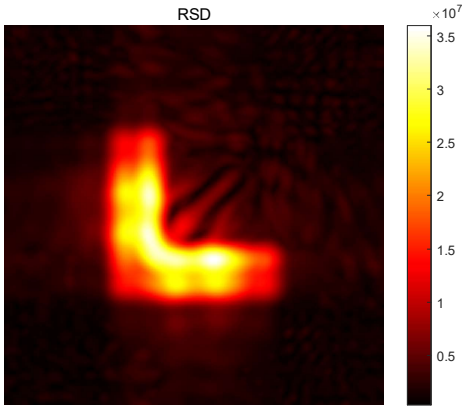
Compared two different ways of padding aperture in 2-stage RSD.

Tried geometry parameter pre-calculate to accelerate but failed (large variable need long load time).

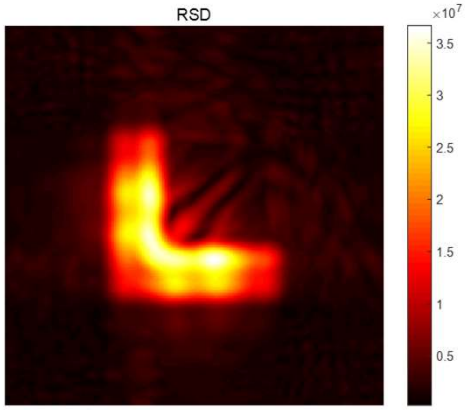
Non-planar



411s
1m Aperture



1126s
First step propagate to 1.5m Aperture



494s
First step zero padding to 1.5m Aperture

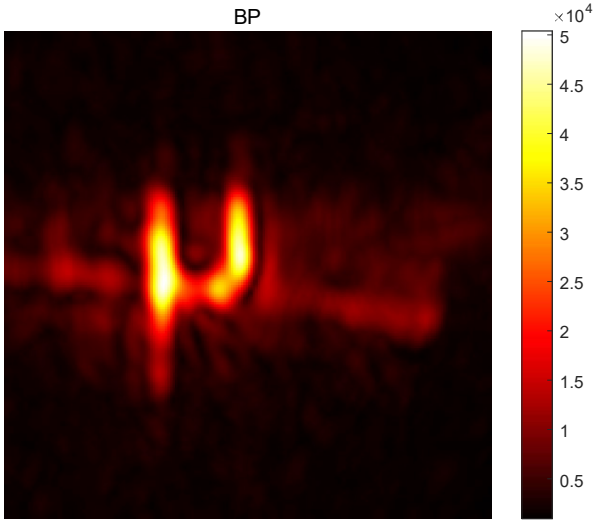
Zero padding is fine and fast for objects smaller than the sampling plane

The first propagation plane should be **larger than the sampling plane**

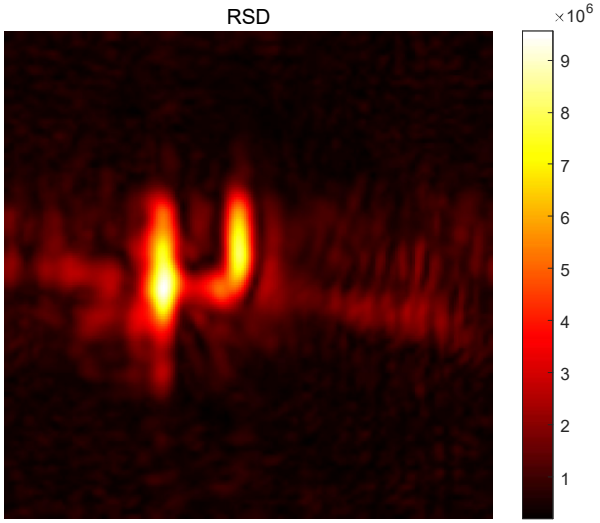
W15: Real Data 2-stage RSD

Verified the 2-step RSD on real fan-on dataset.

