Parameter Estimation and Inverse Theory
Assignment 2

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13th September 2023

1 Experimental Procedure:

In this experiment I created a travel time tomography simulation, using low resolution images from popular videogame minecraft.

1.1 Forward Modelling Operator:

I considered the pixel values of black and white images as the travel time.
Then I passed rays of light through these cells, in the end getting total travel time as the sum of each pixel crossed by the ray.
To build the forward modelling operator I did the following:

- Convert the image into greyscale.
- Pass parallel rays from the left, bottom and 2 diagonals of the image and record the travel time of each ray.
- Create a zero array with rows for each ray and columns for each pixel.
- Assign value 1 to cells in each row that were in the path of the ray. This gives us forward modelling operator F.
- In the corresponding position place the sum of the pixel values of the rays path as the data value. This gives the d matrix.
- 5% noise gaussian was added in d for noise computations.

1.2 Tikonov Estimation:

Performed Tikonov estimation using the following formula:

$$m_{est} = (F^T F + kI)^{-1} F^T d$$

$$F^{\dagger} = (F^T F + kI)^{-1} F^T$$

Where $k > 0$
I used $k = 0.1$ for all calulations.

2 Results:

2.1 Outputs:

Listed below are the original images, recovered images, model resolution matrix, and the data resolution matix for many images calculated using above scheme. The following images are taken from the popular videogame minecraft.
All images are less than 32x32 pixels in size

2.1.1 Without Noise:

Inverted images without noise:

