

Effects of Illumination Shadows in Interference Pattern Structured Illumination Imaging

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ABSTRACT

Effects of Illumination Shadows in Interference Pattern Structured Illumination Imaging

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Here I present a study on the effect of "large" three-dimensional objects in Interference Pattern Structured Illumination Imaging (IPSII). Due to the nature of the IPSII method, objects with a lot of depth in the imaging field create "shadows" or areas where the structured illumination fails. This is because IPSII's structured illumination may be projected at a given angle θ from the object normal. These shadows are characterized by the absence of interference, not always the absence of light, and cause blurring around edges in the resulting image. The more depth an object has, the more fringe effects appear in the resulting image. This thesis reviews simulations that capture this reduced interference and therefore breakdown of IPSII due to shadowing. Also, initial experimental results are presented in an effort to demonstrate this effect. Finally, a discussion of what next steps should be taken is presented.

Keywords: senior thesis, undergraduate research, IPSII, imaging, optics

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Chapter 1

Introduction

Throughout recent years, a wide array of imaging methods have been developed and better constructed for scientific research. Magnetic Resonance Imaging (MRI) in medicine provides clear images of inside the body, allowing doctors and healthcare professionals to give better patient care. Microscopy uses well-placed optical lenses to allow biologists to see and classify organisms invisible to the naked eye, organisms like the SARS-CoV-2 virus which causes the COVID-19 disease. Interference Pattern Structured Illumination Imaging (IPSII) supplies scientists with a non-invasive way to image objects on a relatively small scale. IPSII is a lensless, single-pixel imaging method meant to circumvent conventional imaging limitations. Currently, it is still in its early stages of development.

Previous iterations of IPSII like DEEP tomography [1], CHIRPT [2], and SWIF [3] have proved the concept successful in imaging. In recent years, a Mechanical Angle Scan (MAS) implementation of IPSII was developed by Jarom Jackson and Dallin Durfee at Brigham Young University [4–7].

Conventional imaging methods like the use of a microscope require high numerical aperture objective lenses to acquire high resolution. That means a large objective lens with a short focal length and a small distance between the objective lens and the object plane. IPSII works around the short working distance by using structured illumination projected onto the object, allowing our

working distance to be as far as we can project the structured illumination pattern. We emphasize here that this restricts the sample volume imaged with MAS-IPSII to the region where the two illuminating beams overlap. In traditional lens-based microscopy, the depth of field (DOF) is the volume where the sample will all remain in focus. Regions outside of the DOF (typically regions axially, or along the beam propagation direction, outside the plane of best focus) will become blurred. The DOF is directly related to the numerical aperture and has an inverse relation to the resolution of the image. Because IPSII only uses flat optics and not an objective lens, the numerical aperture is as wide as we make it to be, allowing us not to be as limited by the DOF.

IPSII has a theoretical maximum resolution of a quarter of the wavelength of light used [4]. Due to the nature of the method however, objects with a lot of axial extent or depth in the imaging field create “shadows” or areas where the structured illumination fails due to one of the structured illuminating beam being blocked by the object. These areas are not necessarily characterized by the absence of light, but rather by the absence of interference, and cause blurring around edges in the resulting image. What follows is an analysis of these effects. In particular, I will discuss how three-dimensional objects cause aberrations in the resulting image due to the method itself and the objects’ size or depth in the imaging field. I will begin by talking more about IPSII and how it works, followed by a more in-depth study of MAS-IPSII and what “shadows” are in this context. In Chapter 2 I will focus on computational simulations of these shadow effects, and in Chapter 3 I will focus on the experimental verification of these shadow effects in MAS-IPSII.

1.1 IPSII

Interference Pattern Structured Illumination Imaging (IPSII) uses structured illumination and a single pixel detector to record the reciprocal or Fourier space (here denoted as k -space) data of an object being imaged, one k -space pixel at a time. Each data point consists of the light reflected off

or transmitted through the object using a unique pattern. The resulting array of pixels is then run through a mathematical transform to make a digital image of the object. Previous versions of this method like DEEP tomography [1] have used acousto-optic modulators to change the structured illumination for each data point.

The basic concept of IPSII uses an arbitrary illumination pattern projected onto an object and a recording of the light reflected or transmitted. Based on the pattern chosen, the detected light is then used to work backward to find what the object looks like. When using sinusoidal illumination patterns, the array of data can be analyzed with the well-known Fourier transform and the method becomes simpler in theory.

1.2 MAS-IPSII

Mechanical Angle Scan (MAS)-IPSII uses a Mach-Zehnder interferometer with motorized mirror adjustments to alter the structured illumination for each data point, and scans the phase using a piezo stack mounted behind a mirror in one of the beam paths as seen in Fig. 1.1. Currently the most advanced design uses an extra set of mirrors in the interferometer to keep the illumination pattern trained on the object and reference pinhole when the mirrors are adjusted to change the pattern. This allows for larger angles between beams. Also, it contains a double bow tie design immediately after the first beamsplitter as shown in Fig. 1.1b to help with balancing.

When two coherent plane waves interfere, a sinusoidal pattern of light and dark fringes are created as in Fig. 1.2. The size of the fringes and the spacing between them is determined by the angle between the incoming waves (i.e. the larger the angle, the smaller the fringe). The smallest fringe size possible is a quarter of the wavelength of light used. In structured illumination (SI) imaging, the resolution is limited to the scale of features that can be created in the illumination. Therefore, using interference fringes, SI should theoretically be able to reach resolutions as small as

