
qpimage Documentation

Release 0.9.0

Paul Müller

Apr 27, 2022

CONTENTS

1	Introduction	3
1.1	The Problem	3
1.2	Why qpimage?	3
1.3	What are the alternatives?	3
1.4	Citing qpimage	4
2	Getting started	5
2.1	Installing qpimage	5
2.2	User API	5
2.2.1	Basic usage	5
2.2.2	Storing QPImage data on disk	6
2.2.3	Dealing with measurement series	6
2.2.4	Notes	7
3	Examples	9
3.1	Simple phase	9
3.2	Background image tilt correction	10
3.3	Background image offset correction	11
3.4	Masked background image correction	13
3.5	Background image 2nd order polynomial correction	16
3.6	Object-mask background image correction	17
3.7	Off-axis hologram of a single cell	19
3.8	Filter choices for interferometric imaging	22
4	HDF5 file format	25
4.1	QPImage	25
4.1.1	Attributes	25
4.1.2	Groups	26
4.2	QPSeries	26
5	Code reference	29
5.1	module level aliases	29
5.2	bg_estimate (background-estimation)	29
5.2.1	Constants	29
5.2.2	Methods	29
5.3	core (QPImage)	30
5.3.1	Constants	30
5.3.2	Classes	31
5.3.3	Methods	35
5.4	image_data (basic image management)	35

5.4.1	Constants	35
5.4.2	Classes	35
5.4.3	Methods	37
5.5	integrity_check (check QImage data)	38
5.5.1	Exceptions	38
5.5.2	Methods	38
5.6	meta (definitions for QImage meta data)	38
5.6.1	Constants	38
5.6.2	Exceptions	39
5.6.3	Classes	39
5.7	series (QPSeries)	39
5.7.1	Classes	39
6	Changelog	41
6.1	version 0.9.0	41
6.2	version 0.8.5	41
6.3	version 0.8.4	41
6.4	version 0.8.3	41
6.5	version 0.8.2	41
6.6	version 0.8.1	42
6.7	version 0.8.0	42
6.8	version 0.7.7	42
6.9	version 0.7.6	42
6.10	version 0.7.5	42
6.11	version 0.7.4	42
6.12	version 0.7.3	42
6.13	version 0.7.2	42
6.14	version 0.7.1	43
6.15	version 0.7.0	43
6.16	version 0.6.4	43
6.17	version 0.6.3	43
6.18	version 0.6.2	43
6.19	version 0.6.1	43
6.20	version 0.6.0	44
6.21	version 0.5.4	44
6.22	version 0.5.3	44
6.23	version 0.5.2	44
6.24	version 0.5.1	44
6.25	version 0.5.0	44
6.26	version 0.4.6	44
6.27	version 0.4.5	45
6.28	version 0.4.4	45
6.29	version 0.4.3	45
6.30	version 0.4.2	45
6.31	version 0.4.1	45
6.32	version 0.4.0	45
6.33	version 0.3.0	45
6.34	version 0.2.1	45
6.35	version 0.2.0	46
6.36	version 0.1.8	46
6.37	version 0.1.7	46
6.38	version 0.1.6	46
6.39	version 0.1.5	46
6.40	version 0.1.4	47

6.41	version 0.1.3	47
6.42	version 0.1.2	47
6.43	version 0.1.1	47
6.44	version 0.1.0	48
7	Bilbliography	49
8	Indices and tables	51
	Bibliography	53
	Python Module Index	55
	Index	57

Qpimage is a Python library that provides a convenient interface to many common functionalities that are used in quantitative phase imaging. This is the documentation of qpimage version 0.9.0.

INTRODUCTION

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 [\[SCG+17\]](#).

GETTING STARTED

2.1 Installing qpimage

Qpimage is written in pure Python and supports Python version 3.6 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 -e .` or

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)
```

(continues on next page)

(continued from previous page)

```

    )
# save the background-corrected phase to a text file
numpy.savetxt("out.txt", qpi.pha)

```

which creates an instance of *QPIImage* 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 QPIImage data on disk

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

```

with qpimage.QPIImage(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 *QPIImage*:

```

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

# or open cached data for writing (e.g. for changing the background)
with qpimage.QPIImage(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 *QPISeries* class for handling multiple instances of *QPIImage* in one hdf5 file. For instance, to combine two QPIImages in one series file, one could use:

```

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

with qpimage.QPISeries(h5file="/path/to/series_file.h5", h5mode="w") as qps:
    for ii, pp in enumerate(paths):

```

(continues on next page)

(continued from previous page)

```
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"]
```

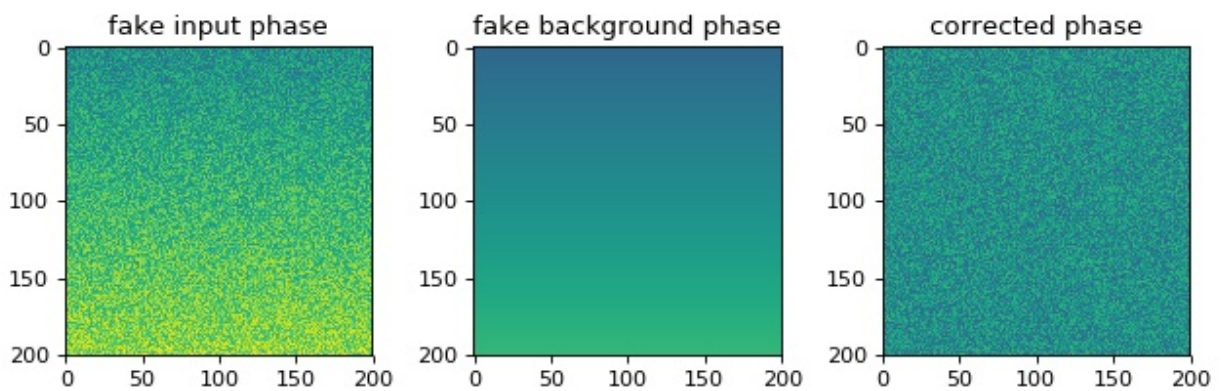
2.2.4 Notes

- 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.

EXAMPLES

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
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,
```

(continues on next page)

(continued from previous page)

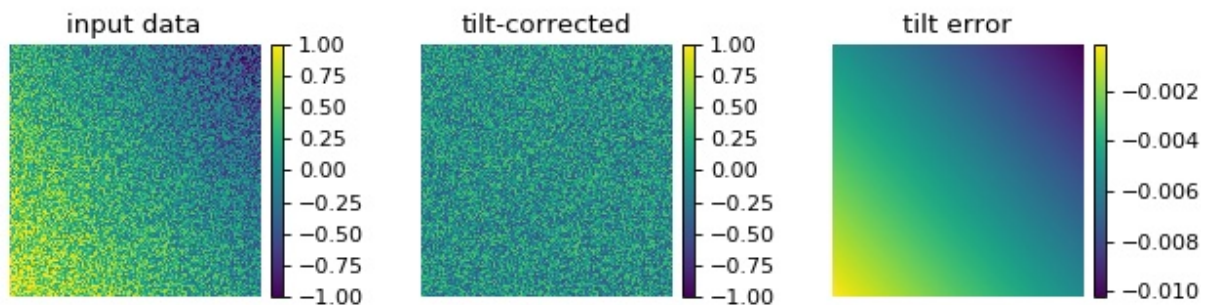
```

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
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

