PTI_Experiment_Recon3D_anisotropic_target_small

March 11, 2024

[ ]:
```
# This notebook-style script requires a ~500 MB download from https://www.ebi.
↪ac.uk/biostudies/files/S-BIAD1063/PTI-BIA/Anisotropic_target_small.zip

import numpy as np
import matplotlib.pyplot as plt
from numpy.fft import fftshift

import waveorder as wo
from waveorder import optics, waveorder_reconstructor, util, visual

import zarr
from pathlib import Path
from iohub import open_ome_zarr
```

[ ]:
```
# Initialization

# Experimental parameters
```

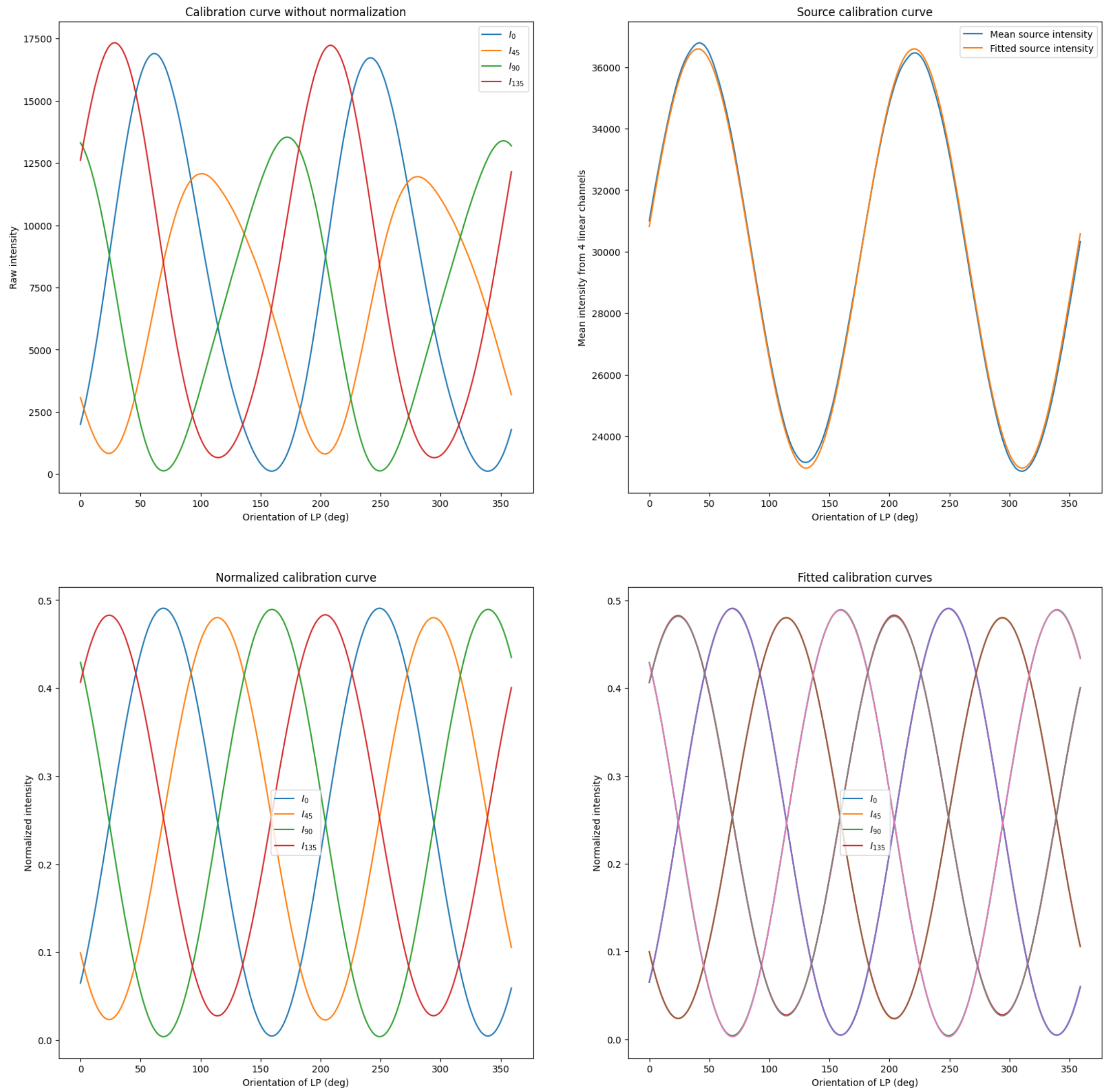
[ ]:
```
n_media = 1.515  # refractive index of the immersed media for objective (oil: 1.
↪512, water: 1.33, air: 1)
lambda_illu = 0.532  # illumination wavelength (um)
mag = 63  # magnification of the microscope
NA_obj = 1.47  # detection NA of the objective
NA_illu = 1.4  # illumination NA of the condenser
N_defocus = 96  # number of defocus images
N_channel = 4  # number of Polscope channels
N_pattern = 9  # number of illumination patterns
z_step = 0.25  # z_step of the stack
z_defocus = (np.r_[:N_defocus] - 0) * z_step  # z positions of the stack
ps = (
    3.45 * 2 / mag
)  # effective pixel size at the sample plane (cam pix/mag in um)
cali = False  # correction for S1/S2 Polscope reconstruction (does not affect␣
↪phase)
bg_option = "global"  # background correction method for Polscope recon (does␣
↪not affect phase)
use_gpu = False  # option to use gpu or not (required cupy)
```

```
gpu_id = 0  # id of gpu to use
```

[ ]:
```
# Load sample images, background images, and calibration data
```

[ ]:
```
# Load data and bg
# Download data from

data_folder = Path(
    "/Users/shalin.mehta/docs/data/waveOrder/Anisotropic_target_small"
)
PTI_file_name = data_folder / "Anisotropic_target_small_raw.zarr"
reader = zarr.open(PTI_file_name, mode="r")
I_meas = np.transpose(
    np.array(reader["Row_0/Col_0/I_meas/array"]), (0, 1, 3, 4, 2)
)
I_bg = np.squeeze(
    np.transpose(np.array(reader["Row_0/Col_1/I_bg/array"]), (0, 1, 3, 4, 2))
)

# Crop the data so that it fits in the GPU memory
I_meas = I_meas[:, :, 50:250, 50:250, :]
I_bg = I_bg[:, :, 50:250, 50:250]

# Load calibration
PTI_file = zarr.open(PTI_file_name, mode="r")
I_cali_mean = np.array(PTI_file.I_cali_mean)

# source polarization, instrument matrix calibration
E_in, A_matrix, I_cali_mean = (
    wo.waveorder_reconstructor.instrument_matrix_and_source_calibration(
        I_cali_mean, handedness="RCP"
    )
)
```

```
Calibrated source field:
[[ 0.7496+0.j     ]
 [-0.1284+0.6494j]]
Calibrated instrument matrix:
[[ 0.2478  0.2433 -0.    ]
 [ 0.252   0.0013  0.2285]
 [ 0.2458 -0.2431 -0.0008]
 [ 0.2543 -0.0016 -0.2277]]
```

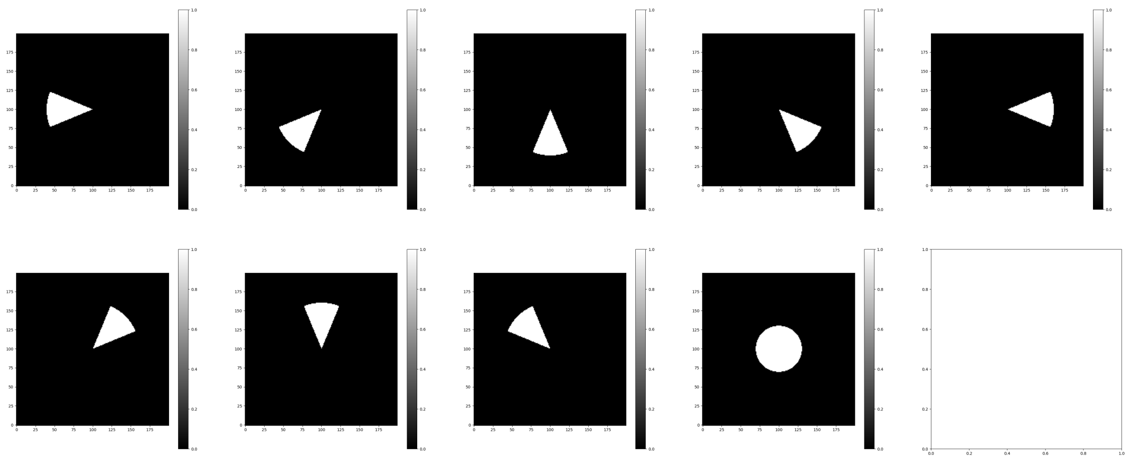


[ ]:
```
# Initiate the reconstruction
```

[ ]:
```
# setup illumination patterns
_, _, Ns, Ms, _ = I_meas.shape

xx, yy, fxx, fyy = util.gen_coordinate((Ns, Ms), ps)
frr = np.sqrt(fxx**2 + fyy**2)

rotation_angle = [
    180 - 22.5,
    225 - 22.5,
    270 - 22.5,
    315 - 22.5,
```

```python
    0 - 22.5,
    45 - 22.5,
    90 - 22.5,
    135 - 22.5,
]
sector_angle = 45

Source_BF = np.array(
    optics.generate_pupil(frr, NA_obj / n_media / 2, lambda_illu / n_media)
)
Source = optics.gen_sector_Pupil(
    fxx,
    fyy,
    NA_obj / n_media,
    lambda_illu / n_media,
    sector_angle,
    rotation_angle,
)
Source.append(Source_BF)
Source = np.array(Source)

# setup polarization state of the illumination
Source_PolState = np.zeros((len(Source), 2), complex)

for i in range(len(Source)):
    Source_PolState[i, 0] = E_in[0]
    Source_PolState[i, 1] = E_in[1]


visual.plot_multicolumn(
    fftshift(Source, axes=(1, 2)), origin="lower", num_col=5
)
```

```
<ipython-input-7-b7a9c1d2dc8b>:38: DeprecationWarning: Conversion of an array
with ndim > 0 to a scalar is deprecated, and will error in future. Ensure you
extract a single element from your array before performing this operation.
(Deprecated NumPy 1.25.)
  Source_PolState[i, 0] = E_in[0]
<ipython-input-7-b7a9c1d2dc8b>:39: DeprecationWarning: Conversion of an array
with ndim > 0 to a scalar is deprecated, and will error in future. Ensure you
extract a single element from your array before performing this operation.
(Deprecated NumPy 1.25.)
  Source_PolState[i, 1] = E_in[1]
```