- alban-modified

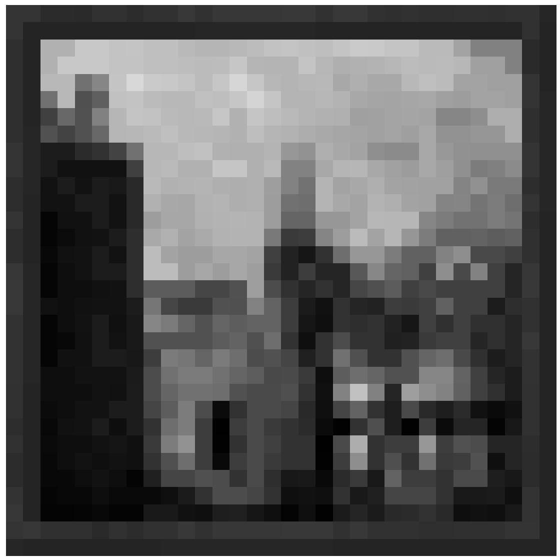

Figure 1: Original Image

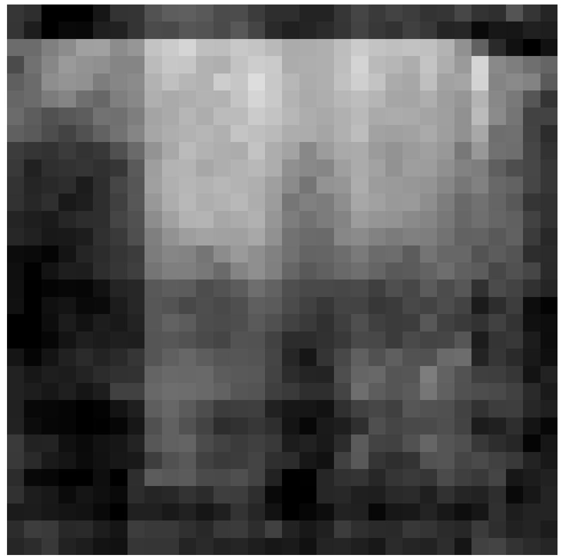

Figure 2: Recovered Image

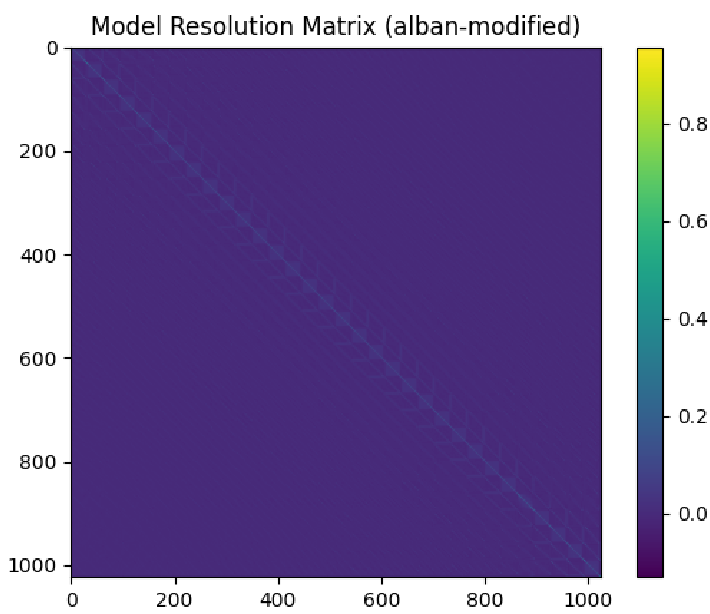

Figure 3: Model Resolution Matrix

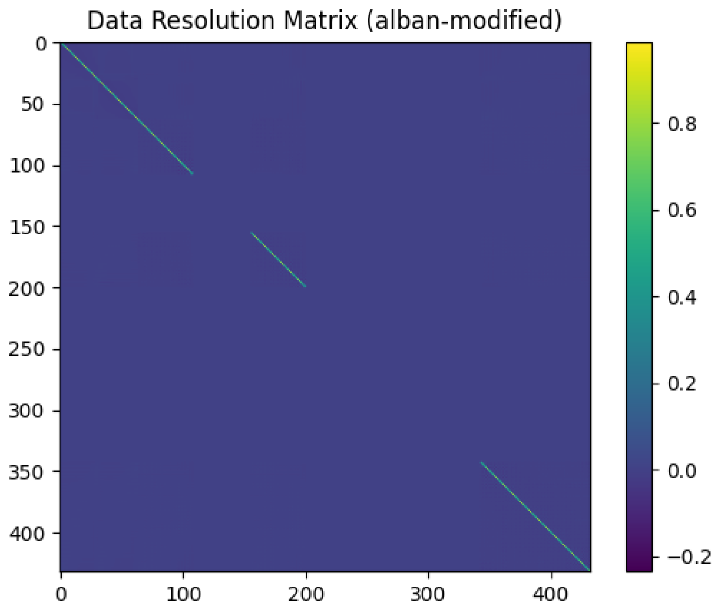

Figure 4: Data Resolution Matrix

- aztec-modified

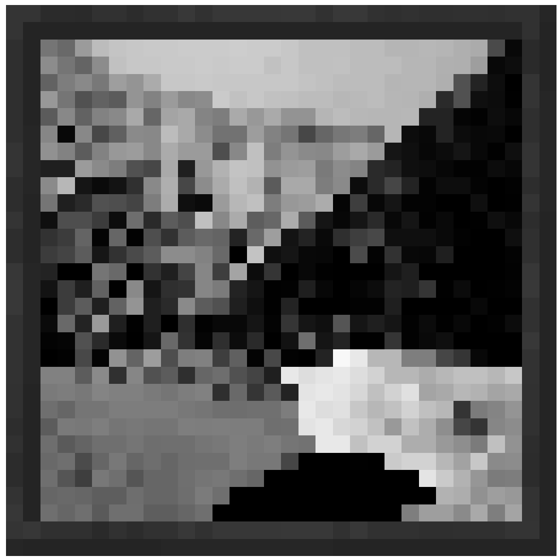

Figure 5: Original Image

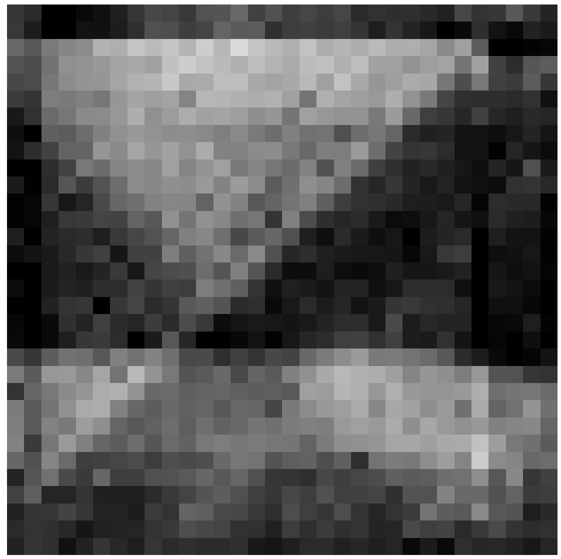

Figure 6: Recovered Image

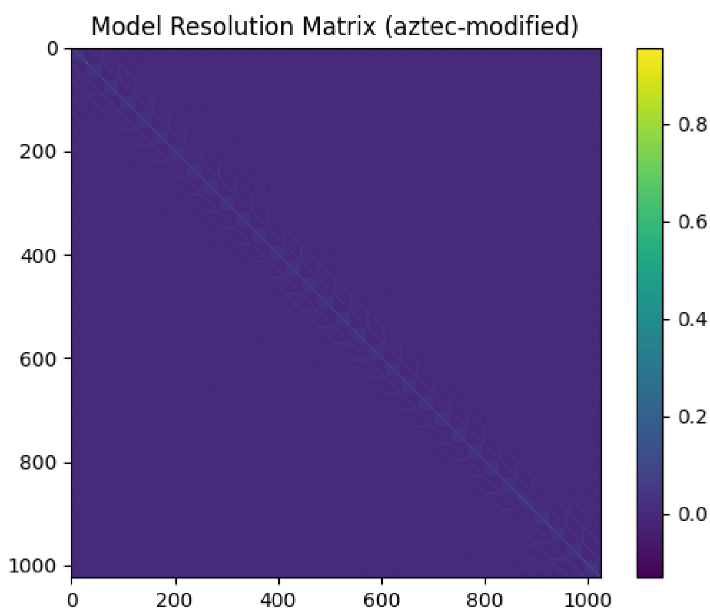

Figure 7: Model Resolution Matrix

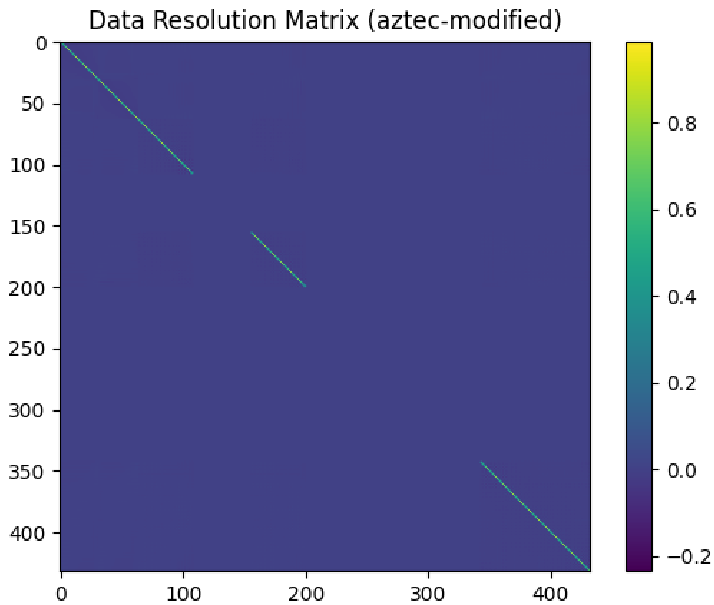

Figure 8: Data Resolution Matrix

- bee_nest_front_honey-modified

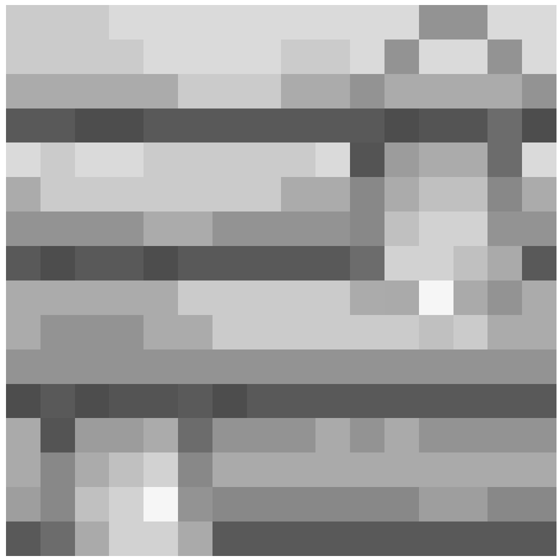

Figure 9: Original Image

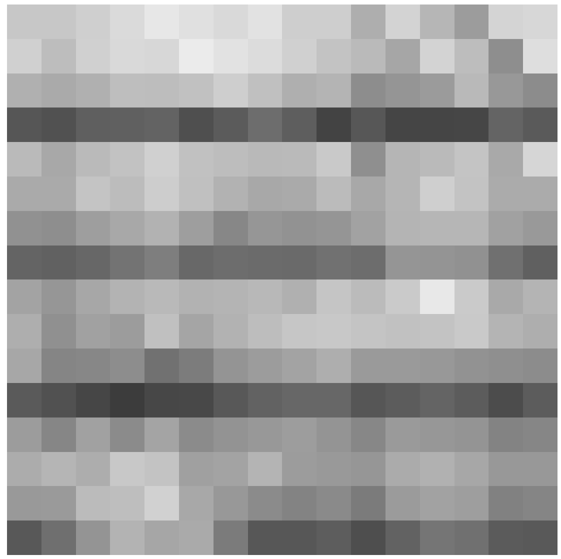

Figure 10: Recovered Image

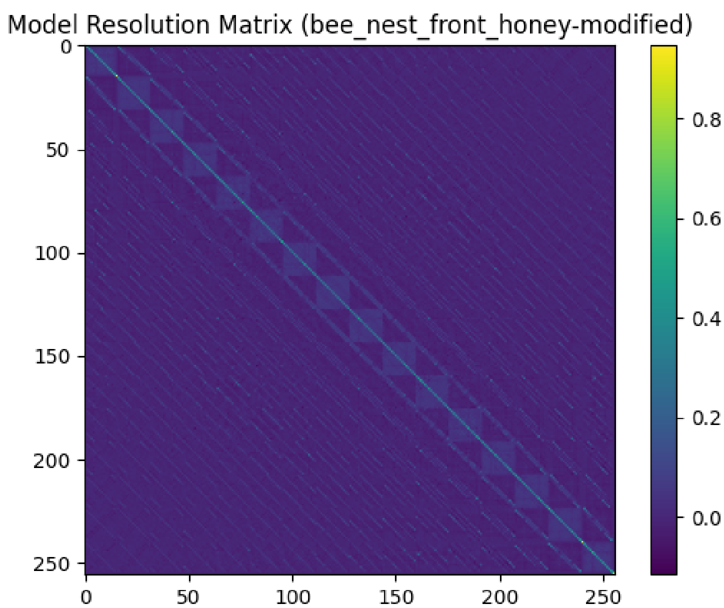

Figure 11: Model Resolution Matrix

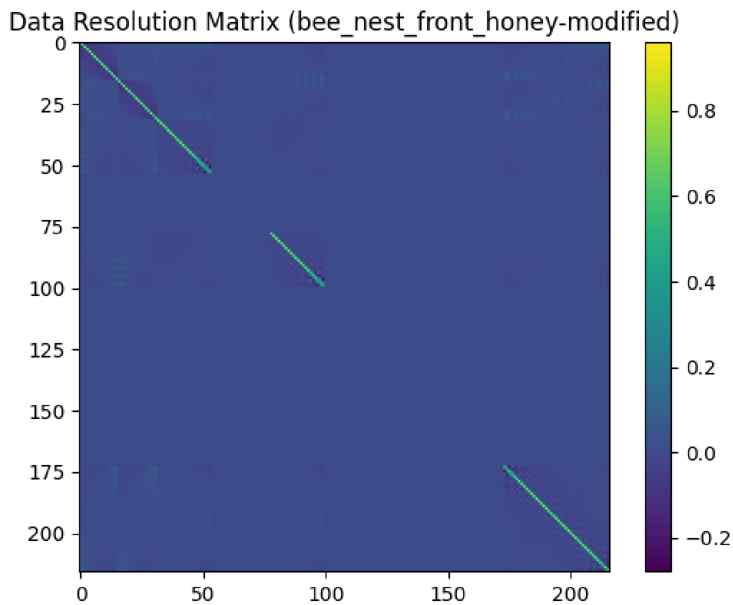

Figure 12: Data Resolution Matrix

- carved_pumpkin-modified

Figure 13: Original Image

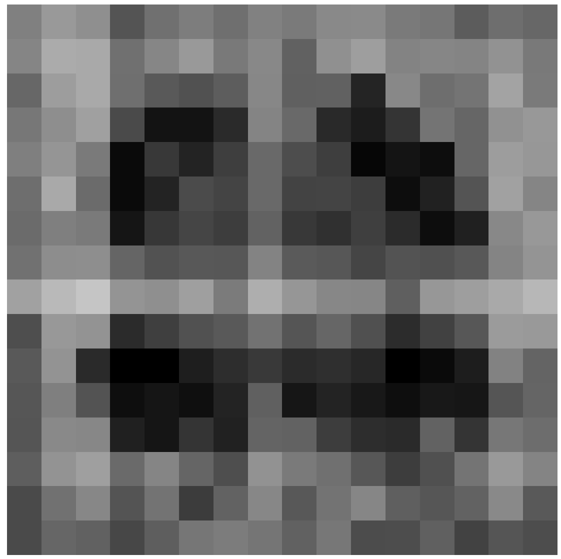

