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# **qpimage Documentation**

***Release 0.2.1***

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**Jul 23, 2018**



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Qpimage is a Python3 library that provides a convenient interface to many common functionalities that are used in quantitative phase imaging. This is the documentation of qpimage version 0.2.1.



### 1.1 The Problem

Quantitative phase imaging (QPI) is a fundamental imaging technique that visualizes the retardation of electromagnetic radiation as it passes through an object. The parameter that governs this retardation is called [refractive index](#). In biological imaging, QPI is an important tool to measure the dry mass or the refractive index (related to mass density [\[Bar52\]](#) [\[DW52\]](#)) of single cells and tissues, which enables a profound characterization of the investigated samples.

### 1.2 Why qpimage?

In the [Guck group](#), we make heavy use of QPI and thus require a reliable and well-documented software library that, independent of the particular QPI setup used, allows us to address QPI-related research questions. Qpimage attempts to unify QPI analysis by providing a unique and user-friendly API for working with QPI data, including the choice of input data (complex field, phase with amplitude or intensity, hologram), memory-efficient and fast storage of large data sets (using [HDF5](#), phase and amplitude data are stored separately), or robust and extendable background correction techniques (tilt and second order polynomial fits, binary mask). The main reason for the development of qpimage is our QPI analysis software [DryMass](#).

### 1.3 What are the alternatives?

There are other open-source Python libraries that address quantitative phase imaging analysis with varying scopes and motivations.

- [HoloPy](#) is an established Python library for digital holographic microscopy (DHM) that comes with several additional features such as scattering calculations and model fitting. The overlap between HoloPy and qpimage is the computation of phase and amplitude from raw hologram data. The main difference is that HoloPy is focused on DHM analysis with a rich set of tools while qpimage is only focused on managing quantitative phase data (data conversion and storage as well as an extended set of background correction algorithms). However, there is a broad set of additional tools in the “qpimage universe”, including [qpformat](#) for loading experimental

data, [qpsphere](#) for scattering calculations and model fitting (focus is on cell-sized objects), and [DryMass](#) as a user interface to these libraries.

- The Python package [shampoo](#) focuses on DHM reconstruction and detection and tracking of biological cells. The overlap between shampoo and the “qpimage universe” (see above) is quite large. The difference is mostly the scope of the projects; While shampoo is an optimized library for DHM analysis, the “qpimage universe” encompasses other quantitative phase imaging (QPI) techniques with the aim to becoming a generic tool in QPI analysis. Experimental .tif files from the shampoo project can be opened with [qpformat](#) (see [Hologram from tif file](#)).
- If you are using electron holography, [HyperSpy](#) might be worth looking at. If you are storing your hologram data in the HyperSpy file format, you can still load it with [qpformat](#) (see [HyperSpy hologram file format](#)) and analyze it with qpimage.

## 1.4 Citing qpimage

If you are using qpimage in a scientific publication, please cite it with:

```
(...) using qpimage version X.X.X (available at  
https://pypi.python.org/pypi/qpimage) .
```

or in a bibliography

```
Paul Müller (2017), qpimage version X.X.X: Phase image analysis  
[Software]. Available at https://pypi.python.org/pypi/qpimage.
```

and replace X.X.X with the version of qpimage that you used.

Furthermore, several ideas implemented in qpimage have been described and published in scientific journals:

- Phase retrieval from holographic images with a gaussian filter is implemented according to [\[SSM+15\]](#).
- Phase background image correction with a tilt fitted to a border of the image data was used in [\[SSM+15\]](#) and [\[SSM+16\]](#).
- Phase background image correction with a polynomial fitted to known background regions was introduced for DHM in [\[CCC+06\]](#) (in this reference the phase correction is applied to the hologram data before field reconstruction).
- Intensity background correction by dividing by a reference intensity image for tomographic imaging was used in [\[SCG+17\]](#).

### 2.1 Installing qpimage

Qpimage is written in pure Python and supports Python version 3.5 and higher. Qpimage depends on several other scientific Python packages, including:

- `numpy`,
- `scipy`,
- `h5py` (caching),
- `lmfit` (background estimation),
- `nrefocus` (numerical focusing), and
- `scikit-image` (phase unwrapping using `skimage.restoration.unwrap_phase()`).

To install qpimage, use one of the following methods (package dependencies will be installed automatically):

- **from PyPI:** `pip install qpimage`
- **from sources:** `pip install .` or `python setup.py install`

### 2.2 User API

The qpimage API is built upon the hdf5 file format using `h5py`. That means that each instance of `qpimage.QPImage` generates an hdf5 file, either on disk or in memory, depending on the preferences of the user. This approach has the advantage that phase and amplitude data can be cached on disk, including all parameters that were used for background correction, which allows to transparently recapture any steps that were performed on a specific data set at a later time point.

## 2.2.1 Basic usage

A typical use case of qpimage is

```
qpi = qpimage.QPImage(data=phase_ndarray, which_data="phase")
# perform phase-tilt background correction
qpi.compute_bg(which_data="phase", # correct phase image
               fit_offset="fit",   # use bg offset from tilt fit
               fit_profile="tilt", # perform 2D tilt fit
               border_px=5,       # use 5 px border around image
               )
# save the background-corrected phase to a text file
numpy.savetxt("out.txt", qpi.pha)
```

which creates an instance of *QPImage* containing otherwise experimentally obtained phase data, performs a phase-tilt background correction and then saves the corrected phase data to the text file “out.txt”. In this case, all data are stored in memory.

## 2.2.2 Storing QPImage data on disk

To cache the QPImage data on disk, use the `with` statement in combination with the `h5file` keyword argument

```
with qpimage.QPImage(data=phase_ndarray, which_data="phase", h5file="/path/to/file.h5
↪") as qpi:
    qpi.compute_bg(which_data="phase",
                   fit_offset="fit",
                   fit_profile="tilt",
                   border_px=5,
                   )
```

where all data is stored in `/path/to/file.h5`. This will create an hdf5 file on disk that, at a later time point, can be used to create an instance of *QPImage*:

```
# open previously cached data for reading
qpi = qpimage.QPImage(h5file="/path/to/file.h5", h5mode="r")

# or open cached data for writing (e.g. for changing the background)
with qpimage.QPImage(h5file="/path/to/file.h5", h5mode="a") as qpi:
    # do something here
```

The default value of `h5mode` is “a”, which means that data will be overridden. In the hdf5 file, the following data is stored:

- all data for reproducing the background-corrected phase (`qpi.pha`) and amplitude (`qpi.amp`) (and thus field `qpi.field`), including
  - the experimental phase data
  - the experimental background data
  - the parameters for reproducing the result of `qpi.compute_bg`
- all measurement specific meta data, given by the keyword argument `meta_data`

### 2.2.3 Dealing with measurement series

Qpimage also comes with a *QPSeries* class for handling multiple instances of *QPImage* in one hdf5 file. For instance, to combine two *QPImages* in one series file, one could use:

```
paths = ["file_a.h5", "file_b.h5", "file_c.h5"]

with qpimage.QPSeries(h5file="/path/to/series_file.h5", h5mode="w") as qps:
    for ii, pp in enumerate(paths):
        qpi = qpimage.QPImage(h5file="/path/to/file.h5", h5mode="r")
        qps.add_qpimage(qpi=qpi, identifier="my_name_{}".format(ii))
```

Note that the function *add\_qpimage* accepts the optional keyword argument “identifier” (overriding the identifier of the *QPImage*) which can also be used for indexing later:

```
with qpimage.QPSeries(h5file="/path/to/series_file.h5", h5mode="r") as qps:
    # these two are equivalent
    qpi = qps[0]
    qpi = qps["my_name_0"]
```

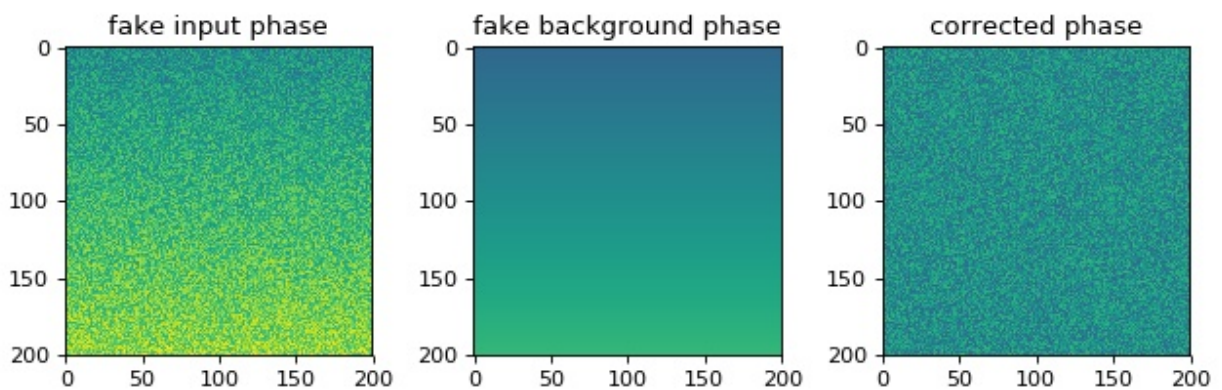
### 2.2.4 Notes

- Even though the hdf5 data is stored as gzip-compressed single precision floating point values, using qpimage hdf5 files may result in file sizes that are considerably larger compared to when only the output of e.g. `qpi.pha` is stored using e.g. `numpy.save()`.
- Units in qpimage follow the international system of units (SI).
- *qpimage.QPSeries* provides a convenient way to manage multiple *qpimage.QPImage*, optionally storing them in a single hdf5 file.