[ ]:

```python
# Initiate reconstruction with experimental parameters
setup = waveorder_reconstructor.waveorder_microscopy(
    (Ns, Ms),
    lambda_illu,
    ps,
    NA_obj,
    NA_illu,
    z_defocus,
    n_media=n_media,
    cali=cali,
    bg_option=bg_option,
    A_matrix=A_matrix,
    phase_deconv=None,
    inc_recon="3D",
    illu_mode="Arbitrary",
    Source=Source,
    Source_PolState=Source_PolState,
    use_gpu=use_gpu,
    gpu_id=gpu_id,
)
```

```
/Users/shalin.mehta/docs/code/waveorder/waveorder/optics.py:321: UserWarning: To
copy construct from a tensor, it is recommended to use
sourceTensor.clone().detach() or
sourceTensor.clone().detach().requires_grad_(True), rather than
torch.tensor(sourceTensor).
  * torch.tensor(z_position_list)[:, None, None]
/Users/shalin.mehta/docs/code/waveorder/waveorder/optics.py:370: UserWarning: To
copy construct from a tensor, it is recommended to use
sourceTensor.clone().detach() or
sourceTensor.clone().detach().requires_grad_(True), rather than
torch.tensor(sourceTensor).
```

```
* torch.tensor(z_position_list)[:, None, None]
```

[ ]:
```
# Compute Stokes volumes and visualize intensity & stokes volumes.

# convert intensity to Stokes parameters
S_image_recon = setup.Stokes_recon(I_meas[:, :, :, :, ::-1])
S_bg_recon = setup.Stokes_recon(I_bg[:, :, :, :])

# background correction to all the Stokes parameter
S_image_tm = np.zeros_like(S_image_recon)
S_image_tm[0] = S_image_recon[0] / S_bg_recon[0, :, :, :, np.newaxis] - 1
S_image_tm[1] = (
    S_image_recon[1] / S_bg_recon[0, :, :, :, np.newaxis]
    - S_bg_recon[1, :, :, :, np.newaxis]
    * S_image_recon[0]
    / S_bg_recon[0, :, :, :, np.newaxis] ** 2
)
S_image_tm[2] = (
    S_image_recon[2] / S_bg_recon[0, :, :, :, np.newaxis]
    - S_bg_recon[2, :, :, :, np.newaxis]
    * S_image_recon[0]
    / S_bg_recon[0, :, :, :, np.newaxis] ** 2
)
```

[ ]:
```
# browse raw intensity stacks (stack_idx_1: z index, stack_idx2: pattern index)
visual.parallel_5D_viewer(
    np.transpose(I_meas[:, :, :, :, ::-1], (4, 1, 0, 2, 3)),
    num_col=4,
    size=10,
    origin="lower",
)
```

```
interactive(children=(IntSlider(value=0, description='stack_idx_1', max=95),␣
↪IntSlider(value=0, description='s…
```

[ ]:
```
<function
waveorder.visual.parallel_5D_viewer.<locals>.interact_plot(stack_idx_1,
stack_idx_2)>
```

[ ]:
```
# browse uncorrected Stokes parameters (stack_idx_1: z index, stack_idx2:␣
↪pattern index)
visual.parallel_5D_viewer(
    np.transpose(S_image_recon, (4, 1, 0, 2, 3)),
    num_col=3,
    size=8,
    set_title=True,
    origin="lower",
```

```
    titles=[r"$S_0$", r"$S_1$", r"$S_2$"],
)
```

```
interactive(children=(IntSlider(value=0, description='stack_idx_1', max=95),␣
↪IntSlider(value=0, description='s…
```

[ ]:
```
<function
waveorder.visual.parallel_5D_viewer.<locals>.interact_plot(stack_idx_1,
stack_idx_2)>
```

[ ]:
```
# browse corrected Stokes parameters (stack_idx_1: z index, stack_idx2: pattern␣
↪index)
visual.parallel_5D_viewer(
    np.transpose(S_image_tm, (4, 1, 0, 2, 3)),
    num_col=3,
    size=8,
    origin="lower",
    titles=[r"$S_0$", r"$S_1$", r"$S_2$"],
    set_title=True,
)
```

```
interactive(children=(IntSlider(value=0, description='stack_idx_1', max=95),␣
↪IntSlider(value=0, description='s…
```

[ ]:
```
<function
waveorder.visual.parallel_5D_viewer.<locals>.interact_plot(stack_idx_1,
stack_idx_2)>
```

[ ]:
```
# 3D PTI reconstruction
```

[ ]:
```
# 3D volumes of the components of scattering potential tensor
```

[ ]:
```
# regularization on each component of the scattering potential tensor
# in the order of [0r, 0i, 1c, 1s, 2c, 2s, 3]
# It is good to set the regularization such that (1c, 1s), (2c, 2s) have the␣
↪same regularization
reg_inc = np.array([2.5, 5, 1, 1, 3, 3, 3]) * 1

# regulairzation for estimating differential permittivity
reg_differential_permittivity = 1e-2

# reconstruct components of scattering potential tensor
f_tensor = setup.scattering_potential_tensor_recon_3D_vec(
    S_image_tm, reg_inc=reg_inc, cupy_det=True
)
```

```
Finished preprocess, elapsed time: 5.92
Finished reconstruction, elapsed time: 35.94
```

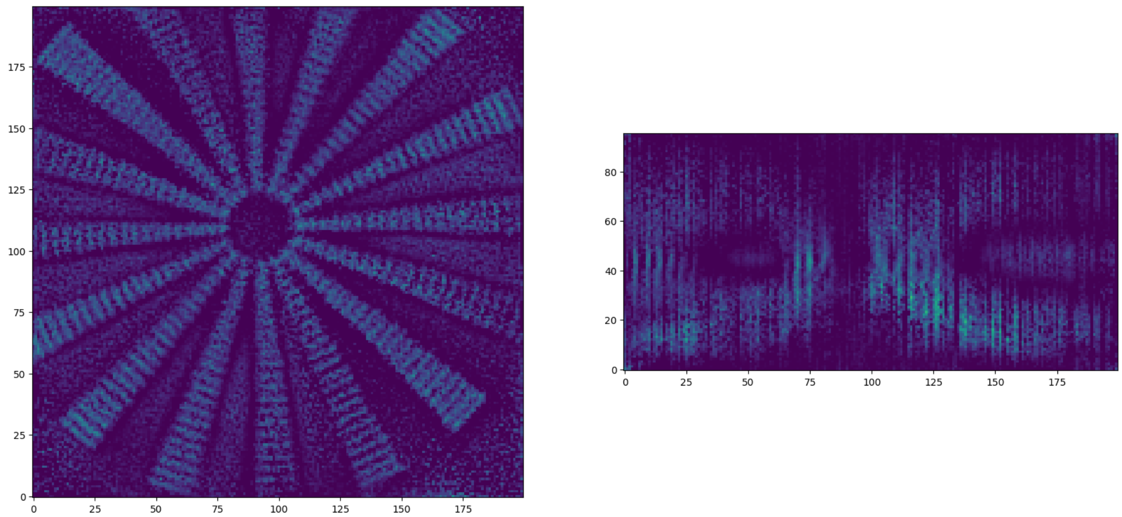
[ ]:
```
# browse the z-stack of components of scattering potential tensor
visual.parallel_4D_viewer(
    np.transpose(f_tensor, (3, 0, 1, 2)),
    num_col=4,
    origin="lower",
    size=8,
    titles=[
        r"$f_{0r}$",
        r"$f_{0i}$",
        r"$f_{1c}$",
        r"$f_{1s}$",
        r"$f_{2c}$",
        r"$f_{2s}$",
        r"$f_{3}$",
    ],
    set_title=True,
)
```

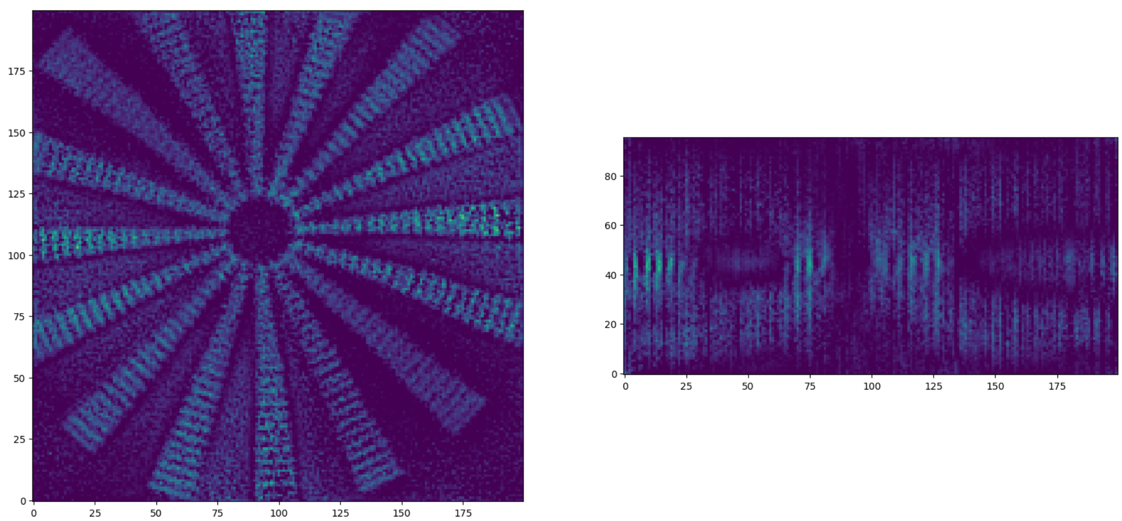
```
interactive(children=(IntSlider(value=0, description='stack_idx', max=95),␣
↪Output()), _dom_classes=('widget-in…
```