Figure 14: Recovered Image

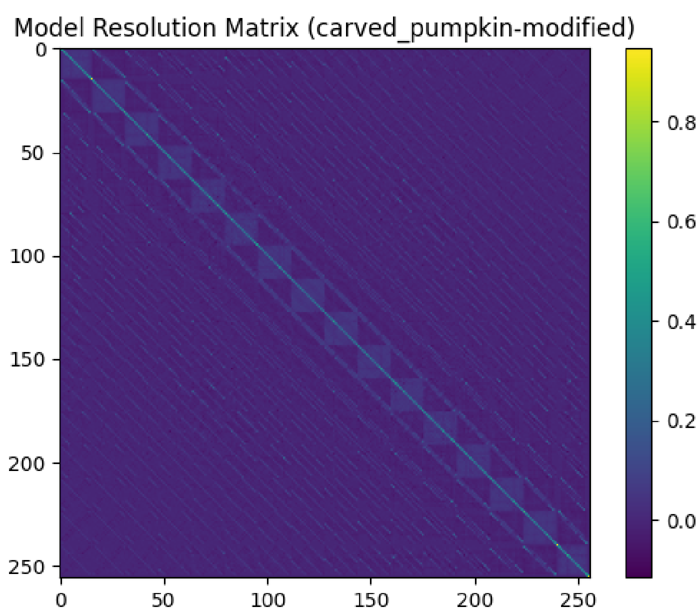

Figure 15: Model Resolution Matrix

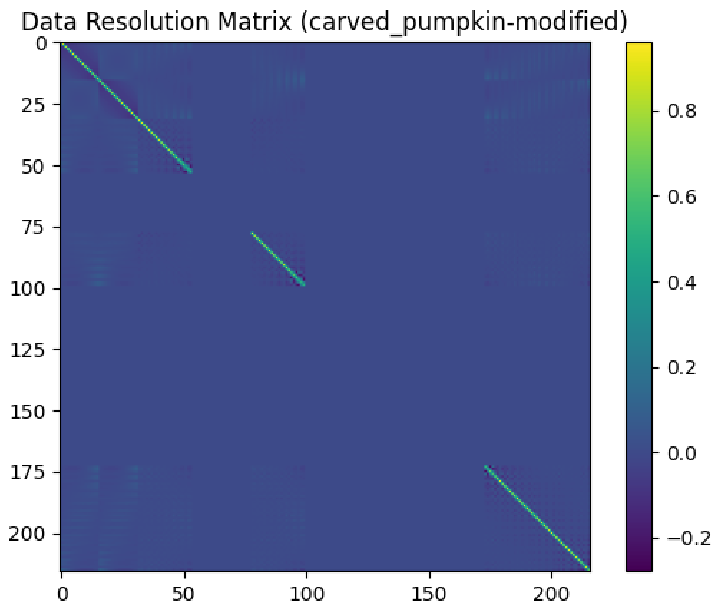

Figure 16: Data Resolution Matrix

- cow

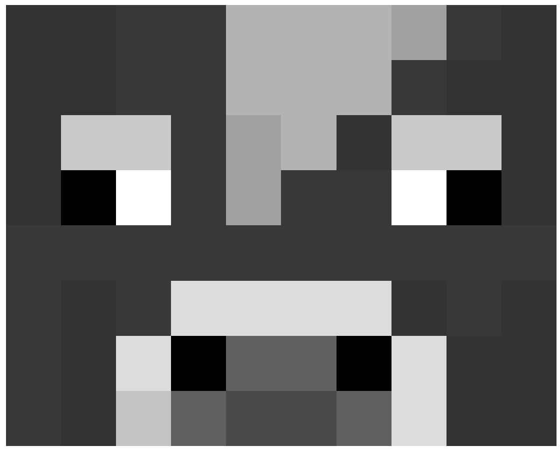

Figure 17: Original Image

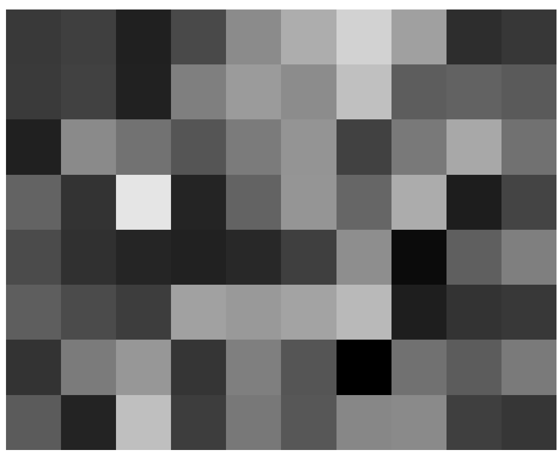

Figure 18: Recovered Image

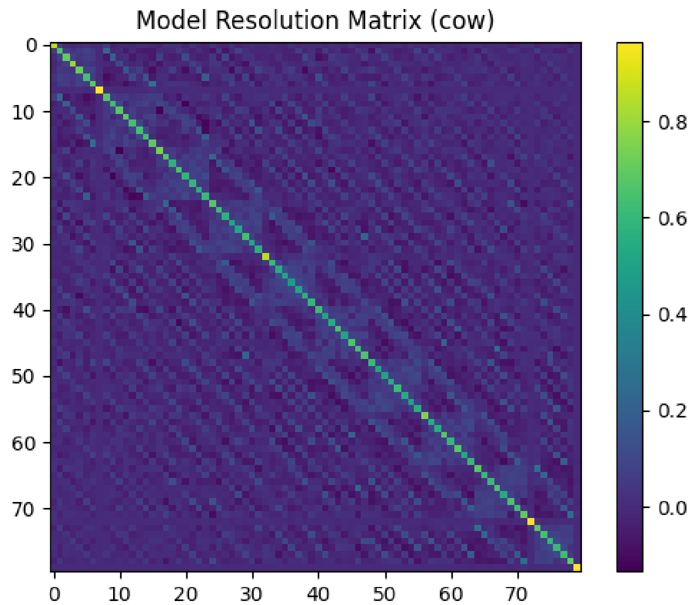

Figure 19: Model Resolution Matrix

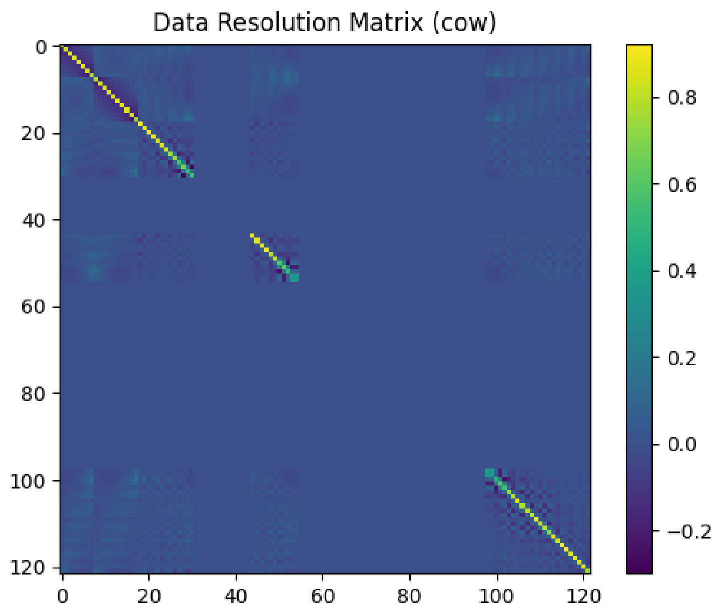

Figure 20: Data Resolution Matrix

- creeper

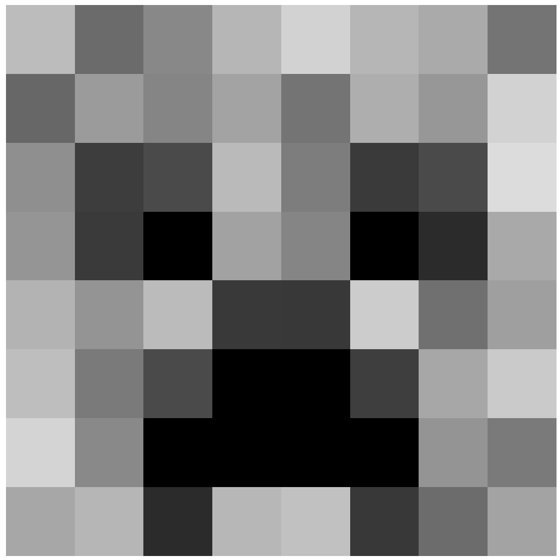

Figure 21: Original Image

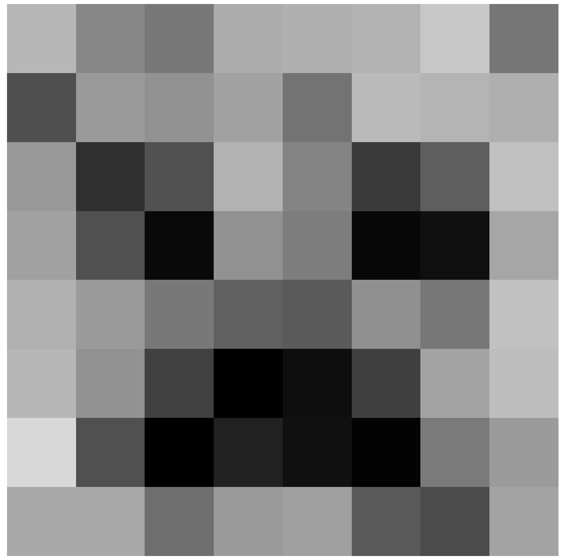

Figure 22: Recovered Image

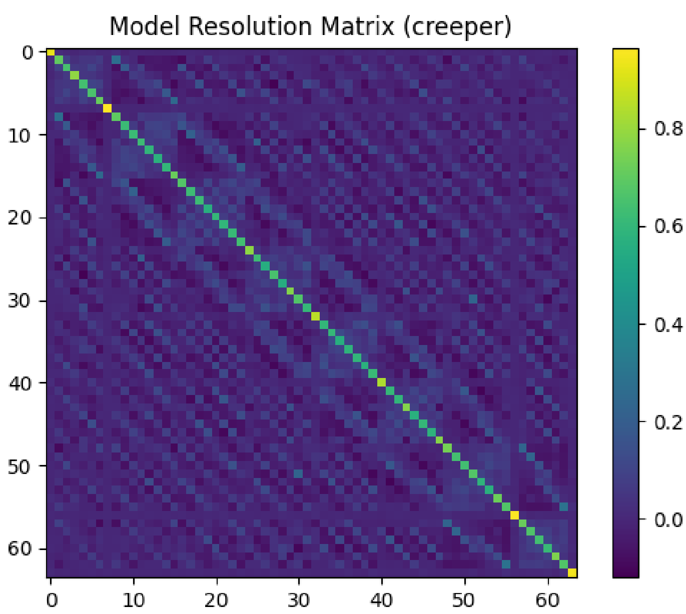

Figure 23: Model Resolution Matrix

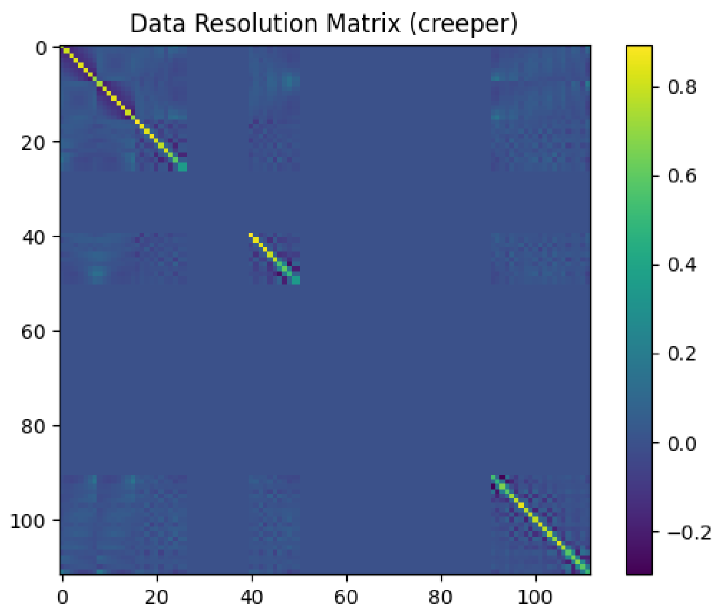

Figure 24: Data Resolution Matrix

- sheep

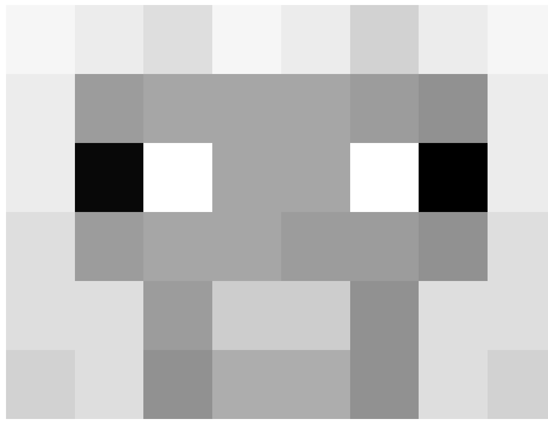

Figure 25: Original Image

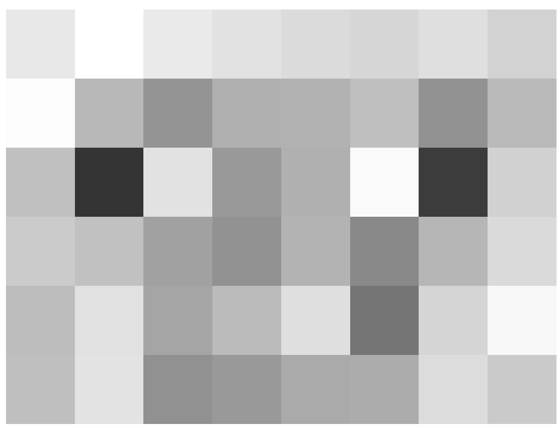

Figure 26: Recovered Image

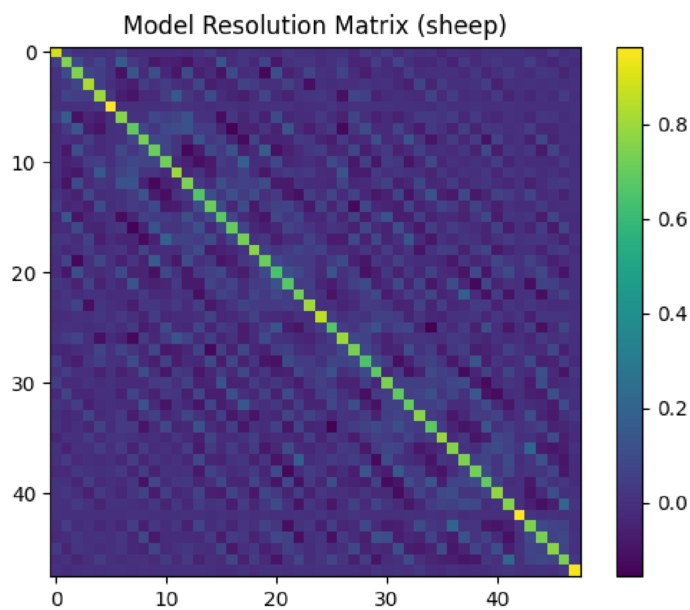

Figure 27: Model Resolution Matrix

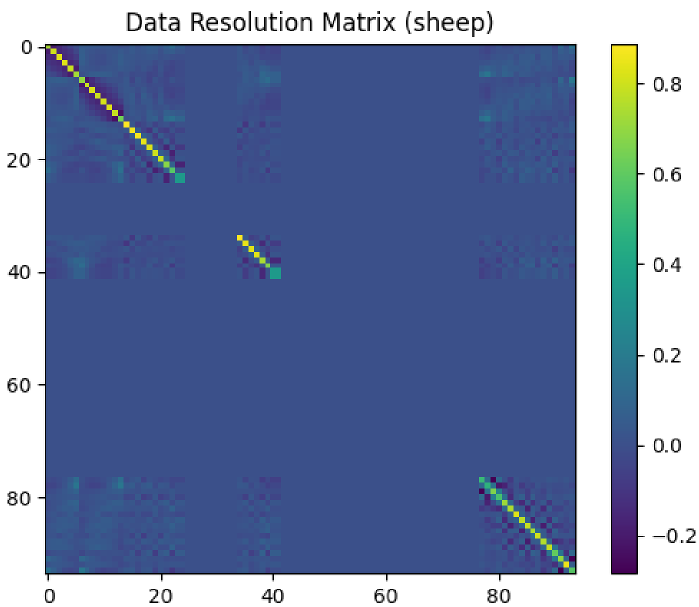