### 3.1 Simple phase

This example illustrates the simple usage of the `qpimage.QPImage` class for reading and managing quantitative phase data. The attribute `QPImage.pha` yields the background-corrected phase data and the attribute `QPImage.bg_pha` yields the background phase image.



simple\_phase.py

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 import qpimage
4
5 size = 200
6 # background phase image with a tilt
7 bg = np.repeat(np.linspace(0, 1, size), size).reshape(size, size)
8 # phase image with random noise
```

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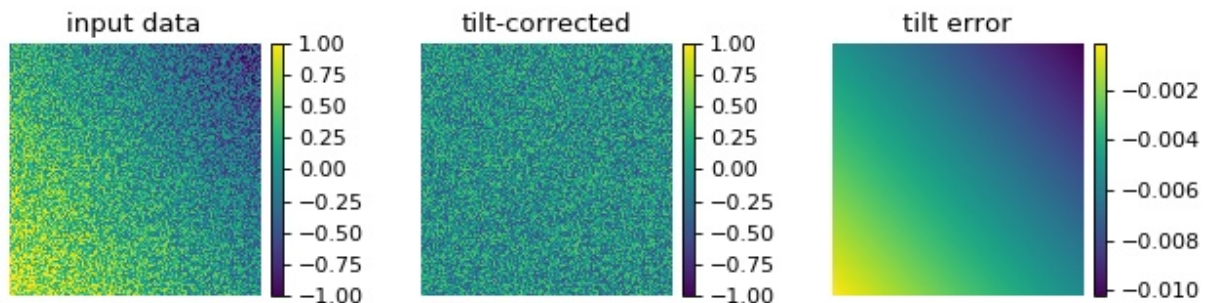
```

9 phase = np.random.rand(size, size) + bg
10
11 # create QPImage instance
12 qpi = qpimage.QPImage(data=phase, bg_data=bg, which_data="phase")
13
14 # plot the properties of `qpi`
15 plt.figure(figsize=(8, 3))
16 plot_kw = {"vmin": -1,
17            "vmax": 2}
18
19 plt.subplot(131, title="fake input phase")
20 plt.imshow(phase, **plot_kw)
21
22 plt.subplot(132, title="fake background phase")
23 plt.imshow(qpi.bg pha, **plot_kw)
24
25 plt.subplot(133, title="corrected phase")
26 plt.imshow(qpi.pha, **plot_kw)
27
28 plt.tight_layout()
29 plt.show()

```

## 3.2 Background image tilt correction

This example illustrates background tilt correction with qpimage. In contrast to the ‘simple\_phase.py’ example, the known background data is not given to the `qpimage.QPImage` class. In this particular example, the background tilt correction achieves an error of about 1% which is sufficient in most quantitative phase imaging applications.



background\_tilt.py

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 import qpimage
4
5 size = 200
6 # background phase image with a tilt
7 bg = np.repeat(np.linspace(0, 1, size), size).reshape(size, size)
8 bg = .6 * bg - .8 * bg.transpose() + .2
9 # phase image with random noise

```

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```

10 rsobj = np.random.RandomState(47)
11 phase = rsobj.rand(size, size) - .5 + bg
12
13 # create QPImage instance
14 qpi = qpimage.QPImage(data=phase, which_data="phase")
15 # compute background with 2d tilt approach
16 qpi.compute_bg(which_data="phase", # correct phase image
17               fit_offset="fit", # use bg offset from tilt fit
18               fit_profile="tilt", # perform 2D tilt fit
19               border_px=5, # use 5 px border around image
20               )
21
22 # plot the properties of `qpi`
23 fig = plt.figure(figsize=(8, 2.5))
24 plot_kw = {"vmin": -1,
25           "vmax": 1}
26
27 ax1 = plt.subplot(131, title="input data")
28 map1 = ax1.imshow(phase, **plot_kw)
29 plt.colorbar(map1, ax=ax1, fraction=.046, pad=0.04)
30
31 ax2 = plt.subplot(132, title="tilt-corrected")
32 map2 = ax2.imshow(qpi.pha, **plot_kw)
33 plt.colorbar(map2, ax=ax2, fraction=.046, pad=0.04)
34
35 ax3 = plt.subplot(133, title="tilt error")
36 map3 = ax3.imshow(bg - qpi.bg_pha)
37 plt.colorbar(map3, ax=ax3, fraction=.046, pad=0.04)
38
39 # disable axes
40 [ax.axis("off") for ax in [ax1, ax2, ax3]]
41
42 plt.tight_layout(pad=0, h_pad=0, w_pad=0)
43 plt.show()

```

### 3.3 Background image offset correction

This example illustrates the different background offset correction methods implemented in qpimage. The phase image data contains two gaussian noise distributions for which these methods yield different background phase offsets.

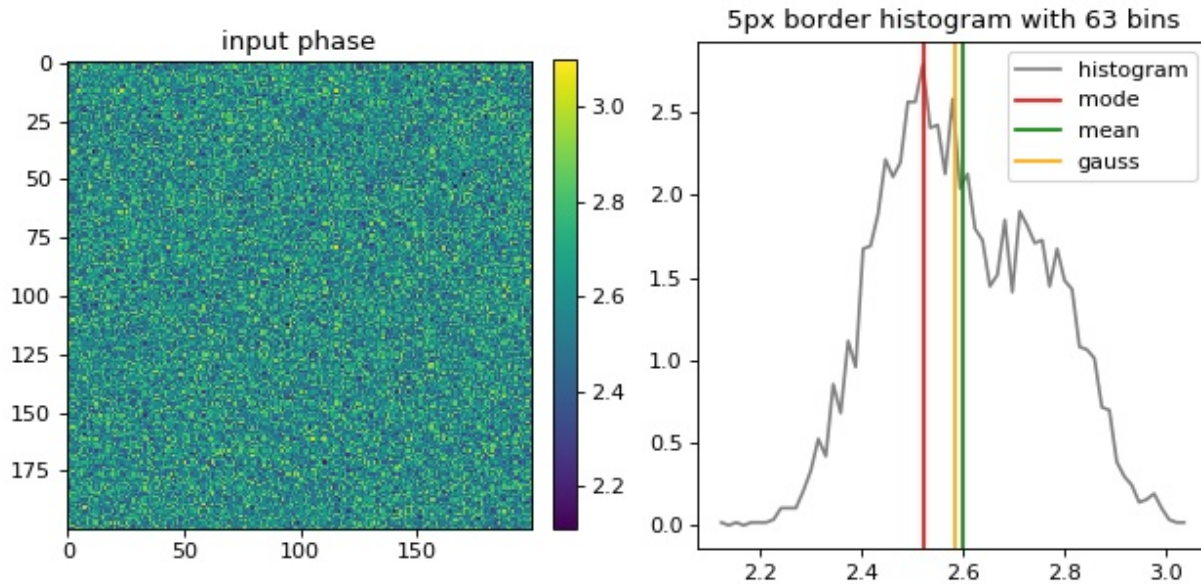
background\_offset.py

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 import qpimage
4
5 size = 200 # the size of the image
6 bg = 2.5 # the center of the background phase distribution
7 scale = .1 # the spread of the background phase distribution
8
9 # compute random phase data
10 rsobj = np.random.RandomState(42)
11 data = rsobj.normal(loc=bg, scale=scale, size=size**2)
12 # Add a second distribution `data2` at random positions `idx`,

