nrefocus Documentation

Release 0.5.3.post1

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CONTENTS:

Nrefocus is a Python 3 library that allows to numerically refocus (including autofocusing) complex wave fields. This is the documentaion of nrefocus version 0.5.3.post1.

CHAPTER

ONE

INTRODUCTION

This package provides methods for numerical propagation of a complex wave in free space. The available propagators are the angular spectrum method (*helmholtz*) and the Fresnel approximation (*fresnel*). Both implementations are convolution-based. The angular spectrum method is suited for near-field propagation (numerical focusing) and yields better results than the Fresnel approximation. The single Fourer transform-based Fresnel propagation method which is suitable for far-field propagation is not implemented in this package.

1.1 Obtaining nrefocus

You can install nrefocus via:

```
pip install nrefocus
```

If you would like to take advantage of fast Fourer transforms with PyFFTW, please also install the *pyfftw* package or use the extras key *FFTW*:

```
pip install nrefocus[FFTW]
```

The source code of nrefocus is available at https://github.com/RI-imaging/nrefocus.

1.2 Citing nrefocus

Please cite this package if you are using it in a scientific publication.

This package should be cited like this[1].

You can find out what version you are using by typing (in a Python console):

```
>>> import nrefocus
>>> nrefocus.__version__
'0.1.2'
```

[1] Paul Müller (2013) *nrefocus: Python algorithms for numerical focusing* (Version x.x.x) [Software]. Available at https://pypi.python.org/pypi/nrefocus/.

1.3 Acknowledgments

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1.4 References

CHAPTER

TWO

THEORY

The derivations given here are treated in more detail in the relevant literature, e.g. [ST91] and [Goo05].

2.1 Optical transfer function

Let us consider a wave field $u(\mathbf{r_0})$ whose values we know at an initial plane $\mathbf{r_0} = (x_0, y_0, z_0)$ (z_0 fixed). The field has a certain vacuum wavelength λ and is traveling through a homogeneous medium with refractive index n_m. From the knowledge of the wave field at the plane $\mathbf{r_0}$ and its wavelength λ/n_m, we can infer the direction of propagation of the wave field for every point in $\mathbf{r_0}$. We rewrite the field at $\mathbf{r_0}$ as an angular spectrum, a sum over all possible directions $\mathbf{s} = (p, q, M)$, assuming that the field is only traveling from left to right

$$\begin{aligned} u(\mathbf{r_0}) &= \iint dpdq\, A(p,q) e^{ik_\mathrm{m}(px_0+qy_0+Mz_0)} \\ |\mathbf{s}| &= p^2+q^2+M^2 = 1 \\ M &= \sqrt{1-p^2-q^2}. \end{aligned}$$

The equation above describes the Huygens-Fresnel principle: the value of the field u at a certain position $\mathbf{r_0}$ at the initial plane (point source) is defined as an integral over all possible plane waves with wavenumber $k_\mathrm{m} = \frac{2\pi n_\mathrm{m}}{\lambda}$, weighted with the amplitude $A(p, q)$.

Let us now consider the 2D Fourier transform of $u(\mathbf{r_0})$.

$$\begin{aligned} \widehat{U}_0(k_\mathrm{x}, k_\mathrm{y}) &= \frac{1}{2\pi} \iint dx_0 dy_0 \iint dpdq\, A(p,q) e^{ik_\mathrm{m}(px_0+qy_0+Mz_0)} e^{-i(k_\mathrm{x}x_0+k_\mathrm{y}y_0)} \\ &= \frac{1}{2\pi} \iint dx_0 dy_0 \iint dpdq\, A(p,q) e^{ik_\mathrm{m}Mz_0} e^{ix_0(k_\mathrm{m}p-k_\mathrm{x})} e^{iy_0(k_\mathrm{m}q-k_\mathrm{y})} \\ &= \frac{2\pi}{k_\mathrm{m}^2} A(k_\mathrm{x}, k_\mathrm{y}) e^{ik_\mathrm{m}Mz_0} \end{aligned}$$

Here we made use of the identity of the delta distribution

$$\begin{aligned} \frac{1}{2\pi} \int dx_0\, e^{ix_0(k_\mathrm{m}p-k_\mathrm{x})} &= \delta(k_\mathrm{m}p - k_\mathrm{x}) = \frac{1}{k_\mathrm{m}} \delta(p - k_\mathrm{x}/k_\mathrm{m}) \\ \frac{1}{2\pi} \int dy_0\, e^{iy_0(k_\mathrm{m}q-k_\mathrm{y})} &= \delta(k_\mathrm{m}q - k_\mathrm{y}) = \frac{1}{k_\mathrm{m}} \delta(q - k_\mathrm{y}/k_\mathrm{m}) \end{aligned}$$

If we now perform the same procedure for a different position $\mathbf{r}_\mathrm{d} = (x_0, y_0, z_\mathrm{d})$, we will see that the Fourier transform of the field becomes

$$\widehat{U}_\mathrm{d}(k_\mathrm{x}, k_\mathrm{y}) = \frac{2\pi}{k_\mathrm{m}^2} A(k_\mathrm{x}, k_\mathrm{y}) e^{ik_\mathrm{m}Mz_\mathrm{d}}.$$