Figure 28: Data Resolution Matrix

- skeleton

Figure 29: Original Image

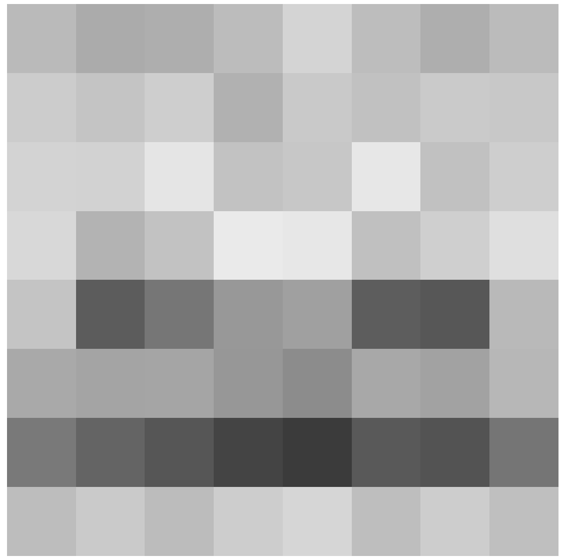

Figure 30: Recovered Image

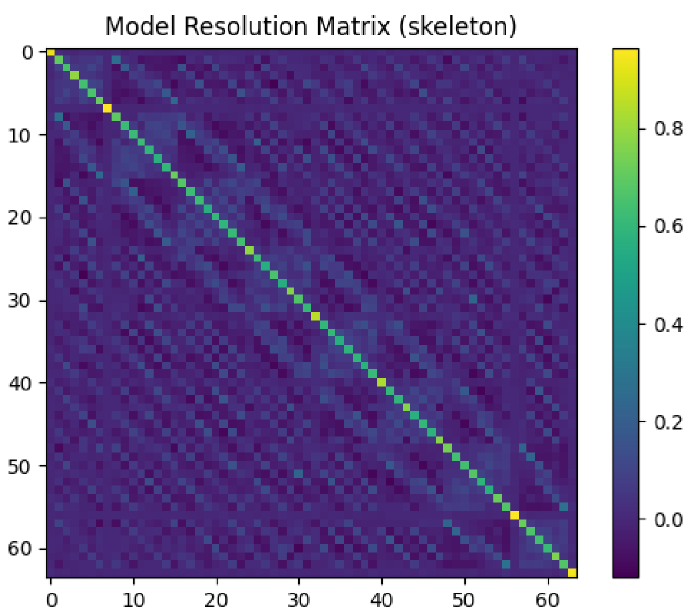

Figure 31: Model Resolution Matrix

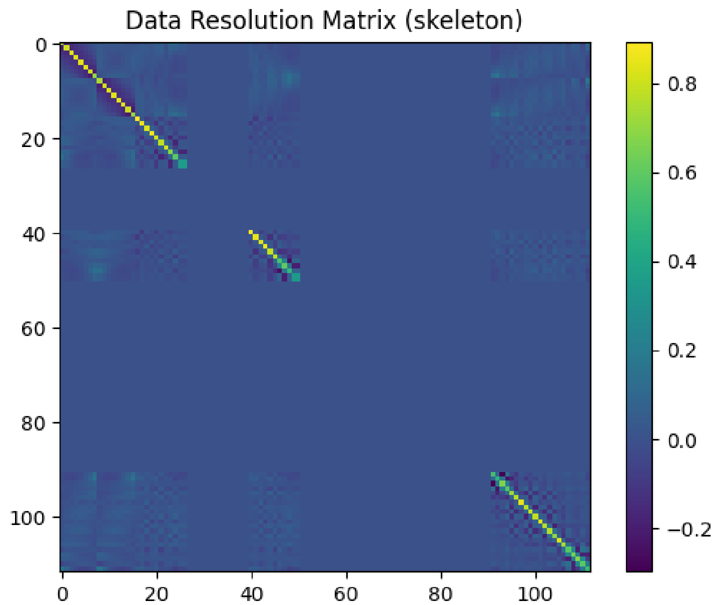

Figure 32: Data Resolution Matrix

- steve

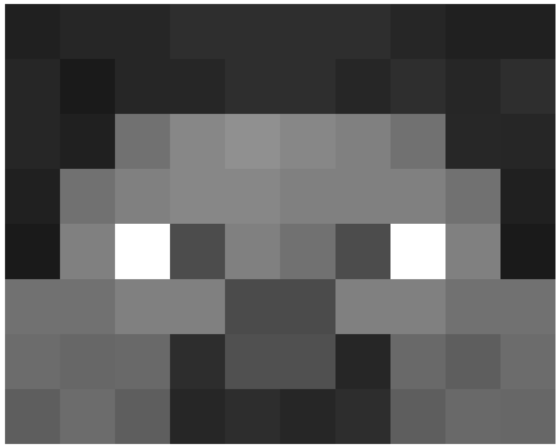

Figure 33: Original Image

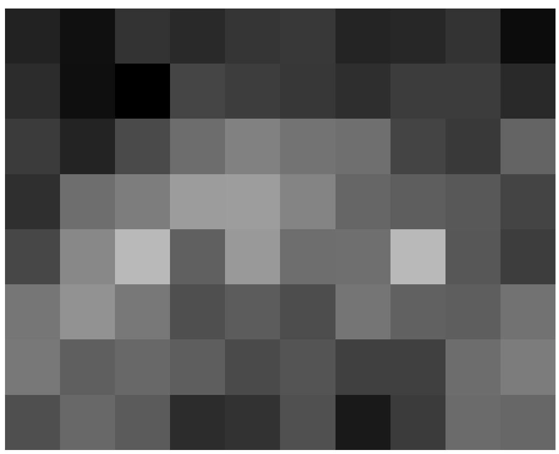

Figure 34: Recovered Image

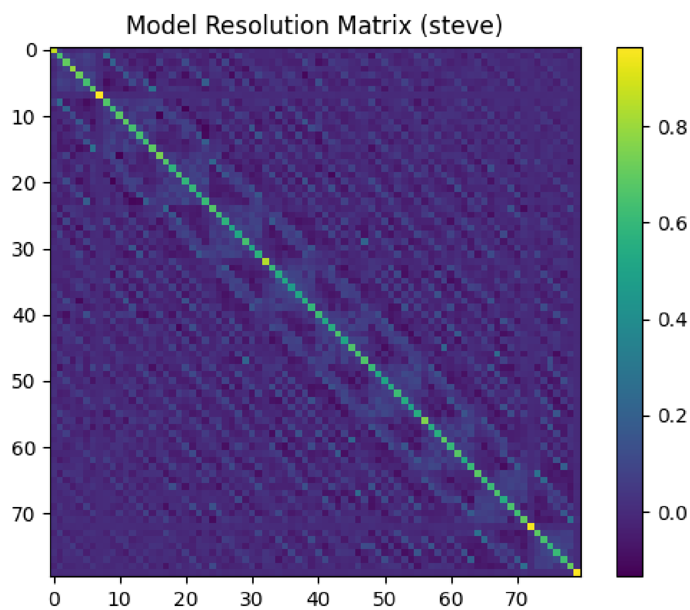

Figure 35: Model Resolution Matrix

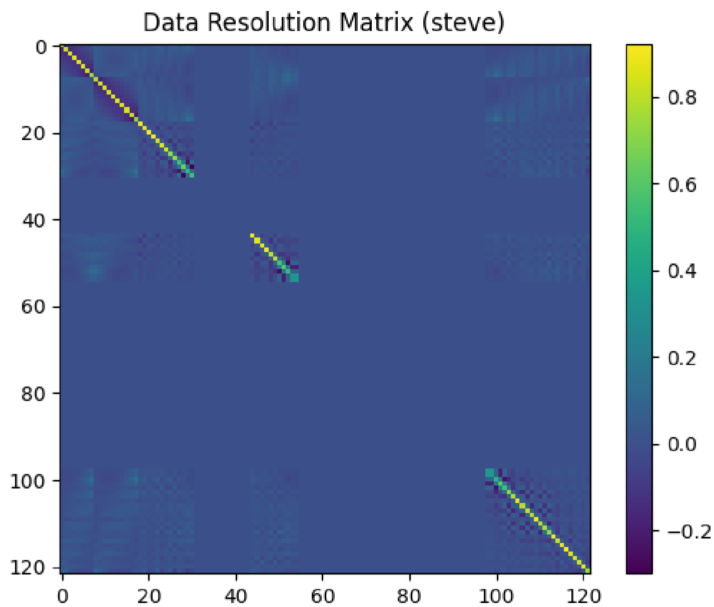

Figure 36: Data Resolution Matrix

- zombie

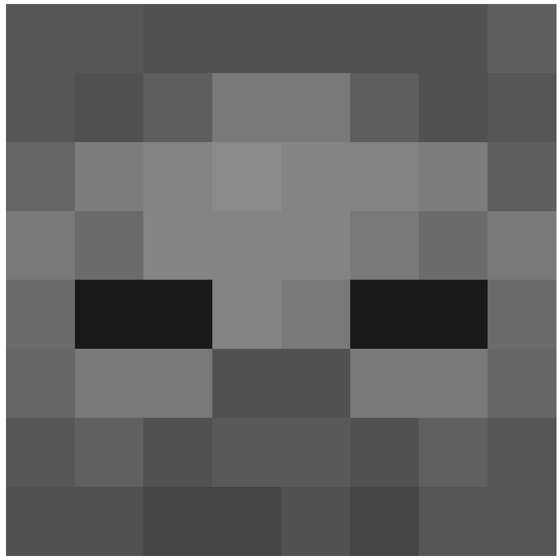

Figure 37: Original Image

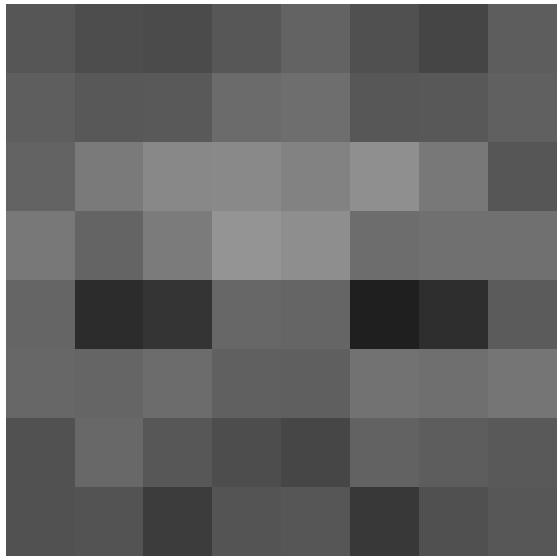

Figure 38: Recovered Image

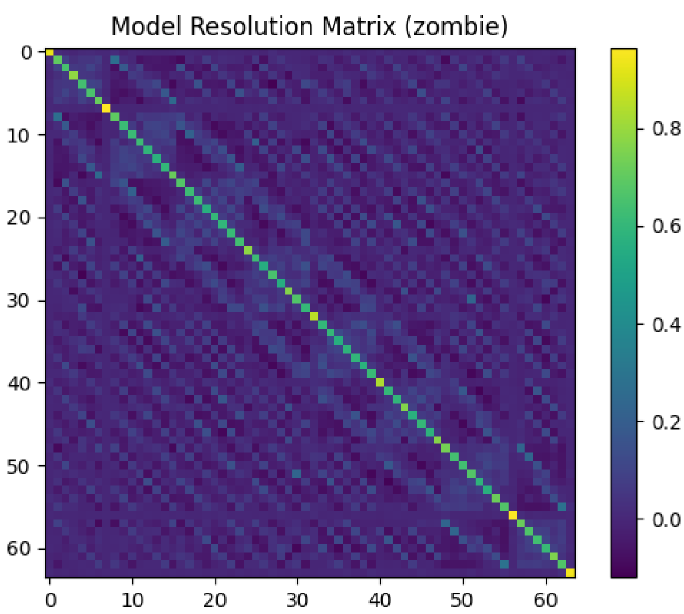

Figure 39: Model Resolution Matrix

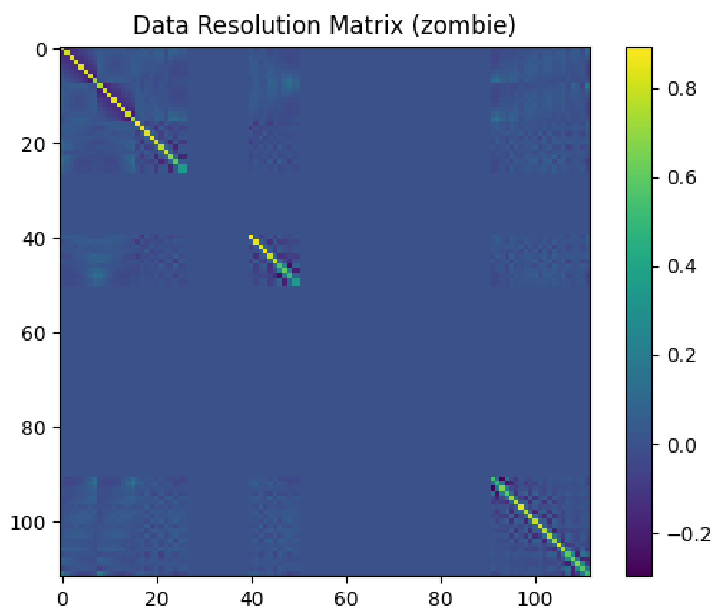

Figure 40: Data Resolution Matrix

2.1.2 With Noise

- alban-modified_noise

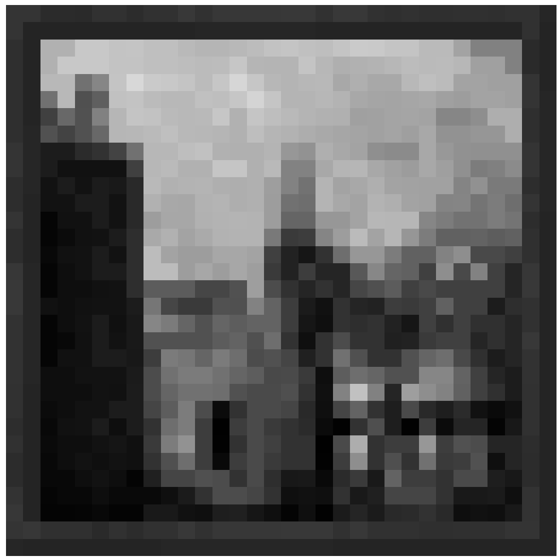

Figure 41: Original Image