```

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```

13 # such that there is no pure gaussian distribution.
14 # (otherwise 'mean' and 'gaussian' cannot be distinguished)
15 data2 = rsobj.normal(loc=bg*1.1, scale=scale, size=size**2//2)
16 idx = rsobj.choice(data.size, data.size//2)
17 data[idx] = data2
18 # reshape `data` to get a 2D array
19 data = data.reshape(size, size)
20
21 qpi = qpimage.QPImage(data=data, which_data="phase")
22
23 cpkw = {"which_data": "phase", # correct the input phase data
24         "fit_profile": "offset", # perform offset correction only
25         "border_px": 5, # use a border of 5px of the input phase
26         "ret_binary": True, # return the binary image for visualization
27         }
28
29 binary = qpi.compute_bg(fit_offset="mode", **cpkw)
30 bg_mode = np.mean(qpi.bg_pha[binary])
31
32 qpi.compute_bg(fit_offset="mean", **cpkw)
33 bg_mean = np.mean(qpi.bg_pha[binary])
34
35 qpi.compute_bg(fit_offset="gauss", **cpkw)
36 bg_gauss = np.mean(qpi.bg_pha[binary])
37
38 bg_data = (qpi.pha + qpi.bg_pha)[binary]
39 # compute histogram
40 nbins = int(np.ceil(np.sqrt(bg_data.size)))
41 mind, maxd = bg_data.min(), bg_data.max()
42 histo = np.histogram(bg_data, nbins, density=True, range=(mind, maxd))
43 dx = abs(histo[1][1] - histo[1][2]) / 2
44 hx = histo[1][1:] - dx
45 hy = histo[0]

```

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```

46
47 # plot the properties of `qpi`
48 plt.figure(figsize=(8, 4))
49
50 ax1 = plt.subplot(121, title="input phase")
51 map1 = plt.imshow(data)
52 plt.colorbar(map1, ax=ax1, fraction=.046, pad=0.04)
53
54
55 t2 = "{}px border histogram with {} bins".format(cpkw["border_px"], nbins)
56 plt.subplot(122, title=t2)
57 plt.plot(hx, hy, label="histogram", color="gray")
58 plt.axvline(bg_mode, 0, 1, label="mode", color="red")
59 plt.axvline(bg_mean, 0, 1, label="mean", color="green")
60 plt.axvline(bg_gauss, 0, 1, label="gauss", color="orange")
61 plt.legend()
62
63 plt.tight_layout()
64 plt.show()

```

## 3.4 Background image binary mask correction

This example illustrates background correction with qpimage using a binary mask to exclude regions that do not contain background information.

The phase image of a microgel bead (top left) has two artifacts; there is a tilt-like phase profile added along the vertical axis and there is a second microgel bead in close proximity to the center bead. A regular phase tilt background correction using the image values around a frame of five pixels (see “background\_tilt.py” example) does not yield a flat background, because the second bead is fitted into the background which leads to a horizontal background phase profile (top right). By defining a binary mask (bottom left image), the phase values of the second bead can be excluded from the background tilt fit and a flat background phase is achieved (bottom right).

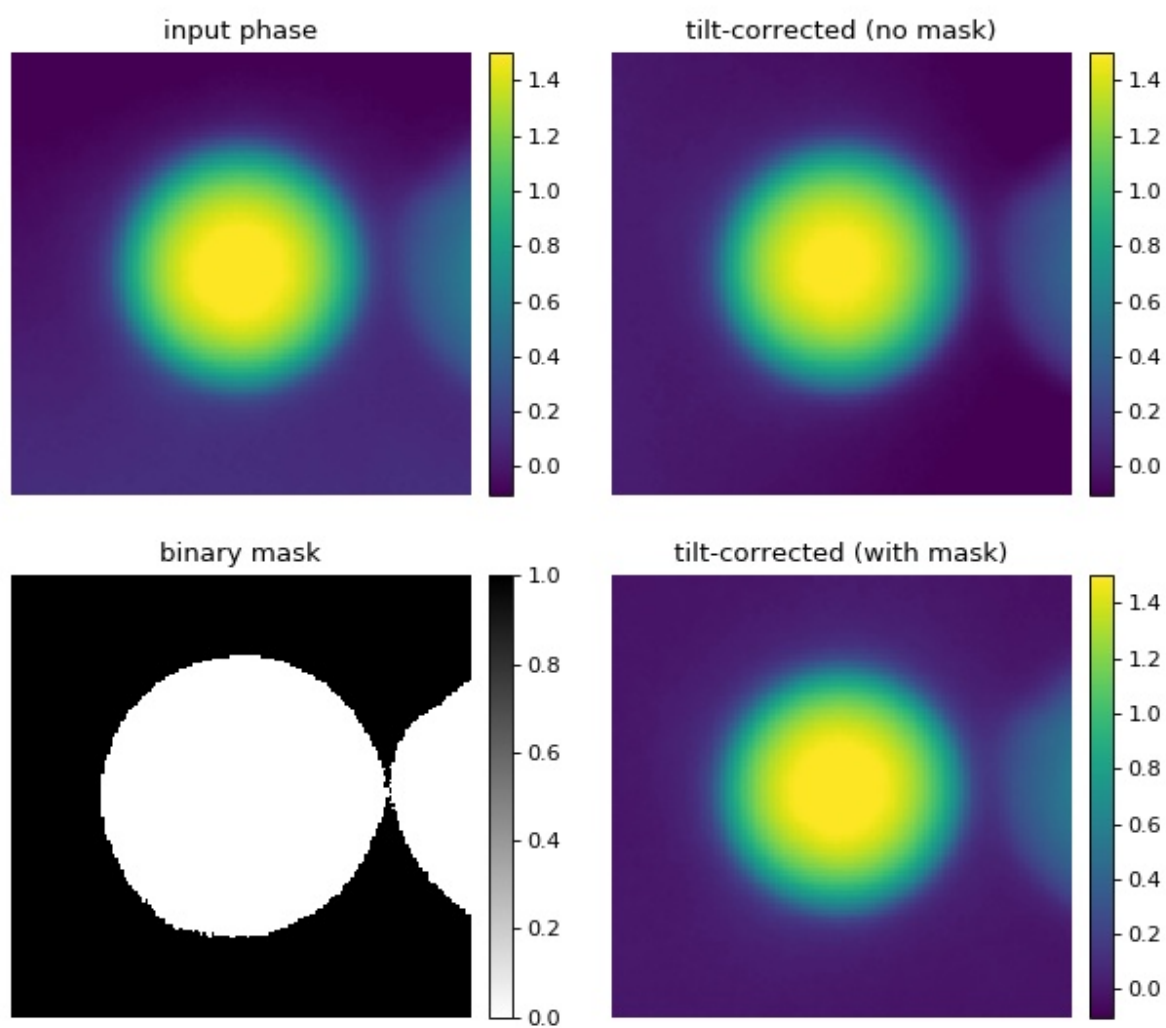
background\_binary\_mask.py

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 import qpimage
4
5
6 # load the experimental data
7 input_phase = np.load("./data/phase_beads_close.npz")["phase"].astype(float)
8
9 # create QPImage instance
10 qpi = qpimage.QPImage(data=input_phase,
11                       which_data="phase")
12
13 # background correction without mask
14 qpi.compute_bg(which_data="phase",
15               fit_offset="fit",
16               fit_profile="tilt",
17               border_px=5,
18               )
19 pha_nomask = qpi.pha
20

```

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```

21 # educated guess for binary mask
22 mask = input_phase < input_phase.max() / 10
23
24 # background correction with mask
25 # (the intersection of `mask` and the 5px border is used for fitting)
26 qpi.compute_bg(which_data="phase",
27                fit_offset="fit",
28                fit_profile="tilt",
29                border_px=5,
30                from_binary=mask
31                )
32 pha_mask = qpi.pha
33
34 # plot
35 fig = plt.figure(figsize=(8, 7))
36 plot_kw = {"vmin": -.1,
37            "vmax": 1.5}
38
39 ax1 = plt.subplot(221, title="input phase")
40 map1 = ax1.imshow(input_phase, **plot_kw)
41 plt.colorbar(map1, ax=ax1, fraction=.044, pad=0.04)
42
43 ax2 = plt.subplot(222, title="tilt-corrected (no mask)")
44 map2 = ax2.imshow(pha_nomask, **plot_kw)
45 plt.colorbar(map2, ax=ax2, fraction=.044, pad=0.04)
46
47 ax3 = plt.subplot(223, title="binary mask")
48 map3 = ax3.imshow(mask, cmap="gray_r")
49 plt.colorbar(map3, ax=ax3, fraction=.044, pad=0.04)
50
51 ax4 = plt.subplot(224, title="tilt-corrected (with mask)")
52 map4 = ax4.imshow(pha_mask, **plot_kw)
53 plt.colorbar(map4, ax=ax4, fraction=.044, pad=0.04)
54
55 # disable axes
56 [ax.axis("off") for ax in [ax1, ax2, ax3, ax3, ax4]]
57
58 plt.tight_layout(h_pad=0, w_pad=0)
59 plt.show()

```

### 3.5 Background image 2nd order polynomial correction

This example extends the tilt correction ('background\_tilt.py') to a second order polynomial correction for samples that exhibit more sophisticated phase aberrations. The phase background correction is computed from a ten pixel wide frame around the image. The phase data shown are computed from a hologram of a single myeloid leukemia cell (HL60) recorded using digital holographic microscopy (DHM) (see [SSM+15]).