Thus, the propagation of the field $u(\mathbf{r_0})$ by a distance $d = z_\mathrm{d} - z_0$ is described by a multiplication with the transfer function

$$\mathcal{H}^\mathrm{Helmholtz} = e^{ik_\mathrm{m}Md}$$

in Fourier space. This is the basis of the convolution-based numerical propagation algorithms implemented in nrefocus. The process of numerical propagation with the angular spectrum method can be written as

$$u(\mathbf{r_d}) = \mathcal{F}^{-1}\left\{\mathcal{F}\{u(\mathbf{r_0})\} \cdot e^{ik_\mathrm{m}Md}\right\}$$

with the Fourier transform $\mathcal{F}$ and its inverse $\mathcal{F}^{-1}$. With the convolution operator $*$, we may rewrite this equation to

$$u(\mathbf{r_d}) = u(\mathbf{r_0}) * \mathcal{F}^{-1}\left\{e^{ik_\mathrm{m}Md}\right\}.$$

2.2 Fresnel approximation

The Fresnel approximation (or paraxial approximation) uses a Taylor expansion to simplify the exponent of the transfer function $e^{ik_\mathrm{m}Md}$. The exponent can be rewritten as

$$ik_\mathrm{m}Md = ik_\mathrm{m}d\left(1 - p^2 - q^2\right)^{1/2}.$$

If the angles of propagation θ_x and θ_y for each plane wave of the angular spectrum is small, then we can make the paraxial approximation:

$$\begin{aligned}\theta_\mathrm{x} &\approx p\\ \theta_\mathrm{y} &\approx q\\ \theta^2 = \theta_\mathrm{x}^2 + \theta_\mathrm{y}^2 &\approx p^2 + q^2\end{aligned}$$

We now Taylor-expand the exponent around small values of θ

$$ik_\mathrm{m}d\left(1 - \theta^2\right)^{1/2} \approx ik_\mathrm{m}d\left(1 - \frac{\theta^2}{2} + \frac{\theta^4}{8} - \dots\right).$$

The Fresnel approximation discards the third term ($\sim \theta^4$) and the transfer function then reads:

$$\begin{aligned}e^{ik_\mathrm{m}Md} &\approx e^{ik_\mathrm{m}d} \cdot e^{-\frac{ik_\mathrm{m}d(p^2+q^2)}{2}}\\ e^{i\sqrt{k_\mathrm{m}^2 - k_\mathrm{x}^2 - k_\mathrm{y}^2}d} &\approx e^{ik_\mathrm{m}d} \cdot e^{-\frac{id(k_\mathrm{x}^2+k_\mathrm{y}^2)}{2k_\mathrm{m}}}\\ \mathcal{H}^\mathrm{Fresnel} &= e^{ik_\mathrm{m}d} \cdot e^{-\frac{id(k_\mathrm{x}^2+k_\mathrm{y}^2)}{2k_\mathrm{m}}}\end{aligned}$$

Thus, the propagation by a distance distance $d = z_\mathrm{d} - d$ in the Fresnel approximation can be written in the form of the convolution

$$u(\mathbf{r_d}) = e^{ik_\mathrm{m}d} \cdot u(\mathbf{r_0}) * \mathcal{F}^{-1}\left\{e^{-\frac{id(k_\mathrm{x}^2+k_\mathrm{y}^2)}{2k_\mathrm{m}}}\right\}.$$

Note that the Fresnel approximation results in paraboloidal waves $(p^2 + q^2)$ whereas spherical waves are used with the Helmholtz equation.

2.3 Transfer functions in nrefocus

The numerical focusing algorithms in this package require the input data u_{in} to be normalized by the incident plane wave $u_0(\mathbf{r_0})$ according to

$$u_{\mathrm{in}}(\mathbf{r_0}) = \frac{u(\mathbf{r_0})}{u_0(\mathbf{r_0})}$$

As a result, the transfer functions change to

$$\mathcal{H}_{\mathrm{norm}}^{\mathrm{Helmholtz}} = e^{ik_{\mathrm{m}}(M-1)d} = e^{id\left(\sqrt{k_{\mathrm{m}}^2 - k_{\mathrm{x}}^2 - k_{\mathrm{y}}^2} - k_{\mathrm{m}}\right)}$$

$$\mathcal{H}_{\mathrm{norm}}^{\mathrm{Fresnel}} = e^{-\frac{id(k_{\mathrm{x}}^2 + k_{\mathrm{y}}^2)}{2k_{\mathrm{m}}}}.$$