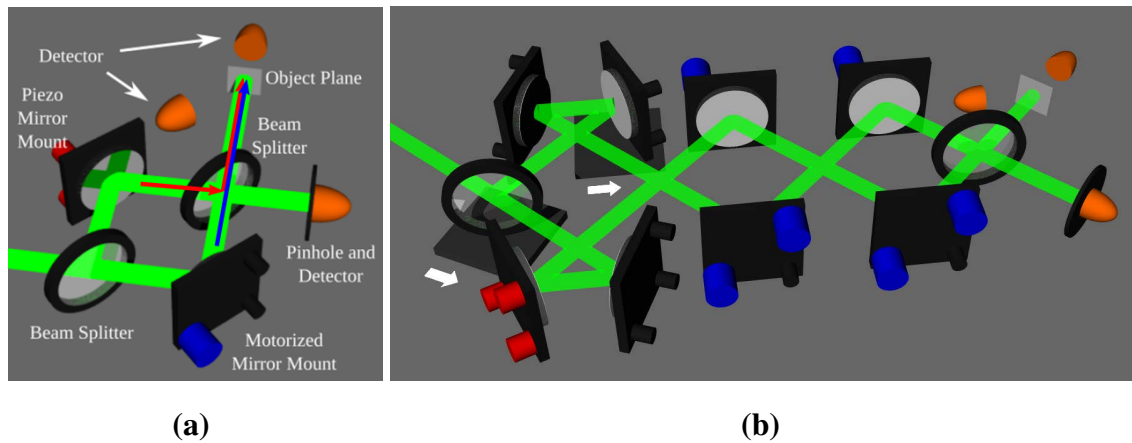


Figure 1.1 (a) Working IPSII setup with minimal amount of optics. (b) A more complex optical design for an interferometer with better beam control and path-length tuning.

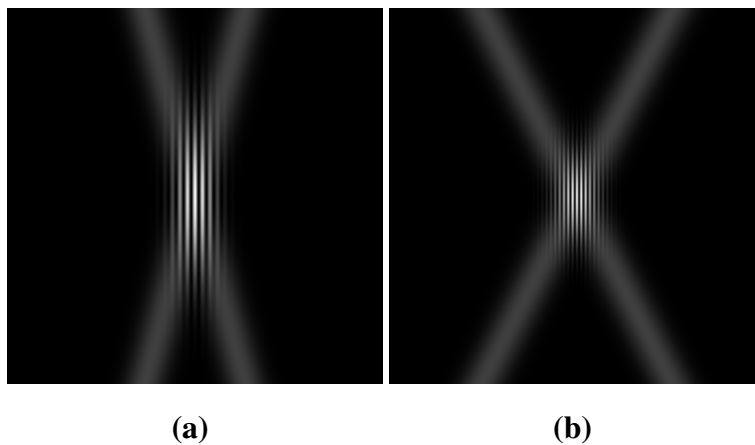


Figure 1.2 Two plane wave beams cross. Where they overlap, the plane waves interfere with each other to produce a sinusoidal pattern of fringes. The size and spacing of the fringes changes as the angle between the beams increases.

a quarter of the wavelength of light. This theoretical limit is one of the reasons MAS-IPSII was designed.

Using the mirror movements to alter the structured illumination makes the necessary transform easy because the projected pattern is approximated to a sinusoidal wave as it is scanned across the object and reference pinhole as in Fig. 1.3 and therefore can be analyzed by means of a Fourier transform.

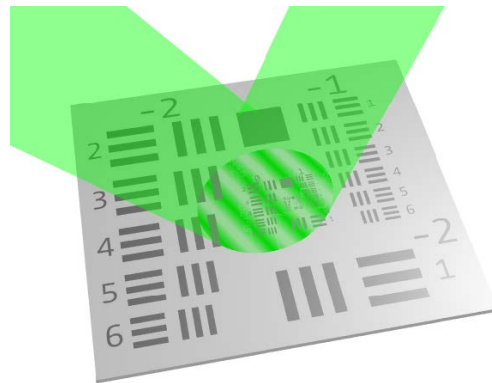


Figure 1.3 Two beams overlap to form a sinusoidal interference pattern on an object.

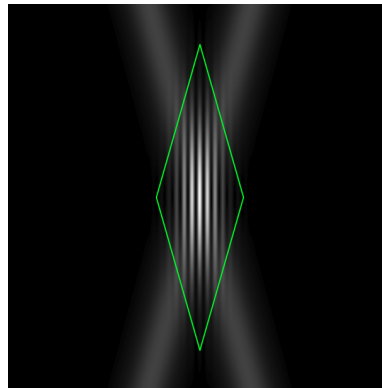


Figure 1.4 Two plane wave beams intersect and interfere. The size and spacing of the fringes changes as the angle between the beams increases. The Depth of Field (DOF) is the area where they interfere (i.e. inside the green diamond).

A difficulty that arises due to the use of an interferometer is the limited depth-of-field (DOF), the region in front of and behind the object plane in which the laser beams interfere. DOF is determined by the diameter of the beams and the angle between them, and is generally characterized by the maintenance of structured illumination (see Fig. 1.4). Clear imaging occurs only when the object is in the DOF, leading to a limitation on the object depth as well as object placement. Object depth refers to objects with axial extent in the direction of the illumination projection.

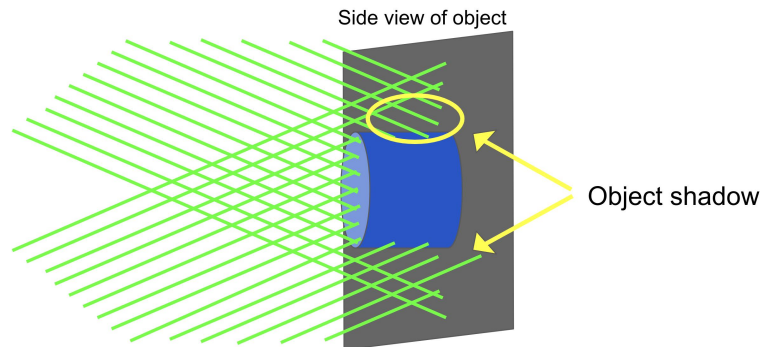


Figure 1.5 Two beams overlap to form a sinusoidal interference pattern on a cylinder as seen from the side. Immediately to the sides of the cylinder, light from only one beam reaches the surface and there is a lack of interference.