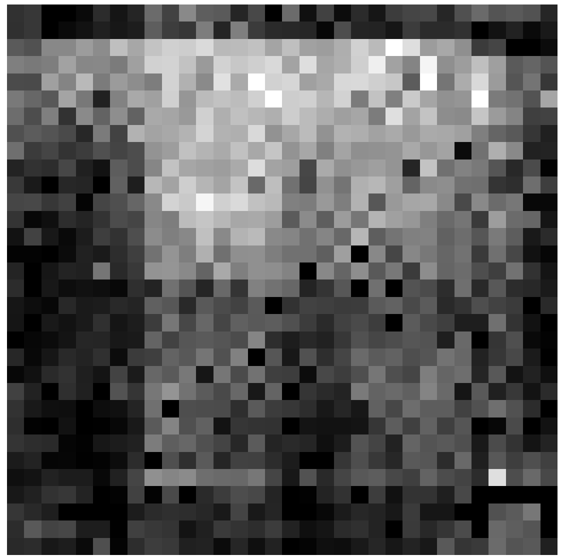

Figure 42: Recovered Image

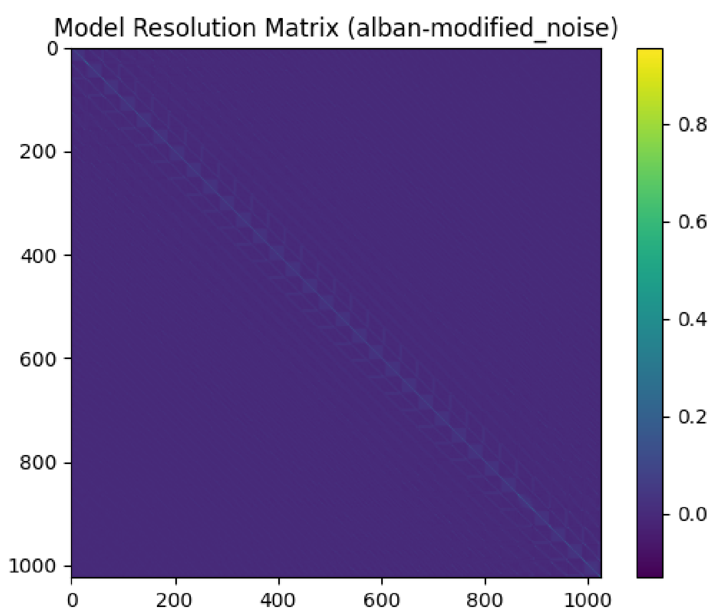

Figure 43: Model Resolution Matrix

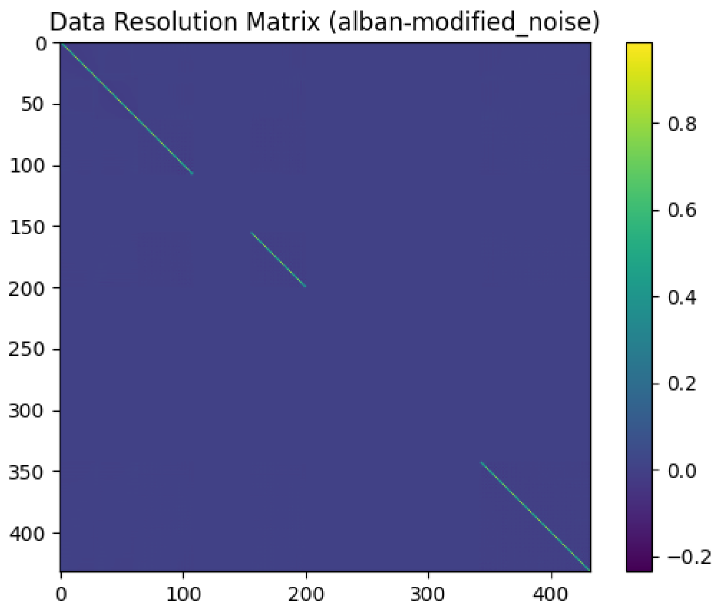

Figure 44: Data Resolution Matrix

- aztec-modified_noise

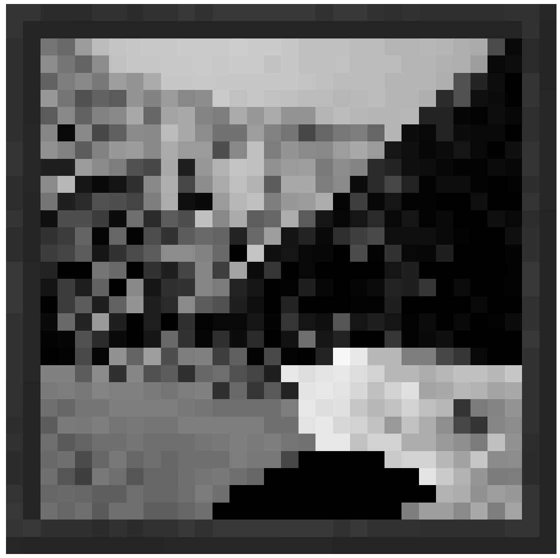

Figure 45: Original Image

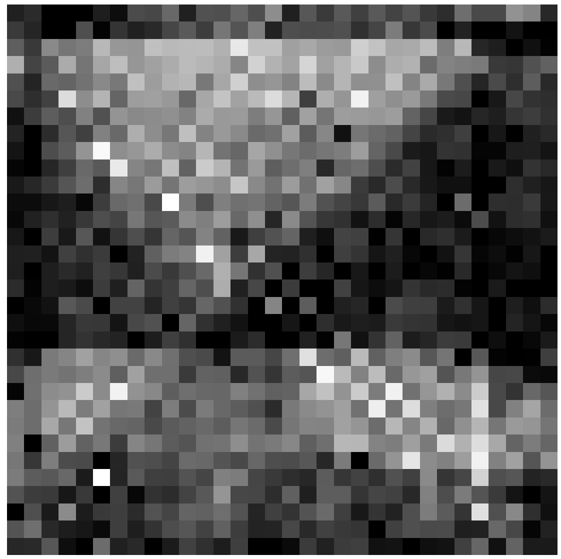

Figure 46: Recovered Image

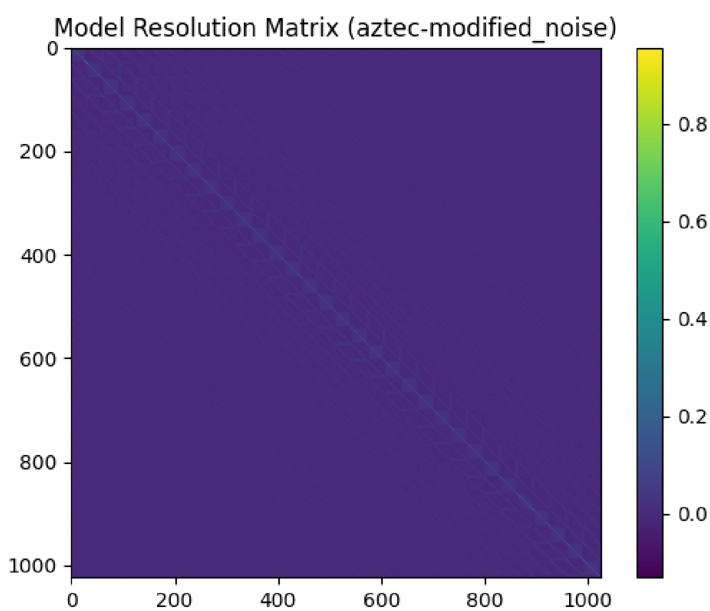

Figure 47: Model Resolution Matrix

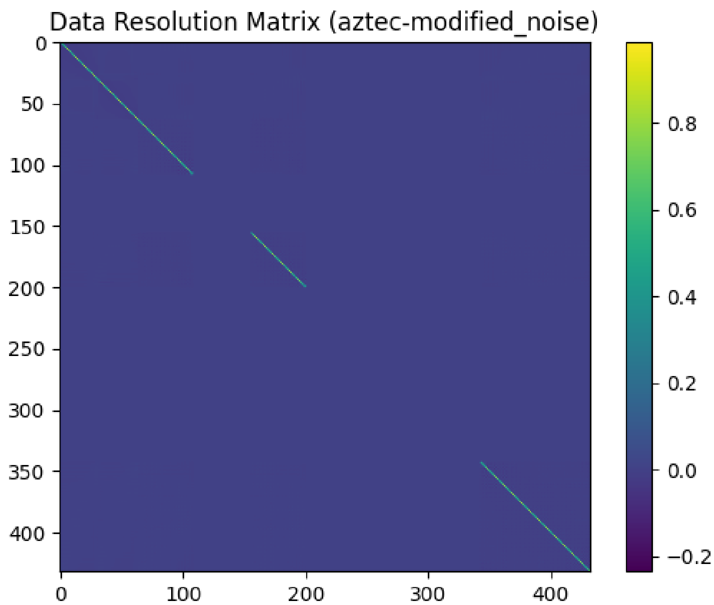

Figure 48: Data Resolution Matrix

- bee_nest_front_honey-modified_noise

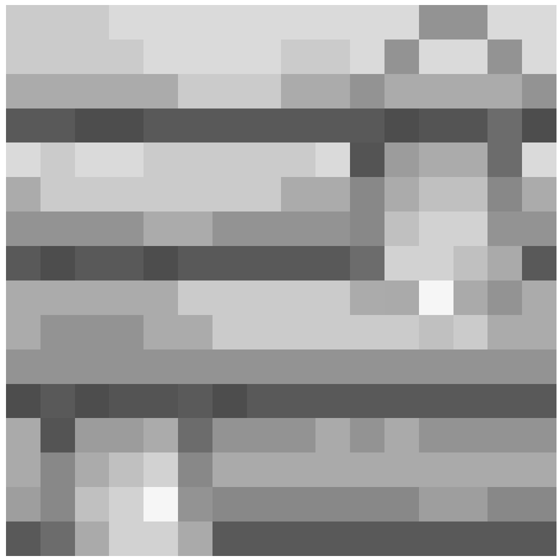

Figure 49: Original Image

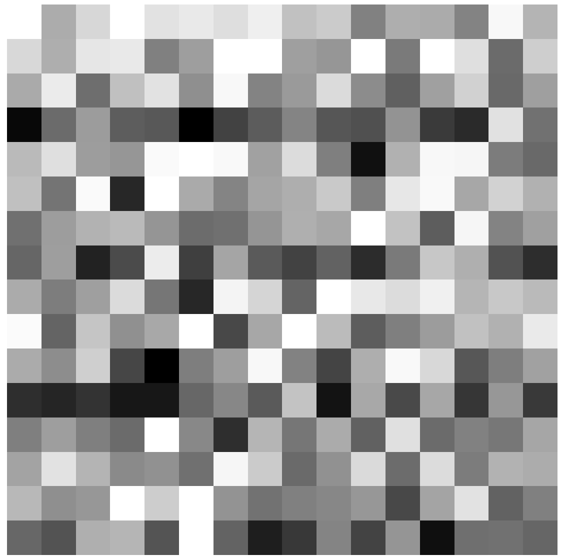

Figure 50: Recovered Image

Figure 51: Model Resolution Matrix

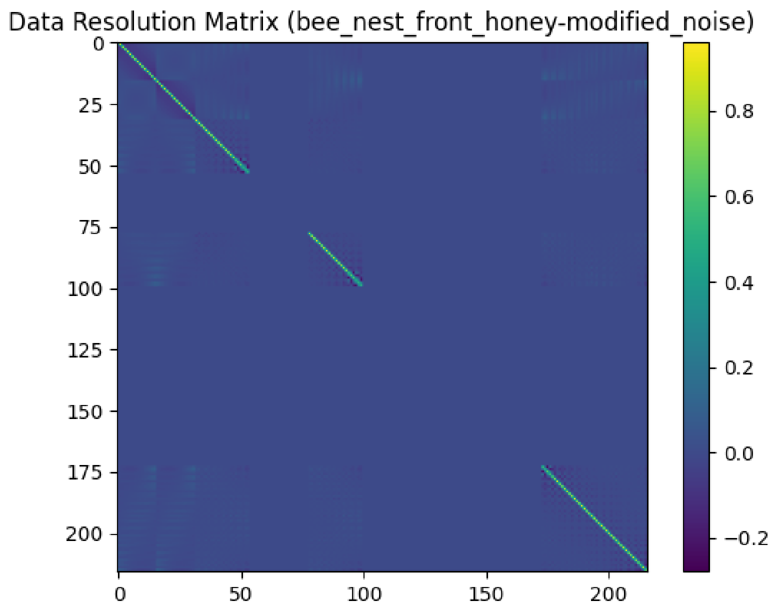

Figure 52: Data Resolution Matrix

- carved_pumpkin-modified_noise

Figure 53: Original Image

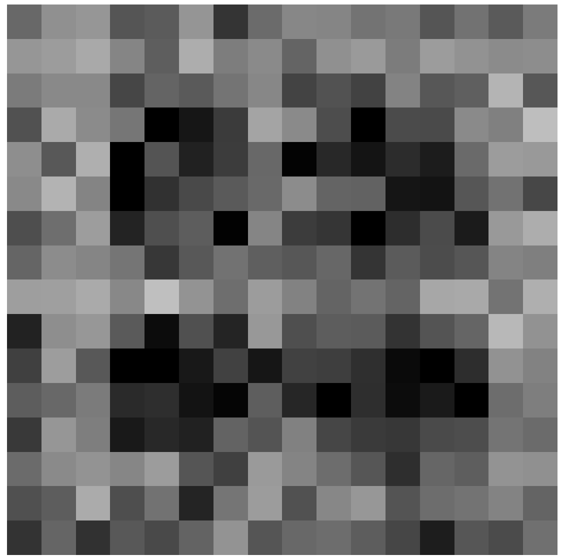

Figure 54: Recovered Image

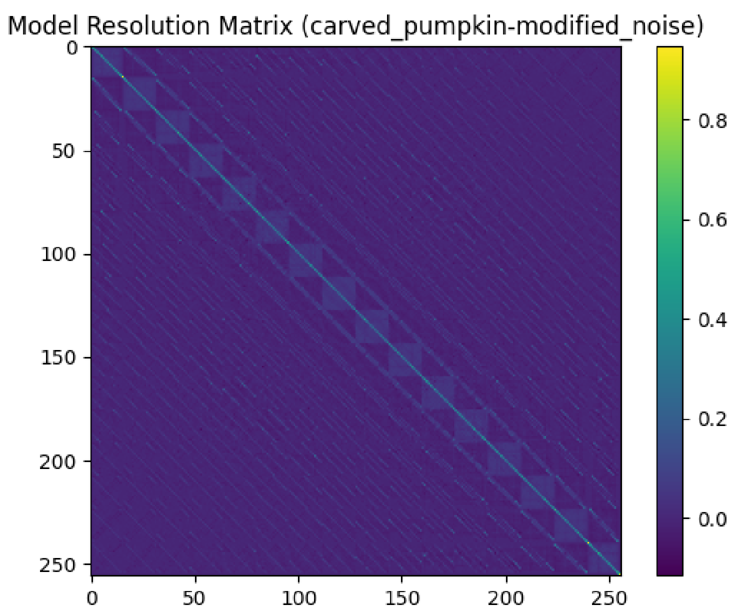

Figure 55: Model Resolution Matrix