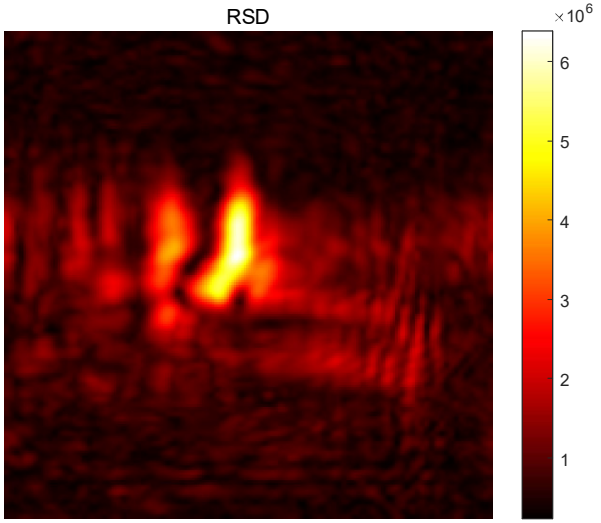
8cm virtual wavelength, 2m*2m*1m 3D reconstruction, spacing 2cm



803s
BP



403s
Fist propagate to z=0.3m plane

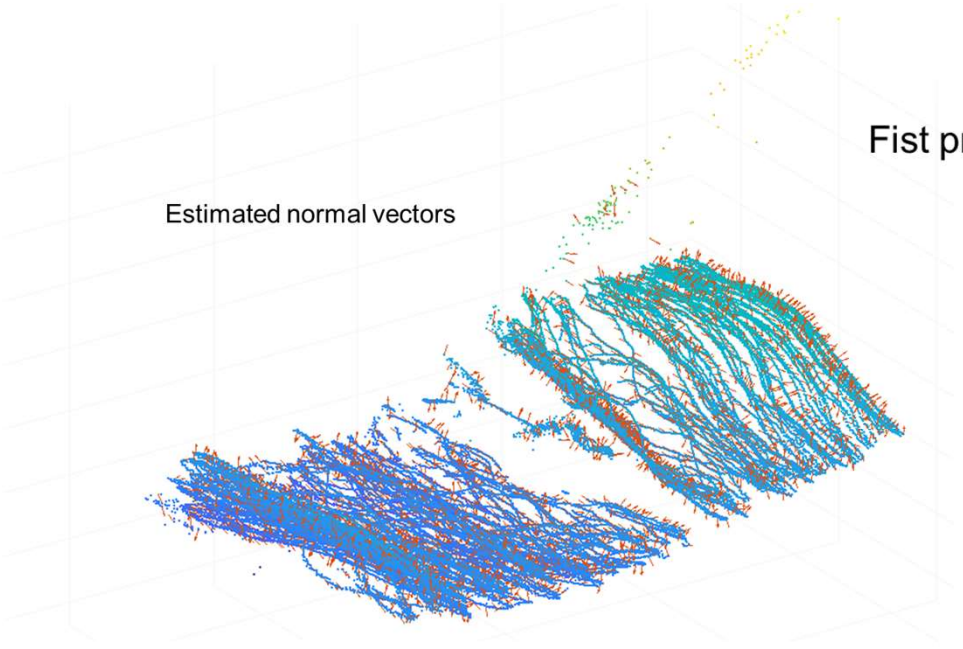


424s
Fist propagate to z=0.1m plane

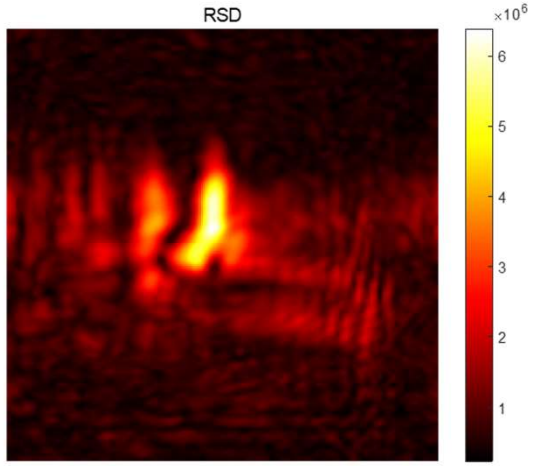
W16: Shading in RSD

Tried to find out the reason for degrade of closer intermediate plane.