1.3 Shadows

"Shadows" in IPSII are regions in the imaging plane where the structured illumination fails. This occurs by complete or partial blockage of the light generally due to axial extent (depth) in the DOF. When an object with significant depth is imaged, these shadows can cause noticeable blurring in the resulting image. As an example, imagine trying to image a cylinder like in Fig. 1.5. As the beam coming from below arrives at the object, it is blocked from reaching the background plane at the base of the cylinder on the top side. The same applies for the beam coming from above, but it is blocked near the base below the cylinder. The structured illumination therefore has failed in those regions near the base of the cylinder opposite to the incoming beams. These areas are what we refer to as IPSII shadows.

Chapter 2

Simulating the Characteristic Effects

In this chapter, I will describe the process I took for developing one- and two-dimensional models for simulating IPSII in Python. I will also present and discuss my IPSII reconstruction image results for three separate situations.

2.1 One dimension

In the beginning of my research I developed a one-dimensional model for proof-of-concept of IPSII shadows, owing to the idea that the shadows would cause simple aberrations in the image surrounding the object.

All things have reflectivity, defining how much light they reflect when it is bounced off their surface. The reflectivity (R) of an object is represented as a number between 0 and 1, 0 being completely absorptive and 1 being completely reflective. The 1D model of MAS-IPSII in reflection geometry that I developed in Python (see Appendix A.1) has three steps to simulate the IPSII process. First, I set the angle of the beams and determine where the shadows are formed. Second, I perform a Fourier transform (2.1) on the reflectivity with the shadow mask (S) multiplied inside the integral. Third, I perform an inverse Fourier transform (2.2) on the answer to Eq. (2.1). I use a

discrete sum to transform the reflectivity of the object:

$$\mathcal{F} = \sum_{n=0}^N S(R e^{-i \frac{2\pi x n}{N}}), \quad (2.1)$$

$$R_{new} = \frac{1}{2\pi} \sum_{n=0}^N \mathcal{F} e^{i \frac{2\pi x n}{N}}, \quad (2.2)$$

where R is the reflectivity, S is the shadow mask, N is the size of the function, and R_{new} is the reflected light we would actually see, or rather, it is the resulting image reconstruction of the reflectivity of the object.

The next section contains a description of the two-dimensional model I made, and also contains IPSII image reconstructions that demonstrate the effects of IPSII shadows.

2.2 Two dimensions

Treating the structured illumination as a sinusoidal pattern from an interferometer output, we can model the IPSII process in reflection geometry using a 2D Fourier transform. The shadows then are represented by a 2D mask (S) in the forward transform (2.3).

$$\mathcal{F} = \sum_{m=0}^{N_{row}} \sum_{n=0}^{N_{col}} S(R e^{-i 2\pi \frac{m_x m_y}{N_{col} N_{row}}}), \quad (2.3)$$

$$R_{new} = \frac{1}{2\pi} \sum_{m=0}^{N_{row}} \sum_{n=0}^{N_{col}} \mathcal{F} e^{i 2\pi \frac{m_x m_y}{N_{col} N_{row}}}, \quad (2.4)$$

where N_{col} is the number of columns (or the "length" in the x-direction), N_{row} is the number of rows, and R_{new} is the resulting image of the reflectivity of the object.

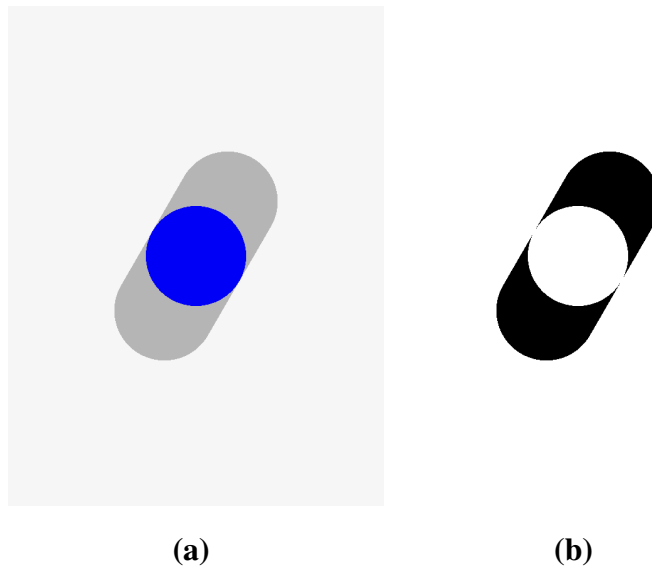


Figure 2.1 POV-Ray cylinder and mask. (a) Blue cylinder as viewed from above. It is illuminated by two light sources placed at very far distances above the viewpoint and opposite to each other. (b) The mask of zeros and ones representing where the shadow is formed.

2.2.1 Asymmetric results

In deriving a two-dimensional model, I needed a way to create a different shadow mask for each k -space value. I used Persistence of Vision Raytracer [8] to create an image of a simple cylinder as viewed from above with two infinitely far light sources coming at opposite and equal angles from each other onto it as in Fig. 2.1a (see Appendix A.2 for code). The light sources approximate to laser beams in the context of the experiment. Each image with different angles for the light sources was then stripped of everything but the shadows and set to zeros and ones as in Fig. 2.1b. The result was a unique shadow mask I could apply to each k -space value during the 2D Fourier transform.

I applied the masks created through POV-ray to the cylinder object with three distinct reflectivities for the object top and background. In Figure 2.3, the top of the object is completely absorptive (zero reflectivity) and the background is completely reflective (reflectivity of one). In that test, the resulting image of the object shows aberrations around the object and the object is definitely visible

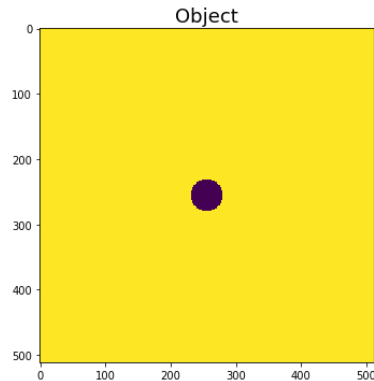


Figure 2.2 A height map of the cylinder object to simulate IPSII made in Python.