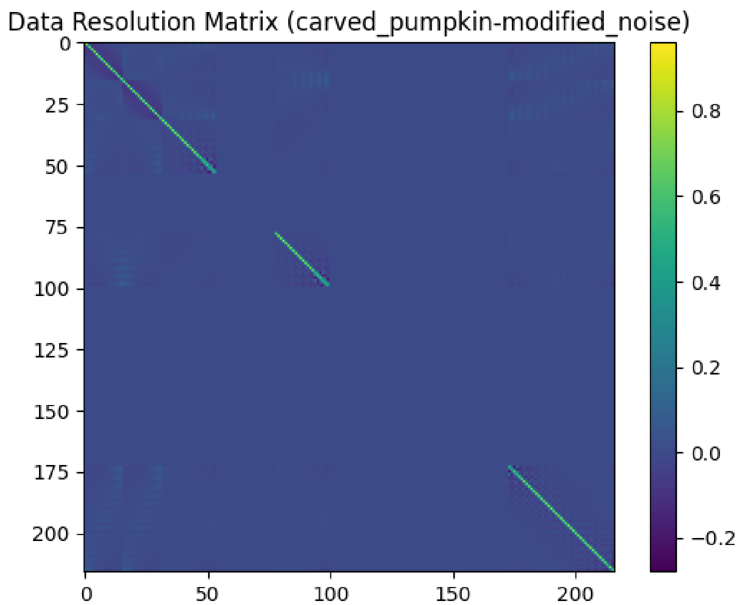

Figure 56: Data Resolution Matrix

- cow_noise

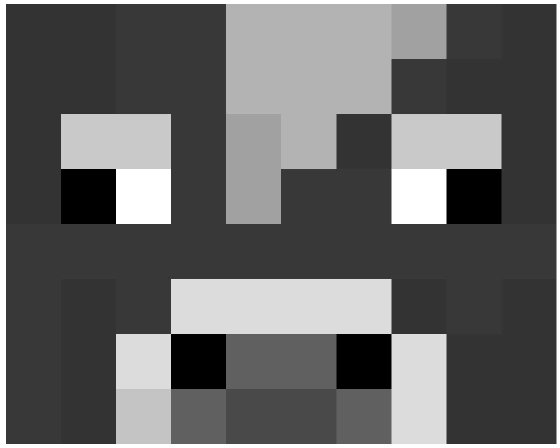

Figure 57: Original Image

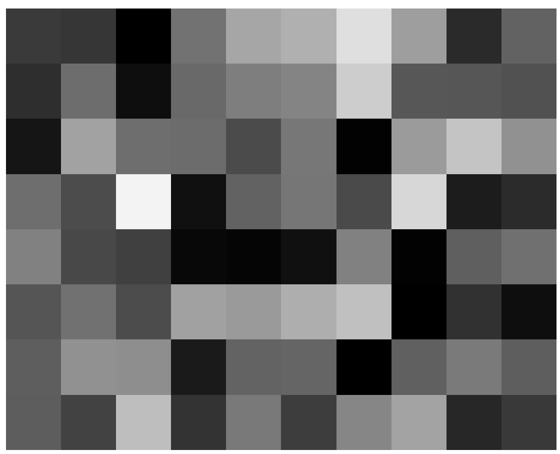

Figure 58: Recovered Image

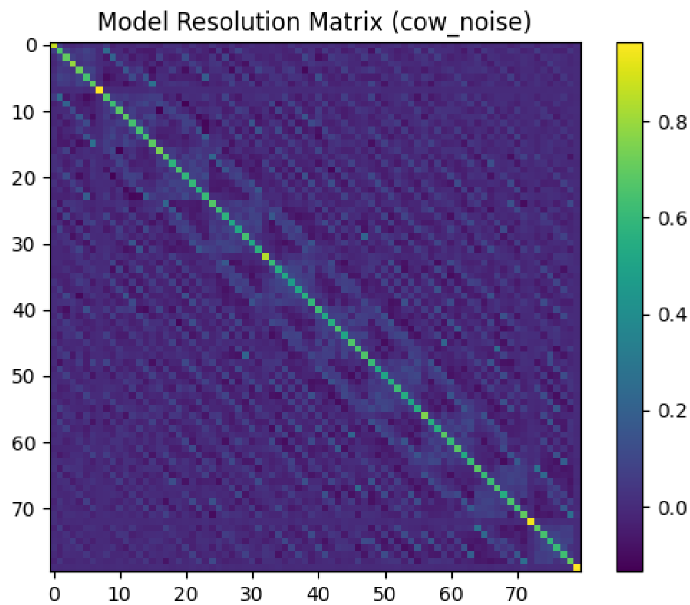

Figure 59: Model Resolution Matrix

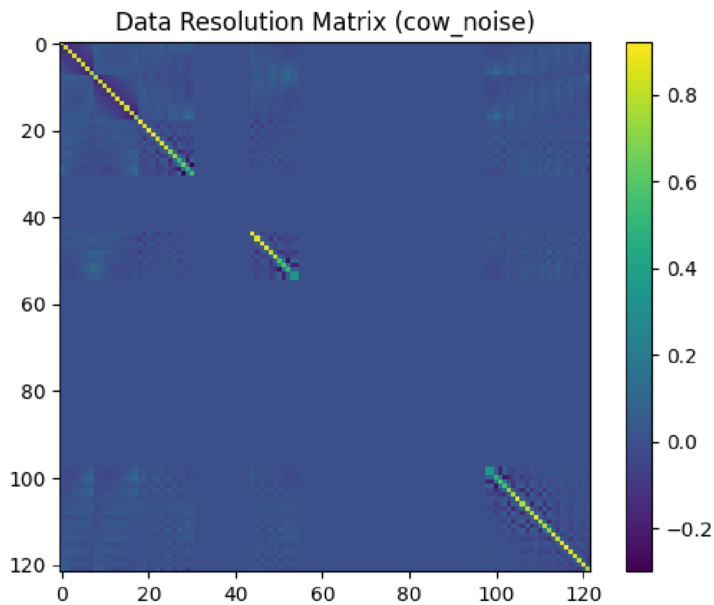

Figure 60: Data Resolution Matrix

- creeper_noise

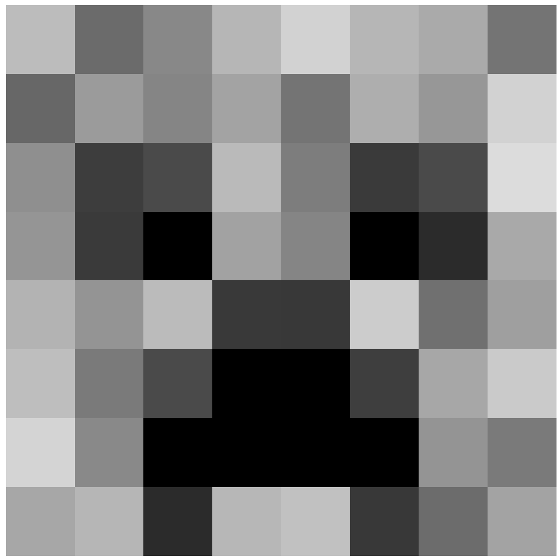

Figure 61: Original Image

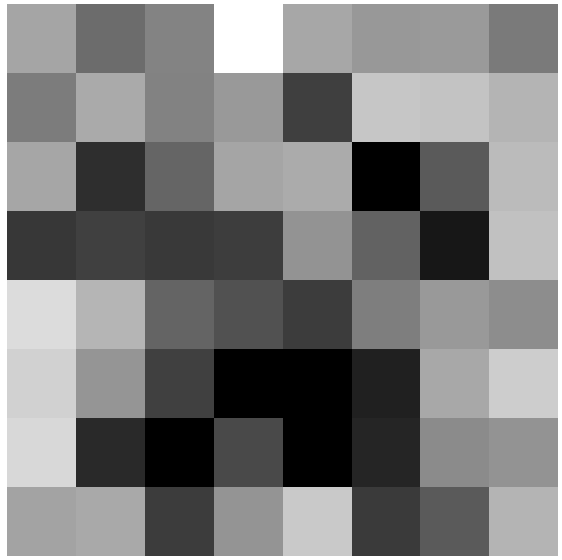

Figure 62: Recovered Image

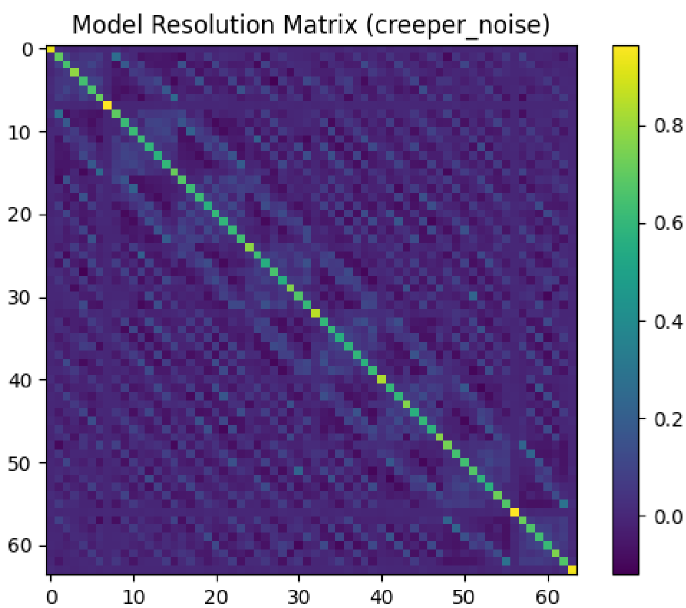

Figure 63: Model Resolution Matrix

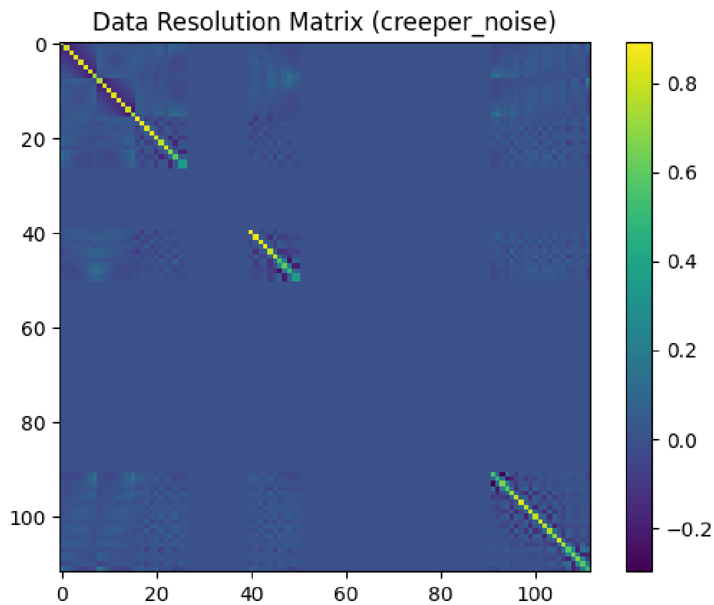

Figure 64: Data Resolution Matrix

- sheep_noise

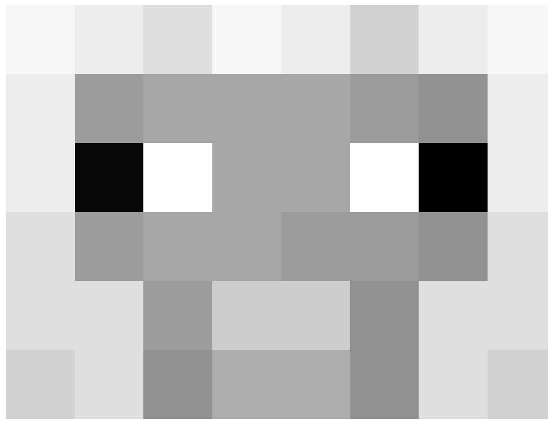

Figure 65: Original Image

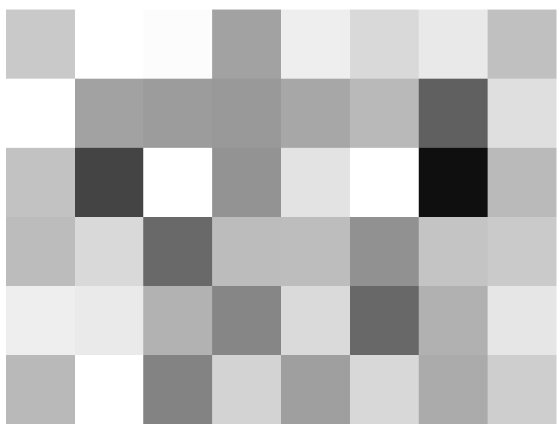

Figure 66: Recovered Image

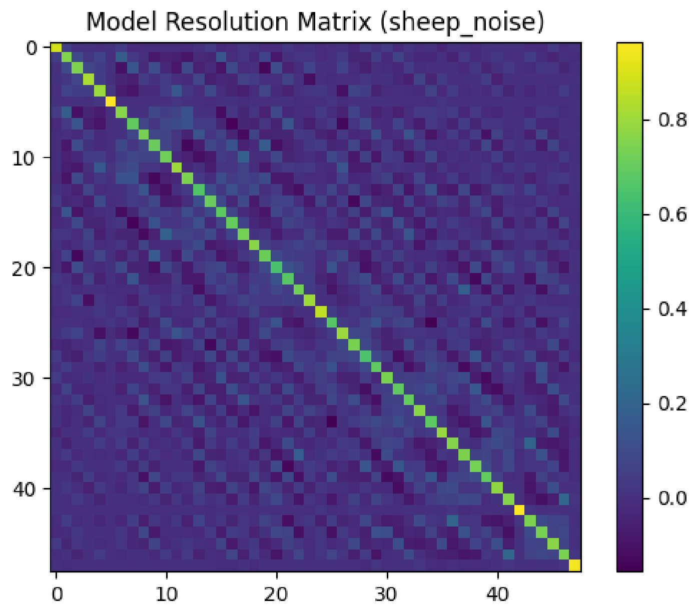

Figure 67: Model Resolution Matrix

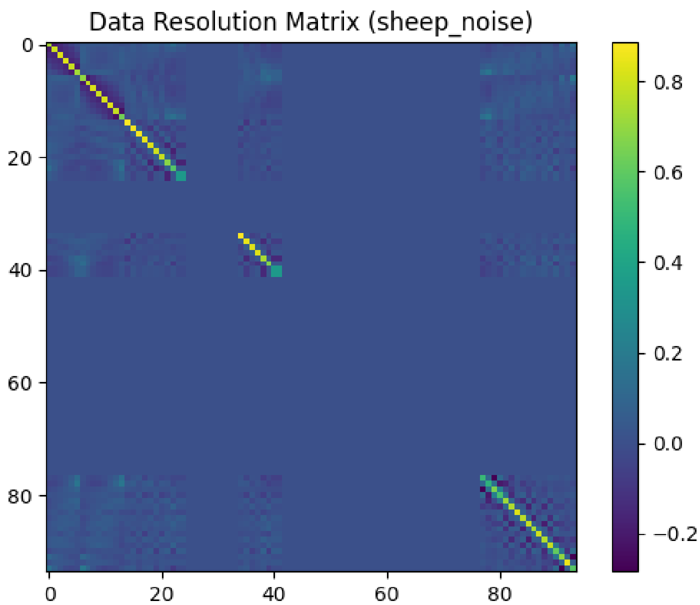

Figure 68: Data Resolution Matrix

- skeleton_noise

Figure 69: Original Image