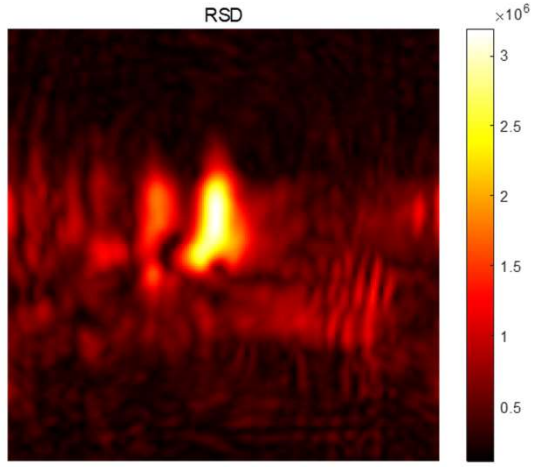
The cos factor didn't change much.



Fist propagate to z=0.1m plane



Without cos factor



With cos factor

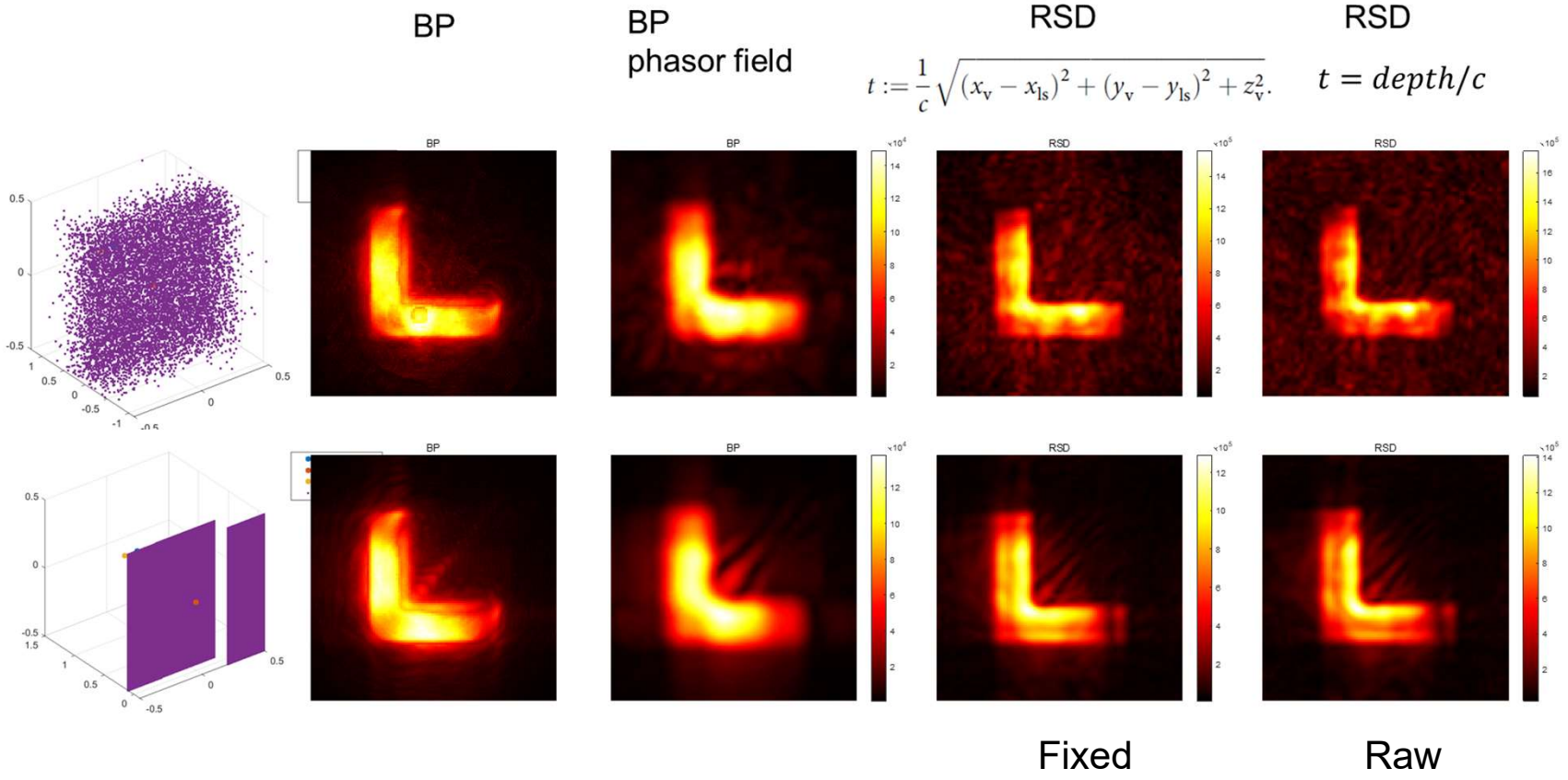
3.5.2 The Rayleigh-Sommerfeld Diffraction Formula