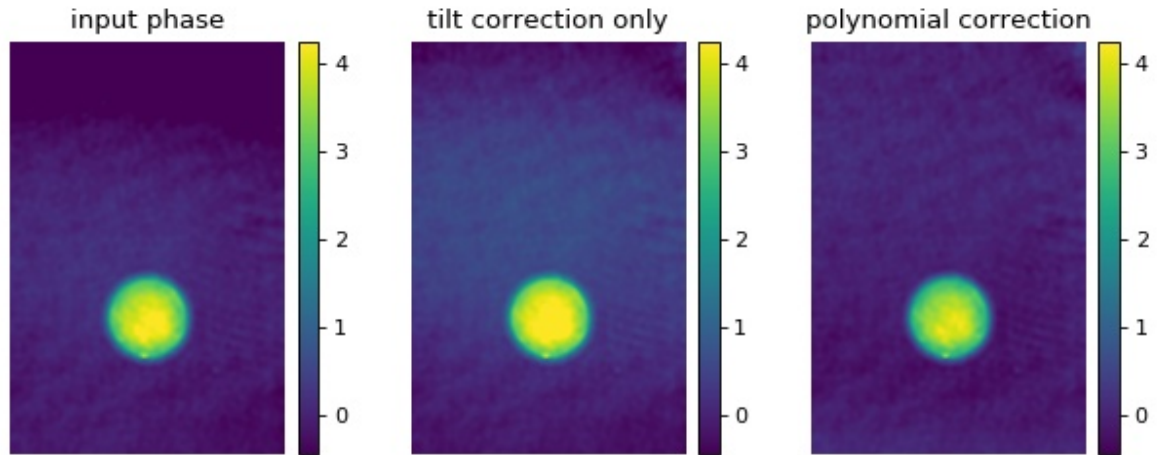
background\_poly2o.py

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 # The data are stored in a .jpg file (lossy compression).
4 # If `PIL` is not found, try installing the `pillow` package.
5 from PIL import Image

```

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```

6  import qpimage
7
8  edata = np.array(Image.open("../data/hologram_cell_curved_bg.jpg"))
9
10 # create QPImage instance
11 qpi = qpimage.QPImage(data=edata, which_data="hologram")
12 pha0 = qpi.pha
13
14 # background correction using tilt only
15 qpi.compute_bg(which_data=["phase"],
16               fit_offset="fit",
17               fit_profile="tilt",
18               border_px=10,
19               )
20 pha_tilt = qpi.pha
21
22 # background correction using polynomial
23 qpi.compute_bg(which_data=["phase"],
24               fit_offset="fit",
25               fit_profile="poly2o",
26               border_px=10,
27               )
28 pha_poly2o = qpi.pha
29
30 # plot phase data
31 fig = plt.figure(figsize=(8, 3.3))
32
33 phakw = {"cmap": "viridis",
34         "interpolation": "bicubic",
35         "vmin": pha_poly2o.min(),
36         "vmax": pha_poly2o.max()}
37
38 ax1 = plt.subplot(131, title="input phase")
39 map1 = ax1.imshow(phas0, **phakw)
40 plt.colorbar(map1, ax=ax1, fraction=.067, pad=0.04)
41
42 ax2 = plt.subplot(132, title="tilt correction only")

```

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```

43 map2 = ax2.imshow(pha_tilt, **phakw)
44 plt.colorbar(map2, ax=ax2, fraction=.067, pad=0.04)
45
46 ax3 = plt.subplot(133, title="polynomial correction")
47 map3 = ax3.imshow(pha_poly2o, **phakw)
48 plt.colorbar(map3, ax=ax3, fraction=.067, pad=0.04)
49
50 # disable axes
51 [ax.axis("off") for ax in [ax1, ax2, ax3]]
52
53 plt.tight_layout(w_pad=0)
54 plt.show()

```

### 3.6 Digital hologram of a single cell

This example illustrates how qpimage can be used to analyze digital holograms. The hologram of a single myeloid leukemia cell (HL60) shown was recorded using digital holographic microscopy (DHM). Because the phase-retrieval method used in DHM is based on the discrete Fourier transform, there always is a residual background phase tilt which must be removed for further image analysis. The setup used for recording these data is described in reference [SSM+15], which also contains a description of the hologram-to-phase conversion and phase background correction algorithms which qpimage is based on.

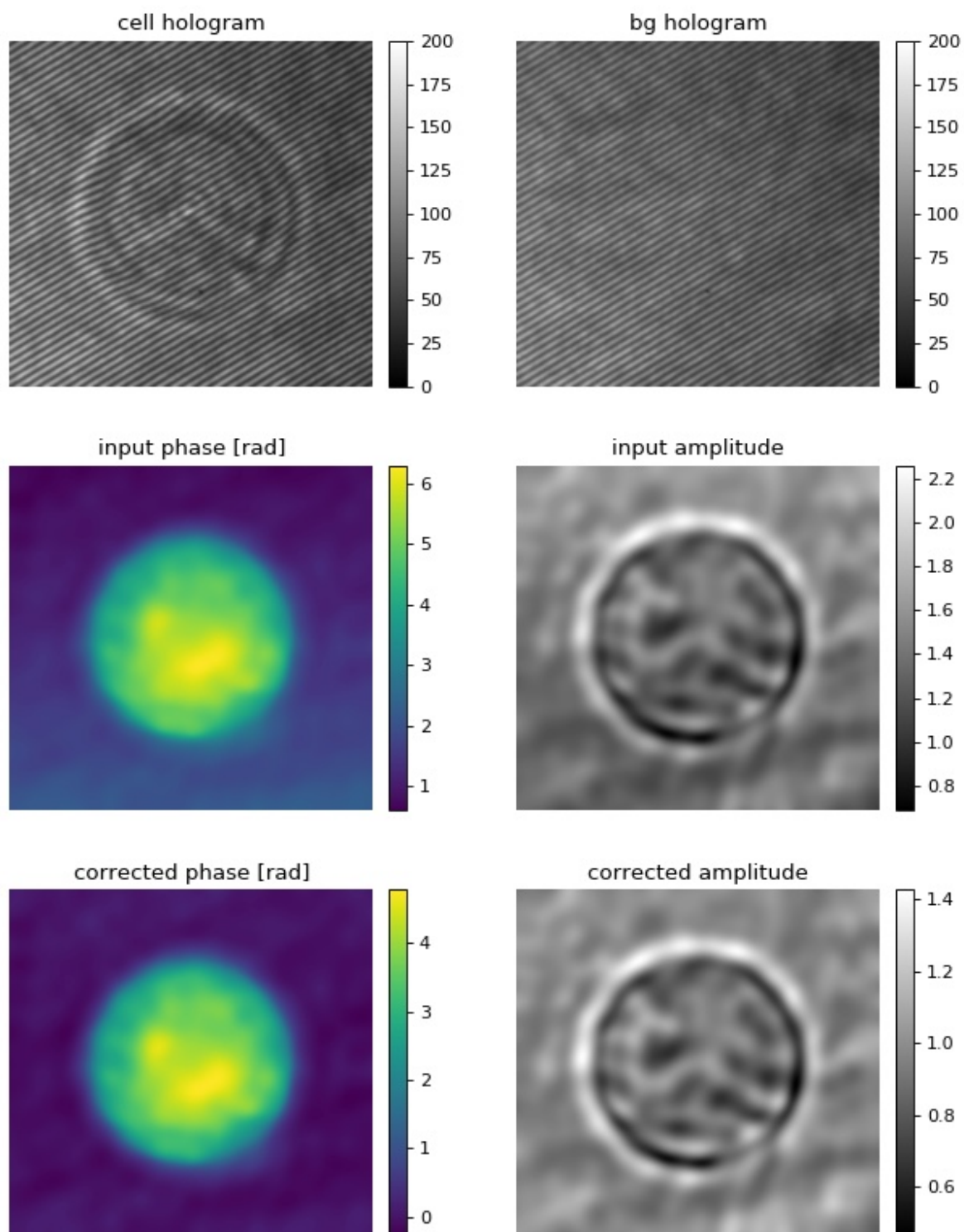
hologram\_cell.py