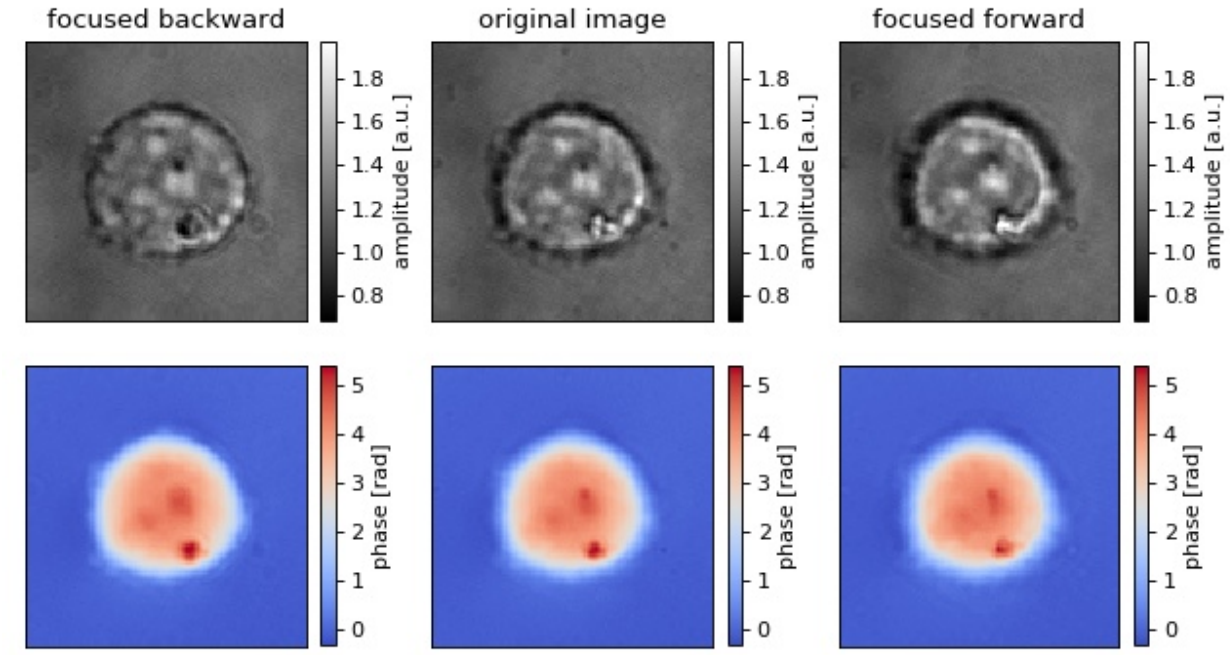
CHAPTER

THREE

EXAMPLES

3.1 2D Refocusing of an HL60 cell

The data show a live HL60 cell imaged with quadriwave lateral shearing interferometry (SID4Bio, Phasics S.A., France). The diameter of the cell is about 20µm.



refocus_cell.py

```
import matplotlib.pylab as plt
import numpy as np
import unwrap

import nrefocus

from example_helper import load_cell

# load initial cell
cell1 = load_cell("HL60_field.zip")
```

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```

# refocus to two different positions
cell2 = nrefocus.refocus(cell1, 15, 1, 1)  # forward
cell3 = nrefocus.refocus(cell1, -15, 1, 1)  # backward

# amplitude range
vmina = np.min(np.abs(cell1))
vmaxa = np.max(np.abs(cell1))
ampkw = {"cmap": plt.get_cmap("gray"),
         "vmin": vmina,
         "vmax": vmaxa}

# phase range
cell1p = unwrap.unwrap(np.angle(cell1))
cell2p = unwrap.unwrap(np.angle(cell2))
cell3p = unwrap.unwrap(np.angle(cell3))
vminp = np.min(cell1p)
vmaxp = np.max(cell1p)
phakw = {"cmap": plt.get_cmap("coolwarm"),
         "vmin": vminp,
         "vmax": vmaxp}

# plots
fig, axes = plt.subplots(2, 3, figsize=(8, 4.5))
axes = axes.flatten()
for ax in axes:
    ax.xaxis.set_major_locator(plt.NullLocator())
    ax.yaxis.set_major_locator(plt.NullLocator())

# titles
axes[0].set_title("focused backward")
axes[1].set_title("original image")
axes[2].set_title("focused forward")

# data
mapamp = axes[0].imshow(np.abs(cell3), **ampkw)
axes[1].imshow(np.abs(cell1), **ampkw)
axes[2].imshow(np.abs(cell2), **ampkw)
mappha = axes[3].imshow(cell3p, **phakw)
axes[4].imshow(cell1p, **phakw)
axes[5].imshow(cell2p, **phakw)

# colobars
cbkwargs = {"fraction": 0.045}
plt.colorbar(mapamp, ax=axes[0], label="amplitude [a.u.]", **cbkwargs)
plt.colorbar(mapamp, ax=axes[1], label="amplitude [a.u.]", **cbkwargs)
plt.colorbar(mapamp, ax=axes[2], label="amplitude [a.u.]", **cbkwargs)
plt.colorbar(mappha, ax=axes[3], label="phase [rad]", **cbkwargs)
plt.colorbar(mappha, ax=axes[4], label="phase [rad]", **cbkwargs)
plt.colorbar(mappha, ax=axes[5], label="phase [rad]", **cbkwargs)