```

(continues on next page)

(continued from previous page)

```

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.

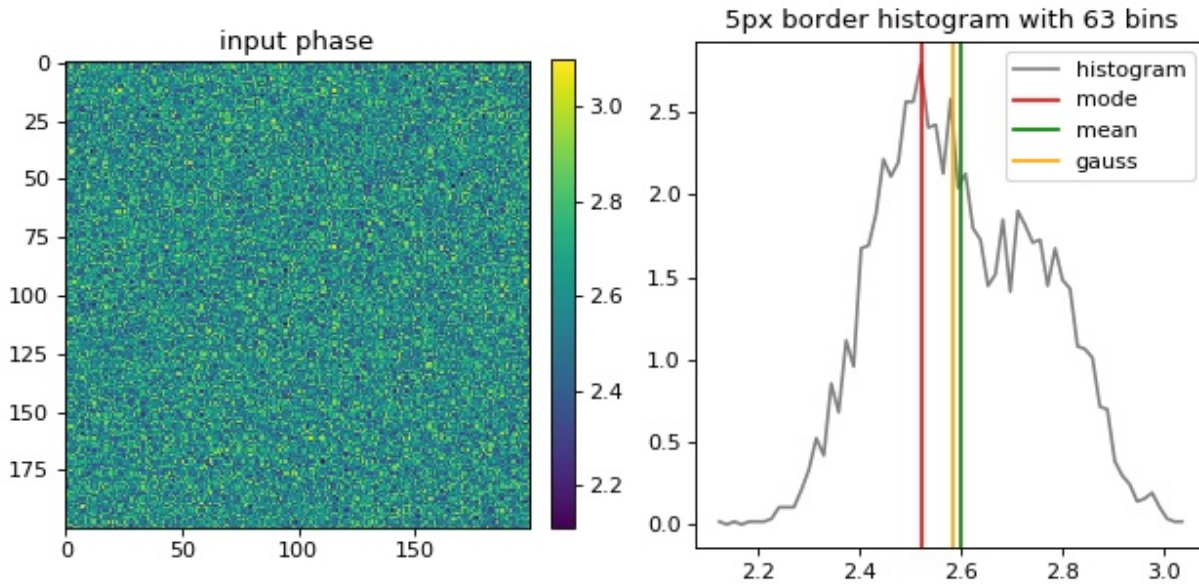
background_offset.py

```

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`,
13 # such that there is no pure gaussian distribution.
14 # (otherwise 'mean' and 'gaussian' cannot be distinguished)

```

(continues on next page)



(continued from previous page)

```

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_mask": True, # return the mask image for visualization
27         }
28
29 mask = qpi.compute_bg(fit_offset="mode", **cpkw)
30 bg_mode = np.mean(qpi.bg pha[mask])
31
32 qpi.compute_bg(fit_offset="mean", **cpkw)
33 bg_mean = np.mean(qpi.bg pha[mask])
34
35 qpi.compute_bg(fit_offset="gauss", **cpkw)
36 bg_gauss = np.mean(qpi.bg pha[mask])
37
38 bg_data = (qpi.pha + qpi.bg pha)[mask]
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]

```

(continues on next page)

(continued from previous page)

```

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 Masked background image correction

This example illustrates background correction with qpimage using a 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 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).

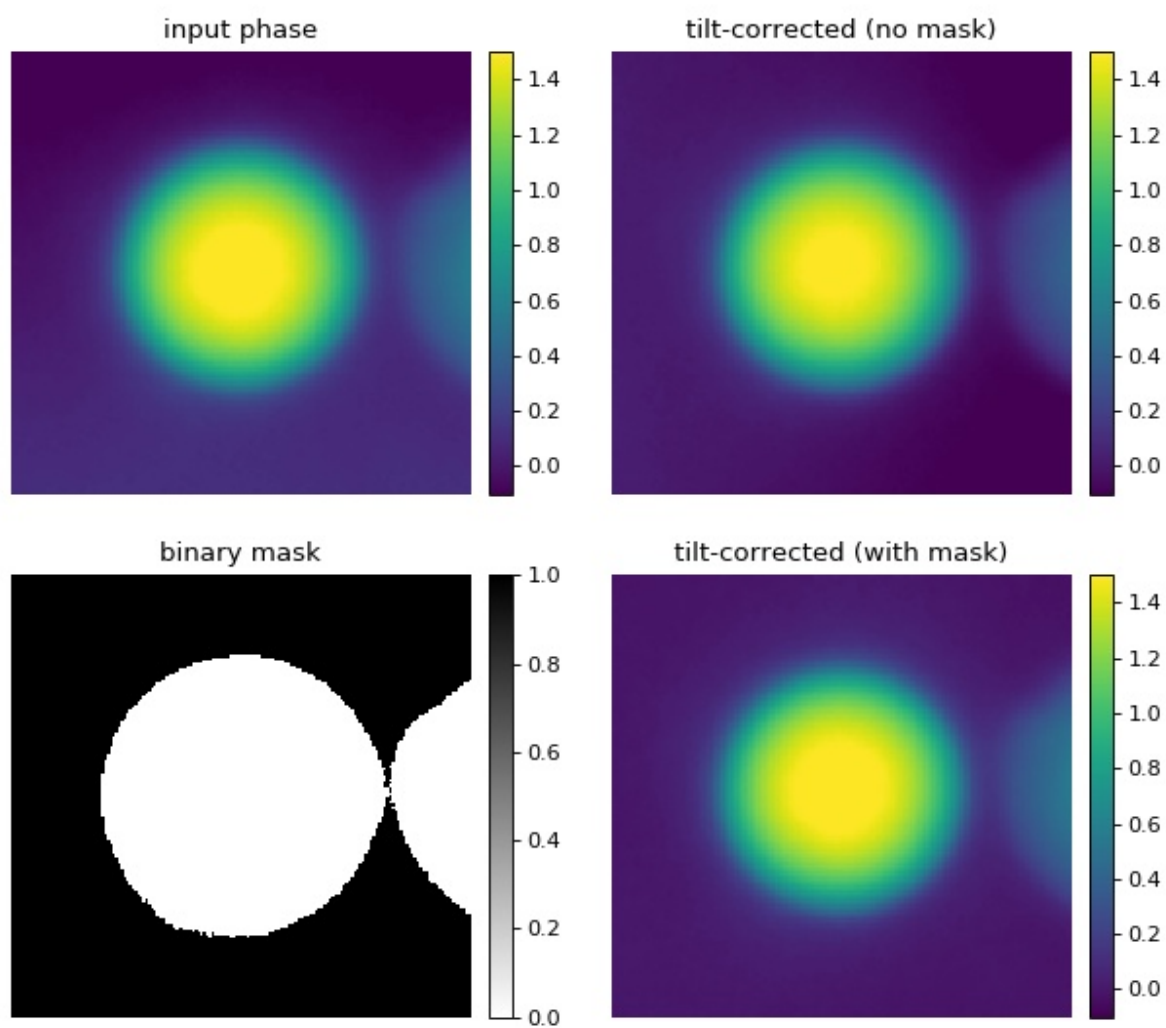
background_mask.py

```

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,