Let the Green's function G_- be substituted for G in Eq. (3-23). Using (3-35), it follows directly that

$$U_I(P_0) = \frac{1}{j\lambda} \iint_{S_1} U(P_1) \frac{\exp(jkr_{01})}{r_{01}} \cos(\vec{n}, \vec{r}_{01})\, ds \qquad (3\text{-}40)$$

W17: Correct Phase RSD

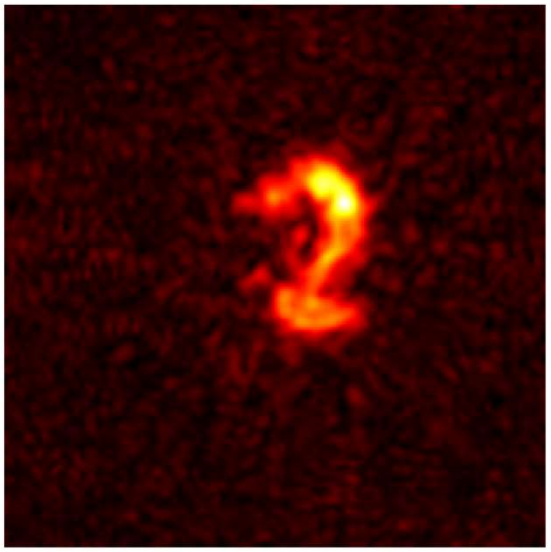
Found an issue regarding the open-source RSD implementation: the phase is approximated. Fixed it.



W18: Planar Verification

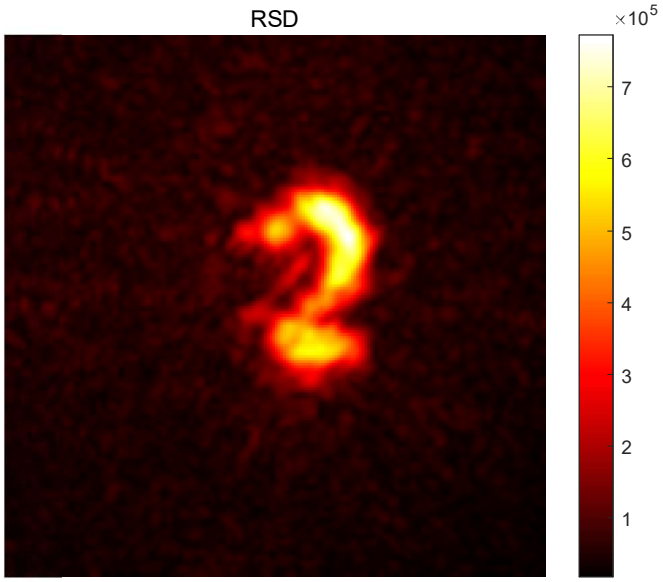
Verified the 2-stage algorithm on planar dataset measured by Yimeng.