plt.tight_layout()
```

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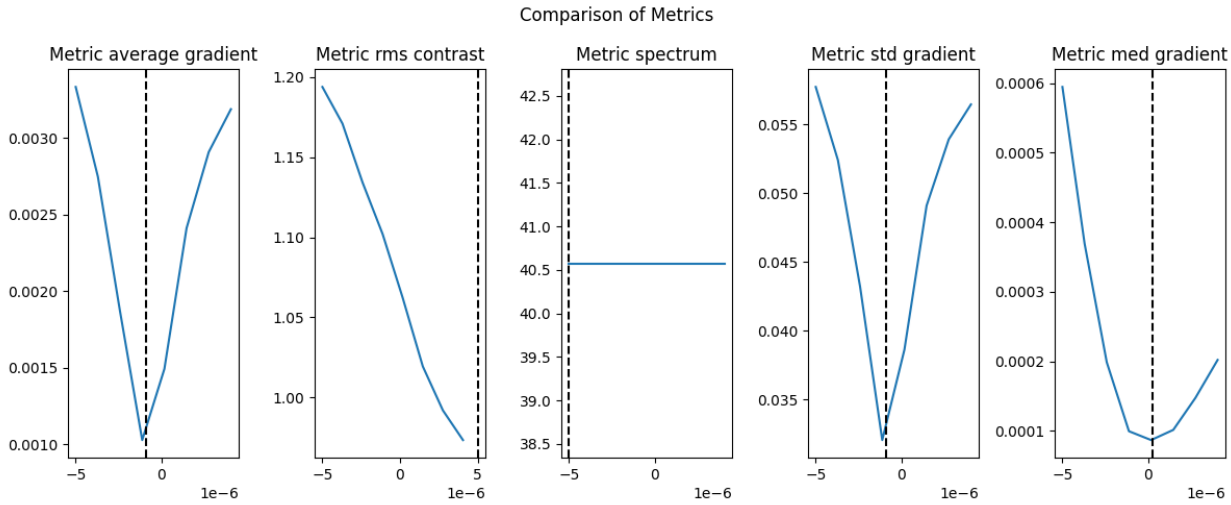
```
plt.show()
```

3.2 Compare available Metrics for Refocusing

The HL60 cell data used is described in *refocus_cell.py*.



compare_metrics.py

```
import nrefocus
from nrefocus.metrics import METRICS
import matplotlib.pyplot as plt

from examples.example_helper import load_cell

# load initial cell and create rf object
rf = nrefocus.iface.RefocusNumpy(field=load_cell("HL60_field.zip"),
                                 wavelength=647e-9,
                                 pixel_size=0.139e-6,
                                 kernel="helmholtz")

# autofocus the image for each metric
my_metrics = list(METRICS.keys())

fig, axes = plt.subplots(1, len(my_metrics), figsize=(12, 5))

for i, mt in enumerate(my_metrics):
    af_vals = rf.autofocus(metric=mt,
                           minimizer="lmfit",
                           interval=(-5e-6, 5e-6),
                           ret_field=True,
                           ret_grid=True)
    d, grid, field = af_vals

```

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```
    axes[i].plot(grid[0], grid[1])
    axes[i].axvline(d, color='k', ls='--')
    axes[i].set_title(f"Metric {mt}")

fig.suptitle("Comparison of Metrics")
fig.tight_layout()
plt.show()
```

CHAPTER

FOUR

CODE REFERENCE

4.1 Refocus interface

Refocus is a user-convenient interface for numerical refocusing. Each class implements refocusing for a specific dimensionality (1D or 2D fields) using a specific method for refocusing (e.g. numpy FFT or FFTW).

nrefocus.**get_best_interface**()
Return the fastest refocusing interface available

If *pyfftw* is installed, *nrefocus.RefocusPyFFTW* is returned. The fallback is *nrefocus.RefocusNumpy*.

class nrefocus.**RefocusPyFFTW**(*field*, *wavelength*, *pixel_size*, *medium_index=1.3333*, *distance=0*, *kernel='helmholtz'*, *padding=True*)
Refocusing with FFTW

New in version 0.4.0.

Parameters

- **field** (*2d complex-valued ndarray*) – Input field to be refocused
- **wavelength** (*float*) – Wavelength of the used light [m]
- **pixel_size** (*float*) – Pixel size of the input image [m]
- **medium_index** (*float*) – Refractive index of the medium, defaults to water (1.3333 at 21.5°C)
- **distance** (*float*) – Initial focusing distance [m]
- **kernel** (*str*) – Propagation kernel, one of
  - "helmholtz": the optical transfer function $\exp\left(id\left(\sqrt{k_\mathrm{m}^2 - k_\mathrm{x}^2 - k_\mathrm{y}^2} - k_\mathrm{m}\right)\right)$
  - "fresnel": paraxial approximation $\exp(-id(k_\mathrm{x}^2 + k_\mathrm{y}^2)/2k_\mathrm{m})$
- **padding** (*bool*) – Whether to perform boundary-padding with linear ramp

autofocus(*interval*, *metric='average gradient'*, *minimizer='lmfit'*, *roi=None*, *minimizer_kwargs=None*, *ret_grid=False*, *ret_field=False*)
Autofocus the initial field

Parameters

- **interval** (*tuple of floats*) – Approximate interval to search for optimal focus [m]
- **metric** (*str*) –
  - "average gradient" : average gradient metric of amplitude

- ”rms contrast” : RMS contrast of phase data
- ”spectrum” : sum of filtered Fourier coefficients
- ”std gradient” : standard deviation of gradient of amplitude
- ”med gradient” : median gradient metric of amplitude

- **minimizer** (*str*) –
  - “legacy”: custom nrefocus minimizer
  - ”lmfit”: lmfit-based minimizer (uses `lmfit.minimize`)
- **roi** (*list or tuple or slice or ndarray*) – Region of interest for which the metric will be minimized. The axes below use the numpy indexing order. Options are: list or tuple or numpy indexing array (old behaviour):

  [axis_0_start, axis_1_start, axis_0_end, axis_1_end] None can be used if no slicing is desired eg.: [None, None, axis_0_end, axis_1_end]

  list or tuple of slices (will be passed directly as is):

  (slice(axis_0_start, axis_0_end), slice(axis_1_start, axis_1_end))