[ ]:
```
<function waveorder.visual.parallel_4D_viewer.<locals>.interact_plot(stack_idx)>
```

[ ]:
```
# reconstruct 3D anisotropy (differential permittivity, 3D orientation, optic␣
↪sign probability)
# material type:
# "positive" -> only solution of positively uniaxial material
# "negative" -> only solution of negatively uniaxial material
# "unknown" -> both solutions of positively and negatively uniaxial material +␣
↪optic sign estimation

differential_permittivity, azimuth, theta, mat_map = (
    setup.scattering_potential_tensor_to_3D_orientation(
        f_tensor,
        S_image_tm,
        material_type="unknown",
        reg_ret_pr=reg_differential_permittivity,
        itr=10,
        fast_gpu_mode=True,
    )
)
```

```
|   10   |  5.08e+11  |    67.70    |
Finish optic sign estimation, elapsed time: 67.74
```






```
[ ]: p_mat_map = optics.optic_sign_probability(mat_map, mat_map_thres=0.2)
     phase = optics.phase_inc_correction(
         f_tensor[0], differential_permittivity[1], theta[1]
     )
     phase_PT, absorption_PT, differential_permittivity_PT = [
         optics.unit_conversion_from_scattering_potential_to_permittivity(
             SP_array, lambda_illu, n_media=n_media, imaging_mode="3D"
         )
         for SP_array in [phase, f_tensor[1].copy(), differential_permittivity]
     ]
     differential_permittivity_PT = np.array(
         [
             ((-1) ** i)
```

```
        * util.wavelet_softThreshold(
            ((-1) ** i) * differential_permittivity_PT[i],
            "db8",
            0.00303,
            level=1,
        )
        for i in range(2)
    ]
)
```

[ ]:
```
# Visualize reconstructed physical properties of the anisotropic glass target
```

[ ]:
```
# Reconstructed phase, absorption, differential permittivity, azimuth, and␣
↪inclination assuming (+) and (-) optic sign
```

[ ]:
```
# browse the reconstructed physical properties
visual.parallel_4D_viewer(
    np.transpose(
        np.stack(
            [
                phase_PT,
                differential_permittivity_PT[0],
                azimuth[0],
                theta[0],
                absorption_PT,
                differential_permittivity_PT[1],
                azimuth[1],
                theta[1],
            ]
        ),
        (3, 0, 1, 2),
    ),
    num_col=4,
    origin="lower",
    set_title=True,
    titles=[
        r"phase",
        r"differential permittivity (+)",
        r"$\omega$ (+)",
        r"$\theta$ (+)",
        r"absorption",
        r"differential permittivity (-)",
        r"$\omega$ (-)",
        r"$\theta$ (-)",
    ],
)
```

```
interactive(children=(IntSlider(value=0, description='stack_idx', max=95),␣
↪Output()), _dom_classes=('widget-in…
```

[ ]: <function waveorder.visual.parallel_4D_viewer.<locals>.interact_plot(stack_idx)>

[ ]:
```
# Save the reconstructed scattering potential tensor to an OME zarr store for␣
↪viewing in napari.
# For best results:
# > pip install napari[all]
# > pip install napari-ome-zarr
# > napari Anisotropic_target_small_processed_OME.zarr
PTI_output_OME_file = (
    data_folder / "Anisotropic_target_small_processed_OME.zarr"
)
output_channel_names = [
    "f_0r",
    "f_0i",
    "f_1c",
    "f_1s",
    "f_2c",
    "f_2s",
    "f_3",
    "phase",
    "absorption",
    "differential_permittivity (-)",
    "azimuth (-)",
    "theta (-)",
]
with open_ome_zarr(
    PTI_output_OME_file,
    layout="fov",
    mode="a",
    channel_names=output_channel_names,
) as writer:
    zyx_shape = f_tensor.shape[1:][::-1]
    array = writer.create_zeros(
        name="0",
        shape=(
            1,
            12,
        )
        + zyx_shape,
        dtype=np.float32,
        chunks=(
            1,
            1,
        )
```

```
        + zyx_shape,
    )
    array[0, :7] = np.transpose(f_tensor, (0, 3, 1, 2))
    array[0, 7] = np.transpose(phase_PT, (2, 1, 0))
    array[0, 8] = np.transpose(absorption_PT, (2, 1, 0))
    array[0, 9] = np.transpose(differential_permittivity_PT[1], (2, 1, 0))
    array[0, 10] = np.transpose(azimuth[1], (2, 1, 0))
    array[0, 11] = np.transpose(theta[1], (2, 1, 0))
```

[ ]:
```
# Load the processed results
# This loads an precomputed store, so this cell does not depend on earlier␣
↪cells.
PTI_output_file = data_folder / "Anisotropic_target_small_processed.zarr"
reader = zarr.open(PTI_output_file, mode="r")
PTI_array = np.array(reader["Row_0/Col_0/f_tensor/array"])
print(PTI_array.shape)
PTI_array = np.transpose(PTI_array, (0, 1, 3, 4, 2))[0]
f_tensor = PTI_array[:7]
mat_map = PTI_array[7:]

# compute the physical properties from the scattering potential tensor

differential_permittivity_p, azimuth_p, theta_p = (
    optics.scattering_potential_tensor_to_3D_orientation_PN(
        f_tensor,
        material_type="positive",
        reg_ret_pr=reg_differential_permittivity,
    )
)
differential_permittivity_n, azimuth_n, theta_n = (
    optics.scattering_potential_tensor_to_3D_orientation_PN(
        f_tensor,
        material_type="negative",
        reg_ret_pr=reg_differential_permittivity,
    )
)
differential_permittivity = np.array(
    [differential_permittivity_p, differential_permittivity_n]
)
azimuth = np.array([azimuth_p, azimuth_n])
theta = np.array([theta_p, theta_n])

p_mat_map = optics.optic_sign_probability(mat_map, mat_map_thres=0.09)
phase = optics.phase_inc_correction(
    f_tensor[0], differential_permittivity[1], theta[1]
)
phase_PT, absorption_PT, differential_permittivity_PT = [
```

```
    optics.unit_conversion_from_scattering_potential_to_permittivity(
        SP_array, lambda_illu, n_media=n_media, imaging_mode="3D"
    )
    for SP_array in [phase, f_tensor[1].copy(), differential_permittivity]
]
differential_permittivity_PT = np.array(
    [
        ((-1) ** i)
        * util.wavelet_softThreshold(
            ((-1) ** i) * differential_permittivity_PT[i],
            "db8",
            0.00303,
            level=1,
        )
        for i in range(2)
    ]
)
```

```
(1, 9, 96, 200, 200)
```

[ ]:
```
# mean permittivity (phase and absorption), differential permittivity, azimuth,␣
↪inclination, and optic sign reconstruction

# mean permittivity reports the isotropic component of the permittivity tensor,␣
↪and the differential permittivity reports the anisotropic component of the␣
↪permittivity tensor.
# phase is the real component of the mean permittivity, and absorption is the␣
↪imaginary component of the mean permittivity.
# The azimuth and inclination report the 3D orientation of the optic axis of␣
↪the anisotropic material.
# The optic sign reports whether the material is positively or negatively␣
↪uniaxial.
```