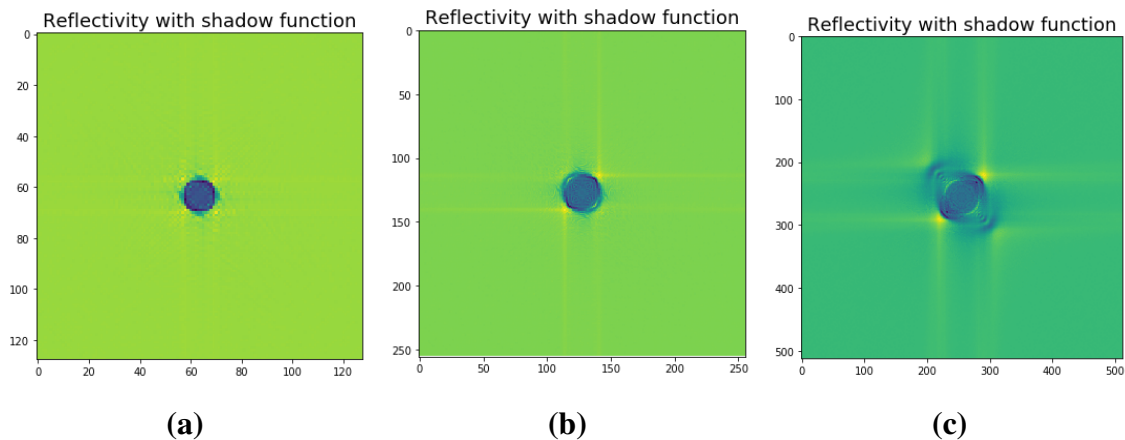


Figure 2.3 Simulation of IPSII reconstruction of cylinder object (Fig. 2.2) with different number of k-space measurements: (a) 128×128 pixels, (b) 256×256 pixels, (c) 512×512 pixels. Object face is completely absorptive ($R = 0$) and background is completely reflective ($R = 1$).

as is expected. In Figure 2.4, both the top of the object and the background are completely reflective (reflectivity of one). Since we are taking an image of the reflectivity and in this case the reflectivity is the same everywhere, we could expect to see a blank image (uniform). However, the resulting image shows aberrations around the object again, and the object is definitely visible contrary to what we expected. In the last case (Fig. 2.5), the reflectivity of the object top and background were both randomized (each point was given a random reflectivity between zero and one). This could represent a bumpy surface where light hitting the surface would bounce off in any direction and only

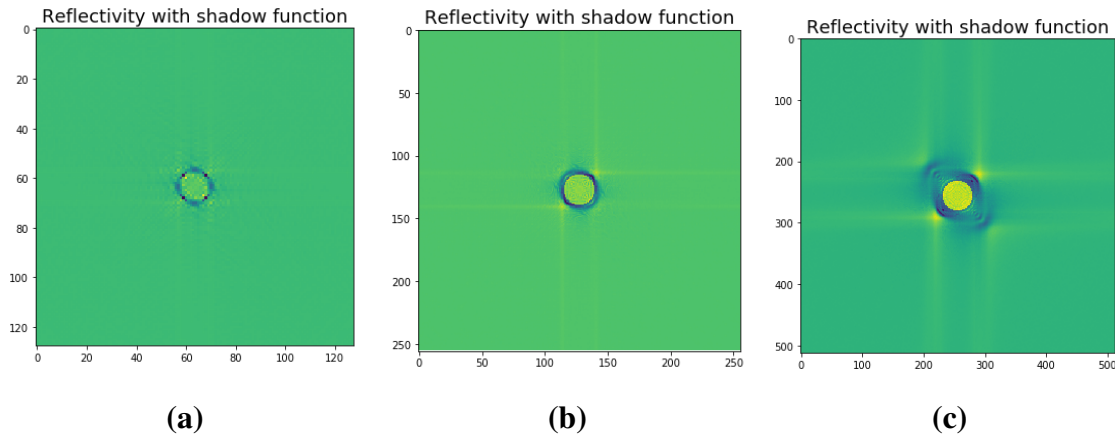


Figure 2.4 Simulation of IPSII reconstruction of cylinder object (Fig. 2.2) with different number of k-space measurements: (a) 128×128 pixels, (b) 256×256 pixels, (c) 512×512 pixels. Object face is completely reflective ($R = 1$) and background is completely reflective ($R = 1$).

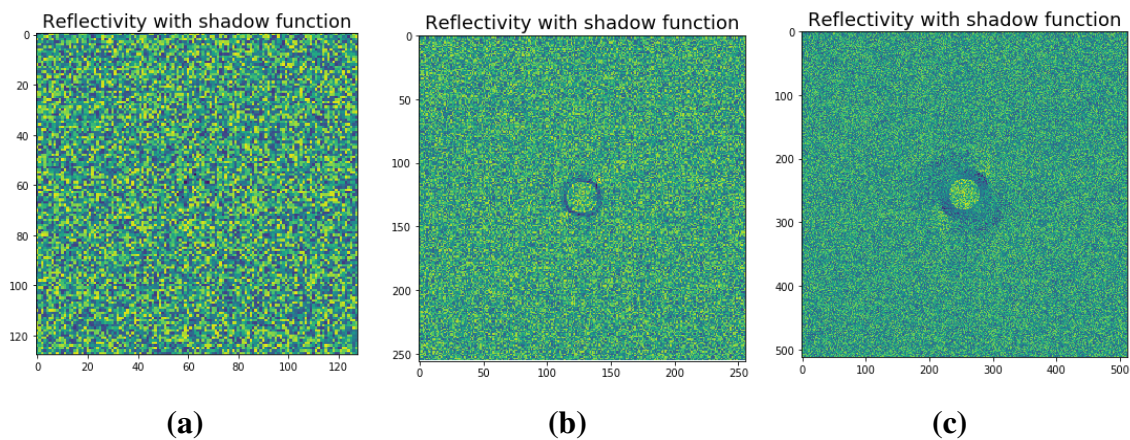


Figure 2.5 Simulation of IPSII reconstruction of cylinder object (Fig. 2.2) with different number of k-space measurements: (a) 128×128 pixels, (b) 256×256 pixels, (c) 512×512 pixels. Object face and background have completely randomized reflectivities ($R =$ random number, $0 \leq R \leq 1$).