```

(continues on next page)



(continued from previous page)

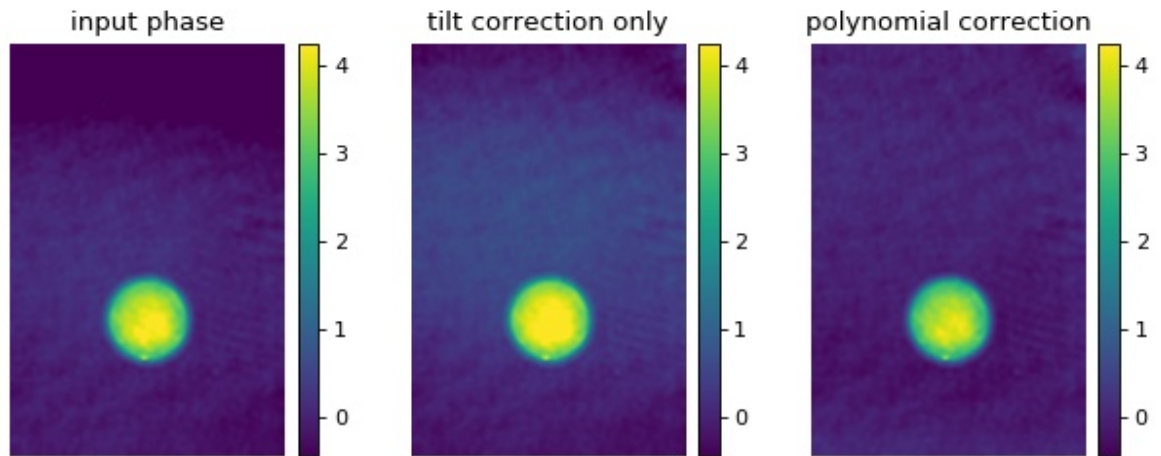
```

18         )
19 pha_nomask = qpi.pha
20
21 # educated guess for 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_mask=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="mask")
48 map3 = ax3.imshow(1.*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, 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
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="raw-oah")
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               )

```

(continues on next page)

(continued from previous page)

```

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(pha0, **phakw)
40 plt.colorbar(map1, ax=ax1, fraction=.067, pad=0.04)
41
42 ax2 = plt.subplot(132, title="tilt correction only")
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 Object-mask background image correction

In some cases, using *only the border of the phase image* for background correction might not be enough. To increase the area of the background image, it is possible to mask only the cell area. The `qpsphere` package provides the convenience method `qpsphere.cnvnc.bg_phase_mask_for_qpi()` which computes the background phase mask based on the position and radius of an automatically detected spherical phase object. The sized of the mask can be tuned with the `radial_clearance` parameter.

Note that the various methods used in the examples for determining such a phase mask can be combined. Also note that before applying the method discussed here, an initial background correction might be necessary.

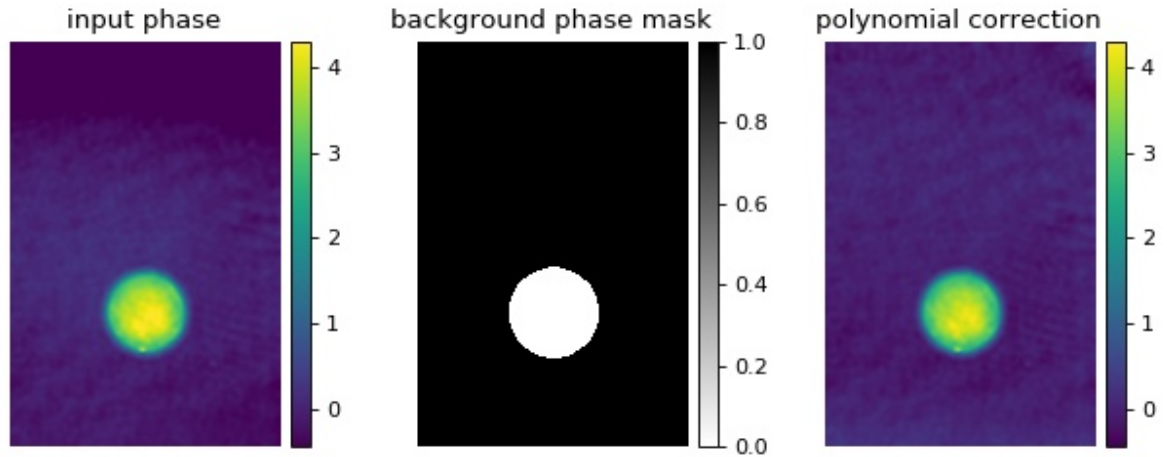
`background_mask_sphere.py`

```

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
6 import qpimage
7 import qpsphere
8
9 edata = np.array(Image.open("./data/hologram_cell_curved_bg.jpg"))
10

```

(continues on next page)



(continued from previous page)

```

11 # create QPImage instance
12 qpi = qpimage.QPImage(data=edata,
13                        which_data="raw-oah",
14                        meta_data={"medium index": 1.335,
15                                "wavelength": 550e-9,
16                                "pixel size": 0.107e-6})
17 pha0 = qpi.pha
18
19 # determine the position of the cell (takes a while)
20 mask = qpsphere.cnvnc.bg_phase_mask_for_qpi(qpi=qpi,
21                                             r0=7e-6,
22                                             method="edge",
23                                             model="projection",
24                                             radial_clearance=1.15)
25
26 # background correction using polynomial and mask
27 qpi.compute_bg(which_data=["phase"],
28               fit_offset="fit",
29               fit_profile="poly2o",
30               from_mask=mask,
31               )
32 pha_corr = qpi.pha
33
34 # plot phase data
35 fig = plt.figure(figsize=(8, 3.3))
36
37 phakw = {"cmap": "viridis",
38         "interpolation": "bicubic",
39         "vmin": pha_corr.min(),
40         "vmax": pha_corr.max()}
41
42 ax1 = plt.subplot(131, title="input phase")
43 map1 = ax1.imshow(phas0, **phakw)
44 plt.colorbar(map1, ax=ax1, fraction=.067, pad=0.04)

```

(continues on next page)

(continued from previous page)