  None The entire field will be used.
- **minimizer_kwargs** (*dict*) – Any additional keyword arguments for the minimizer
- **ret_grid** (*bool*) – return focus positions and metric values of the coarse grid search
- **ret_field** (*bool*) – return the optimal refocused field for user convenience

Returns

- **af_distance** (*float*) – Autofocusing distance
- **(d_grid, metrid_grid)** (*ndarray*) – Coarse grid search values (only if *ret_grid* is True)
- **af_field** (*ndarray*) – Autofocused field (only if *ret_field* is True)
- *[other]* – Any other objects returned by *minimizer*; may be definable via *minimizer_kwargs* (depends on minimizer)

get_kernel(*distance*)

Return the current kernel

Ther kernel type *self.kernel* is used (see `Refocus.__init__()`)

propagate(*distance*)

Propagate the initial field to a certain distance

Parameters **distance** (*float*) – Absolute focusing distance [m]

Returns **refocused_field** – Initial field refocused at *distance*

Return type 2d ndarray

Notes

Any subclass should perform padding with `nrefocus.pad.pad_rem()` during initialization.

property shape
Shape of the padded input field or Fourier transform

class nrefocus.**RefocusNumpy**(*field*, *wavelength*, *pixel_size*, *medium_index=1.3333*, *distance=0*, *kernel='helmholtz'*, *padding=True*)
Refocusing with numpy-based Fourier transform

New in version 0.3.0.

Parameters

- **field** (*2d complex-valued ndarray*) – Input field to be refocused
- **wavelength** (*float*) – Wavelength of the used light [m]
- **pixel_size** (*float*) – Pixel size of the input image [m]
- **medium_index** (*float*) – Refractive index of the medium, defaults to water (1.3333 at 21.5°C)
- **distance** (*float*) – Initial focusing distance [m]
- **kernel** (*str*) – Propagation kernel, one of
  - "helmholtz": the optical transfer function $\exp\left(id\left(\sqrt{k_\mathrm{m}^2 - k_\mathrm{x}^2 - k_\mathrm{y}^2} - k_\mathrm{m}\right)\right)$
  - "fresnel": paraxial approximation $\exp(-id(k_\mathrm{x}^2 + k_\mathrm{y}^2)/2k_\mathrm{m})$
- **padding** (*bool*) – Whether to perform boundary-padding with linear ramp

autofocus(*interval*, *metric='average gradient'*, *minimizer='lmfit'*, *roi=None*, *minimizer_kwargs=None*, *ret_grid=False*, *ret_field=False*)
Autofocus the initial field

Parameters

- **interval** (*tuple of floats*) – Approximate interval to search for optimal focus [m]
- **metric** (*str*) –
  - "average gradient" : average gradient metric of amplitude
  - "rms contrast" : RMS contrast of phase data
  - "spectrum" : sum of filtered Fourier coefficients
  - "std gradient" : standard deviation of gradient of amplitude
  - "med gradient" : median gradient metric of amplitude
- **minimizer** (*str*) –
  - "legacy": custom nrefocus minimizer
  - "lmfit": lmfit-based minimizer (uses `lmfit.minimize`)
- **roi** (*list or tuple or slice or ndarray*) – Region of interest for which the metric will be minimized. The axes below use the numpy indexing order. Options are: list or tuple or numpy indexing array (old behaviour):

  [axis_0_start, axis_1_start, axis_0_end, axis_1_end] None can be used if no slicing is desired eg.: [None, None, axis_0_end, axis_1_end]

list or tuple of slices (will be passed directly as is):

(slice(axis_0_start, axis_0_end), slice(axis_1_start, axis_1_end))

None The entire field will be used.

- **minimizer_kwargs** (*dict*) – Any additional keyword arguments for the minimizer
- **ret_grid** (*bool*) – return focus positions and metric values of the coarse grid search
- **ret_field** (*bool*) – return the optimal refocused field for user convenience

Returns

- **af_distance** (*float*) – Autofocusing distance
- **(d_grid, metrid_grid)** (*ndarray*) – Coarse grid search values (only if *ret_grid* is True)
- **af_field** (*ndarray*) – Autofocused field (only if *ret_field* is True)
- *[other]* – Any other objects returned by *minimizer*; may be definable via *minimizer_kwargs* (depends on minimizer)

get_kernel(*distance*)

Return the current kernel

Ther kernel type *self.kernel* is used (see `Refocus.__init__()`)

propagate(*distance*)

Propagate the initial field to a certain distance

Parameters **distance** (*float*) – Absolute focusing distance [m]

Returns **refocused_field** – Initial field refocused at *distance*

Return type 2d ndarray

Notes

Any subclass should perform padding with `nrefocus.pad.pad_rem()` during initialization.

property shape

Shape of the padded input field or Fourier transform

class nrefocus.**RefocusNumpy1D**(*field*, *wavelength*, *pixel_size*, *medium_index=1.3333*, *distance=0*, *kernel='helmholtz'*, *padding=True*)

Refocus a 1D field with numpy

New in version 0.3.0.