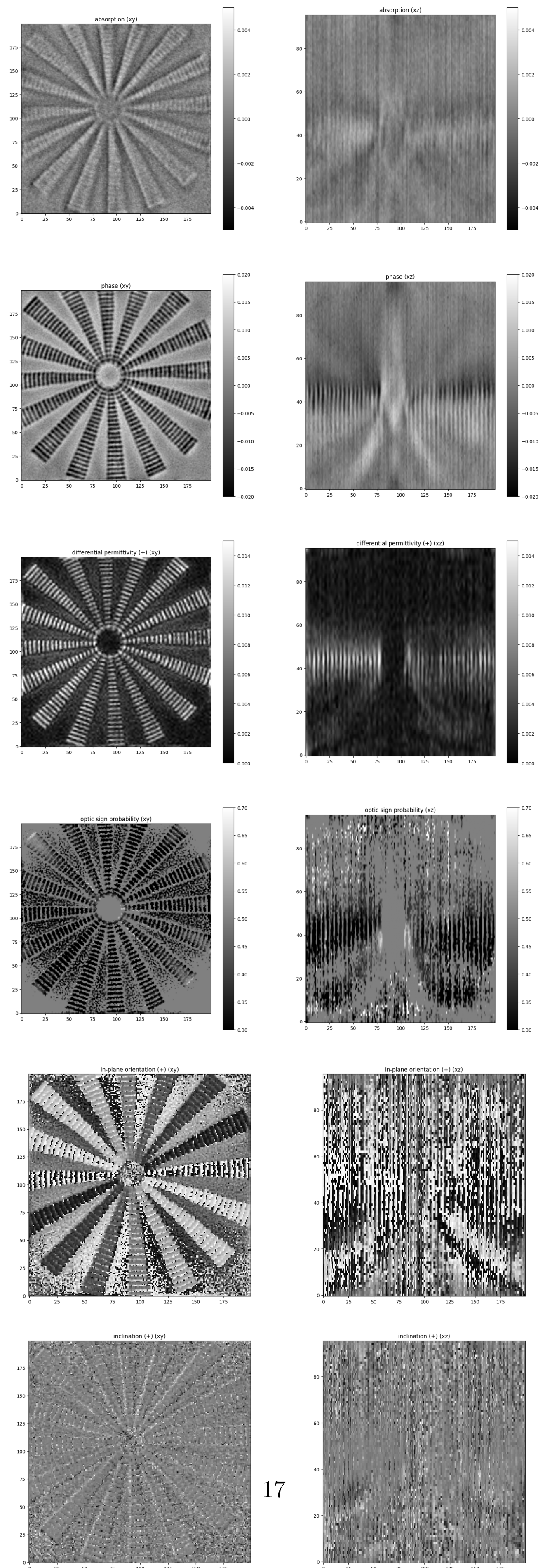
[ ]:
```
z_layer = 44
y_layer = 109
phase_min = -0.02
phase_max = 0.02
abs_min = -0.005
abs_max = 0.005
ret_min = 0
ret_max = 0.015
p_min = 0.3
p_max = 0.7

fig, ax = plt.subplots(6, 2, figsize=(20, 60))
sub_ax = ax[0, 0].imshow(
    absorption_PT[:, :, z_layer],
```

```
    cmap="gray",
    origin="lower",
    vmin=abs_min,
    vmax=abs_max,
)
ax[0, 0].set_title("absorption (xy)")
plt.colorbar(sub_ax, ax=ax[0, 0])

sub_ax = ax[0, 1].imshow(
    np.transpose(absorption_PT[y_layer, :, :]),
    cmap="gray",
    origin="lower",
    vmin=abs_min,
    vmax=abs_max,
    aspect=z_step / ps,
)
ax[0, 1].set_title("absorption (xz)")
plt.colorbar(sub_ax, ax=ax[0, 1])

sub_ax = ax[1, 0].imshow(
    phase_PT[:, :, z_layer],
    cmap="gray",
    origin="lower",
    vmin=phase_min,
    vmax=phase_max,
)
ax[1, 0].set_title("phase (xy)")
plt.colorbar(sub_ax, ax=ax[1, 0])

sub_ax = ax[1, 1].imshow(
    np.transpose(phase_PT[y_layer, :, :]),
    cmap="gray",
    origin="lower",
    vmin=phase_min,
    vmax=phase_max,
    aspect=z_step / ps,
)
ax[1, 1].set_title("phase (xz)")
plt.colorbar(sub_ax, ax=ax[1, 1])

sub_ax = ax[2, 0].imshow(
    np.abs(differential_permittivity_PT[0, :, :, z_layer]),
    cmap="gray",
    origin="lower",
    vmin=ret_min,
    vmax=ret_max,
)
```

```
ax[2, 0].set_title("differential permittivity (+) (xy)")
plt.colorbar(sub_ax, ax=ax[2, 0])

sub_ax = ax[2, 1].imshow(
    np.transpose(np.abs(differential_permittivity_PT[0, y_layer, :, :])),
    cmap="gray",
    origin="lower",
    vmin=ret_min,
    vmax=ret_max,
    aspect=z_step / ps,
)
ax[2, 1].set_title("differential permittivity (+) (xz)")
plt.colorbar(sub_ax, ax=ax[2, 1])

sub_ax = ax[3, 0].imshow(
    np.abs(p_mat_map[:, :, z_layer]),
    cmap="gray",
    origin="lower",
    vmin=p_min,
    vmax=p_max,
)
ax[3, 0].set_title("optic sign probability (xy)")
plt.colorbar(sub_ax, ax=ax[3, 0])

sub_ax = ax[3, 1].imshow(
    np.transpose(np.abs(p_mat_map[y_layer, :, :])),
    cmap="gray",
    origin="lower",
    vmin=p_min,
    vmax=p_max,
    aspect=z_step / ps,
)
ax[3, 1].set_title("optic sign probability (xz)")
plt.colorbar(sub_ax, ax=ax[3, 1])

sub_ax = ax[4, 0].imshow(
    azimuth[0, :, :, z_layer], cmap="gray", origin="lower", vmin=0, vmax=np.pi
)
ax[4, 0].set_title("in-plane orientation (+) (xy)")

sub_ax = ax[4, 1].imshow(
    np.transpose(azimuth[0, y_layer, :, :]),
    cmap="gray",
    origin="lower",
    vmin=0,
    vmax=np.pi,
    aspect=z_step / ps,
```

```
)
ax[4, 1].set_title("in-plane orientation (+) (xz)")

sub_ax = ax[5, 0].imshow(
    theta[0, :, :, z_layer], cmap="gray", origin="lower", vmin=0, vmax=np.pi
)
ax[5, 0].set_title("inclination (+) (xy)")

sub_ax = ax[5, 1].imshow(
    np.transpose(theta[0, y_layer, :, :]),
    cmap="gray",
    origin="lower",
    vmin=0,
    vmax=np.pi,
    aspect=z_step / ps,
)
ax[5, 1].set_title("inclination (+) (xz)")
```

[ ]: Text(0.5, 1.0, 'inclination (+) (xz)')


absorption (xy)
absorption (xz)
phase (xy)
phase (xz)
differential permittivity (+) (xy)
differential permittivity (+) (xz)
optic sign probability (xy)
optic sign probability (xz)
in-plane orientation (+) (xy)
in-plane orientation (+) (xz)
inclination (+) (xy)
inclination (+) (xz)

[ ]:
```
# browse XY planes of the phase and differential permittivity
visual.parallel_4D_viewer(
    np.transpose(
        [
            np.clip(phase_PT, phase_min, phase_max),
            np.clip(np.abs(differential_permittivity_PT[1]), ret_min, ret_max),
        ],
        (3, 0, 1, 2),
    ),
    origin="lower",
    size=20,
)
```

```
interactive(children=(IntSlider(value=0, description='stack_idx', max=95),␣
↪Output()), _dom_classes=('widget-in…
```

[ ]:
```
<function waveorder.visual.parallel_4D_viewer.<locals>.interact_plot(stack_idx)>
```

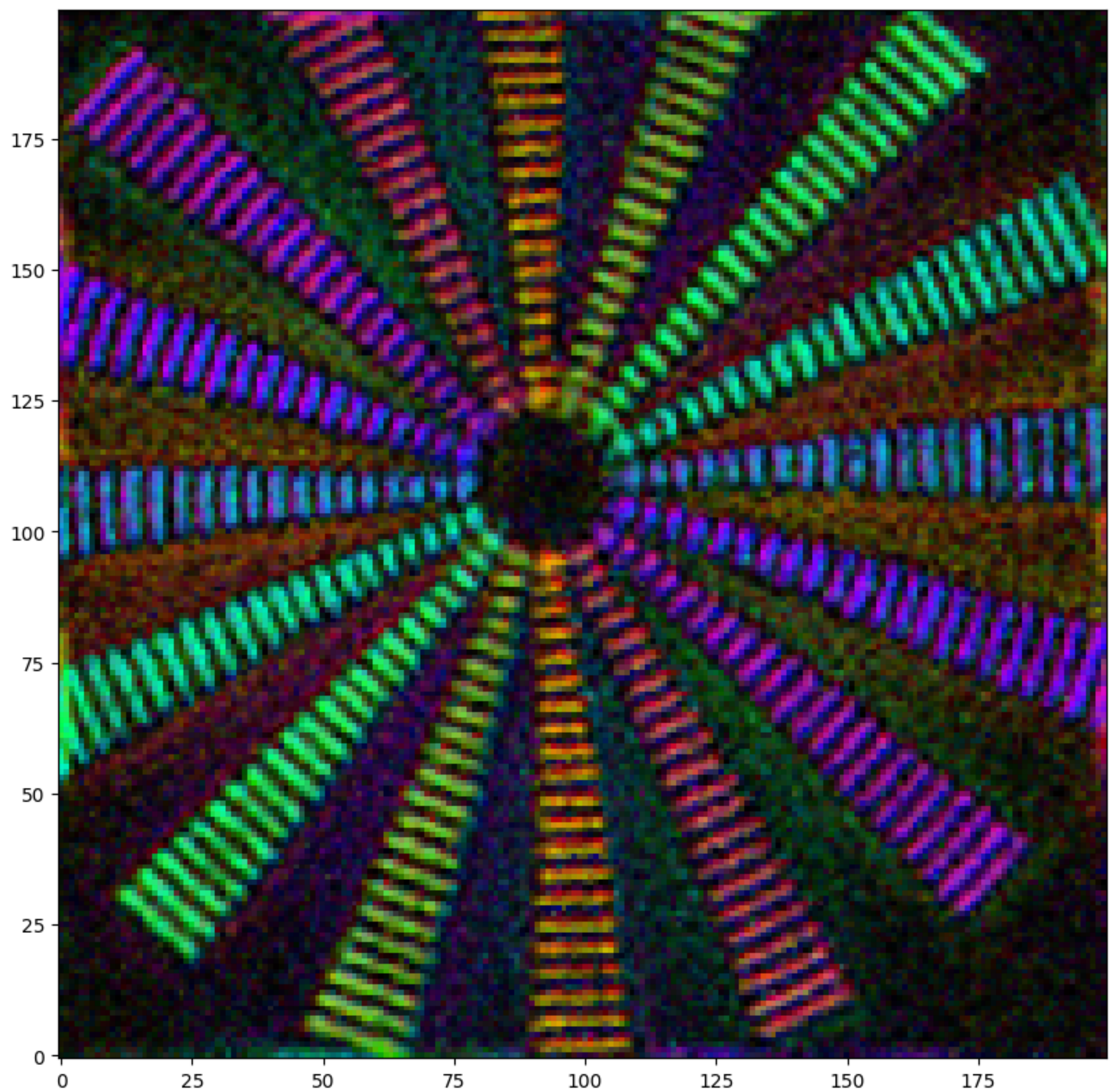
[ ]:
```
# Render 3D orientation with 3D colorsphere (azimuth and inclination)
```