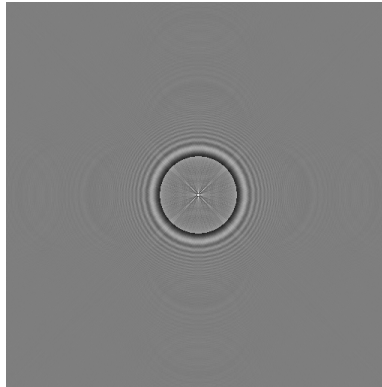


Figure 2.6 This image was made by Dr. Dallin Durfee in Python in an effort to recreate my results. The aberrations shown appear to be circularly symmetric unlike my images above. This is the best example of the shadow effects we expect to see using the IPSII method.

the light hitting certain points would bounce straight back to the detector. Similar to the completely reflective example, we could expect to see no definitions of the object but the resulting images show them all the same.

In each case, the definition of the object increases as the resolution and number of pixels increase, but the aberrations caused by IPSII shadows also increase their effect as resolution goes up. This is because as the number of pixels is increased, the max angle between the laser beams taking the data also increases, making the "shadows" of each beam grow larger (i.e. the higher the resolution, the bigger the shadows, the greater the aberrational effects).

During the IPSII reconstruction process, we go through the k-space data and rotate the direction of the shadows for each point, acquiring a radially symmetric effect. In these tests the aberrational effects of IPSII shadows were not circularly symmetric as we would expect the aberrations to be. Fig. 2.6 was made using a different program in Python, and shows the aberrational effects that we should see in the test case of the object top and background both being completely reflective.

Chapter 3

Experimental IPSII Shadows

Having simulated the IPSII process in Python and seen the aberrational effects the shadows had on resulting images, the next step for me was to perform IPSII on objects with depth to verify our computational results. This chapter describes my efforts to construct a working IPSII setup and showcases the images we created with it.

3.1 Recreating IPSII

MAS-IPSII was designed by Jarom Jackson as a PhD project at BYU [4]. My research in that same lab therefore focused on IPSII shadows using Python simulations and a MAS-IPSII setup and design for experimental verification. I decided to replicate Dr. Jackson's physical setup as exactly as possible for my experiment to avoid any unnecessary nuances. Fig. 3.1 represents the kind of test object he had imaged using his setup, and Fig. 3.2 contains some of his results. My goal was to first achieve similar image results with my own setup, and then move on to imaging IPSII shadows.

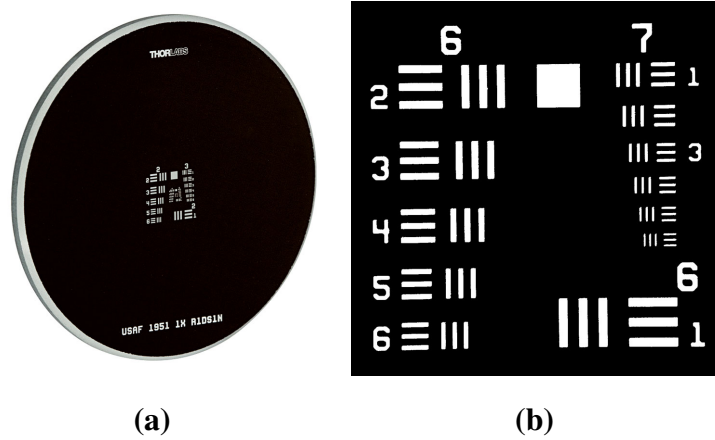


Figure 3.1 (a) Picture of a negative U.S. Air Force Resolution Test Target from Thorlabs [9] (1951 USAF Resolution Test Target (negative), $\emptyset 1''$). Our lab used one just like it. (b) a zoomed in view of the pattern on the Test Target.

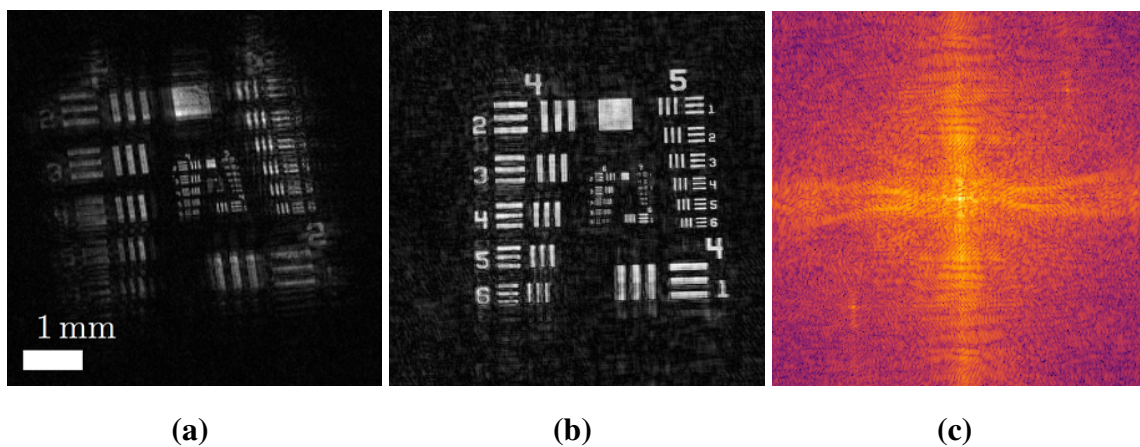


Figure 3.2 Taken from [4] (a,b) IPSII images of an Air Force test pattern made by Dr. Jarom Jackson during his PhD research. (c) example of good k-space data corresponding to an IPSII image

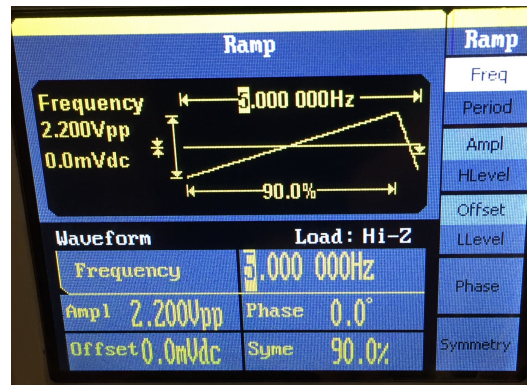


Figure 3.3 Ramp signal to drive the piezo stack for phase scanning, 2.2 V at 5 Hz with 90% symmetry