Parameters

- **field** (*1d complex-valued ndarray*) – Input 1D field to be refocused
- **wavelength** (*float*) – Wavelength of the used light [m]
- **pixel_size** (*float*) – Pixel size of the input image [m]
- **medium_index** (*float*) – Refractive index of the medium, defaults to water (1.3333 at 21.5°C)
- **distance** (*float*) – Initial focusing distance [m]
- **kernel** (*str*) – Propagation kernel, one of
  - "helmholtz": the optical transfer function $\exp\left(id\left(\sqrt{k_\mathrm{m}^2 - k_\mathrm{x}^2} - k_\mathrm{m}\right)\right)$

- ”fresnel”: paraxial approximation $\exp(-idk_x^2/2k_m)$

- **padding** (*bool*) – Wheter to perform boundary-padding with linear ramp

autofocus(*interval*, *metric='average gradient'*, *minimizer='lmfit'*, *roi=None*, *minimizer_kwargs=None*, *ret_grid=False*, *ret_field=False*)

Autofocus the initial field

Parameters

- **interval** (*tuple of floats*) – Approximate interval to search for optimal focus [m]
- **metric** (*str*) –
  - “average gradient” : average gradient metric of amplitude
  - ”rms contrast” : RMS contrast of phase data
  - ”spectrum” : sum of filtered Fourier coefficients
  - ”std gradient” : standard deviation of gradient of amplitude
  - ”med gradient” : median gradient metric of amplitude
- **minimizer** (*str*) –
  - “legacy”: custom nrefocus minimizer
  - ”lmfit”: lmfit-based minimizer (uses `lmfit.minimize`)
- **roi** (*list or tuple or slice or ndarray*) – Region of interest for which the metric will be minimized. The axes below use the numpy indexing order. Options are: list or tuple or numpy indexing array (old behaviour):

  [axis_0_start, axis_1_start, axis_0_end, axis_1_end] None can be used if no slicing is desired eg.: [None, None, axis_0_end, axis_1_end]

  list or tuple of slices (will be passed directly as is):

  (slice(axis_0_start, axis_0_end), slice(axis_1_start, axis_1_end))

  None The entire field will be used.
- **minimizer_kwargs** (*dict*) – Any additional keyword arguments for the minimizer
- **ret_grid** (*bool*) – return focus positions and metric values of the coarse grid search
- **ret_field** (*bool*) – return the optimal refocused field for user convenience

Returns

- **af_distance** (*float*) – Autofocusing distance
- **(d_grid, metrid_grid)** (*ndarray*) – Coarse grid search values (only if *ret_grid* is True)
- **af_field** (*ndarray*) – Autofocused field (only if *ret_field* is True)
- *[other]* – Any other objects returned by *minimizer*; may be definable via *minimizer_kwargs* (depends on minimizer)

get_kernel(*distance*)

Return the kernel for a 1D propagation

propagate(*distance*)

Propagate the initial field to a certain distance

Parameters **distance** (*float*) – Absolute focusing distance [m]

Returns **refocused_field** – Initial 1D field refocused at *distance*

Return type 1d ndarray

property shape
Shape of the padded input field or Fourier transform

4.2 Metrics

nrefocus.metrics.**metric_average_gradient**(*rfi*, *distance*, *roi=None*, ***kwargs*)
Compute mean average gradient norm of the amplitude

Notes

The absolute value of the gradient is returned.

nrefocus.metrics.**metric_med_gradient**(*rfi*, *distance*, *roi=None*, ***kwargs*)
Compute median gradient norm of the amplitude

Notes

The absolute value of the gradient is returned.

nrefocus.metrics.**metric_rms_contrast**(*rfi*, *distance*, *roi=None*, ***kwargs*)
Compute RMS contrast of the phase

Notes

The negative angle of the field is used for contrast estimation.

nrefocus.metrics.**metric_spectrum**(*rfi*, *distance*, *roi=None*, ***kwargs*)
Compute spectral contrast

Performs bandpass filtering in Fourier space according to optical limit of detection system, approximated by twice the wavelength.

nrefocus.metrics.**metric_std_gradient**(*rfi*, *distance*, *roi=None*, ***kwargs*)
Compute standard deviation (std) gradient of the amplitude

Notes

The absolute value of the gradient is returned.

nrefocus.metrics.**METRICS = {'average gradient': <function metric_average_gradient>, 'med gradient': <function metric_med_gradient>, 'rms contrast': <function metric_rms_contrast>, 'spectrum': <function metric_spectrum>, 'std gradient': <function metric_std_gradient>}**
Available metrics

4.3 Minimizers

nrefocus.minimizers.**minimize_legacy**(*rf*, *metric_func*, *interval*, *roi=None*, *coarse_acc=1*, *fine_acc=0.005*, *ret_grid=False*, *ret_field=False*)

Legacy minimizer

Find the focus by minimizing the *metric* of an image. This is the implementation of the legacy nrefocus minimizer.

Parameters

- **rf** (*nrefocus.iface.Refocus*) – Refocus interface
- **metric_func** (*callable*) – metric called during minimization. The metric should take the following arguments: *rf*, *distance*, and *roi*
- **interval** (*tuple of floats*) – (minimum, maximum) of interval to search [m]
- **roi** (*tuple of slices or np.ndarray*) – Region of interest for which the metric will be minimized. If not given, the entire field will be used.
- **coarse_acc** (*float*) – accuracy for determination of global minimum in pixels; *coarse_acc=1* means that 100 fields are computed in the initial step; *coarse_acc=0.5* means 200 fields are computed
- **fine_acc** (*float*) – accuracy for fine localization percentage of gradient change
- **ret_grid** (*bool*) – return focus positions and metric values of the coarse grid search
- **ret_field** (*bool*) – return the optimal refocused field for user convenience

Returns

- **af_dist** (*float*) – Autofocusing distance [m]
- **(d_grid, metrid_grid)** (*ndarray*) – Coarse grid search values (only if *ret_grid* is True)
- **af_field** (*ndarray*) – Autofocused field (only if *ret_field* is True)

nrefocus.minimizers.**minimize_lmfit**(*rf*, *metric_func*, *interval*, *roi=None*, *lmfitkw=None*, *ret_grid=False*, *ret_field=False*)

A minimizer that wraps lmfit

Find the focus by minimizing the *metric* of an image A coarse grid search over *interval* with step size of *2*rf.wavelength* is performed, followed by a "regular" minimization for the best candidate.