```

45 ax2 = plt.subplot(132, title="background phase mask")
46 map2 = ax2.imshow(1.*mask, cmap="gray_r")
47 plt.colorbar(map2, ax=ax2, fraction=.067, pad=0.04)
48
49 ax3 = plt.subplot(133, title="polynomial correction")
50 map3 = ax3.imshow(pha_corr, **phakw)
51 plt.colorbar(map3, ax=ax3, fraction=.067, pad=0.04)
52
53
54 # disable axes
55 [ax.axis("off") for ax in [ax1, ax2, ax3]]
56
57 plt.tight_layout(w_pad=0)
58 plt.show()

```

3.7 Off-axis 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.

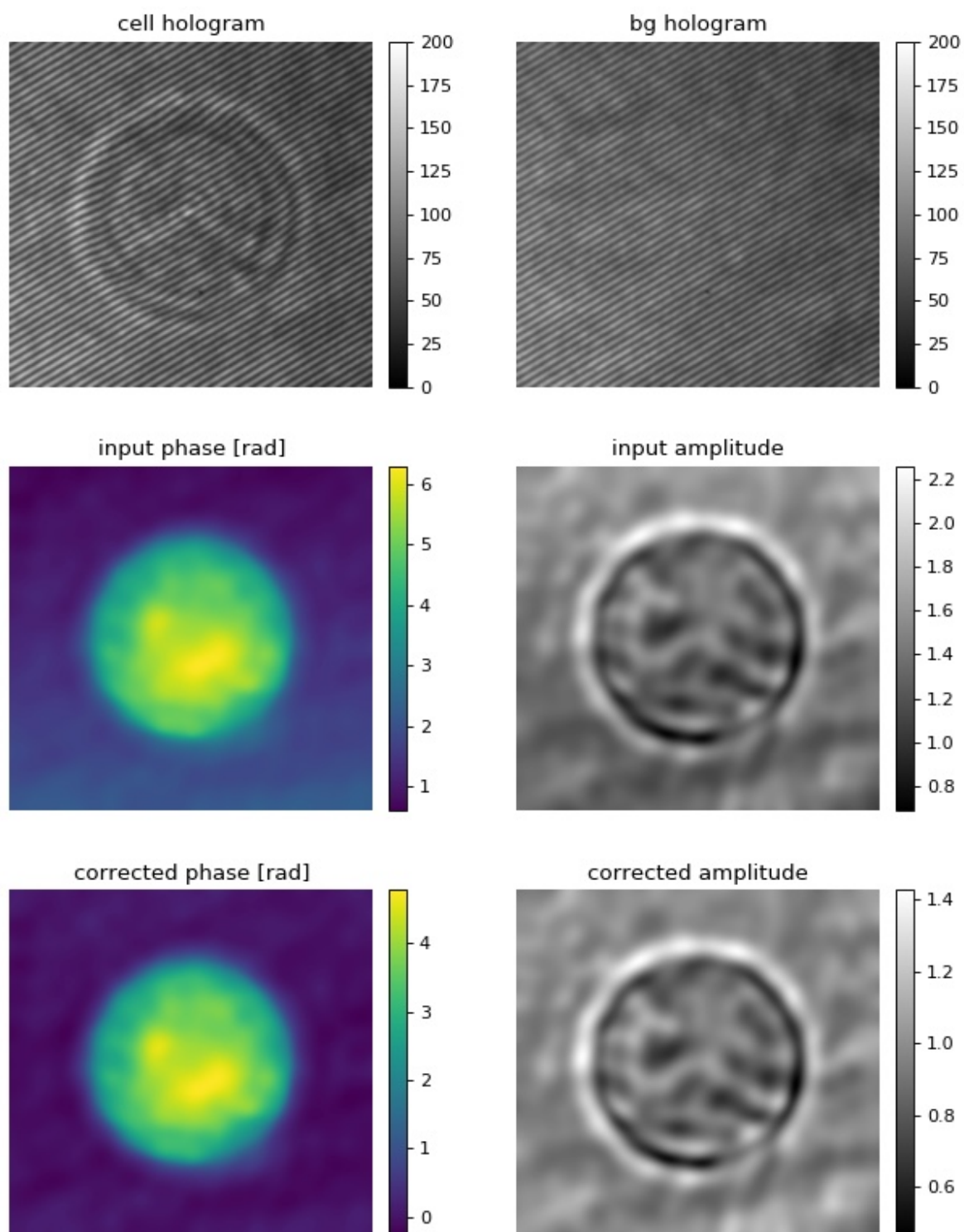
hologram_cell.py

```

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="raw-oah",
13                        # This parameter allows passing arguments to the
14                        # hologram-analysis algorithm in qpretrieve.
15                        qpretrieve_kw={
16                            # For this hologram, the "smooth disk"
17                            # filter yields the best trade-off
18                            # between interference from the central
19                            # band and image resolution.
20                            "filter_name": "smooth disk",
21                            # Set the filter size to half the distance
22                            # between the central band and the sideband.
23                            "filter_size": 1/2
24                        })

```

(continues on next page)



(continued from previous page)

```

25         )
26
27     amp0 = qpi.amp
28     pha0 = qpi.pha
29
30     # background correction
31     qpi.compute_bg(which_data=["amplitude", "phase"],
32                   fit_offset="fit",
33                   fit_profile="tilt",
34                   border_px=5,
35                   )
36
37     # plot the properties of `qpi`
38     fig = plt.figure(figsize=(8, 10))
39
40     matplotlib.rcParams["image.interpolation"] = "bicubic"
41     holkw = {"cmap": "gray",
42             "vmin": 0,
43             "vmax": 200}
44
45     ax1 = plt.subplot(321, title="cell hologram")
46     map1 = ax1.imshow(edata["data"], **holkw)
47     plt.colorbar(map1, ax=ax1, fraction=.046, pad=0.04)
48
49     ax2 = plt.subplot(322, title="bg hologram")
50     map2 = ax2.imshow(edata["bg_data"], **holkw)
51     plt.colorbar(map2, ax=ax2, fraction=.046, pad=0.04)
52
53     ax3 = plt.subplot(323, title="input phase [rad]")
54     map3 = ax3.imshow(pha0)
55     plt.colorbar(map3, ax=ax3, fraction=.046, pad=0.04)
56
57     ax4 = plt.subplot(324, title="input amplitude")
58     map4 = ax4.imshow(amp0, cmap="gray")
59     plt.colorbar(map4, ax=ax4, fraction=.046, pad=0.04)
60
61     ax5 = plt.subplot(325, title="corrected phase [rad]")
62     map5 = ax5.imshow(qpi.pha)
63     plt.colorbar(map5, ax=ax5, fraction=.046, pad=0.04)
64
65     ax6 = plt.subplot(326, title="corrected amplitude")
66     map6 = ax6.imshow(qpi.amp, cmap="gray")
67     plt.colorbar(map6, ax=ax6, fraction=.046, pad=0.04)
68
69     # disable axes
70     [ax.axis("off") for ax in [ax1, ax2, ax3, ax4, ax5, ax6]]
71
72     plt.tight_layout()
73     plt.show()

```

3.8 Filter choices for interferometric imaging

There are several parameters that influence the quality of phase and amplitude data retrieved from data recorded via interferometric techniques. This example demonstrates the advantages and disadvantages of three filtering strategies in qpimage. For more information, please have a look at the [qpretrieve](#) library.

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.

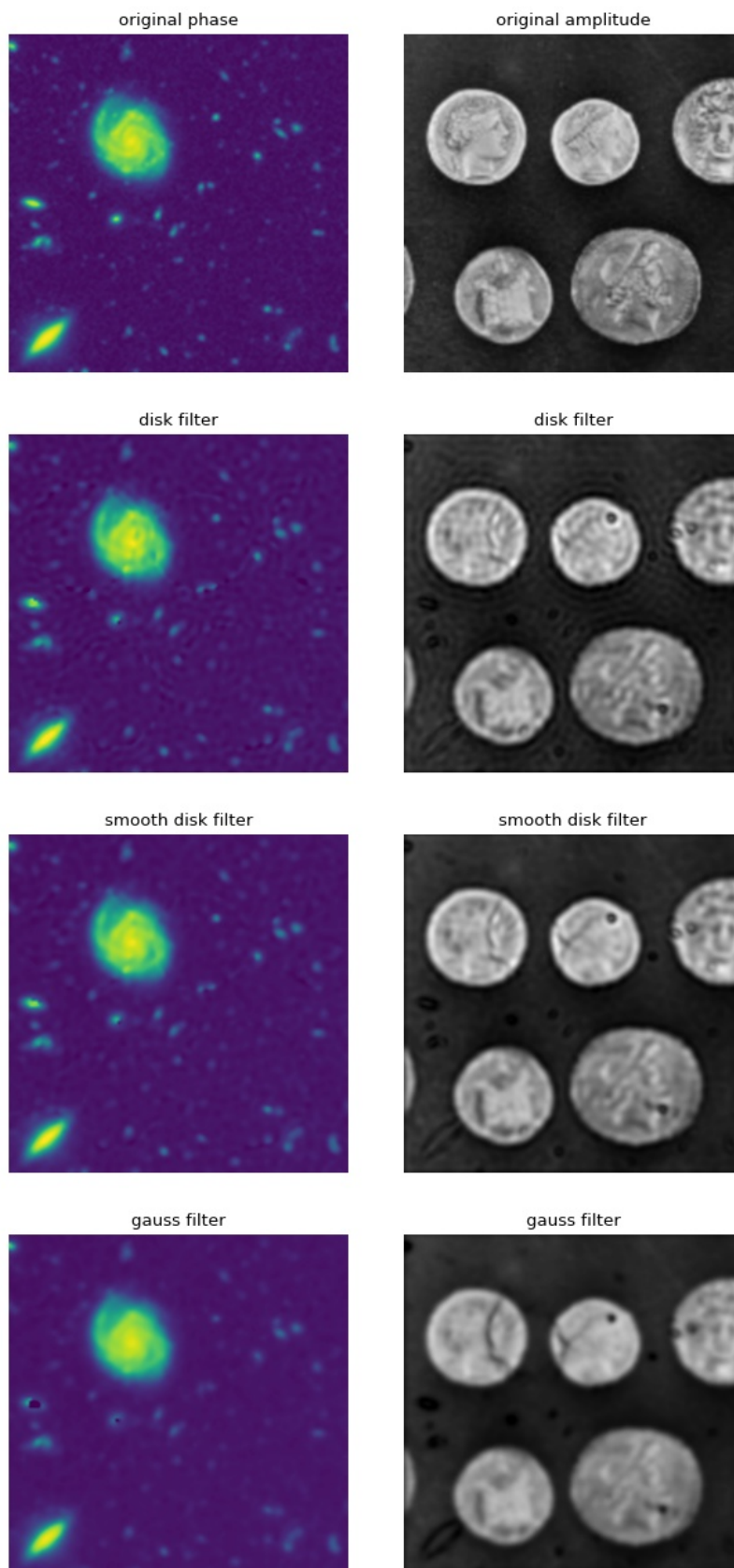
To correctly interpret the data shown, please note that:

- 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 to 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.rgb2gray(data.hubble_deep_field())[354:504, 70:220]
8 # image of a coin
9 img2 = 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:
```