RSD, 6s

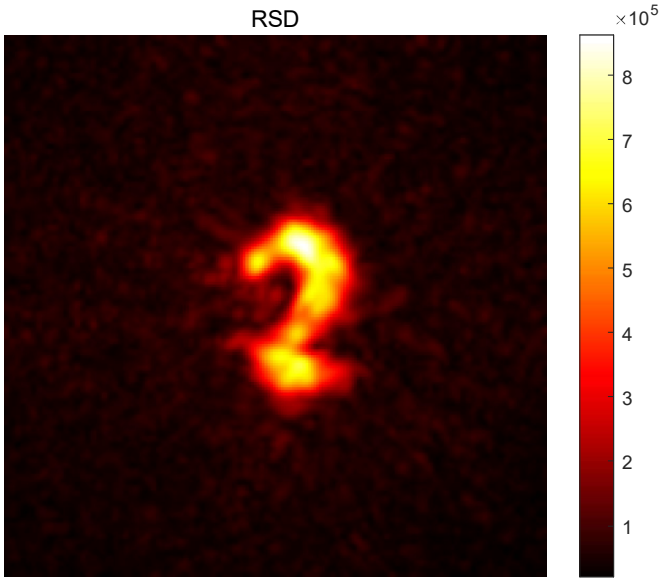


Generated position

2-stage RSD, 79s



Generated position

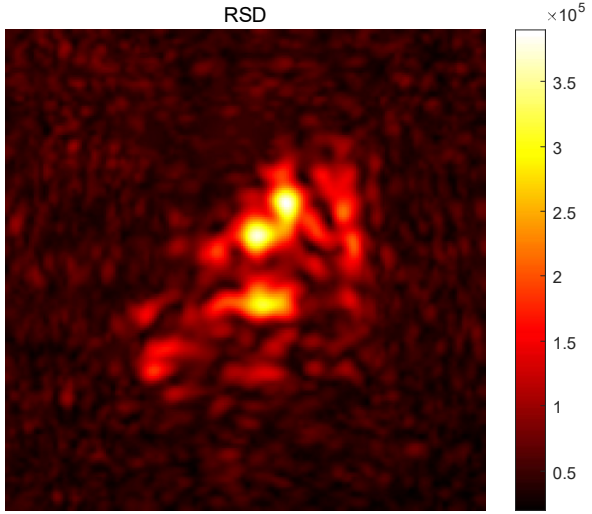


Measured position

W19: Non-planar Verification

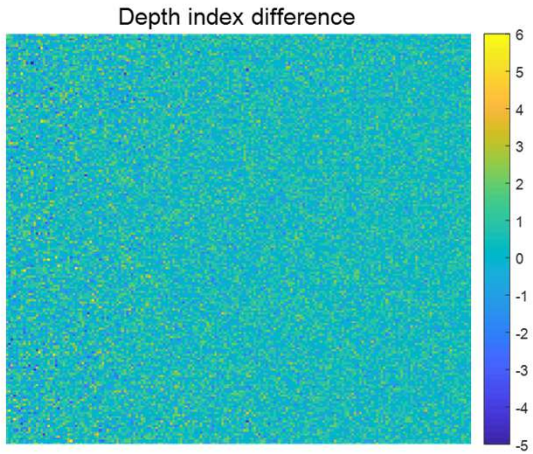
- Verified the 2-stage algorithm on non-planar dataset measured by Yimeng;
- Checked the credibility of first-bounce measurement by applying different filters to see how the peaks change.

Non-planar dataset is too noisy.