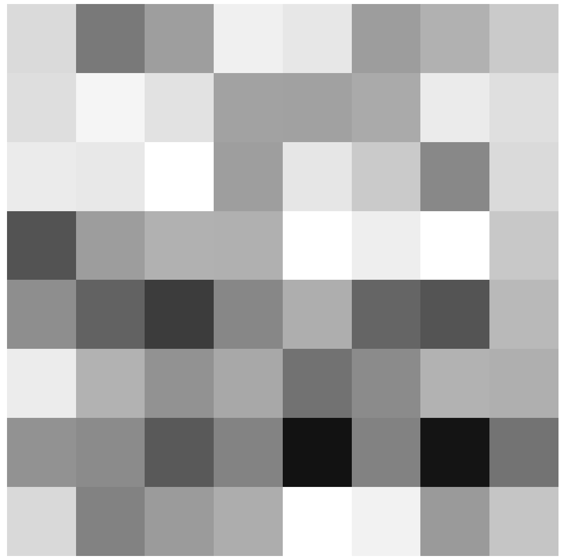

Figure 70: Recovered Image

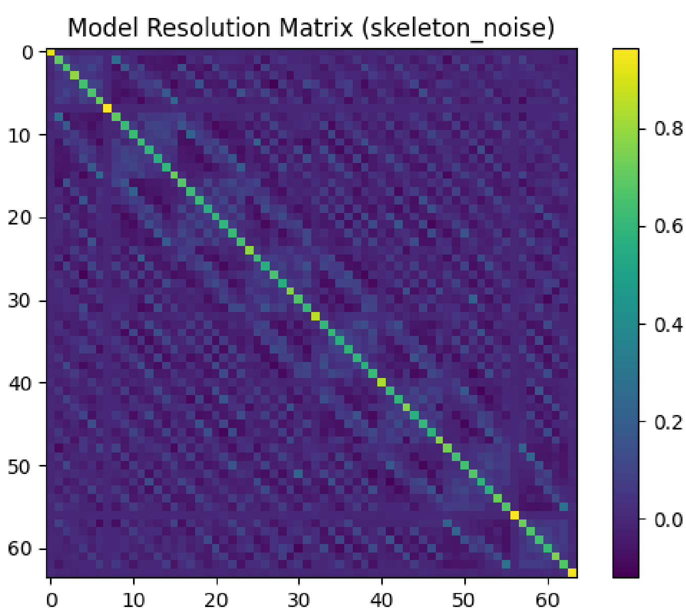

Figure 71: Model Resolution Matrix

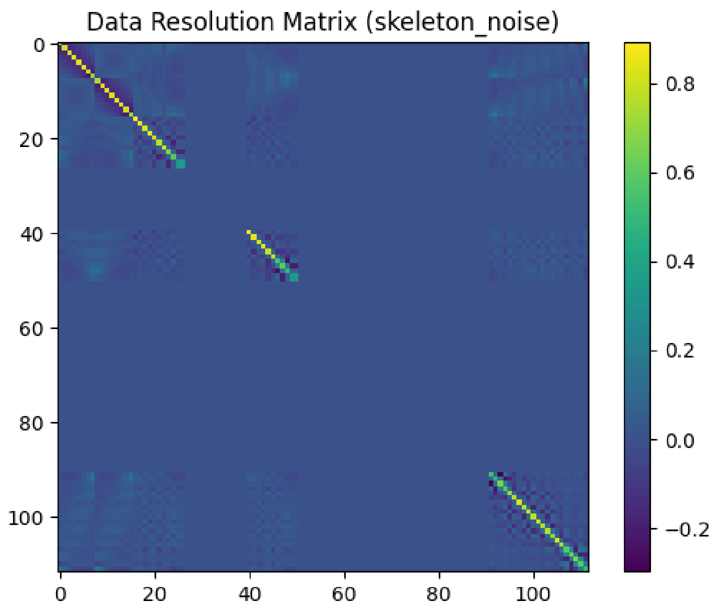

Figure 72: Data Resolution Matrix

- steve_noise

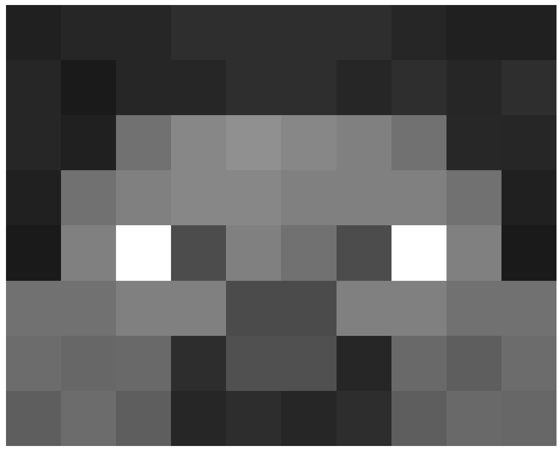

Figure 73: Original Image

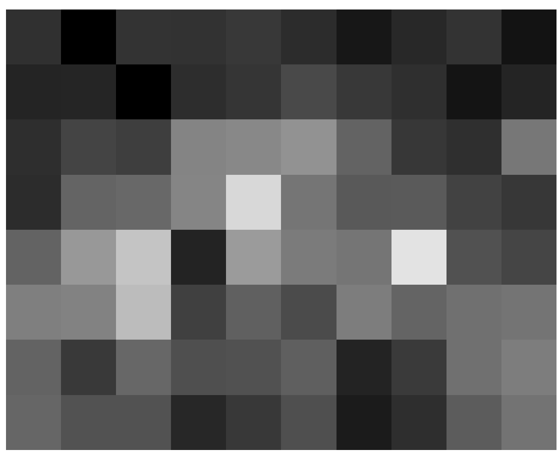

Figure 74: Recovered Image

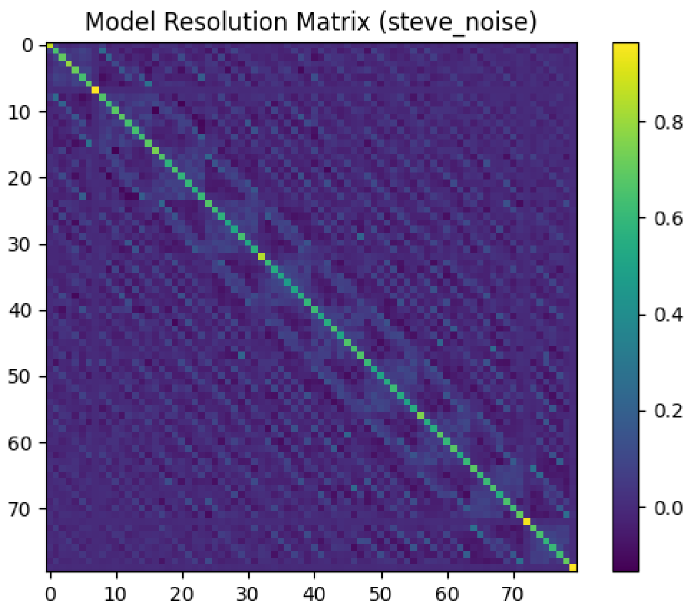

Figure 75: Model Resolution Matrix

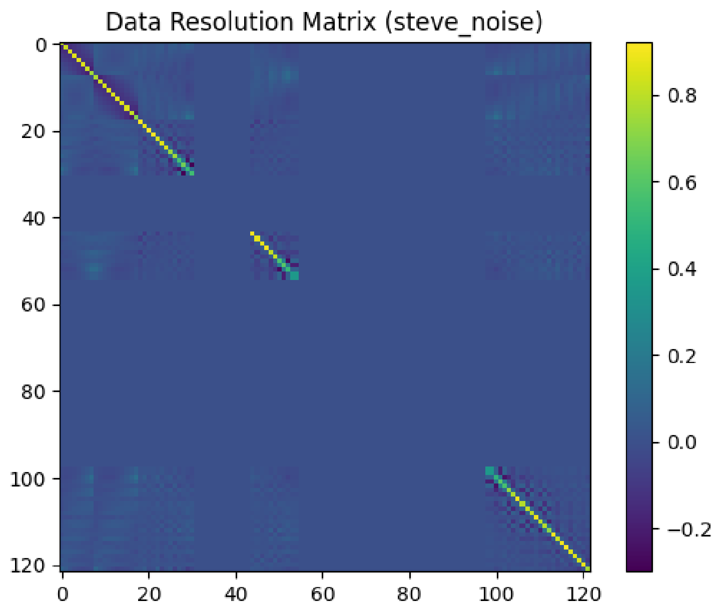

Figure 76: Data Resolution Matrix

- zombie_noise

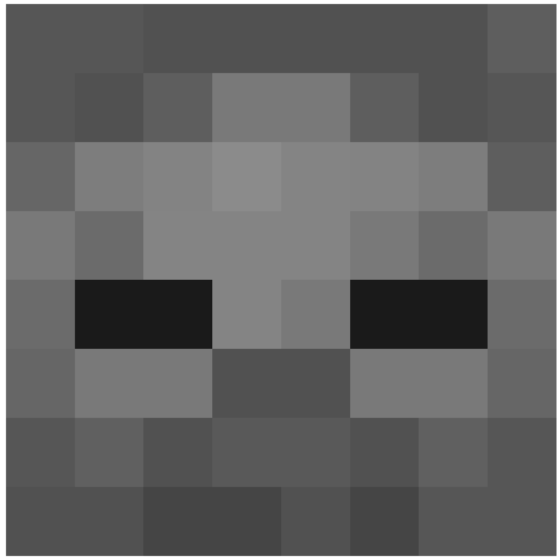

Figure 77: Original Image

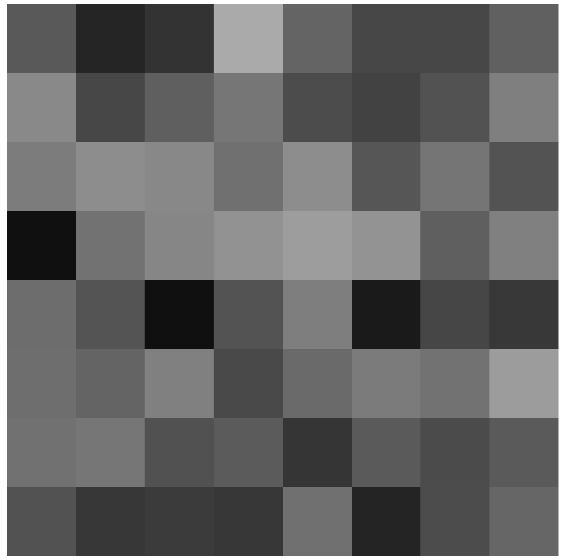

Figure 78: Recovered Image

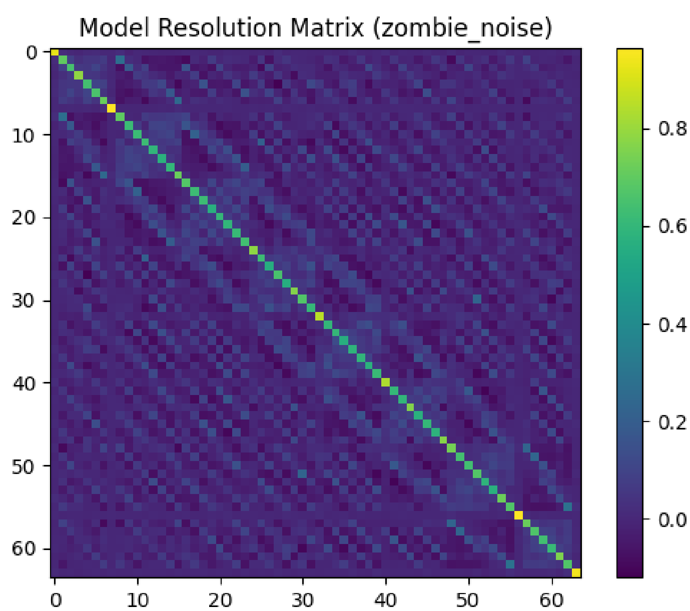

Figure 79: Model Resolution Matrix

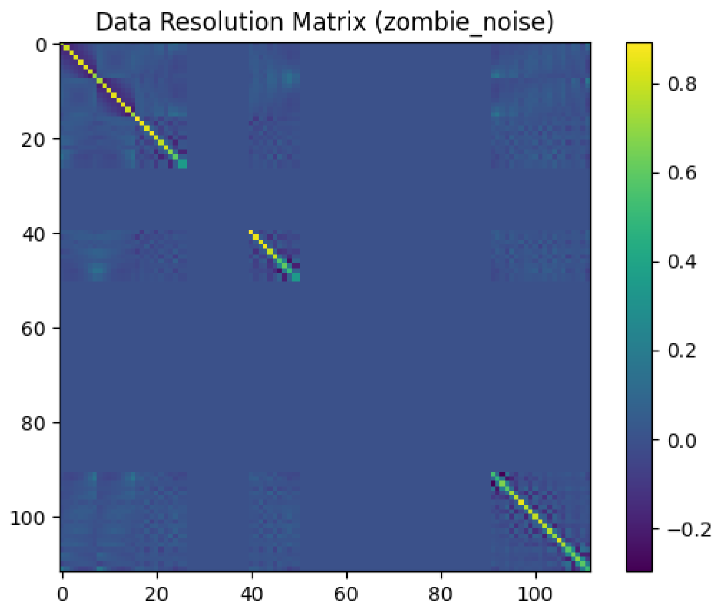

Figure 80: Data Resolution Matrix

2.2 Observations:

- Smaller resolution images were recovered more accurately.
- Images that had more contrast were recovered mroe acurately.
- Images were clearer along the lines of rays used.