```

1  import matplotlib
2  import matplotlib.pyplot as plt
3  import numpy as np
4  import qpimage
5
6  # load the experimental data
7  edata = np.load("./data/hologram_cell.npz")
8
9  # create QPImage instance
10 qpi = qpimage.QPImage(data=edata["data"],
11                        bg_data=edata["bg_data"],
12                        which_data="hologram",
13                        # This parameter allows to pass arguments to the
14                        # hologram-analysis algorithm of qpimage.
15                        # (see qpimage.holo.get_field)
16                        holo_kw={
17                            # For this hologram, the "smooth disk"
18                            # filter yields the best trade-off
19                            # between interference from the central
20                            # band and image resolution.
21                            "filter_name": "smooth disk",
22                            # As can be seen in the hologram image,
23                            # the sidebands are not positioned at
24                            # an angle of 45° from the central band.
25                            # If the filter size is 1/3 (default),
26                            # the central band introduces line-
27                            # artifacts to the reconstructed image.
28                            "filter_size": 1/4
29                        })
30

```

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```

31
32 amp0 = qpi.amp
33 pha0 = qpi.pha
34
35 # background correction
36 qpi.compute_bg(which_data=["amplitude", "phase"],
37               fit_offset="fit",
38               fit_profile="tilt",
39               border_px=5,
40               )
41
42 # plot the properties of `qpi`
43 fig = plt.figure(figsize=(8, 10))
44
45 matplotlib.rcParams["image.interpolation"] = "bicubic"
46 holkw = {"cmap": "gray",
47          "vmin": 0,
48          "vmax": 200}
49
50 ax1 = plt.subplot(321, title="cell hologram")
51 map1 = ax1.imshow(edata["data"], **holkw)
52 plt.colorbar(map1, ax=ax1, fraction=.046, pad=0.04)
53
54 ax2 = plt.subplot(322, title="bg hologram")
55 map2 = ax2.imshow(edata["bg_data"], **holkw)
56 plt.colorbar(map2, ax=ax2, fraction=.046, pad=0.04)
57
58 ax3 = plt.subplot(323, title="input phase [rad]")
59 map3 = ax3.imshow(pha0)
60 plt.colorbar(map3, ax=ax3, fraction=.046, pad=0.04)
61
62 ax4 = plt.subplot(324, title="input amplitude")
63 map4 = ax4.imshow(amp0, cmap="gray")
64 plt.colorbar(map4, ax=ax4, fraction=.046, pad=0.04)
65
66 ax5 = plt.subplot(325, title="corrected phase [rad]")
67 map5 = ax5.imshow(qpi.pha)
68 plt.colorbar(map5, ax=ax5, fraction=.046, pad=0.04)
69
70 ax6 = plt.subplot(326, title="corrected amplitude")
71 map6 = ax6.imshow(qpi.amp, cmap="gray")
72 plt.colorbar(map6, ax=ax6, fraction=.046, pad=0.04)
73
74 # disable axes
75 [ax.axis("off") for ax in [ax1, ax2, ax3, ax4, ax5, ax6]]
76
77 plt.tight_layout()
78 plt.show()

```

## 3.7 Hologram filter choice

There are several parameters that influence the quality of phase and amplitude data retrieved from holograms. This example demonstrates the advantages and disadvantages of a three hologram filters in qpimage. For more information, please have a look at `qpimage.holo.get_field()`.

Several observations can be made:

- There appears to be a “bleed-through” of phase data into the amplitude data.
- A (sharp) disk filter introduces ringing artifacts in the amplitude and phase images.
- A smooth disk filter does not lead to such artifacts, but a dark halo is introduced around the coins in the amplitude image.
- The amplitude reconstruction with the gaussian filter does not exhibit the dark halo but, due to blurring, reveals less details.

To correctly interpret the data shown, please note that:

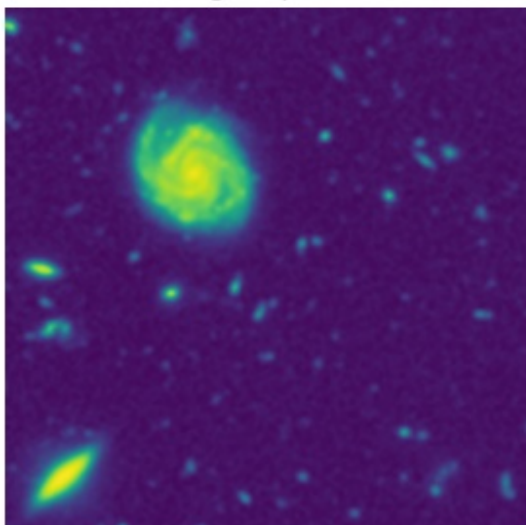
- This is a simulated hologram with *no* central band. For real data, the “filter\_size” parameter also affects the reconstruction quality. Contributions from the central band can lead to strong artifacts. A balance between high resolution (large filter size) and small contributions from the central band (small filter size) usually has be found.
- It is not trivial to compare a gaussian filter with a disk filter in terms of filter size (sigma vs. radius). The gaussian filter takes into account larger frequencies and suppresses low frequencies. In qpimage, the actual gaussian filter size is chosen such that the resolution approximately matches that of the disk filter with a corresponding radius. In general however, the filter size parameter has to be examined when comparing the two.
- There is an inherent loss of information (resolution) in the holographic reconstruction process. The side band is isolated with a low-pass filter in Fourier space. The size and shape of this filter determine the resolution of the phase and amplitude images. As a result, the level of detail of all reconstructions shown is lower than that of the original images.

hologram\_filters.py

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 import qpimage
4 from skimage import color, data
5
6 # image of a galaxy recorded with the Hubble telescope
7 img1 = color.rgb2grey(data.hubble_deep_field())[354:504, 70:220]
8 # image of a coin
9 img2 = color.rgb2grey(data.coins())[150:300, 70:220]
10
11 pha = img1/img1.max() * 2 * np.pi
12 amp = img2/img2.mean()
13
14 # create a hologram
15 x, y = np.mgrid[0:150, 0:150]
16 hologram = 2 * amp * np.cos(-2 * (x + y) + pha)
17
18 filters = ["disk", "smooth disk", "gauss"]
19 qpis = []
20
21 for filter_name in filters:
22     qpi = qpimage.QPImage(data=hologram,
23                           which_data="hologram",
24                           holo_kw={"filter_size": .5,
25                                    "filter_name": filter_name})
26     qpis.append(qpi)
27
28 fig = plt.figure(figsize=(8, 16))
29
30 phakw = {"interpolation": "bicubic",
```

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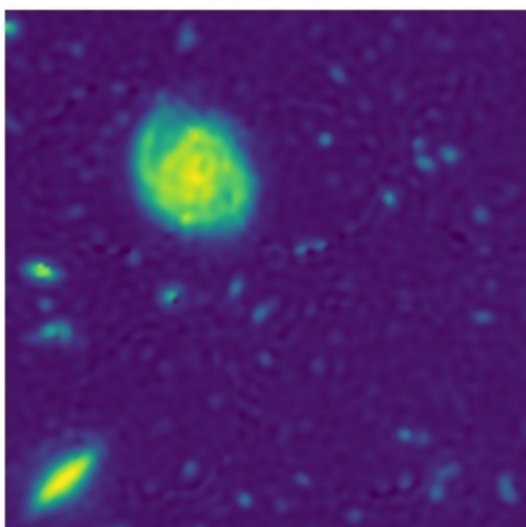
original phase



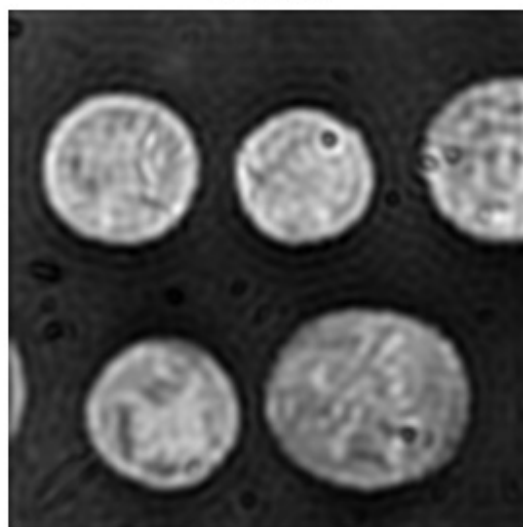
original amplitude



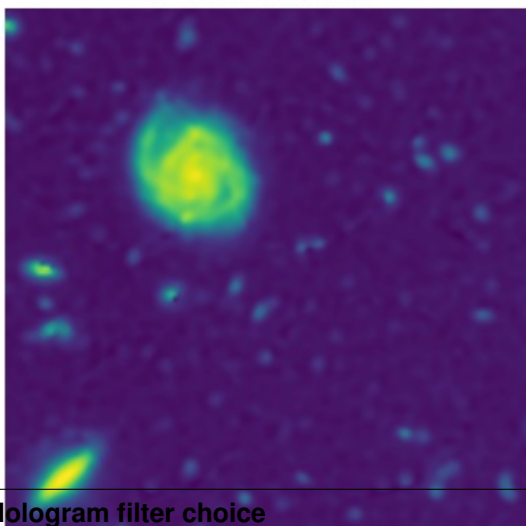
disk filter



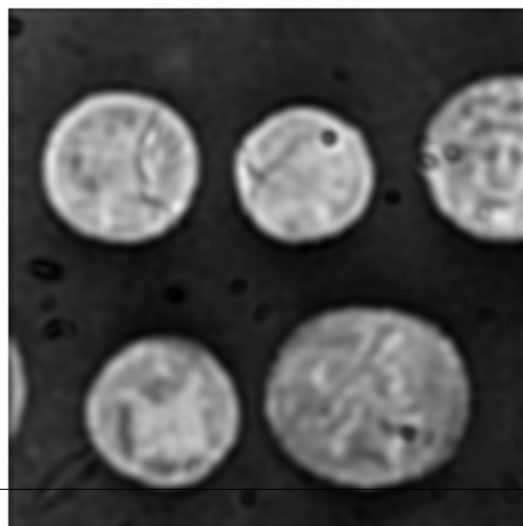
disk filter



smooth disk filter



smooth disk filter



gauss filter



gauss filter



(continued from previous page)