(continues on next page)



(continued from previous page)

```

22     qpi = qpimage.QPImage(data=hologram,
23                           which_data="raw-oah",
24                           qpretrieve_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",
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()

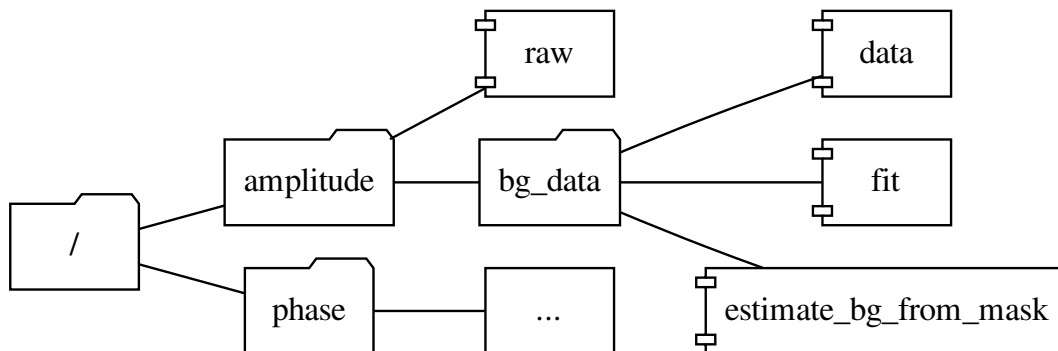
```

HDF5 FILE FORMAT

The data of a `qpimage.QPImage` or `qpimage.QPSeries` can be stored on disk, using the `h5file` parameter upon class instantiation. This section describes the scheme used to store the data using the [HDF5 file format](#).

4.1 QPImage

The following graph visualized the HDF5 file structure of a `QPImage` instance:



4.1.1 Attributes

These attributes of the root group (`/`) describe physical parameters of the data:

key	description
medium index	refractive index of the medium
pixel size	detector pixel size [m]
time	acquisition time of the image [s]
wavelength	imaging wavelength [m]

These other attributes may be used by e.g. data simulators such as [qpsphere](#) or [cellsino](#):

key	description
angle	tomographic acquisition angle [rad]
date	acquisition date 'YYYY-MM-DD'
device	imaging device used
focus	focus position [m]
identifier	image identifier
numerical aperture	numerical aperture
pos x	x position [m]
pos y	y position [m]
qpimage version	qpimage software version used
sim center	simulation: center of object [px]
sim index	simulation: refractive index of object
sim model	simulation: model used
sim radius	simulation: object radius [m]
software	imaging software used

4.1.2 Groups

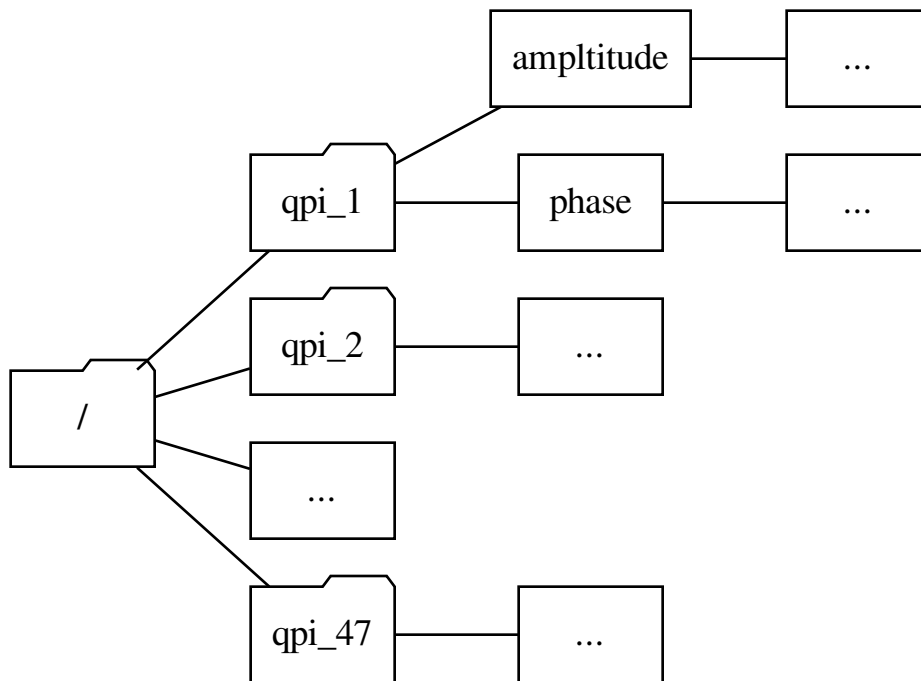
Both groups, *amplitude* and *phase*, do not hold attributes. Each of the groups contain a dataset called *raw* (the raw image, by default stored as 32bit floating point values) and a group called *bg_data* which contains information about background correction. If background correction was used, then the *bg_data* group may contain the following datasets:

- *data*: simple background image
- *fit*: fitted background image; has the additional attributes `fit_offset`, `fit_profile`, and `border_px` (see [`qpimage.core.QPImage.compute_bg\(\)`](#) for possible values)
- *estimate_bg_from_mask*: binary mask image that defines regions in *raw* that resemble background data; used for background fitting

All of these datasets have the same shape as *raw*. The *data* and *fit* datasets form the background data that are internally removed from the *raw* data when requesting the `QPImage.amp` or `QPImage.pha` properties.

4.2 QPSeries

The following graph visualized the HDF5 file structure of a QPSeries instance (with a total of 48 QPImages):



Note that the name of each QPImage group always starts with “qpi_” and that the enumeration does not contain leading zeros. The root node (*/*) of a QPSeries may have the *identifier* attribute.

CODE REFERENCE

5.1 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
```

5.2 bg_estimate (background-estimation)

5.2.1 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()
```

5.2.2 Methods

```
qpimage.bg_estimate.estimate(data, fit_offset='mean', fit_profile='tilt', border_px=0, from_mask=None,
                             ret_mask=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_mask** (*boolean np.ndarray or None*) – Use a boolean array to define the background area. The boolean mask must have the same shape as the input data. *True* elements are used for background estimation.
- **ret_mask** (*bool*) – Return the boolean mask used to compute the background.

Notes

If both *border_px* and *from_mask* are given, the intersection of the two is used, i.e. the positions where both, the frame mask and *from_mask*, 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 $\sqrt{\text{data.size}}$ bins

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

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

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

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

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

lmfit 2nd order polynomial model

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

lmfit 2nd order polynomial residuals

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

lmfit tilt model

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

lmfit tilt residuals

5.3 core (QPIImage)

5.3.1 Constants

`qpimage.core.VALID_INPUT_DATA = ['field', 'hologram', 'raw-oah', 'raw-qlsi', 'phase', ('phase', 'amplitude'), ('phase', 'intensity')]`

valid combinations for keyword argument *which_data*

5.3.2 Classes

```
class qpimage.core.QPImage(data=None, bg_data=None, which_data='phase', meta_data=None,
                           qpretrieve_kw=None, holo_kw=None, proc_phase=True, 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* or *tuple*) – String or comma-separated list of strings indicating the order and type of input data. Valid values are defined in [VALID_INPUT_DATA](#), where phase and amplitude/intensity data require an indexable object with the phase data as first element.
- **meta_data** (*dict* or *qpimage.MetaDict*) – Metadata associated with the input data. see [qpimage.meta.META_KEYS](#)
- **qpretrieve_kw** (*dict*) – Keyword arguments passed to [qpretrieve](#) for phase retrieval from interferometric data.
- **holo_kw** (*dict*) – This is deprecated, please use *qpretrieve_kw* instead. Special keyword arguments for phase retrieval from hologram data (*which_data="raw-oah"*).

New in version 0.1.6.

- **proc_phase** (*bool*) – Process the phase data. This includes phase unwrapping using [skimage.restoration.unwrap_phase\(\)](#) and correcting for 2PI phase offsets (The offset is estimated from a 1px-wide border around the image).

New in version 0.6.0: Previous versions always performed phase unwrapping and did so without offset correction

- **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 *h5py: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 metadata, but with all background corrections merged.

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

qpretrieve_kw

hologram processing keyword arguments

property bg_amp

background amplitude image

property bg pha

background phase image

property amp

background-corrected amplitude image

property dtype

dtype of the phase data array

property field

background-corrected complex field

property info

list of tuples with QPIImage metadata

property meta

dictionary with imaging meta data

property pha

background-corrected phase image

property raw_amp

raw amplitude image

property raw pha

raw phase image

property 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_mask*=None, *ret_mask*=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_mask** (*boolean np.ndarray* or *None*) – Use a boolean array to define the background area. The boolean mask must have the same shape as the input data. *True* elements are used for background estimation.
- **ret_mask** (*bool*) – Return the boolean mask used to compute the background.

Notes

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

If any of the *border_** arguments are non-zero and *from_mask* is given, the intersection of the two is used, i.e. the positions where both, the frame mask and *from_mask*, 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*, *kernel='helmholtz'*, *padding=True*, *h5file=None*, *h5mode='a'*, *ret_refocus_iface=False*, *method=None*)

Compute a numerically refocused QPIImage

Parameters

- **distance** (*float*) – Focusing distance [m]
- **kernel** (*str*) – Refocusing method, one of [“helmholtz”, “fresnel”]

- **padding** (*bool*) – Whether to perform padding during refocusing. You may disable padding if your input image does not have any discontinuities at the border (i.e. you can tile your input image, and it would look good), otherwise you will experience ringing artifacts.
- **h5file** (*str*, *h5py.Group*, *h5py.File*, or *None*) – A path to an HDF5 data file where the QPImage is cached. If set to *None* (default), all data will be handled in memory using the “core” driver of the h5py’s *h5py: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)
- **ret_refocus_iface** (*bool*) – Whether or not to also return the *nrefocus.Refocus** class used for refocusing; this might be useful if you wish to do quick manual refocusing or have to create a refocusing series.
- **method** (*str*) – deprecated, use *kernel* instead

Returns *qpi* – Refocused phase and amplitude data

Return type *qpimage.QPImage*

See also:

- *mod:nrefocus*: library used for numerical focusing
- *ref:nrefocus:sec_refocus_interface*: refocusing interface

set_bg_data(*bg_data*, *which_data=None*, *proc_phase=True*)

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.
- **proc_phase** (*bool*) – Process the phase data. This includes phase unwrapping using *skimage.restoration.unwrap_phase()* and correcting for 2PI phase offsets (The offset is estimated from a 1px-wide border around the image).

5.3.3 Methods

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

Recursively copy all HDF5 data from one group to another

Data from links is copied.

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.

5.4 image_data (basic image management)

5.4.1 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

5.4.2 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”.

property **bg**

combined background image data

property **image**

background corrected image data

property **info**

list of background correction parameters

property **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_mask*=None, *ret_mask*=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_mask** (*boolean np.ndarray or None*) – Use a boolean array to define the background area. The mask image must have the same shape as the input data. `True` elements are used for background estimation.
- **ret_mask** (*bool*) – Return the mask image used to compute the background.