Parameters

- **rf** (*nrefocus.iface.Refocus*) – Refocus interface
- **metric_func** (*callable*) – metric called during minimization. The metric should take the following arguments: *rf*, *distance*, and *roi*
- **interval** (*tuple of floats*) – (minimum, maximum) of interval to search [m]
- **roi** (*tuple of slices or np.ndarray*) – Region of interest for which the metric will be minimized. If not given, the entire field will be used.
- **lmfitkw** – Additional keyword arguments for `lmfit.minimize` used in the fine grid search. The default *method* is "leastsq".
- **ret_grid** (*bool*) – return focus positions and metric values of the coarse grid search
- **ret_field** (*bool*) – return the optimal refocused field for user convenience

Returns

- **af_dist** (*float*) – Autofocusing distance [m]
- **(d_grid, metrid_grid)** (*ndarray*) – Coarse grid search values (only if *ret_grid* is True)
- **af_field** (*ndarray*) – Autofocused field (only if *ret_field* is True)

nrefocus.minimizers.**MINIMIZERS = {'legacy': <function minimize_legacy>, 'lmfit': <function minimize_lmfit>}**
Available minimizers

4.4 Legacy methods

These methods are legacy functions which are kept for backwards-compatibility.

4.4.1 Refocusing

nrefocus.**refocus**(*field*, *d*, *nm*, *res*, *method='helmholtz'*, *padding=True*)
Refocus a 1D or 2D field

Parameters

- **field** (*1d or 2d array*) – 1D or 2D background corrected electric field (Ex/BEx)
- **d** (*float*) – Distance to be propagated in pixels (negative for backwards)
- **nm** (*float*) – Refractive index of medium
- **res** (*float*) – Wavelenth in pixels
- **method** (*str*) – Defines the method of propagation; one of
  - "helmholtz" : the optical transfer function *exp(idk(M-1))*
  - "fresnel" : paraxial approximation $exp(idk^2/k)$
- **padding** (*bool*) – perform padding with linear ramp from edge to average to reduce ringing artifacts.

  New in version 0.1.4.

Returns

Return type Electric field at *d*.

Notes

This method uses *nrefocus.RefocusNumpy* for refocusing of 2D fields. This is because the *nrefocus.refocus_stack()* function uses *async* which appears to not work with e.g. pyfftw.

nrefocus.**refocus_stack**(*fieldstack*, *d*, *nm*, *res*, *method='helmholtz'*, *num_cpus=2*, *copy=True*, *padding=True*)
Refocus a stack of 1D or 2D fields

Parameters

- **fieldstack** (*2d or 3d array*) – Stack of 1D or 2D background corrected electric fields (Ex/BEx). The first axis iterates through the individual fields.
- **d** (*float*) – Distance to be propagated in pixels (negative for backwards)
- **nm** (*float*) – Refractive index of medium

- **res** (*float*) – Wavelenth in pixels
- **method** (*str*) – Defines the method of propagation; one of
  - "helmholtz" : the optical transfer function *exp(idk(M-1))*
  - "fresnel" : paraxial approximation *exp(idk²/k)*
- **num_cpus** (*int*) – Defines the number of CPUs to be used for refocusing.
- **copy** (*bool*) – If False, overwrites input stack.
- **padding** (*bool*) – Perform padding with linear ramp from edge to average to reduce ringing artifacts.

  New in version 0.1.4.

Returns

Return type Electric field stack at *d*.

4.4.2 Autofocusing

nrefocus.**autofocus**(*field*, *nm*, *res*, *ival*, *roi=None*, *metric='average gradient'*, *minimizer='lmfit'*, *minimizer_kwargs=None*, *padding=True*, *num_cpus=1*)

Numerical autofocusing of a field using the Helmholtz equation.

Parameters

- **field** (*1d or 2d ndarray*) – Electric field is BG-Corrected, i.e. field = EX/BEx
- **nm** (*float*) – Refractive index of medium.
- **res** (*float*) – Size of wavelength in pixels.
- **ival** (*tuple of floats*) – Approximate interval to search for optimal focus in px.
- **roi** (*rectangular region of interest (x1, y1, x2, y2)*) – Region of interest of *field* for which the metric will be minimized. If not given, the entire *field* will be used.
- **metric** (*str*) –
  - "average gradient" : average gradient metric of amplitude
  - "rms contrast" : RMS contrast of phase data
  - "spectrum" : sum of filtered Fourier coefficients
  - "std gradient" : standard deviation of gradient metric of amplitude
  - "med gradient" : median gradient metric of amplitude
- **minimizer** (*str*) –
  - "lmfit" : lmfit-based minimizer
  - "legacy" : only use for reproducing old results
- **minimizer_kwargs** (*dict*) – Optional keyword arguments to the *minimizer* function
- **padding** (*bool*) – Perform padding with linear ramp from edge to average to reduce ringing artifacts.