```
31     "cmap": "viridis",
32     "vmin": pha.min(),
33     "vmax": pha.max(),
34     }
35
36     ampkw = {"interpolation": "bicubic",
37             "cmap": "gray",
38             "vmin": amp.min(),
39             "vmax": amp.max()
40             }
41
42     numrows = len(filters) + 1
43
44     plt.subplot(numrows, 2, 1, title="original phase")
45     plt.imshow(pha, **phakw)
46
47     ax2 = plt.subplot(numrows, 2, 2, title="original amplitude")
48     plt.imshow(amp, **ampkw)
49
50     for ii in range(len(filters)):
51         # phase
52         plt.subplot(numrows, 2, 2*ii+3, title=filters[ii]+" filter")
53         plt.imshow(qpis[ii].pha, **phakw)
54         # amplitude
55         plt.subplot(numrows, 2, 2*ii+4, title=filters[ii]+" filter")
56         plt.imshow(qpis[ii].amp, **ampkw)
57
58     # disable axes
59     for ax in fig.get_axes():
60         ax.axis("off")
61
62     plt.tight_layout()
63     plt.show()
```

## 4.1 module level aliases

For user convenience, the following objects are available at the module level.

```
class qpimage.QPImage
    alias of qpimage.core.QPImage

class qpimage.QPSeries
    alias of qpimage.series.QPSeries

qpimage.META_KEYS
    alias of qpimage.meta.META_KEYS
```

## 4.2 bg\_estimate (background-estimation)

### 4.2.1 Constants

```
qpimage.bg_estimate.VALID_FIT_OFFSETS = ['fit', 'gauss', 'mean', 'mode']
    valid values for keyword argument fit_offset in estimate()

qpimage.bg_estimate.VALID_FIT_PROFILES = ['offset', 'poly2o', 'tilt']
    valid values for keyword argument fit_profile in estimate()
```

### 4.2.2 Methods

```
qpimage.bg_estimate.estimate(data, fit_offset='mean', fit_profile='tilt', border_px=0,
                             from_binary=None, ret_binary=False)
```

Estimate the background value of an image

#### Parameters

- **data** (*np.ndarray*) – Data from which to compute the background value

- **fit\_profile** (*str*) – The type of background profile to fit:
  - "offset": offset only
  - "poly2o": 2D 2nd order polynomial with mixed terms
  - "tilt": 2D linear tilt with offset (default)
- **fit\_offset** (*str*) – The method for computing the profile offset
  - "fit": offset as fitting parameter
  - "gauss": center of a gaussian fit
  - "mean": simple average
  - "mode": mode (see *qpimage.bg\_estimate.mode*)
- **border\_px** (*float*) – Assume that a frame of *border\_px* pixels around the image is background.
- **from\_binary** (*boolean np.ndarray or None*) – Use a boolean array to define the background area. The binary image must have the same shape as the input data. *True* elements are used for background estimation.
- **ret\_binary** (*bool*) – Return the binary image used to compute the background.

## Notes

If both *border\_px* and *from\_binary* are given, the intersection of the two is used, i.e. the positions where both, the binary frame and *from\_binary*, are *True*.

`qpimage.bg_estimate.offset_gaussian(data)`

Fit a gaussian model to *data* and return its center

`qpimage.bg_estimate.offset_mode(data)`

Compute Mode using a histogram with *sqrt(data.size)* bins

`qpimage.bg_estimate.profile_tilt(data, binary)`

Fit a 2D tilt to *data[binary]*

`qpimage.bg_estimate.profile_poly2o(data, binary)`

Fit a 2D 2nd order polynomial to *data[binary]*

`qpimage.bg_estimate.poly2o_model(params, shape)`

Imfit 2nd order polynomial model

`qpimage.bg_estimate.poly2o_residual(params, data, binary)`

Imfit 2nd order polynomial residuals

`qpimage.bg_estimate.tilt_model(params, shape)`

Imfit tilt model

`qpimage.bg_estimate.tilt_residual(params, data, binary)`

Imfit tilt residuals

## 4.3 core (QPImage)

### 4.3.1 Constants

`qpimage.core.VALID_INPUT_DATA = ['field', 'hologram', 'phase', ('phase', 'amplitude'), ('phase', 'intensity')]`  
 valid combinations for keyword argument *which\_data*

### 4.3.2 Classes

**class** `qpimage.core.QPImage` (*data=None, bg\_data=None, which\_data='phase', meta\_data={}, holo\_kw={}, h5file=None, h5mode='a', h5dtype='float32'*)

Quantitative phase image manipulation

This class implements various tasks for quantitative phase imaging, including phase unwrapping, background correction, numerical focusing, and data export.

#### Parameters

- **data** (*2d ndarray (float or complex) or list*) – The experimental data (see *which\_data*)
- **bg\_data** (*2d ndarray (float or complex), list, or None*) – The background data (must be same type as *data*)
- **which\_data** (*str*) – String or comma-separated list of strings indicating the order and type of input data. Valid values are “hologram”, “field”, “phase”, “phase,amplitude”, or “phase,intensity”, where the latter two require an indexable object with the phase data as first element.
- **meta\_data** (*dict*) – Meta data associated with the input data. see `qpimage.meta.META_KEYS`
- **holo\_kw** (*dict*) – Special keyword arguments for phase retrieval from hologram data (*which\_data*=“hologram”). See `qpimage.holo.get_field()` for valid keyword arguments.

New in version 0.1.6.

- **h5file** (*str, pathlib.Path, h5py.Group, h5py.File, or None*) – A path to an hdf5 data file where all data is cached. If set to *None* (default), all data will be handled in memory using the “core” driver of the `h5py`’s `File` class. If the file does not exist, it is created. If the file already exists, it is opened with the file mode defined by *hdf5\_mode*. If this is an instance of `h5py.Group` or `h5py.File`, then this will be used to internally store all data.
- **h5mode** (*str*) – Valid file modes are (only applies if *h5file* is a path)
  - “r”: Readonly, file must exist
  - “r+”: Read/write, file must exist
  - “w”: Create file, truncate if exists
  - “w-” or “x”: Create file, fail if exists
  - “a”: Read/write if exists, create otherwise (default)
- **h5dtype** (*str*) – The datatype in which to store the image data. The default is “float32” which is sufficient for 2D image analysis and consumes only half the disk space of the numpy default “float64”.

## Notes

QPIImage is slicable; the following returns a new QPIImage with the same meta data, but with all background corrections merged into the raw data:

```
qpi = QPIImage(data=...)
qpi_scliced = qpi[10:20, 40:30]
```

**bg\_amp**

background amplitude image

**bg pha**

background phase image

**amp**

background-corrected amplitude image

**field**

background-corrected complex field

**info**

list of tuples with QPIImage meta data

**meta**

dictionary with imaging meta data

**pha**

background-corrected phase image

**raw\_amp**

raw amplitude image

**raw pha**

raw phase image

**shape**

size of image dimensions

**clear\_bg** (*which\_data*=(*'amplitude'*, *'phase'*), *keys*=*'fit'*)

Clear background correction

**Parameters**

- **which\_data** (*str* or *list of str*) – From which type of data to remove the background information. The list contains either “amplitude”, “phase”, or both.
- **keys** (*str* or *list of str*) – Which type of background data to remove. One of:
  - “fit”: the background data computed with `qpimage.QPIImage.compute_bg()`
  - “data”: the experimentally obtained background image

**compute\_bg** (*which\_data*=*'phase'*, *fit\_offset*=*'mean'*, *fit\_profile*=*'tilt'*, *border\_m*=0, *border\_perc*=0, *border\_px*=0, *from\_binary*=None, *ret\_binary*=False)

Compute background correction

**Parameters**

- **which\_data** (*str* or *list of str*) – From which type of data to remove the background information. The list contains either “amplitude”, “phase”, or both.
- **fit\_profile** (*str*) – The type of background profile to fit:
  - “offset”: offset only

- “poly2o”: 2D 2nd order polynomial with mixed terms
- “tilt”: 2D linear tilt with offset (default)
- **fit\_offset** (*str*) – The method for computing the profile offset
  - “fit”: offset as fitting parameter
  - “gauss”: center of a gaussian fit
  - “mean”: simple average
  - “mode”: mode (see *qpimage.bg\_estimate.mode*)
- **border\_m** (*float*) – Assume that a frame of *border\_m* meters around the image is background. The value is converted to pixels and rounded.
- **border\_perc** (*float*) – Assume that a frame of *border\_perc* percent around the image is background. The value is converted to pixels and rounded. If the aspect ratio of the image is not one, then the average of the data’s shape is used to compute the percentage in pixels.
- **border\_px** (*float*) – Assume that a frame of *border\_px* pixels around the image is background.
- **from\_binary** (*boolean np.ndarray or None*) – Use a boolean array to define the background area. The binary image must have the same shape as the input data. *True* elements are used for background estimation.
- **ret\_binary** (*bool*) – Return the binary image used to compute the background.

## Notes

The *border\_\** values are translated to pixel values and the largest pixel border is used to generate a binary image for background computation.

If any of the *border\_\** arguments are non-zero and *from\_binary* is given, the intersection of the two is used, i.e. the positions where both, the binary frame and *from\_binary*, are *True*.

### See also:

*qpimage.bg\_estimate.estimate()*

### **copy** (*h5file=None*)

Create a copy of the current instance

This is done by recursively copying the underlying hdf5 data.

**Parameters** *h5file* (*str, h5py.File, h5py.Group, or None*) – see *QPIImage.\_\_init\_\_*

### **refocus** (*distance, method='helmholtz', h5file=None, h5mode='a'*)

Compute a numerically refocused QPIImage

#### Parameters

- **distance** (*float*) – Focusing distance [m]
- **method** (*str*) – Refocusing method, one of [“helmholtz”, “fresnel”]
- **h5file** (*str, h5py.Group, h5py.File, or None*) – A path to an hdf5 data file where the QPIImage is cached. If set to *None* (default), all data will be handled in memory using the “core” driver of the *h5py*’s *File* class. If the file does not exist, it is created. If the file already exists, it is opened with the file mode defined by *hdf5\_mode*. If

this is an instance of `h5py.Group` or `h5py.File`, then this will be used to internally store all data.

- **h5mode** (*str*) – Valid file modes are (only applies if *h5file* is a path)
  - “r”: Readonly, file must exist
  - “r+”: Read/write, file must exist
  - “w”: Create file, truncate if exists
  - “w-” or “x”: Create file, fail if exists
  - “a”: Read/write if exists, create otherwise (default)

**Returns** `qpi` – Refocused phase and amplitude data

**Return type** `qpimage.QPImage`

**See also:**

`nrefocus` library used for numerical focusing

**set\_bg\_data** (*bg\_data*, *which\_data=None*)

Set background amplitude and phase data

**Parameters**

- **bg\_data** (2d ndarray (float or complex), list, `QPImage`, or `None`) – The background data (must be same type as *data*). If set to `None`, the background data is reset.
- **which\_data** (*str*) – String or comma-separated list of strings indicating the order and type of input data. Valid values are “field”, “phase”, “phase,amplitude”, or “phase,intensity”, where the latter two require an indexable object for *bg\_data* with the phase data as first element.

### 4.3.3 Methods

`qpimage.core.copyh5` (*inh5*, *outh5*)

Recursively copy all hdf5 data from one group to another

**Parameters**

- **inh5** (*str*, `h5py.File`, or `h5py.Group`) – The input hdf5 data. This can be either a file name or an hdf5 object.
- **outh5** (*str*, `h5py.File`, `h5py.Group`, or `None`) – The output hdf5 data. This can be either a file name or an hdf5 object. If set to `None`, a new hdf5 object is created in memory.

#### Notes

All data in *outh5* are overridden by the *inh5* data.

## 4.4 holo (hologram analysis)

### 4.4.1 Methods

`qpimage.holo.find_sideband(ft_data, which=1, copy=True)`

Find the side band position of a hologram

The hologram is Fourier-transformed and the side band is determined by finding the maximum amplitude in Fourier space.

#### Parameters

- **ft\_data** (*2d ndarray*) – Fourier transform of the hologram image
- **which** (*+1 or -1*) – which sideband to search for:
  - +1: upper half
  - -1: lower half
- **copy** (*bool*) – copy *ft\_data* before modification

**Returns** *fsx, fsy* – coordinates of the side band in Fourier space frequencies

**Return type** tuple of floats

`qpimage.holo.fourier2dpad(data, zero_pad=True)`

Compute the 2D Fourier transform with zero padding

#### Parameters

- **data** (*2d fload ndarray*) – real-valued image data
- **zero\_pad** (*bool*) – perform zero-padding to next order of 2

`qpimage.holo.get_field(hologram, sideband=1, filter_name='disk', filter_size=0.3333333333333333, subtract_mean=True, zero_pad=True, copy=True)`

Compute the complex field from a hologram using Fourier analysis

#### Parameters

- **hologram** (*real-valued 2d ndarray*) – hologram data
- **sideband** (*+1, -1, or tuple of (float, float)*) – specifies the location of the sideband:
  - +1: sideband in the upper half in Fourier space, exact location is found automatically
  - -1: sideband in the lower half in Fourier space, exact location is found automatically
  - (float, float): sideband coordinates in frequencies in interval  $[1/\text{"axes size"}, .5]$
- **filter\_name** (*str*) – specifies the filter to use, one of
  - "disk": binary disk with radius *filter\_size*
  - "smooth disk": disk with radius *filter\_size* convolved with a radial gaussian (*sigma=filter\_size/5*)
  - "gauss": radial gaussian (*sigma=0.6\*filter\_size*)
  - "square": binary square with side length *filter\_size*
  - "smooth square": square with side length *filter\_size* convolved with square gaussian (*sigma=filter\_size/5*)

- “tukey”: a square tukey window of width  $2*filter\_size$  and  $alpha=0.1$
- **filter\_size** (*float*) – Size of the filter in Fourier space in fractions of the distance between central band and sideband. See *filter\_shape* for interpretation of *filter\_size*.
- **subtract\_mean** (*bool*) – If True, remove the mean of the hologram before performing the Fourier transform. This setting is recommended as it can reduce artifacts from frequencies around the central band.
- **zero\_pad** (*bool*) – Perform zero-padding before applying the FFT. Setting *zero\_pad* to *False* increases speed but might introduce image distortions such as tilts in the phase and amplitude data or dark borders in the amplitude data.
- **copy** (*bool*) – If set to True, input *data* is not edited.
- **and y0 are center of the filter** (*x0*) –
- **is factor for "radius" of filter** ( $\sqrt{x0^2 + y0^2}/np.pi$ ) (*R*) –
- **can be "disk" or "gauss"** (*filter\_type*) –

## Notes

Even though the size of the “gauss” filter approximately matches the frequencies of the “disk” filter, it takes into account higher frequencies as well and thus suppresses ringing artifacts for data that contain jumps in the phase image.

## 4.5 image\_data (basic image management)

### 4.5.1 Constants

```
qpimage.image_data.COMPRESSION = {'compression': 'gzip', 'compression_opts': 9}
    default hdf5 compression keyword arguments
```

```
qpimage.image_data.VALID_BG_KEYS = ['data', 'fit']
    valid background data identifiers
```

### 4.5.2 Classes

```
class qpimage.image_data.Amplitude(h5, h5dtype='float32')
```

Bases: [`qpimage.image\_data.ImageData`](#)

Dedicated class for amplitude image data

For amplitude image data, background correction is defined by dividing the raw image by the background image.

#### Parameters

- **h5** (*h5py.Group*) – HDF5 group where all data is kept
- **h5dtype** (*str*) – The datatype in which to store the image data. The default is “float32” which is sufficient for 2D image analysis and consumes only half the disk space of the numpy default “float64”.