Notes

If both *border_px* and *from_mask* are given, the intersection of the two resulting mask 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=None*)

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

5.4.3 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* or *dtype*) – 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`

5.5 integrity_check (check QPImage data)

5.5.1 Exceptions

exception `qpimage.integrity_check.IntegrityCheckError`

Raised when a QPImage data set is incomplete or corrupt

5.5.2 Methods

`qpimage.integrity_check.check(qpi_or_h5file, checks=None)`

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

5.6 meta (definitions for QPImage meta data)

5.6.1 Constants

`qpimage.meta.META_KEYS = ['medium index', 'pixel size', 'time', 'wavelength', 'angle', 'date', 'device', 'focus', 'identifier', 'numerical aperture', 'pos x', 'pos y', 'qpimage version', 'sim center', 'sim index', 'sim model', 'sim radius', 'software']`

valid `qpimage.core.QPImage` meta data keys

5.6.2 Exceptions

exception `qpimage.meta.MetadataMissingError`

Raised when metadata is missing

5.6.3 Classes

class `qpimage.meta.MetaDict(*args, **kwargs)`

Bases: `collections.UserDict`

Management of meta data variables

Valid key names are defined in `qpimage.meta.META_KEYS`.

```
valid_keys = ['medium index', 'pixel size', 'time', 'wavelength', 'angle', 'date',
              'device', 'focus', 'identifier', 'numerical aperture', 'pos x', 'pos y', 'qpimage
              version', 'sim center', 'sim index', 'sim model', 'sim radius', 'software']
```

5.7 series (QPSeries)

5.7.1 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*) – Metadata associated with the input data (see `qpimage.META_KEYS`). This overrides the metadata of the QPImages in `qpimage_list` and, if `h5file` is given and `h5mode` is not “r”, overrides the metadata 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 *h5py: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)

property identifier

unique identifier of the series

add_qpimage(*qpi*, *identifier=None*, *bg_from_idx=None*)

Add a QPImage instance to the QPSeries

Parameters

- **qpi** (`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 shorthand `qps[index]`.

CHANGELOG

List of changes in-between qpimage releases.

6.1 version 0.9.0

- feat: support QLSI data via qpretrieve
- ref: background data is handled differently internally to support gradient-based background subtraction in QLSI
- setup: bump qpretrieve from 0.2.2 to 0.2.6

6.2 version 0.8.5

- setup: bump qpretrieve from 0.2.1 to 0.2.2 (multiprocessing)

6.3 version 0.8.4

- setup: bump qpretrieve from 0.2.0 to 0.2.1

6.4 version 0.8.3

- fix: inverted phase when deprecated holo_kw were used

6.5 version 0.8.2

- fix: correctly parse invert_phase in deprecated holo_kw dictionary

6.6 version 0.8.1

- fix: correctly parse sideband in deprecated holo_kw dictionary

6.7 version 0.8.0

- ref: migrate hologram analysis to qpretrieve
- ref: deprecate “holo_kw” keyword argument in favor of “qpretrieve_kw”

6.8 version 0.7.7

- enh: add QPImage meta data keys “date”, “numerical aperture”, “pos x”, “pos y”, and “time”
- ref: minor cleanup

6.9 version 0.7.6

- ref: deprecate “hologram” input type in favor of “raw-oah”

6.10 version 0.7.5

- enh: write HDF5 image metadata so that HDFView 3.1.1 can visualize the phase data
- docs: several minor fixes

6.11 version 0.7.4

- enh: add QPImage meta data keys “angle”, “focus”, “device”, and “software”

6.12 version 0.7.3

- fix: strip third axis from input hologram images

6.13 version 0.7.2

- fix: subclass MetaDict from collections.UserDict instead of dict (TypeError super() argument 1 must be type, not dict)
- docs: fix rtd build

6.14 version 0.7.1

- fix: easy fix for regression in h5py with backing_store=False

6.15 version 0.7.0

- feat: allow to set hologram filter size in Fourier indices (Fourier space pixels) instead of relative to the distance between central band and side band by setting the argument “filter_size_interpretation” to “frequency index”
- fix: Fourier filter size for holograms is now inclusive, i.e. points *on* the perimeter of the filter are included
- setup: bump nrefocus from 0.2.1 to 0.4.3 (use new interface)
- ref: remove IMAGE_* attributes from HDF5 datasets, because they anyway only work with uint8 data, and not with float data
- ref: code cleanup

6.16 version 0.6.4

- setup: bump nrefocus from 0.2.0 to 0.2.1

6.17 version 0.6.3

- docs: fix sphinx build
- tests: fix tests due to newer h5py version
- ref: fix numpy 1.20.0 deprecation warnings
- ci: migrate to GitHub Actions
- setup: setup.py test is deprecated

6.18 version 0.6.2

- maintenance release

6.19 version 0.6.1

- maintenance release

6.20 version 0.6.0

- feat: automatically remove 2PI phase offsets when instantiating a QPImage (The phase offset is estimated from a 1px-wide border around the image)
- feat: allow to disable the processing of phase data (unwrapping and correcting for phase offset) using `proc_phase=False` when instantiating a QPImage

6.21 version 0.5.4

- docs: minor improvements

6.22 version 0.5.3

- tests: minor improvements

6.23 version 0.5.2

- enh: do not compress image data when HDF5 “core” driver is used
- ref: fix deprecated `.value` (h5py)

6.24 version 0.5.1

- ref: allow to subclass `meta.MetaDict`
- docs: fixed several minor typos

6.25 version 0.5.0

- feat: slicing of QPImage objects preserves background data, but background is merged from existing background data

6.26 version 0.4.6

- docs: fix typos

6.27 version 0.4.5

- docs: add HDF5 file format description

6.28 version 0.4.4

- maintenance release

6.29 version 0.4.3

- fix: use memory address in QPImage.__repr__ if identifier not given
- fix: only use meta.DATA_KEYS in QPImage.__eq__
- cleanup: remove unused “dm exclude” meta.DATA_KEYS definition

6.30 version 0.4.2

- fix: minor identifier ambiguity

6.31 version 0.4.1

- docs: add example of mask-based correction with qpsphere
- docs: minor cleanup

6.32 version 0.4.0

- BREAKING CHANGE: replace all occurrences of “binary” with “mask” to avoid ambiguities

6.33 version 0.3.0

- feat: new meta data key “sim model”

6.34 version 0.2.1

- ci: automate PyPI release with travis-ci

6.35 version 0.2.0

- drop support for Python 3.5
- docs: add QPSeries example to user API section
- feat: *QPSeries.get_qpimage* supports QPImage identifier as index
- feat: allow to set data storage dtype, which now defaults to float32 to save disk space.
- fix: set default gzip compression level to 9
- ref: unify image data storage, set hdf5 chunks to image size

6.36 version 0.1.8

- code cleanup

6.37 version 0.1.7

- fix: bad default keyword argument in *bg_estimate.estimate*

6.38 version 0.1.6

- implement qpimage refocusing function *QPImage.refocus*
- API change: renamed “ramp” correction to “tilt” correction
- add identifier to representation string in QPImage
- hologram analysis:
 - add disk, square, and tukey filters
 - standard “gauss” filter is replaced by “disk” filter
 - standard filter size is set to one third of the distance between the sideband and the central band
 - allow to set hologram-retrieval parameters as a keyword argument “holo_kw” in QPImage

6.39 version 0.1.5

- support nan values in phase data
- add fletcher32 checksums and gzip compression to hdf5 files (#10)
- allow to hard-link background-correction data in QPSeries