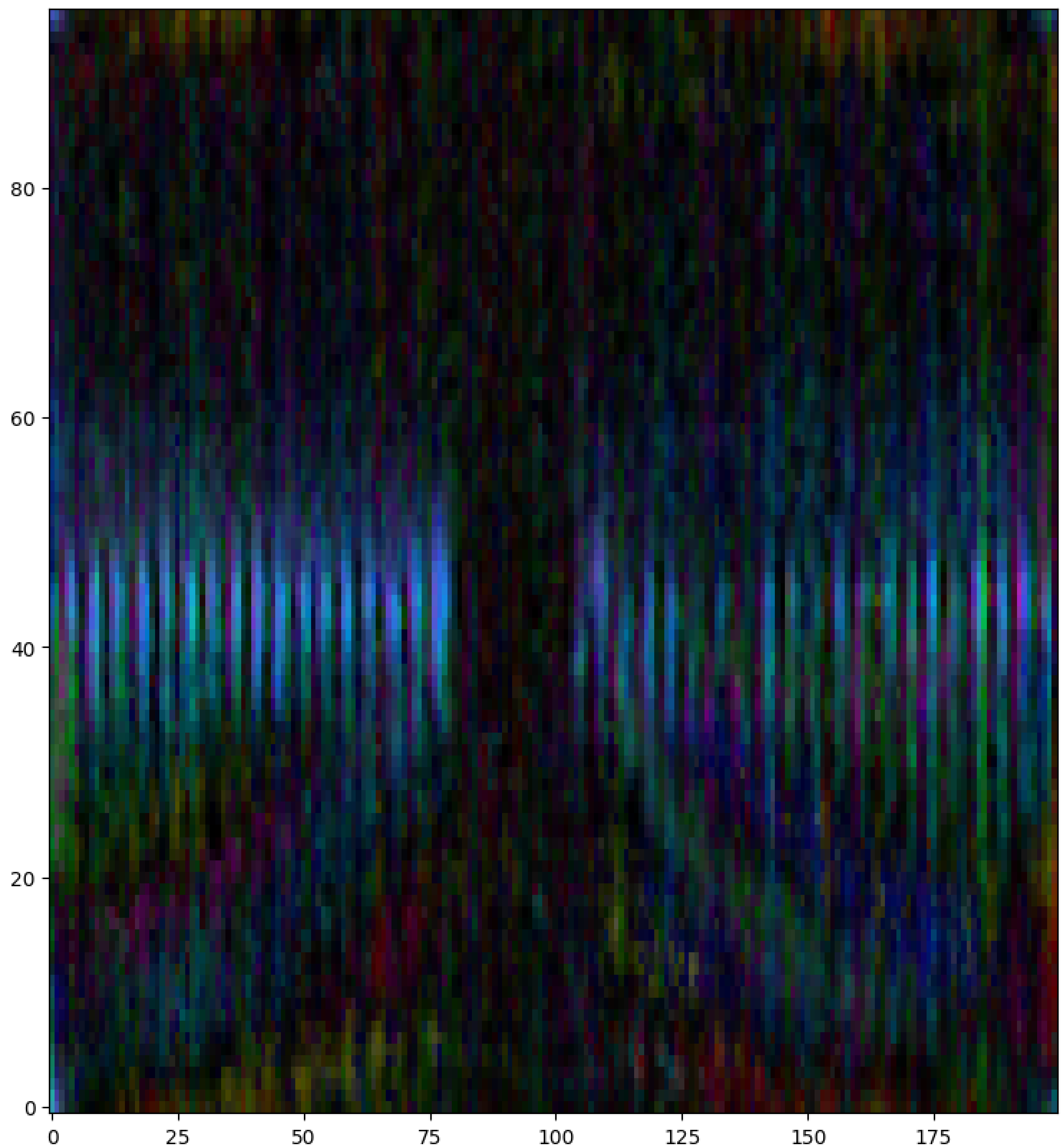
[ ]:
```
# create color-coded orientation images

ret_min_color = 0
ret_max_color = 0.012

orientation_3D_image = np.transpose(
    np.array(
        [
            azimuth[1] / 2 / np.pi,
            theta[1],
            (
                np.clip(
                    np.abs(differential_permittivity_PT[1]),
                    ret_min_color,
                    ret_max_color,
                )
                - ret_min_color
            )
            / (ret_max_color - ret_min_color),
        ]
    ),
    (3, 1, 2, 0),
)
orientation_3D_image_RGB = visual.orientation_3D_to_rgb(
    orientation_3D_image, interp_belt=20 / 180 * np.pi, sat_factor=1
```

```
)
```

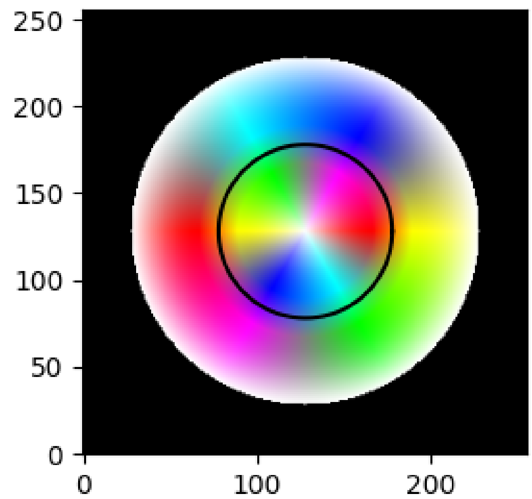
[ ]:
```
plt.figure(figsize=(10, 10))
plt.imshow(orientation_3D_image_RGB[z_layer], origin="lower")
plt.figure(figsize=(10, 10))
plt.imshow(
    orientation_3D_image_RGB[:, y_layer], origin="lower", aspect=z_step / ps
)

# plot the top view of 3D orientation colorsphere
plt.figure(figsize=(3, 3))
visual.orientation_3D_colorwheel(
    wheelsize=256, circ_size=50, interp_belt=20 / 180 * np.pi, sat_factor=1
)
```

[ ]:
```
<matplotlib.image.AxesImage at 0x2a3b6c8b0>
```





80
60
40
20
0
0
25
50
75
100
125
150
175



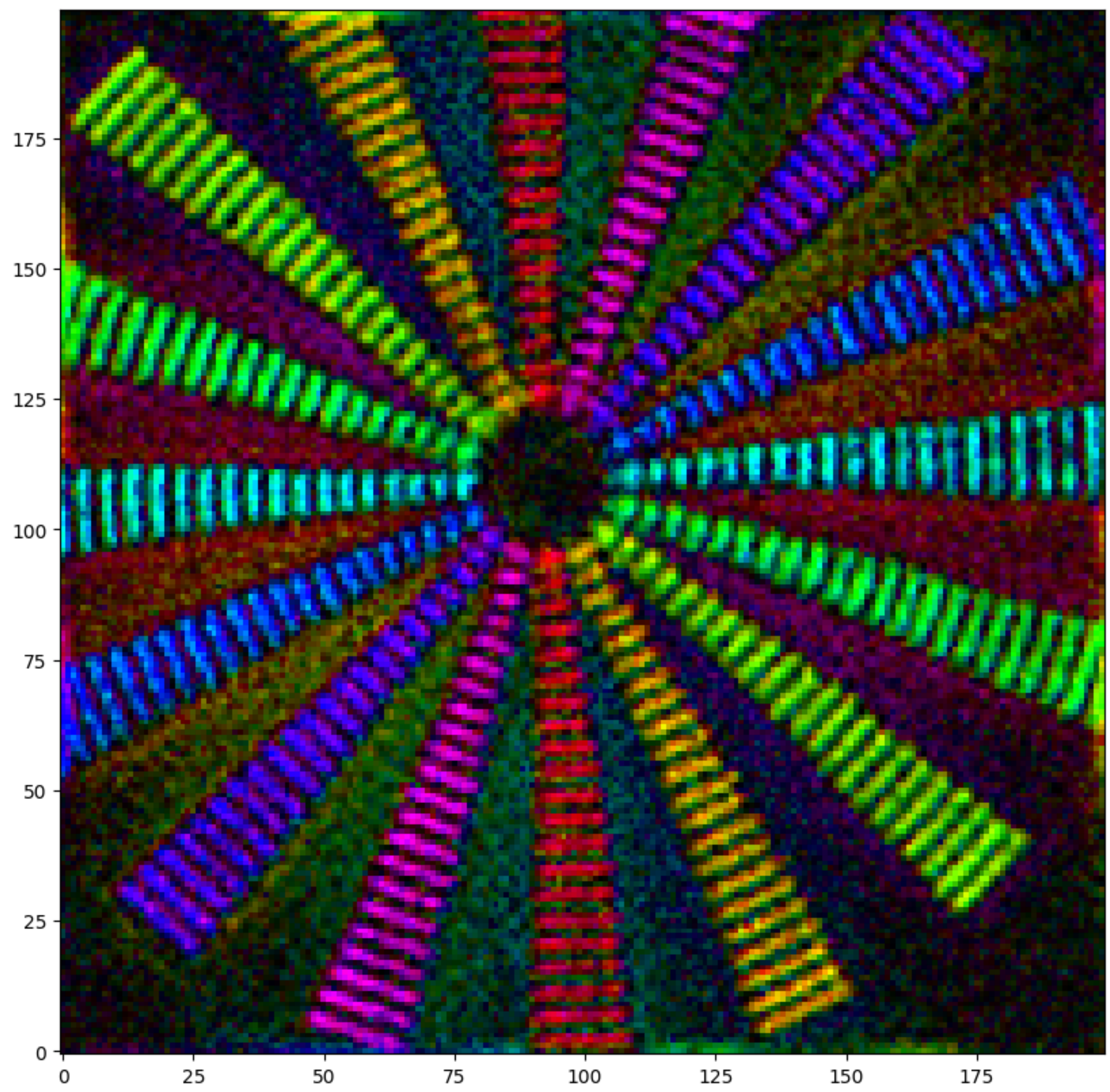
[ ]:
```
# Render 3D orientation with 2 channels (in-plane orientation and out-of-plane
↪tilt)
```