3.1.1 Setup

Using the design provided by Jarom Jackson (see Fig. 1.1b) Ben Whetten, a fellow undergraduate, and I were able to setup the interferometer as hoped. Near the beginning, a lot my of time was spent simply learning about all the parts and how they work. We glued a piezo stack to the back of a one inch mirror placed in one of the bow tie configurations, and setup the controller to ramp the stack signal for the phase scanning (see Fig. 3.3). To keep costs low, we used a low quality laser pointer as our source, attenuated by a $10\mu\text{m}$ pinhole. The motorized mirror mounts were controlled by a BeagleBone Black [10]. The reference and object signals were sent to a trans-impedance amplifier connected to a Labjack T7 [11] which read the data and saved it to an external hard drive mounted to the BeagleBone. I ran the experiment using Python [12]. The main body of the interferometer can be seen in Fig. 3.4.

I balanced the interferometer (Fig. 3.4) as best I could so that each beam leg was equal in length. It took me a while to set up the Labjack and BeagleBone to use Dr. Jackson's code for run the experiment autonomously. I also created a circuit for the Photo Multiplier Tube (PMT) [13] used to read in the reference signal. For a while, we were were struggling to understand why the PMT was not reading the expected signal, until we realized we needed to switch the polarity to negative.

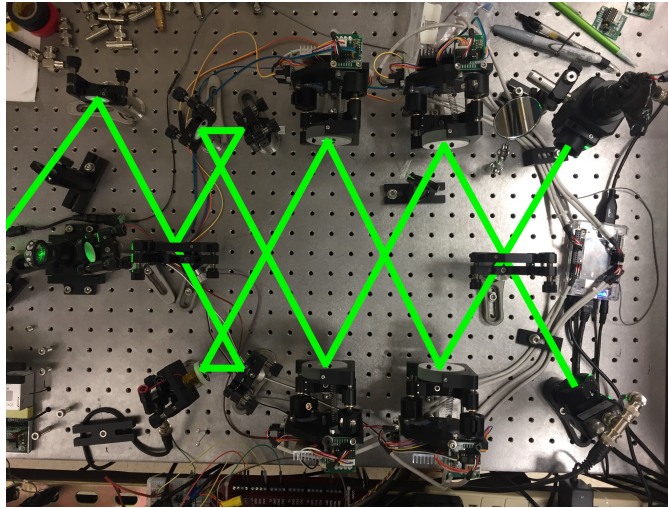


Figure 3.4 Seen here is the setup we used for the experimental verification of IPSII shadows, with the green lines representing the laser beam path(s).

After that, it worked well.

As I was about to start taking data, a power outage occurred that affected the lab, and there were quite a few nuances to get everything back up and running again. My first successful images are shown below.

3.1.2 Image Results

Using a pinhole and some aluminum foil to block out unnecessary light, I took an IPSII image of an USAF test pattern (negative) like the one in Fig. 3.1. The Field of View (FOV) was set to be $500\mu\text{m} \times 500\mu\text{m}$ which was smaller than the exposed area of the test pattern. Fig. 3.5a shows the resulting image. This run was the first successful one (it showed something resembling a part of the test pattern), and appears to present a ghosting effect of the pattern lines. Fig. 3.5b shows almost the same image, shifted, and with a slightly higher resolution.

We decided to try taking an image of the whole pattern to see how large of an FOV we could have while still acquiring a reasonable image. Fig. 3.6 is an image of the test pattern with a $4\text{mm} \times 4\text{mm}$

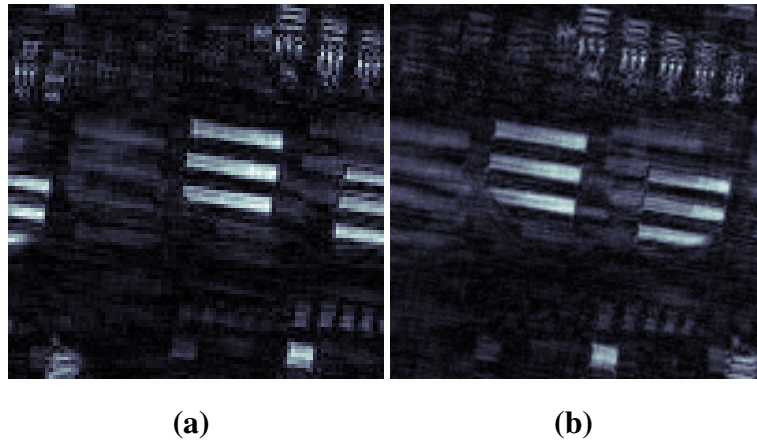


Figure 3.5 (a) First run with channels correctly determined with 101×101 k-space measurements and $500 \mu\text{m} \times 500 \mu\text{m}$ FOV. (b) Second run with correct channels. 151×151 k-space measurements and $500 \mu\text{m} \times 500 \mu\text{m}$ FOV.

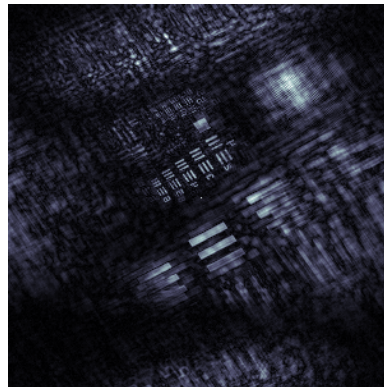


Figure 3.6 First IPSII run with no aperture before object. Also first run with $4 \text{mm} \times 4 \text{mm}$ FOV size of test pattern, and 301×301 k-space measurements.

FOV and a relatively high resolution. It shows lots of blurring where the outermost ring of lines appears, and then goes into focus nearer the center. The effects of this blurring is due to phase errors and is the subject of Ben Whetten's undergraduate senior thesis [14].