  Changed in version 0.1.4: improved padding value and padding location
- **num_cpus** (*int*) – Not implemented.

Returns The focusing distance, the field, and optionally any other data returned by the minimizer (specify via *minimizer_kwargs*).

Return type d, field [, other]

Notes

This method uses *nrefocus.RefocusNumpy* for refocusing of 2D fields. This is because the *nrefocus.refocus_stack()* function uses *async* which appears to not work with e.g. pyfftw.

nrefocus.**autofocus_stack**(*fieldstack*, *nm*, *res*, *ival*, *roi=None*, *metric='average gradient'*, *minimizer='lmfit'*, *minimizer_kwargs=None*, *padding=True*, *same_dist=False*, *num_cpus=2*, *copy=True*)

Numerical autofocusing of a stack using the Helmholtz equation.

Parameters

- **fieldstack** (*2d or 3d ndarray*) – Electric field is BG-Corrected, i.e. Field = EX/BEx
- **nm** (*float*) – Refractive index of medium.
- **res** (*float*) – Size of wavelength in pixels.
- **ival** (*tuple of floats*) – Approximate interval to search for optimal focus in px.
- **roi** (*rectangular region of interest (x1, y1, x2, y2)*) – Region of interest of *field* for which the metric will be minimized. If not given, the entire *field* will be used.
- **metric** (*str*) – see *autofocus_field*.
- **minimizer** (*str*) –
  - "lmfit" : lmfit-based minimizer
  - "legacy" : only use for reproducing old results
- **minimizer_kwargs** (*dict*) – Optional keyword arguments to the *minimizer* function
- **padding** (*bool*) – Perform padding with linear ramp from edge to average to reduce ringing artifacts.

  Changed in version 0.1.4: improved padding value and padding location
- **same_dist** (*bool*) – Refocus entire sinogram with one distance.
- **num_cpus** (*int*) – Number of CPUs to use
- **copy** (*bool*) – If False, overwrites input array.

Returns

- **dopt** (*float or list of float*) – The focusing distance(s) (only one value if *same_dist*)
- **field_stack** (*np.ndarray*) – The refocused field stack

CHAPTER

FIVE

CHANGELOG

List of changes in-between nrefocus releases.

5.1 version 0.5.3

- enh: add std and median metrics (#19)
- docs: make docs build on Windows

5.2 version 0.5.2

- enh: clarify roi argument for Refocus.autofocus method (#17)

5.3 version 0.5.1

- fix: internally normalize focusing distance to the wavelength for autofocusing with lmfit, because the scale seemed to affect the minimizer convergence (#14)

5.4 version 0.5.0

- BREAKING CHANGE: The "legacy" minimizer is deprecated in favor of the new lmfit-based minimizer. The default minimizer is now "lmfit".
- BREAKING CHANGE: Removed the "ret_grad" and "ret_d" keyword argument from autofocusing methods; there is now "ret_grid" and "ret_field" instead
- BREAKING CHANGE: By default, the minimizers do not anymore return the refocused field, this can be re-enabled by using the *ret_field* option
- build: lmfit is now a dependency
- fix: check for None instead of boolean evaluation for metrics dealing with ROIs

5.5 version 0.4.3

- ref: deprecate minimizer argument
- ref: legacy minimizer now thinks in SI units
- ref: minor cleanup in autofocusing code

5.6 version 0.4.2

- docs: minor improvements

5.7 version 0.4.1

- fix: *autofocus* method of Refocus was not functional
- ref: use *Refocus.autofocus* for legacy autofocus method
- docs: fix rtd builds

5.8 version 0.4.0

- feat: implement nrefocus.RefocusPyFFTW for faster refocusing using pyfftw (#11)
- enh: speed-up propagation kernel computation using numexpr
- docs: cleanup

5.9 version 0.3.1

- dist: include submodules in wheel/dist

5.10 version 0.3.0

- feat: introduce nrefocus.RefocusNumpy and nrefocus.RefocusNumpy1D interface class for user-convenience and efficiency
- docs: cleanup
- ref: new submodule for metrics and metrics now accept a Refocus instance as an argument
- ref: new submodule for minimizers and minimizers now accept a Refocus instance
- ref: make legacy autofocusing code use the new Refocus class

5.11 version 0.2.1

- fix: fix several minor bugs (deprecations?) that caused the tests to faile
- ci: migrate to GitHub Actions
- setup: setup.py test is deprecated
- docs: refurbish documentation

5.12 version 0.2.0

- Drop support for Python 2 (#8)
- Code cleanup

5.13 version 0.1.8

- Include docs in sdist

5.14 version 0.1.7

- Update documentation and examples

5.15 version 0.1.6

- Move documentation from GitHub to readthedocs.io
- Add universal wheel on PyPI
- Update tests on travis with new versions of NumPy

5.16 version 0.1.5

- Code cleanup

5.17 version 0.1.4

- Padding is now available in all methods (#2)
- Added new convenient submodule *pad*
- Bugfix: autofocusing did not return the correct focusing distance. This resulted in a slight offset in the refocusing distance for the method *autofocus_stack* when *same_dist=True* was set.
- New test functions for *pad*

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