3 Appendix Code:

Make folder images
Make subfolders
images/greyscale
images/outputs
images/outputs/datares
images/outputs/modelres
images/outputs/noise
Place your greyscale images in images/greyscale, make sure not to use images with resolution higher than 64x64.

3.1 main.py

```
from matrix_tools import *
from img_tools import *
from grid import *
# note to self everything other than Line is
    generalisable to n dims in this code
def prod(lst):
    p = 1
    for a in lst:
        p *= a
    return p

def arr_indx_to_lst_indx(indx,arr_shape):
    lst_idx = 0
    for i in range(len(indx)):
        lst_idx += indx[i]*prod(arr_shape[:i])
    return lst_idx

def lst_indx_to_arr_indx(indx,arr_shape):
    arr_idx = []
    for i in range(len(arr_shape)-1,-1,-1):
        m = prod(arr_shape[:i])
        idx = indx//m
        indx = indx%m
        arr_idx.append(idx)
```

```
    arr_idx.reverse()
    return arr_idx

with_noise = True

img_names = ["alban-modified","aztec-modified","aztec2-modified","bee_nest_front_honey-modified","carved_pumpkin-modified","cow","creeper","fletching_table_front-modified","grass_block_side-modified","sheep","skeleton","steve","zombie"]
for img_name in img_names:
    img = get_img(img_name+".png")
    arr = get_array(img)

    # img.show()
    img_shape = arr.shape
    print(img_shape)
    new_img = Image.fromarray(arr)
    # new_img.show()

    #making grid for passing light
    grid = Grid(1,dim=2)

    #passing light
    cells_information = []
    # light passing from below to up
    for x in range(img_shape[0]):
        source = (x+0.5,-1)
        ray = Line(91,source)
        cells = get_crossing_cells(grid,ray,((0,
            img_shape[0]),(0,img_shape[1])))
        cells_information.append(cells)
    #light passing from left to right
    for y in range(img_shape[1]):
        source = (-1,y+0.5)
        ray = Line(1,source)
        cells = get_crossing_cells(grid,ray,((0,
            img_shape[0]),(0,img_shape[1])))
        cells_information.append(cells)

    #light passing from diagonals
    line1 = Line(135,(-1,-1))
    num_sources = int(2*mt.ceil((img_shape[0]**2 +
        img_shape[1]**2)**(1/2)))
    sources = line1.get_points_distanced(0.5,
        num_sources)
```

```
    sources.extend(line1.get_points_distanced(-0.5, num_sources))
    for source in sources:
        ray = Line(45,source)
        cells = get_crossing_cells(grid,ray,((0, img_shape[0]),(0,img_shape[1])))
        cells_information.append(cells)

    line2 = Line(45,(img_shape[0]+1,img_shape[1]+1))
    sources = line2.get_points_distanced(0.5, num_sources)
    sources.extend(line2.get_points_distanced(-0.5, num_sources))
    for source in sources:
        ray = Line(135,source)
        cells = get_crossing_cells(grid,ray,((0, img_shape[0]),(0,img_shape[1])))
        cells_information.append(cells)





    #making F and d
    F = np.zeros((len(cells_information),prod( img_shape)))

    for i in range(len(cells_information)):
        # print(i)
        cells = cells_information[i]
        for cell in cells:
            lst_idx = arr_indx_to_lst_indx(cell, img_shape)
            F[i,lst_idx] = 1


    m_real = np.reshape(arr,(prod(img_shape),1))

    d = np.matmul(F,m_real)
    if with_noise:
        img_name += "_noise"
        d = d + 0.05*d*np.random.normal(0,1,d.shape)

    print(F.shape)
    F_dag = tikonov_inverse(F)
    m_est = np.matmul(F_dag,d)
```

```
    model_res = np.matmul(F_dag,F)
    data_res = np.matmul(F,F_dag)
    matrix_img(model_res,"Model Resolution Matrix ("+
        img_name+")")
    plt.savefig("images/outputs/modelres/"+img_name)
    plt.show()
    matrix_img(data_res,"Data Resolution Matrix ("+
        img_name+")")
    plt.savefig("images/outputs/datares/"+img_name)
    plt.show()
    est_arr = np.reshape(m_est,img_shape)
    print(est_arr.shape)
    est_img = Image.fromarray(est_arr)
    est_img.show()
    est_img = est_img.convert('RGB')
    if with_noise:
        est_img.save("images/outputs/noise/"+img_name+
            ".png")
    else:
        est_img.save("images/outputs/"+img_name+".png"
            )
```

3.2 grid.py

```
import math as mt
# module for grid making and using the grid
'''
class makes a grid with cells numbered as (x,y,z)
    with no central cell
The has centroid as coordinate point (0,0,0) is
    located at the intercetion of 8 cells
Grid extends infinitely on all sides
Cells are represented as a tuple of integers
'''

class Grid:
    def __init__(self,cell_dims,dim = 3):
        if not isinstance(cell_dims,tuple):
            self.is_cubic = True
            self.cell_size = cell_dims
            self.cell_dims = tuple([self.cell_size
                ]*dim)
        else:
            self.is_cubic = False
            self.cell_dims = cell_dims
```

```python
        self.dim = dim
    def get_cell(self, coords): #returns which cell the coords belong to
        if not isinstance(coords,tuple):
            raise Exception("Please enter a tuple")
        elif len(coords) != self.dim:
            raise Exception("Coordinate of ",self.dim,"dimensions expected")
        else:
            cell = []
            for i in range(self.dim):
                x = coords[i]
                cell.append(int(x//self.cell_dims[i]))
        return tuple(cell)

    def get_cell_center(self,cell): #returns the center of the cell
        center_coords = []
        for i in range(self.dim):
            l = self.cell_dims[i]*cell[i]
            if l > 0:
                coord = l - 0.5*self.cell_dims[i]
            else:
                coord = l + 0.5*self.cell_dims[i]
            center_coords.append(coord)
        return tuple(center_coords)

class Line:
    #creates a line passing through a point and having angle theta with +X axis (counter clockwise in degrees)
    def __init__(self,theta,point):
        self.theta = theta
        self.point = point
        self.m = mt.tan(mt.radians(theta))
        self.c = point[1]-self.m*point[0]

    def y(self,x):
        return self.m*x+self.c

    def x(self,y):
        return (y-self.c)/self.m

```

```
    def get_point(self,d): #point at distance d from source
        x0, y0 = self.point[0], self.point[1]
        cstheta = mt.cos(mt.radians(self.theta))
        sntheta = mt.sin(mt.radians(self.theta))
        x, y = x0 + d*cstheta, y0 + d*sntheta
        return x,y

    def get_points_distanced(self,s,n): #n points equally distanced (s) from source
        points = []
        for i in range(n):
            d = (i+1)*s
            points.append(self.get_point(d))
        return points

    def get_points_distanced_starting(self,start_dist,s,n):
        points = []
        for i  in range(n):
            d = start_dist + (i+1)*s
            points.append(self.get_point(d))
        return points

def dist(x,y):
    S = 0
    for i,j in zip(x,y):
        S += (i-j)**2
    S **= 1/2
    return S

def get_crossing_cells(grid:Grid,line:Line,rang=((0,1000),(0,1000))): #get all the cells that the line crosses in a given range
    #0 included and 1000 not included
    sizes = []
    for pair in rang:
        sizes.append(pair[1]-pair[0])
    num_points_to_check = 0
    for s in sizes:
        num_points_to_check += s**2
    num_points_to_check **= 1/2
    num_points_to_check = int(mt.ceil(num_points_to_check))
    num_points_to_check *= 2
    points = []
```

```python
        source = line.point
        pos_point1 = (rang[0][0],line.y(rang[0][0]))
        pos_point2 = (rang[0][1],line.y(rang[0][1]))
        pos_point3 = (line.x(rang[1][0]),rang[1][0])
        pos_point4 = (line.x(rang[1][1]),rang[1][1])
        pos_points = [pos_point1,pos_point2,pos_point3,pos_point4]
        to_remove = []
        for pos_point in pos_points:
            if pos_point[0] < rang[0][0] or pos_point[0] > rang[0][1] or pos_point[1] < rang[1][0] or pos_point[1] > rang[1][1]:
                to_remove.append(pos_point)
        for del_point in to_remove:
            pos_points.remove(del_point)
        if pos_points != []:
            pos_points.sort(key= lambda x: dist(source,x))
            closest_pt = pos_points[0]
            # print(closest_pt)
            start_dist = dist(source,closest_pt) - 0.5
            # print(start_dist)
            points.extend(line.get_points_distanced_starting(start_dist,0.5,num_points_to_check))
            points.extend(line.get_points_distanced_starting(start_dist,-0.5,num_points_to_check))
            points.extend(line.get_points_distanced_starting(-start_dist,-0.5,num_points_to_check))
            points.extend(line.get_points_distanced_starting(-start_dist,0.5,num_points_to_check))
        else:
            points = []
        cells = []
        for point in points:
            cell = grid.get_cell(point)
            if cell in cells:
                continue
            for i in range(len(cell)):
                c = cell[i]
                lr = rang[i][0]
                ur = rang[i][1]
                if c < lr or c >= ur:
```

```
                    break
                else:
                    cells.append(cell)

        return cells

    # line = Line(90,(5.5,15))

    # grid = Grid(1,dim=2)
    # cells = get_crossing_cells(grid,line,((0,10)
        ,(0,10)))
    # print(cells)
```

3.3 img_tools.py

```
from PIL import Image
import numpy as np

def get_img(img_name):
    img = Image.open("images/greyscale/"+img_name)
    return img

def get_array(img):
    arr = np.array(img)[:,:,0]
    return arr
```

3.4 matrix_tools.py

```
import numpy as np
import matplotlib.pyplot as plt
np.random.seed(0)

def tikonov_inverse(F:np.ndarray,k = 0.1):
    return np.matmul(np.linalg.inv((np.matmul(F.
        transpose(),F)+k*np.identity(F.shape[1]))),F.
        transpose())

def tikonov_est(F:np.ndarray,d:np.ndarray,k = 0.1):
    return np.matmul(tikonov_inverse(F,k),d)

def generate_random_model(deg:int,rng:tuple):
    '''
    Enter a degree and a range and a model is
        generated for that range and degree
```

```python
    '''
    m = np.random.uniform(low = rng[0], high = rng[1], size = (deg+1,1))
    return m

def gen_random_data(model:np.ndarray,size = 20, noise = 0.1,rng = (-10,10)):
    '''
    Enter a model, and data is generated for that model with added guassian noise
    '''
    f_0 = np.random.uniform(low = rng[0], high = rng[1], size = (size,1))
    F = np.concatenate([f_0**i for i in range(len(model))], axis=1)
    d_true = np.matmul(F,model)
    d = d_true + noise*d_true*np.random.normal(0,1,d_true.shape)
    return F,d

def plot_model(m:np.ndarray,label:str,color:str):
    P = list(m.transpose()[0])
    P.reverse()
    poly_obj = np.poly1d(P)
    X = np.linspace(-10,10,100)
    plt.plot(X,poly_obj(X),label = label,c = color)

def matrix_img(M:np.ndarray,title:str):
    plt.imshow(M)
    plt.title(title)
    plt.colorbar()


# m = generate_random_model(6,(-1,1))
# F,d = gen_random_data(m,size =3 ,noise=0)
# m_est = tikonov_est(F,d,k=1)
# plot_model(m,"True",'g')
# # plot_model(m_est,"Est",'r')
# plt.show()
```