Due to this relation and limit, we wanted to hone in on a more appropriate FOV for our images. Also, to avoid getting aberrational effects from light beyond our FOV we taped aluminum foil over the parts of the pattern found outside said FOV. Fig. 3.7 shows low resolution images with smaller FOVs and aluminum foil blocking the rest of the pattern.

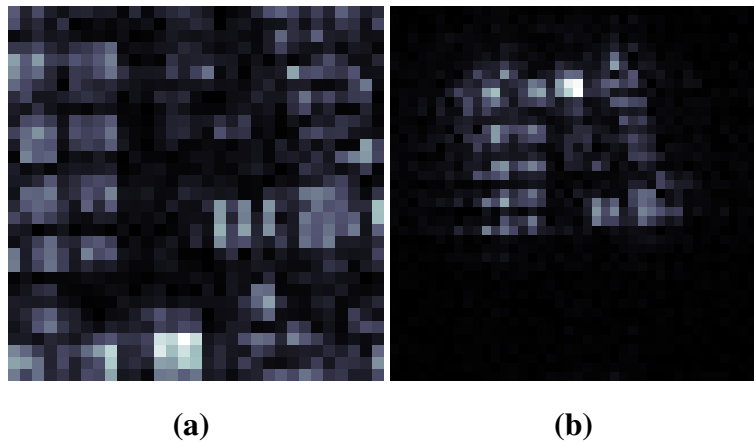


Figure 3.7 (a) First run with aluminum foil as aperture. FOV $1\text{mm}\times 1\text{mm}$, and 31×31 k-space measurements. We should see the edges of the aluminum foil easily. (b) Second try with aluminum foil at low resolution. 41×41 k-space measurements and $2\text{mm}\times 2\text{mm}$ FOV.

Fig. 3.8a shows the same image as Fig. 3.7b taken at a much higher resolution, and we can see that everything seems to be more blurred. It also shows the k-space data (Fig. 3.8b) of that image and, as seen by the streaks and black space, that something caused the setup to stop taking data. The cause of the black streaks and consequent lack of data for images like this was often a mirror mount adjustment screw that disconnected in the middle of taking data. Upon gluing the screw back together and reconnecting we attempted to take the image various times. Each subsequent time, either the same or a different screw disconnected, probably from an excess of torque when adjusting the mirrors. Once we took data and the screws stopped disconnecting, we found that the motors were still not functioning properly. They would fail to return to physical home after movement although they displayed digital home according to the computer. Upon switching out the motors and trying again, the problem persisted, even though the code was the same as before when successfully taking images of the test pattern.

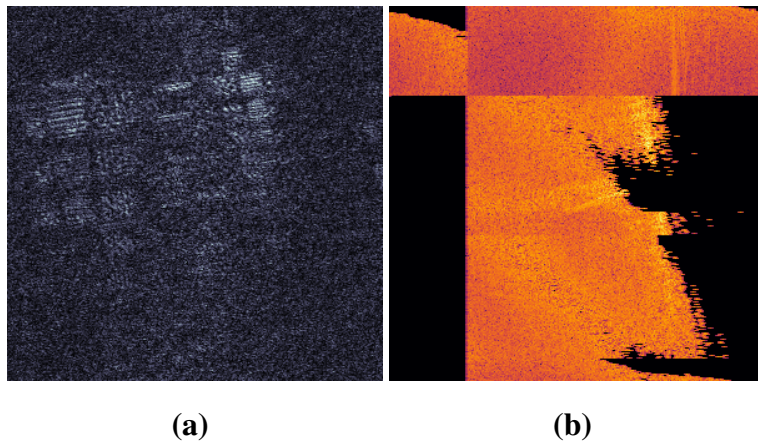


Figure 3.8 (a) IPSII image where something was off in the k-space data. (b) K-space data of image. Parts of it show errors in the data, probably from a motor disconnecting from a mirror mount.

Chapter 4

Conclusion

I was able to create simulated examples of the aberrational effects of IPSII shadows which, while not creating the most accurate representation of the object being imaged, do provide some level of object definition in the resulting image. When the reflectivity of the object and background are the same, these shadow effects provide the only defining characteristics of the object in the image itself.

We failed to verify the effects of illumination shadows in IPSII experimentally, but were successful in reconstructing the IPSII setup used by Jackson in [4], and partially successful in taking images of an Air Force test pattern.

The next step to take involves successfully performing IPSII using a MAS-IPSII setup on an object with significant axial extent.

Appendix A

This appendix contains relevant code I made to simulate IPSII in Python. For the code used to autonomously run our IPSII setup, see Dr. Jackson's dissertation [4].

A.1 1D IPSII Simulation Code

This code is not exactly what was used, but is an accurate representation of the one-dimensional simulation process as described in 2.1. It takes the Fourier transform (Eq. 2.1) of the Reflectivity multiplied by a shadow mask, and then the resulting image is the inverse Fourier transform (ifft here) of that result.

Python Code:

```
import numpy as np

R = Reflectivity
N = len(R)
FOV = FieldOfView
lambda = wavelength

for n in range(N):
    dk = 1/FOV
    theta = 2*np.arcsin(n*lambda*dk/2)
    #apply shadow mask
    data[n] = np.sum(R*np.exp(n*(-1j)*x*2*np.pi/N)*shadow)
```

```
image = np.fft.ifft(data)
```

A.2 2D IPSII Shadow Mask Code (POV-Ray)

I used version 3.8 of POV-Ray [8] from <http://www.povray.org/>. This code created an above-view image of a cylinder and its shadows from two infinitely far away light sources at a specific angle from each other. The angle between the light sources was determined by a given pixel number. The number of pixels desired in the IPSII image determined the number of POV-Ray images I made using this code.