6.40 version 0.1.4

- more `__init__` checks for QPImage and QPSeries (user convenience)
- allow negative indices in QPSeries.get_qpimage
- Bugfix: *bg_estimate* does not compute intersection but union (#9)

6.41 version 0.1.3

- add QPImage.raw_amp and QPImage.raw pha
- improve QPImage.__eq__
- add “identifier”:
 - meta data key
 - keyword for QPSeries.add_qpimage
 - property of and keyword for QPSeries
- add convenience functions for item access in QPImage and QPSeries
- moved to pathlib
- minor API changes

6.42 version 0.1.2

- allow strings and lists for *which_data* everywhere (#1)
- check for valid background keys in image_data.py (#2)
- add QPImage.info property (#5)
- add slicing (#6)
- add references to documentation (#7)

6.43 version 0.1.1

- QPImage.set_bg_data now accepts QPImage objects
- add QPSeries for managing multiple QPImages in one hdf5 file (#3)

6.44 version 0.1.0

- initial release

BILBLIOGRAPHY

INDICES AND TABLES

- `genindex`
- `modindex`
- `search`

BIBLIOGRAPHY

- [Bar52] R. Barer. Interference Microscopy and Mass Determination. *Nature*, 169(4296):366–367, 1952. doi:10.1038/169366b0.
- [CCC+06] T. Colomb, E. Cuche, F. Charrière, J. Kühn, N. Aspert, F. Montfort, P. Marquet, and C. Depeursinge. Automatic procedure for aberration compensation in digital holographic microscopy and applications to specimen shape compensation. *Applied Optics*, 45(5):851, feb 2006. doi:10.1364/ao.45.000851.
- [DW52] H. G. Davies and M. H. F. Wilkins. Interference Microscopy and Mass Determination. *Nature*, 169(4300):541, 1952. doi:10.1038/169541a0.
- [SCG+17] M. Schürmann, G. Cojoc, S. Girardo, E. Ulbricht, J. Guck, and P. Müller. Three-dimensional correlative single-cell imaging utilizing fluorescence and refractive index tomography. *Journal of Biophotonics*, 11(3):e201700145, aug 2017. doi:10.1002/jbio.201700145.
- [SSM+15] M. Schürmann, J. Scholze, P. Müller, C. J. Chan, A. E. Ekpenyong, K. J. Chalut, and J. Guck. Chapter 9 - Refractive index measurements of single, spherical cells using digital holographic microscopy. In Ewa K Paluch, editor, *Biophysical Methods in Cell Biology*, volume 125 of *Methods in Cell Biology*, pages 143–159. Academic Press, 2015. doi:10.1016/bs.mcb.2014.10.016.
- [SSM+16] M. Schürmann, J. Scholze, P. Müller, J. Guck, and C. J. Chan. Cell nuclei have lower refractive index and mass density than cytoplasm. *Journal of Biophotonics*, 9(10):1068–1076, oct 2016. doi:10.1002/jbio.201500273.

PYTHON MODULE INDEX

q

`qpimage.bg_estimate`, [29](#)
`qpimage.image_data`, [35](#)
`qpimage.integrity_check`, [38](#)

A

`add_qpimage()` (*qpimage.series.QPSeries* method), 39
`amp` (*qpimage.core.QPImage* property), 32
Amplitude (class in *qpimage.image_data*), 35

B

`bg` (*qpimage.image_data.ImageData* property), 36
`bg_amp` (*qpimage.core.QPImage* property), 32
`bg_pha` (*qpimage.core.QPImage* property), 32

C

`check()` (in module *qpimage.integrity_check*), 38
`check_attributes()` (in module *qpimage.integrity_check*), 38
`check_background()` (in module *qpimage.integrity_check*), 38
`clear_bg()` (*qpimage.core.QPImage* method), 32
`COMPRESSION` (in module *qpimage.image_data*), 35
`compute_bg()` (*qpimage.core.QPImage* method), 32
`copy()` (*qpimage.core.QPImage* method), 33
`copyh5()` (in module *qpimage.core*), 35

D

`del_bg()` (*qpimage.image_data.ImageData* method), 36
`dtype` (*qpimage.core.QPImage* property), 32

E

`estimate()` (in module *qpimage.bg_estimate*), 29
`estimate_bg()` (*qpimage.image_data.ImageData* method), 36

F

`field` (*qpimage.core.QPImage* property), 32

G

`get_bg()` (*qpimage.image_data.ImageData* method), 37
`get_qpimage()` (*qpimage.series.QPSeries* method), 40

I

`identifier` (*qpimage.series.QPSeries* property), 39
`image` (*qpimage.image_data.ImageData* property), 36

ImageData (class in *qpimage.image_data*), 36
`info` (*qpimage.core.QPImage* property), 32
`info` (*qpimage.image_data.ImageData* property), 36
IntegrityCheckError, 38

M

`meta` (*qpimage.core.QPImage* property), 32
`META_KEYS` (in module *qpimage.meta*), 38
MetaDataMissingError, 39
MetaDict (class in *qpimage.meta*), 39
module
 qpimage.bg_estimate, 29
 qpimage.image_data, 35
 qpimage.integrity_check, 38

O

`offset_gaussian()` (in module *qpimage.bg_estimate*), 30
`offset_mode()` (in module *qpimage.bg_estimate*), 30

P

`pha` (*qpimage.core.QPImage* property), 32
Phase (class in *qpimage.image_data*), 35
`poly2o_model()` (in module *qpimage.bg_estimate*), 30
`poly2o_residual()` (in module *qpimage.bg_estimate*), 30
`profile_poly2o()` (in module *qpimage.bg_estimate*), 30
`profile_tilt()` (in module *qpimage.bg_estimate*), 30

Q

QPImage (class in *qpimage.core*), 31
qpimage.bg_estimate
 module, 29
qpimage.image_data
 module, 35
qpimage.integrity_check
 module, 38
qpimage.META_KEYS (built-in variable), 29
qpimage.QPImage (built-in class), 29
qpimage.QPSeries (built-in class), 29
`qpretrieve_kw` (*qpimage.core.QPImage* attribute), 32

QPSeries (*class in qpimage.series*), 39

R

raw (*qpimage.image_data.ImageData property*), 36

raw_amp (*qpimage.core.QPImage property*), 32

raw_pha (*qpimage.core.QPImage property*), 32

refocus() (*qpimage.core.QPImage method*), 33

S

set_bg() (*qpimage.image_data.ImageData method*), 37

set_bg_data() (*qpimage.core.QPImage method*), 34

shape (*qpimage.core.QPImage property*), 32

T

tilt_model() (*in module qpimage.bg_estimate*), 30

tilt_residual() (*in module qpimage.bg_estimate*), 30

V

VALID_BG_KEYS (*in module qpimage.image_data*), 35

VALID_FIT_OFFSETS (*in module qpimage.bg_estimate*),
29

VALID_FIT_PROFILES (*in module qpim-
age.bg_estimate*), 29

VALID_INPUT_DATA (*in module qpimage.core*), 30

valid_keys (*qpimage.meta.MetaDict attribute*), 39

W

write_image_dataset() (*in module qpim-
age.image_data*), 37