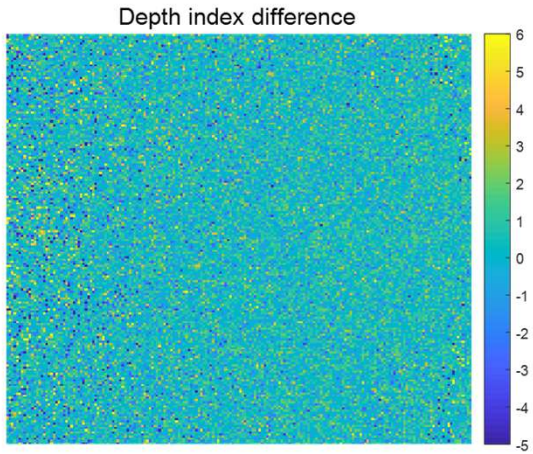
First bounce validity

Planar Case



Max total photon count: 7412
Standard deviation: 0.99

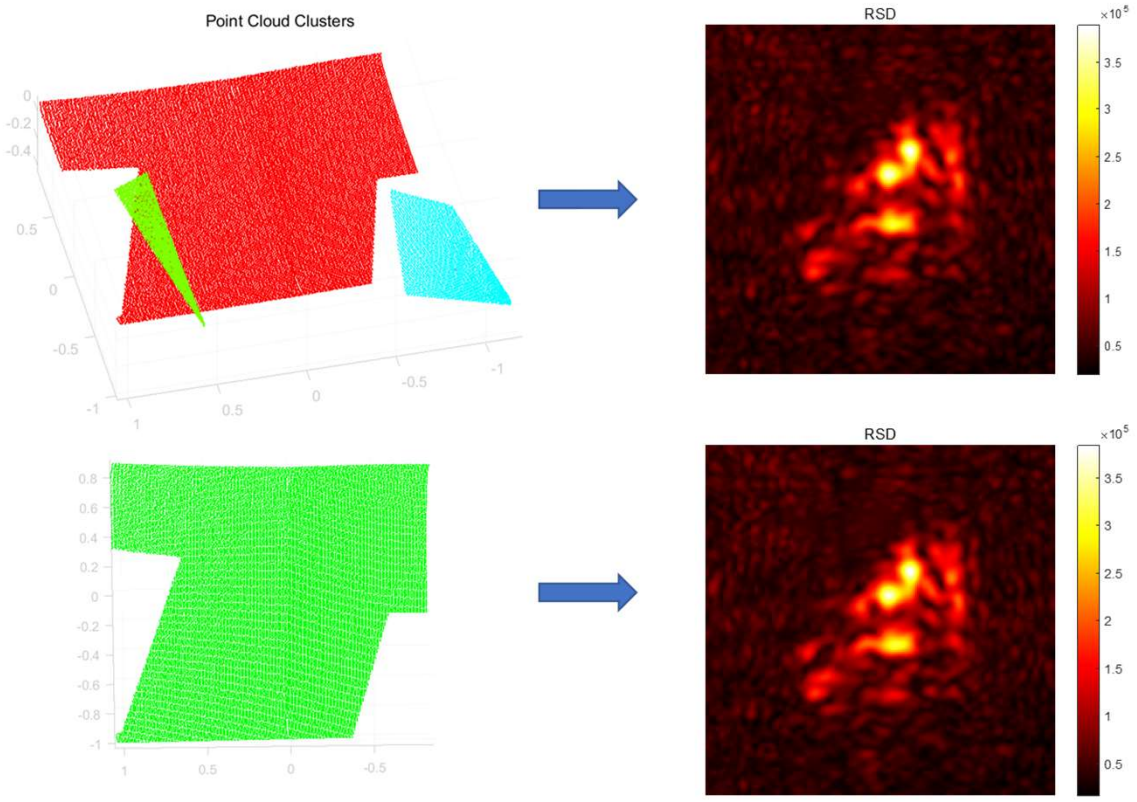
Non-planar Case



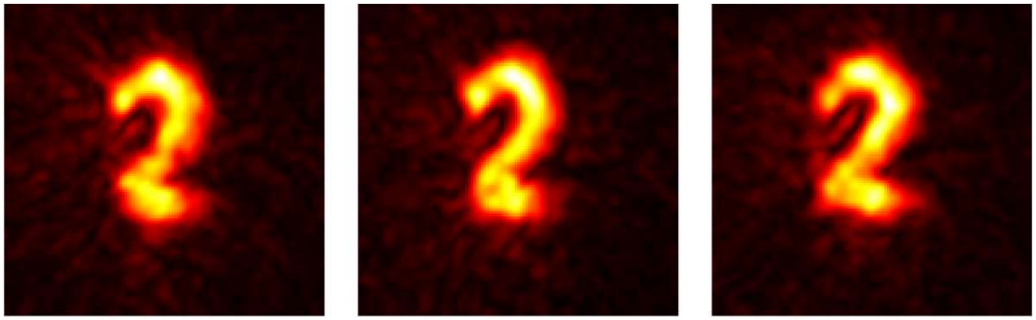
Max total photon count: 2473
Standard deviation: 4.25

W20: Non-planar Debug

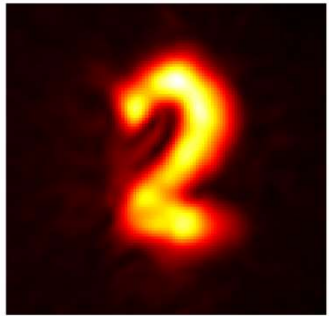
Applied point cloud segmentation to test whether the non-planar positions are measured correctly. It seems they are.



W21: Stitch SPADs



9 SPADs in total



Combined the results of different SPADs in the array to test whether the SPADs' positions are measured correctly. It seems they are.

Yet two of them are strange.