```
class qpimage.image_data.Phase(h5, h5dtype='float32')
```

Bases: [`qpimage.image\_data.ImageData`](#)

Dedicated class for phase image data

For phase image data, background correction is defined by subtracting the background image from the raw image.

#### Parameters

- **h5** (*h5py.Group*) – HDF5 group where all data is kept
- **h5dtype** (*str*) – The datatype in which to store the image data. The default is “float32” which is sufficient for 2D image analysis and consumes only half the disk space of the numpy default “float64”.

**class** qpimage.image\_data.**ImageData** (*h5, h5dtype='float32'*)

Base class for image management

See also:

**Amplitude** ImageData with amplitude background correction

**Phase** ImageData with phase background correction

#### Parameters

- **h5** (*h5py.Group*) – HDF5 group where all data is kept
- **h5dtype** (*str*) – The datatype in which to store the image data. The default is “float32” which is sufficient for 2D image analysis and consumes only half the disk space of the numpy default “float64”.

**bg**

combined background image data

**image**

background corrected image data

**info**

list of background correction parameters

**raw**

raw (uncorrected) image data

**del\_bg** (*key*)

Remove the background image data

**Parameters** **key** (*str*) – One of [VALID\\_BG\\_KEYS](#)

**estimate\_bg** (*fit\_offset='mean', fit\_profile='tilt', border\_px=0, from\_binary=None, ret\_binary=False*)

Estimate image background

#### Parameters

- **fit\_profile** (*str*) – The type of background profile to fit:
  - “offset”: offset only
  - “poly2o”: 2D 2nd order polynomial with mixed terms
  - “tilt”: 2D linear tilt with offset (default)
- **fit\_offset** (*str*) – The method for computing the profile offset
  - “fit”: offset as fitting parameter
  - “gauss”: center of a gaussian fit
  - “mean”: simple average

- “mode”: mode (see `qpimage.bg_estimate.mode`)
- **border\_px** (*float*) – Assume that a frame of *border\_px* pixels around the image is background.
- **from\_binary** (*boolean np.ndarray or None*) – Use a boolean array to define the background area. The binary image must have the same shape as the input data. ‘True’ elements are used for background estimation.
- **ret\_binary** (*bool*) – Return the binary image used to compute the background.

## Notes

If both *border\_px* and *from\_binary* are given, the intersection of the two resulting binary images is used.

The arguments passed to this method are stored in the hdf5 file *self.h5* and are used for optional integrity checking using `qpimage.integrity_check.check`.

See also:

`qpimage.bg_estimate.estimate()`

**get\_bg** (*key=None, ret\_attrs=False*)  
Get the background data

### Parameters

- **key** (*None or str*) – A user-defined key that identifies the background data. Examples are “data” for experimental data, or “fit” for an estimated background correction (see `VALID_BG_KEYS`). If set to *None*, returns the combined background image (`ImageData.bg`).
- **ret\_attrs** (*bool*) – Also returns the attributes of the background data.

**set\_bg** (*bg, key='data', attrs={}*)  
Set the background data

### Parameters

- **bg** (*numbers.Real, 2d ndarray, ImageData, or h5py.Dataset*) – The background data. If *bg* is an *h5py.Dataset* object, it must exist in the same hdf5 file (a hard link is created). If set to *None*, the data will be removed.
- **key** (*str*) – One of `VALID_BG_KEYS`
- **attrs** (*dict*) – List of background attributes

See also:

`del_bg()` removing background data

## 4.5.3 Methods

`qpimage.image_data.write_image_dataset` (*group, key, data, h5dtype=None*)  
Write an image to an hdf5 group as a dataset

This convenience function sets all attributes such that the image can be visualized with HDFView, sets the compression and fletcher32 filters, and sets the chunk size to the image shape.

### Parameters

- **group** (*h5py.Group*) – HDF5 group to store data to

- **key** (*str*) – Dataset identifier
- **data** (*np.ndarray of shape (M,N)*) – Image data to store
- **h5dtype** (*str*) – The datatype in which to store the image data. The default is the datatype of *data*.

**Returns** **dataset** – The created HDF5 dataset object

**Return type** `h5py.Dataset`

## 4.6 integrity\_check (check QPImage data)

### 4.6.1 Exceptions

**exception** `qpimage.integrity_check.IntegrityCheckError`

Raised when a QPImage data set is incomplete or corrupt

### 4.6.2 Methods

`qpimage.integrity_check.check(qpi_or_h5file, checks=['attributes', 'background'])`

Checks various properties of a `qpimage.core.QPImage` instance

**Parameters**

- **qpi\_or\_h5file** (`qpimage.core.QPImage` or *str*) – A QPImage object or a path to an hdf5 file
- **checks** (*list of str*) – Which checks to perform (“attributes” and/or “background”)

**Raises** `IntegrityCheckError` – if the checks fail

`qpimage.integrity_check.check_attributes(qpi)`

Check QPimage attributes

**Parameters** **qpi** (`qpimage.core.QPImage`) –

**Raises** `IntegrityCheckError` – if the check fails

`qpimage.integrity_check.check_background(qpi)`

Check QPimage background data

**Parameters** **qpi** (`qpimage.core.QPImage`) –

**Raises** `IntegrityCheckError` – if the check fails

## 4.7 meta (definitions for QPImage meta data)

### 4.7.1 Constants

`qpimage.meta.META_KEYS = ['medium index', 'pixel size', 'time', 'wavelength', 'dm exclude', ...]`  
valid `qpimage.core.QPImage` meta data keys

## 4.7.2 Exceptions

**exception** `qpimage.meta.MetaDataMissingError`  
Raised when meta data is missing

## 4.7.3 Classes

**class** `qpimage.meta.MetaDict` (\*args, \*\*kwargs)  
Bases: `dict`  
Management of meta data variables  
Valid key names are combined in the `qpimage.meta.META_KEYS` variable.

## 4.8 series (QPSeries)

### 4.8.1 Classes

**class** `qpimage.series.QPSeries` (*qpimage\_list*=[], *meta\_data*={}, *h5file*=None, *h5mode*='a', *identifier*=None)  
Quantitative phase image series

#### Parameters

- **qpimage\_list** (*list*) – A list of instances of `qpimage.QPImage`.
- **meta\_data** (*dict*) – Meta data associated with the input data (see `qpimage.META_KEYS`). This overrides the meta data of the QPImages in *qpimage\_list* and, if *h5file* is given and *h5mode* is not “r”, overrides the meta data in *h5file*.
- **h5file** (*str*, *h5py.Group*, *h5py.File*, or *None*) – A path to an hdf5 data file where all data is cached. If set to *None* (default), all data will be handled in memory using the “core” driver of the *h5py*’s `File` class. If the file does not exist, it is created. If the file already exists, it is opened with the file mode defined by *hdf5\_mode*. If this is an instance of *h5py.Group* or *h5py.File*, then this will be used to internally store all data. If *h5file* is given and *qpimage\_list* is not empty, all QPImages in *qpimage\_list* are appended to *h5file* in the given order.
- **h5mode** (*str*) – Valid file modes are (only applies if *h5file* is a path):
  - “r”: Readonly, file must exist
  - “r+”: Read/write, file must exist
  - “w”: Create file, truncate if exists
  - “w-” or “x”: Create file, fail if exists
  - “a”: Read/write if exists, create otherwise (default)

#### identifier

unique identifier of the series

**add\_qpimage** (*qpi*, *identifier*=None, *bg\_from\_idx*=None)  
Add a QPImage instance to the QPSeries

#### Parameters

- **qpimage** (`qpimage.QPImage`) – The QPImage that is added to the series

- **identifier** (*str*) – Identifier key for *qpi*
- **bg\_from\_idx** (*int* or *None*) – Use the background data from the data stored in this index, creating hard links within the hdf5 file. (Saves memory if e.g. all qpimages is corrected with the same data)

**get\_qpimage** (*index*)

Return a single QPImage of the series

**Parameters** **index** (*int* or *str*) – Index or identifier of the QPImage

### Notes

Instead of `qps.get_qpimage(index)`, it is possible to use the short-hand `qps[index]`.



## CHAPTER 5

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### Bibliography

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## CHAPTER 6

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### Indices and tables

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