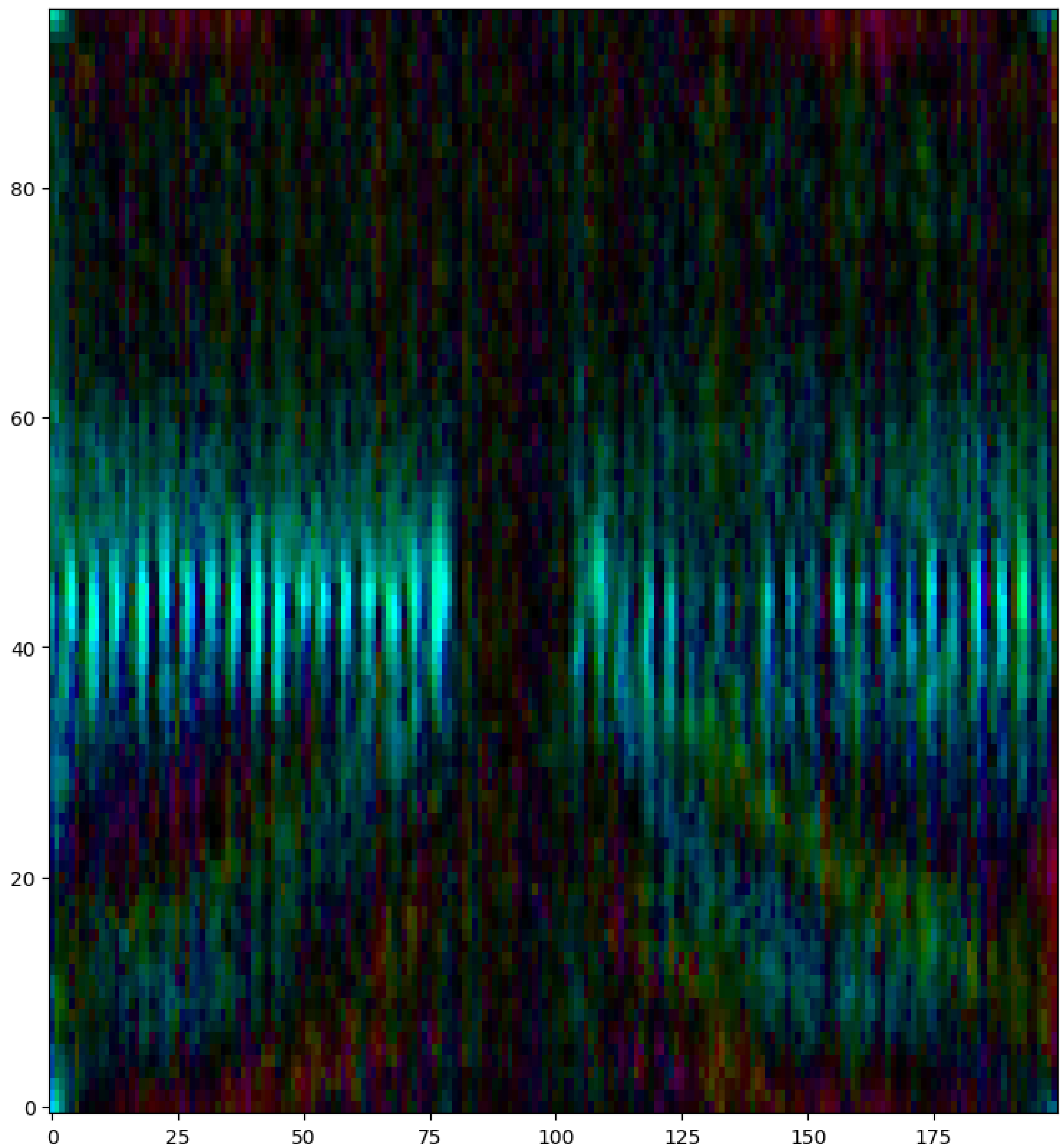
[ ]:
```
# in-plane orientation
from matplotlib.colors import hsv_to_rgb

I_hsv = np.transpose(
    np.array(
        [
            (azimuth[1]) % np.pi / np.pi,
            np.ones_like(differential_permittivity_PT[1]),
            (
                np.clip(
                    np.abs(differential_permittivity_PT[1]),
                    ret_min_color,
                    ret_max_color,
                )
                - ret_min_color
            )
            / (ret_max_color - ret_min_color),
        ]
    ),
    (3, 1, 2, 0),
)
in_plane_orientation = hsv_to_rgb(I_hsv.copy())
```

[ ]:
```
plt.figure(figsize=(10, 10))
plt.imshow(in_plane_orientation[z_layer], origin="lower")
plt.figure(figsize=(10, 10))
```

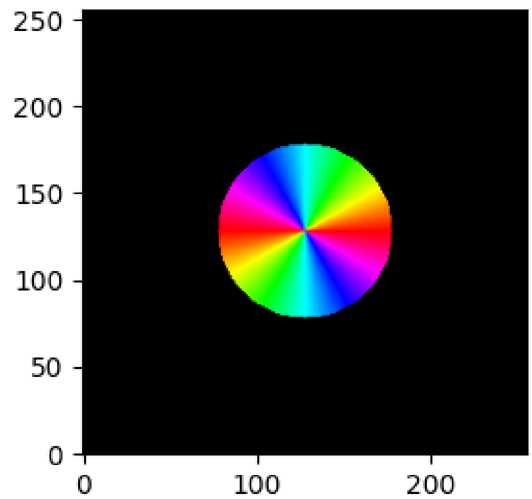
```
plt.imshow(
    in_plane_orientation[:, y_layer], origin="lower", aspect=z_step / ps
)
plt.figure(figsize=(3, 3))
visual.orientation_2D_colorwheel()
```

[ ]: <matplotlib.image.AxesImage at 0x2a3c57fd0>





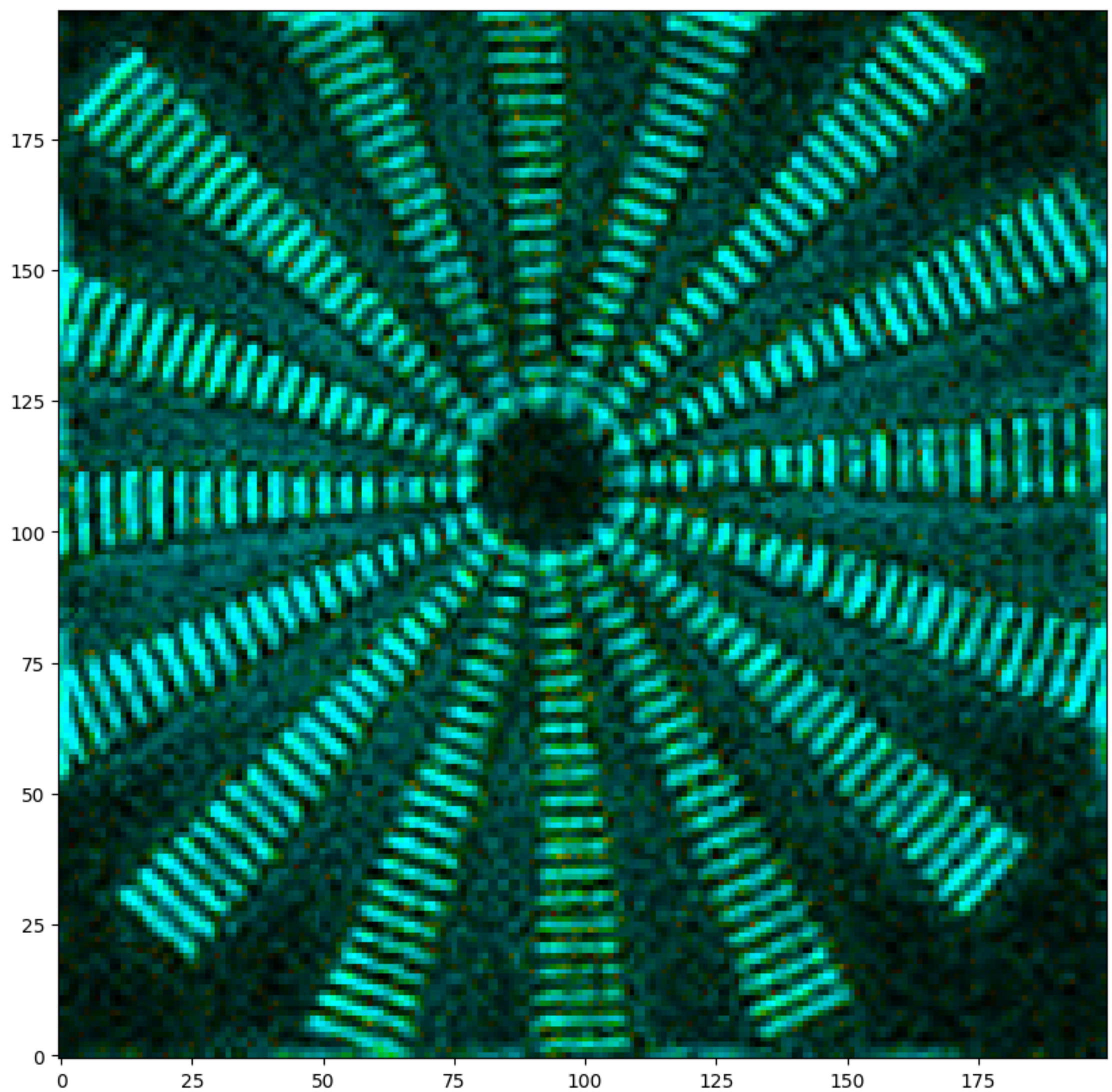
0
20
40
60
80
0
25
50
75
100
125
150
175