POV-Ray Code:

```
#version 3.8;
global_settings{ assumed_gamma 1.0 }

#declare l = 0.00532;
#declare Angle = 0.006;
#declare Camera_Distance = 20000;
#declare deltakm = 1/(Camera_Distance*tan(Angle*pi/180));
#declare deltakn = 1/(Camera_Distance*tan(Angle*pi/180));
#declare theta = asin(l*sqrt(pow(m*deltakm,2)+pow(n*deltakn,2))/2);
#declare phi = atan2(Nrow/2-m,n-Ncol/2);

#debug concat("\n", str(theta*180/pi,1,3), "\n\n")

camera {
  orthographic
  location <0, Camera_Distance, 0>
  look_at <0, 0, 0>
  sky <0, 0, 1>
  angle Angle
}

light_source{<-cos(phi)*sin(theta), cos(theta), -sin(phi)*sin(theta)
  >*100000 color rgb 1 }
light_source{<cos(phi)*sin(theta), cos(theta), sin(phi)*sin(theta)
  >*100000 color rgb 1 }
```

```

plane{ <0,1,0>, 0
  texture{ pigment { color rgb 1 }
    finish { ambient 0 diffuse 1 }
  }
}

cylinder{<0,0,0>, <0,0.1,0>, 0.1
  texture{ pigment { color rgb <0,0,1> }
    finish { ambient 0 diffuse 1 }
  }
}

```

A.3 2D IPSII Simulation Code

This is the code that was used to simulate the two-dimensional IPSII process as described in 2.2. It takes the two-dimensional Fourier transform (Eq. 2.3) of the Reflectivity multiplied by a shadow mask, and then the resulting image is the inverse Fourier transform (ifft2 here) of that result.

Python Code:

```

import numpy as np
import matplotlib.image as mpimg

#####
#Forward Fourier transform function with shadow mask inside the
  integrand
#####

def transform_with_shadow(object_arr, reflectivity_arr, folder, size,
  num_digits):
  Object = object_arr
  Reflectivity = reflectivity_arr

  Nrow = np.shape(Object)[0] # num rows
  Ncol = np.shape(Object)[1] # num columns

  xr = range(Nrow)
  xc = range(Ncol)
  XC, XR = np.meshgrid(xc, xr)

```

```

integrand = np.empty(np.shape(Object), dtype=np.complex)
IPSII = np.empty(np.shape(Object), dtype=np.complex)
image_filepath = "/home/carter/Documents/Research/simple cylinder
2/"+folder+"/shadows"

for m in range(size):
    for n in range(size):

        shadow = mpimg.imread(image_filepath+'/m'+str(m+1).zfill(
num_digits)+"/test"+str(m+1).zfill(num_digits)+str(n+1).zfill(
num_digits)+".png")[:, :, 0]

        integrand = Reflectivity*np.exp((-1j)*2*np.pi*(m*XR/Nrow
+ n*XC/Ncol))*shadow
        IPSII[m,n] = sum(sum(integrand))

# theta = np.arcsin(1*np.sqrt(((m*deltakm)**2)+((n*deltakn)**2))/2)
# phi = np.arctan()

return IPSII

#####
#Simulating IPSII with the forward transform, then taking the inverse
transform for the resulting image
#####

IPSII128random = transform_with_shadow(gimg128, randomgimg128, "128
x128", 128, 3)
IPSII256random = transform_with_shadow(gimg256, randomgimg256, "256
x256", 256, 3)
IPSII512random = transform_with_shadow(gimg512, randomgimg512, "512
x512", 512, 3)

plt.imshow(np.fft.ifft2(IPSII128random).real)
plt.imshow(np.fft.ifft2(IPSII256random).real)
plt.imshow(np.fft.ifft2(IPSII512random).real)

```


Appendix B

The original analysis program designed by Jarom Jackson used a sine fit method to create the images from IPSII data. Later, I switched to using a lock-in amplification method that, while achieving slightly more blurry images, was about ten times faster than Dr. Jackson's sine fit program.

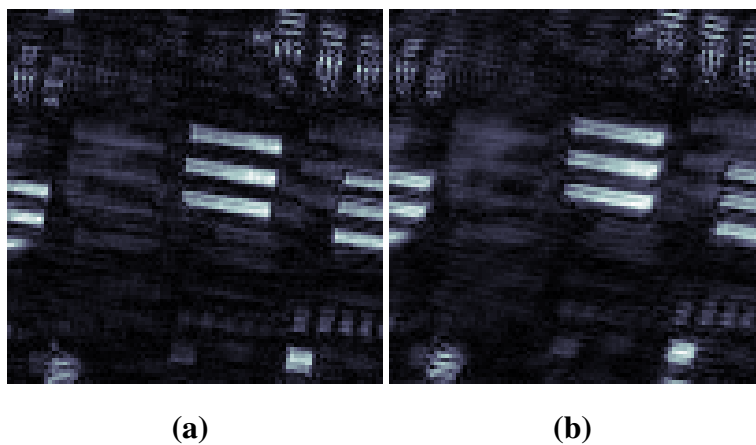


Figure B.1 (a) Using a sin fit function to retrieve the phase and create the image. (b) Using lock-in detection to retrieve the phase and create the image.

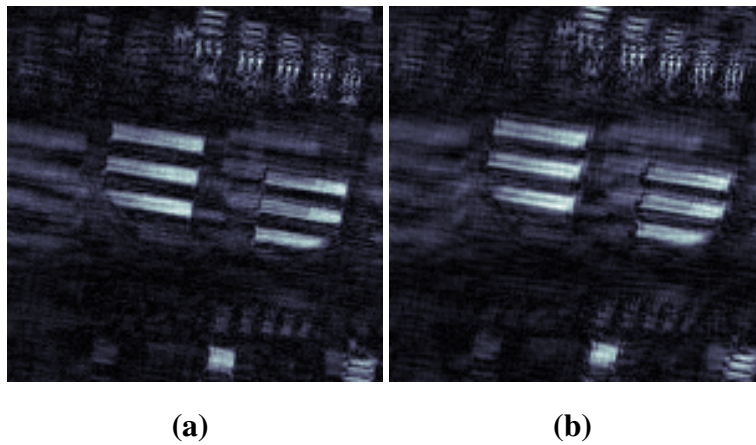


Figure B.2 (a) Using a sin fit function to retrieve the phase and create the image. (b) Using lock-in detection to retrieve the phase and create the image.

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