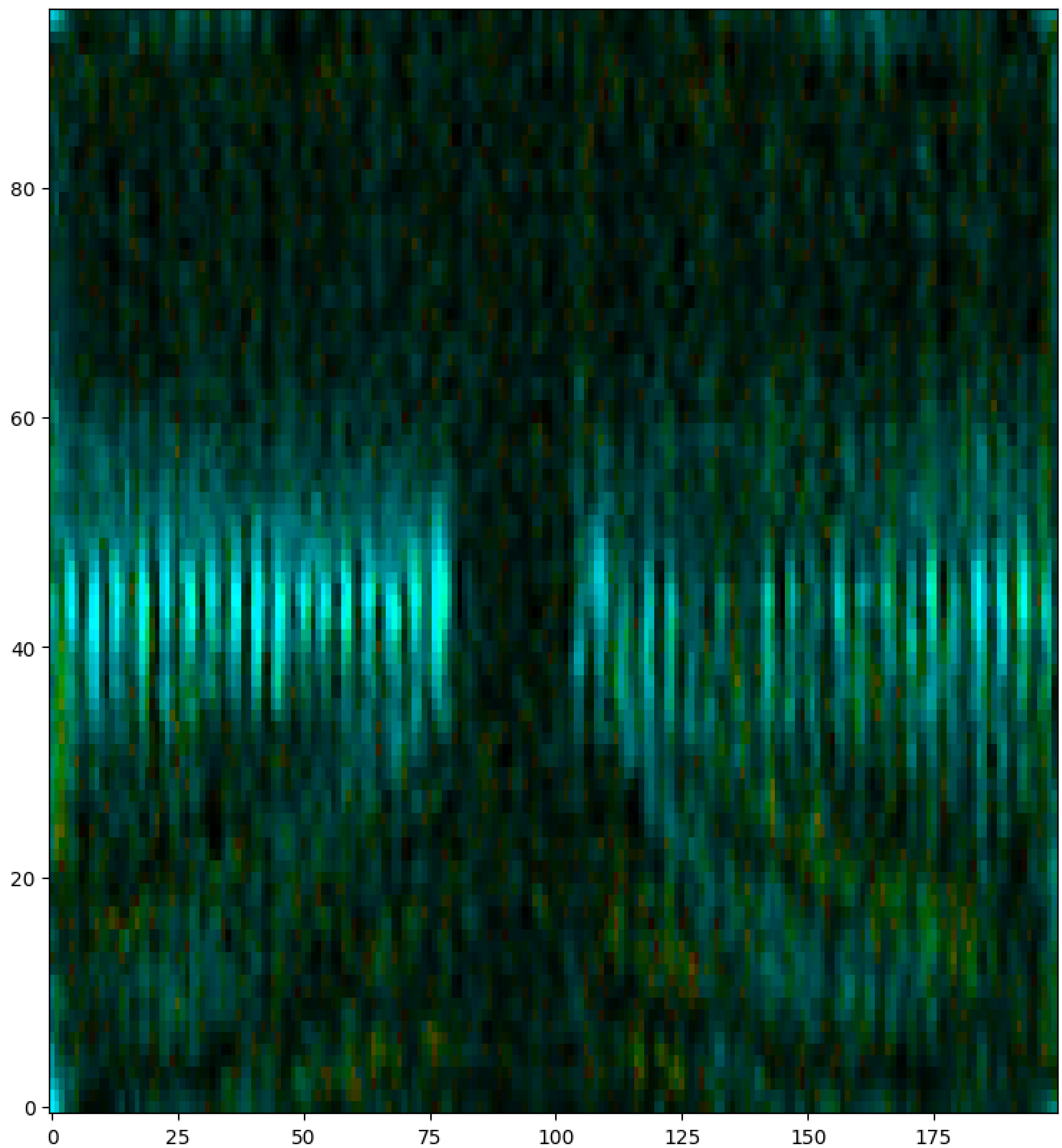


[ ]:
```
# out-of-plane tilt

threshold_inc = np.pi / 90

I_hsv = np.transpose(
    np.array(
        [
            (
                -np.maximum(0, np.abs(theta[1] - np.pi / 2) - threshold_inc)
                + np.pi / 2
                + threshold_inc
            )
            / np.pi,
            np.ones_like(differential_permittivity_PT[1]),
            (
                np.clip(
                    np.abs(differential_permittivity_PT[1]),
                    ret_min_color,
                    ret_max_color,
                )
                - ret_min_color
            )
            / (ret_max_color - ret_min_color),
        ]
    ),
    (3, 1, 2, 0),
)
out_of_plane_tilt = hsv_to_rgb(I_hsv.copy())
```

[ ]:
```
plt.figure(figsize=(10, 10))
plt.imshow(out_of_plane_tilt[z_layer], origin="lower")
plt.figure(figsize=(10, 10))
plt.imshow(out_of_plane_tilt[:, y_layer], origin="lower", aspect=z_step / ps)
```

[ ]: <matplotlib.image.AxesImage at 0x29e2f1ff0>



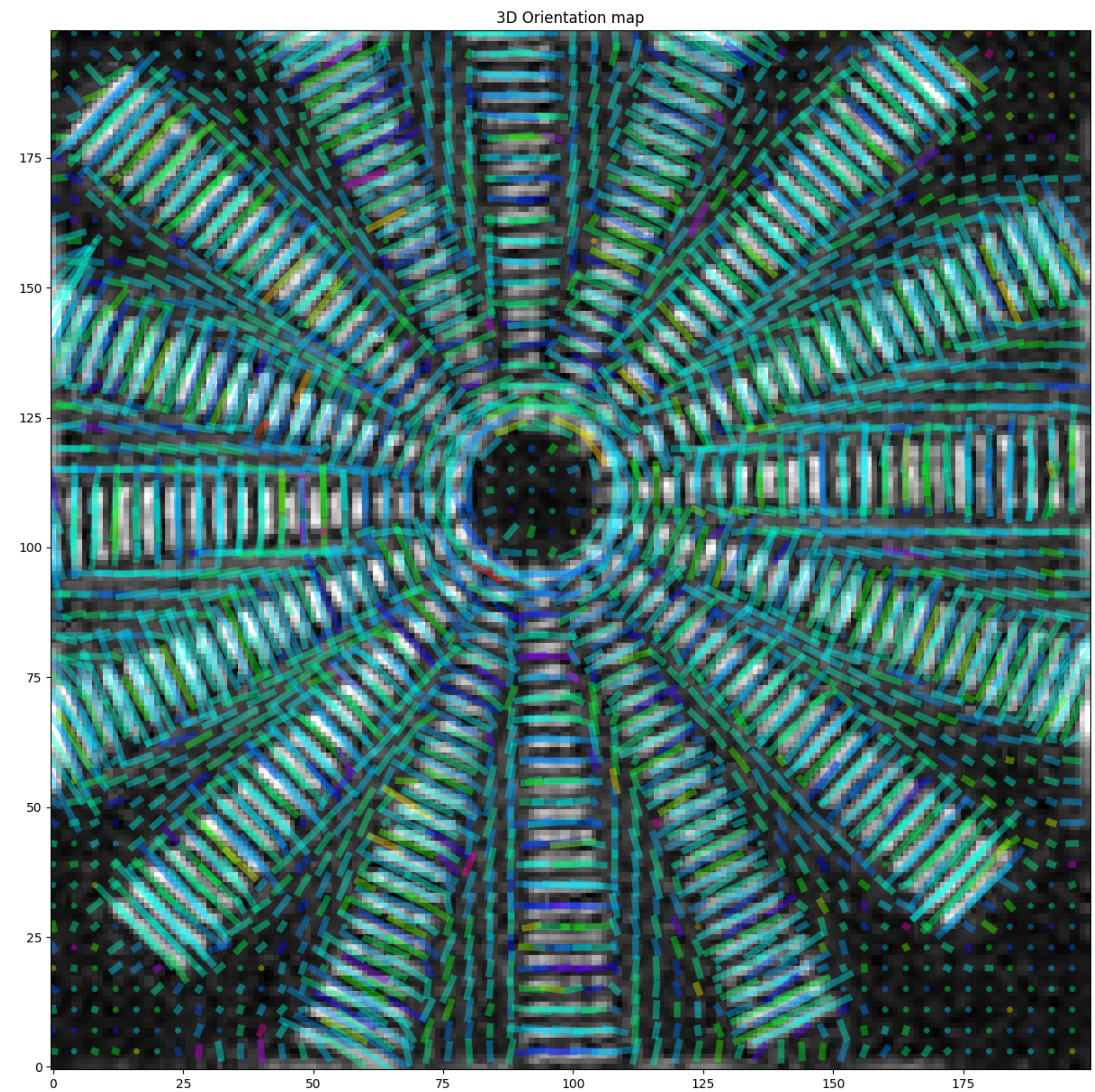


[ ]:
```
# Angular histogram of computed 3D orientation
```

[ ]:
```
spacing = 4
z_layer = 44

fig, ax = plt.subplots(1, 1, figsize=(15, 15))

visual.plot3DVectorField(
    np.abs(differential_permittivity_PT[1, :, :, z_layer]),
    azimuth[1, :, :, z_layer],
```

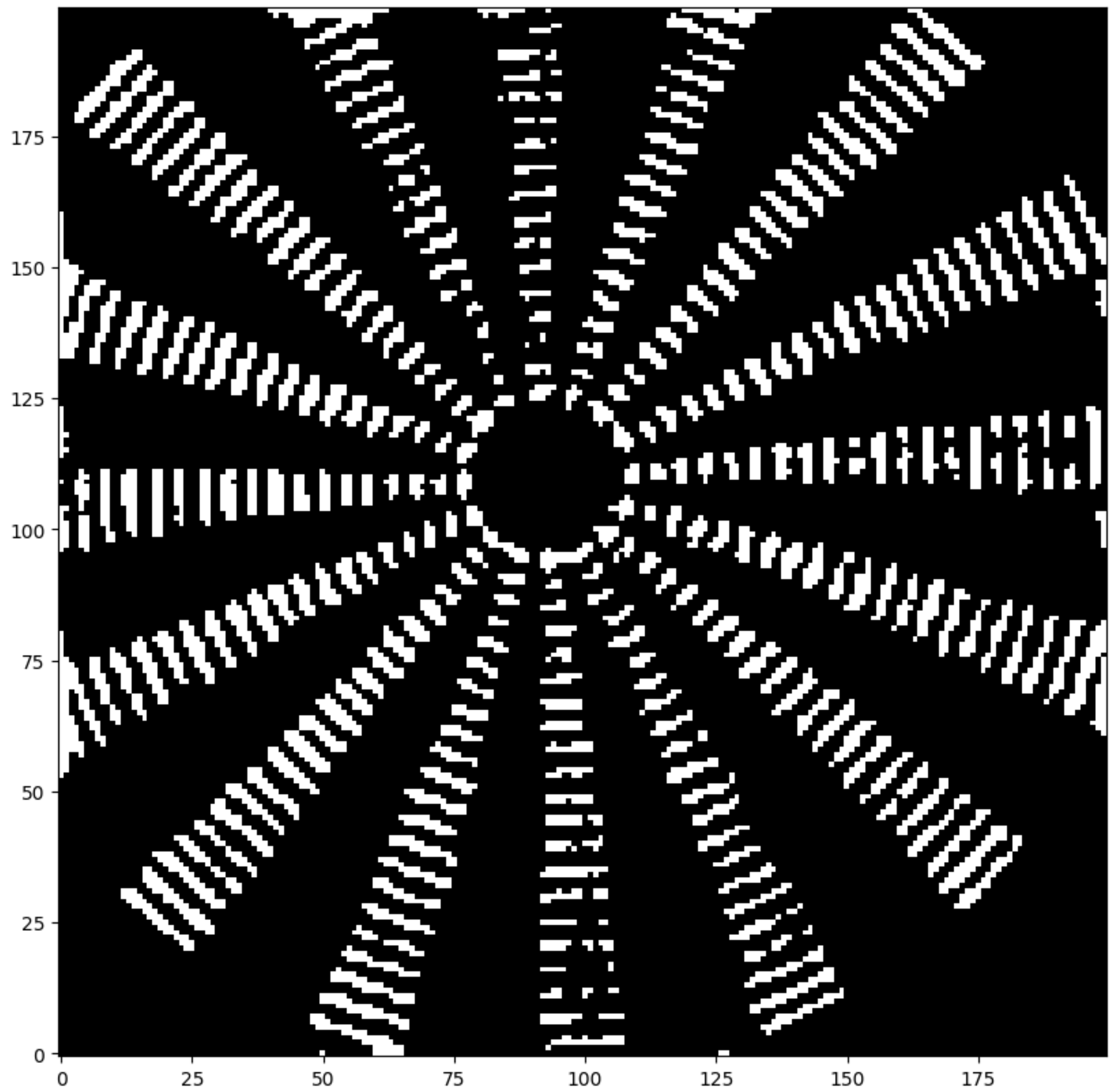
```
    theta[1, :, :, z_layer],
    anisotropy=40 * np.abs(differential_permittivity_PT[1, :, :, z_layer]),
    cmapImage="gray",
    clim=[ret_min, ret_max],
    aspect=1,
    spacing=spacing,
    window=spacing,
    linelength=spacing * 1.8,
    linewidth=1.3,
    cmapAzimuth="hsv",
    alpha=0.4,
)
```

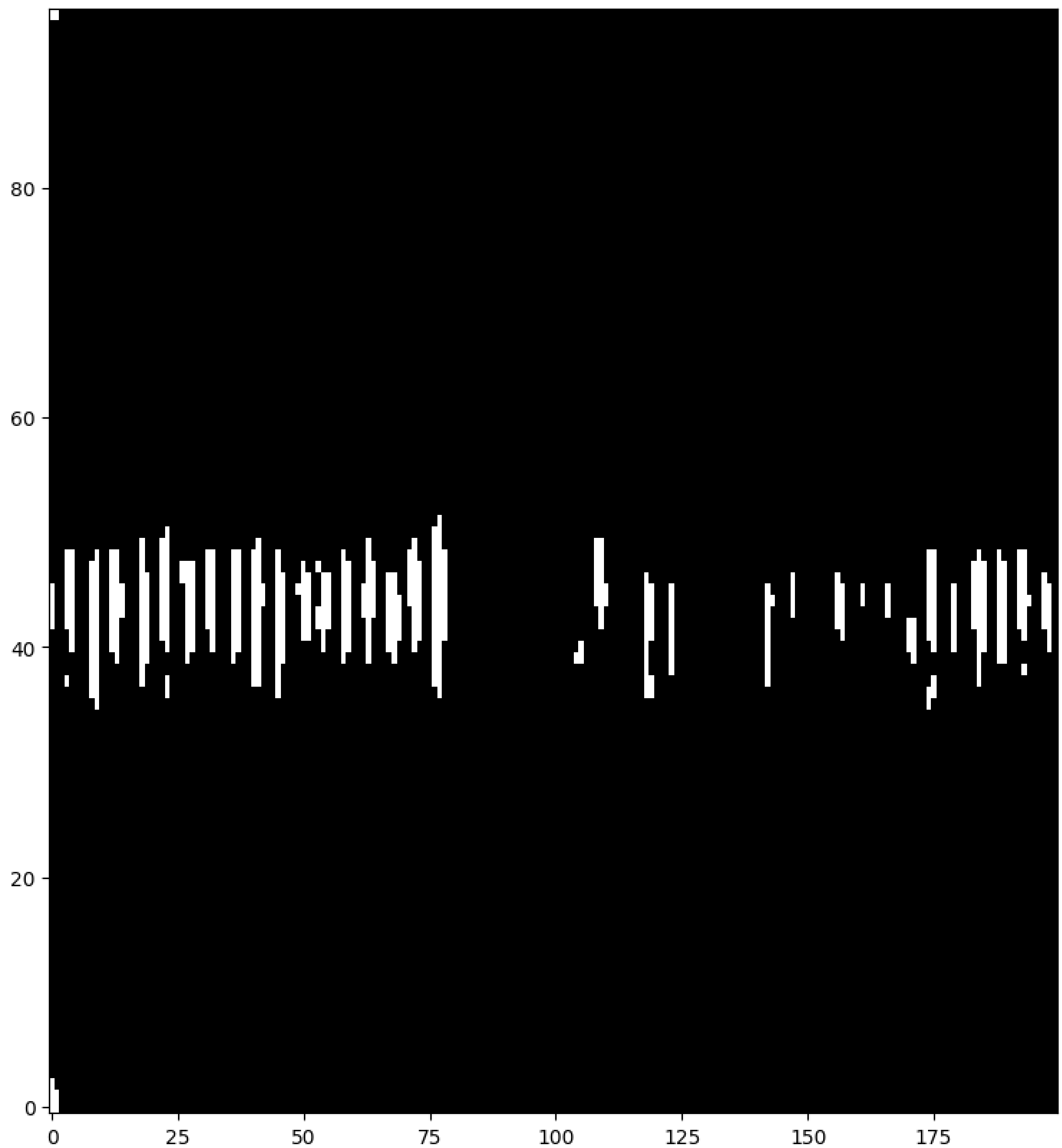
[ ]: <matplotlib.image.AxesImage at 0x2a3c1df30>



[ ]:
```
ret_mask = np.abs(differential_permittivity_PT[1]).copy()
ret_mask[ret_mask < 0.0075] = 0
ret_mask[ret_mask > 0.0075] = 1


plt.figure(figsize=(10, 10))
plt.imshow(ret_mask[:, :, z_layer], cmap="gray", origin="lower")
plt.figure(figsize=(10, 10))
plt.imshow(
    np.transpose(ret_mask[y_layer, :, :]),
    cmap="gray",
    origin="lower",
    aspect=z_step / ps,
)
```

[ ]:
```
<matplotlib.image.AxesImage at 0x2a1194730>
```


0
25
50
75
100
125
150
175



[ ]:
```
# Angular histogram of 3D orientation

visual.orientation_3D_hist(
    azimuth[1].flatten(),
    theta[1].flatten(),
    ret_mask.flatten(),
    bins=72,
    num_col=1,
    size=10,
    contour_level=100,
```

```
    hist_cmap="gray",
    top_hemi=True,
)
```

[ ]: (<Figure size 1000x1000 with 2 Axes>, <PolarAxes: >)