
nrefocus Documentation

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Paul Müller

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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.

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 Fourier 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 Fourier 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 this¹.

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

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

$$\begin{aligned} u(\mathbf{r}_0) &= \iint dp dq A(p, q) e^{ik_m(px_0 + qy_0 + Mz_0)} \\ |\mathbf{s}| &= p^2 + q^2 + M^2 = 1 \\ M &= \sqrt{1 - p^2 - q^2}. \end{aligned}$$

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 $k_m = \frac{2\pi n_m}{\lambda}$, weighted with the amplitude $A(p, q)$.

Let us now consider the 2D Fourier transform of $u(\mathbf{r}_0)$.

$$\begin{aligned} \hat{U}_0(k_x, k_y) &= \frac{1}{2\pi} \iint dx_0 dy_0 \iint dp dq A(p, q) e^{ik_m(px_0 + qy_0 + Mz_0)} e^{-i(k_x x_0 + k_y y_0)} \\ &= \frac{1}{2\pi} \iint dx_0 dy_0 \iint dp dq A(p, q) e^{ik_m M z_0} e^{ix_0(k_m p - k_x)} e^{iy_0(k_m q - k_y)} \\ &= \frac{2\pi}{k_m^2} A(k_x, k_y) e^{ik_m M z_0} \end{aligned}$$

Here we made use of the identity of the delta distribution

$$\begin{aligned} \frac{1}{2\pi} \int dx_0 e^{ix_0(k_m p - k_x)} &= \delta(k_m p - k_x) = \frac{1}{k_m} \delta(p - k_x/k_m) \\ \frac{1}{2\pi} \int dy_0 e^{iy_0(k_m q - k_y)} &= \delta(k_m q - k_y) = \frac{1}{k_m} \delta(q - k_y/k_m) \end{aligned}$$

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

$$\hat{U}_d(k_x, k_y) = \frac{2\pi}{k_m^2} A(k_x, k_y) e^{ik_m M z_d}.$$

Thus, the propagation of the field $u(\mathbf{r}_0)$ by a distance $d = z_d - z_0$ is described by a multiplication with the transfer function

$$\mathcal{H}^{\text{Helmholtz}} = e^{ik_m M d}$$

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

$$u(\mathbf{r}_d) = \mathcal{F}^{-1} \{ \mathcal{F} \{ u(\mathbf{r}_0) \} \cdot e^{ik_m M d} \}$$

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

$$u(\mathbf{r}_d) = u(\mathbf{r}_0) * \mathcal{F}^{-1} \{ e^{ik_m M d} \}.$$

2.2 Fresnel approximation

The Fresnel approximation (or paraxial approximation) uses a Taylor expansion to simplify the exponent of the transfer function $e^{ik_m M d}$. The exponent can be rewritten as

$$ik_m M d = ik_m d (1 - p^2 - q^2)^{1/2}.$$

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:

$$\begin{aligned} \theta_x &\approx p \\ \theta_y &\approx q \\ \theta^2 &= \theta_x^2 + \theta_y^2 \approx p^2 + q^2 \end{aligned}$$

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

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

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

$$\begin{aligned} e^{ik_m M d} &\approx e^{ik_m d} \cdot e^{-\frac{ik_m d(p^2 + q^2)}{2}} \\ e^{i\sqrt{k_m^2 - k_x^2 - k_y^2} d} &\approx e^{ik_m d} \cdot e^{-\frac{id(k_x^2 + k_y^2)}{2k_m}} \\ \mathcal{H}^{\text{Fresnel}} &= e^{ik_m d} \cdot e^{-\frac{id(k_x^2 + k_y^2)}{2k_m}} \end{aligned}$$

Thus, the propagation by a distance $d = z_d - d$ in the Fresnel approximation can be written in the form of the convolution

$$u(\mathbf{r}_d) = e^{ik_m d} \cdot u(\mathbf{r}_0) * \mathcal{F}^{-1} \left\{ e^{-\frac{id(k_x^2 + k_y^2)}{2k_m}} \right\}.$$

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

$$u_{\text{in}}(\mathbf{r}_0) = \frac{u(\mathbf{r}_0)}{u_0(\mathbf{r}_0)}$$

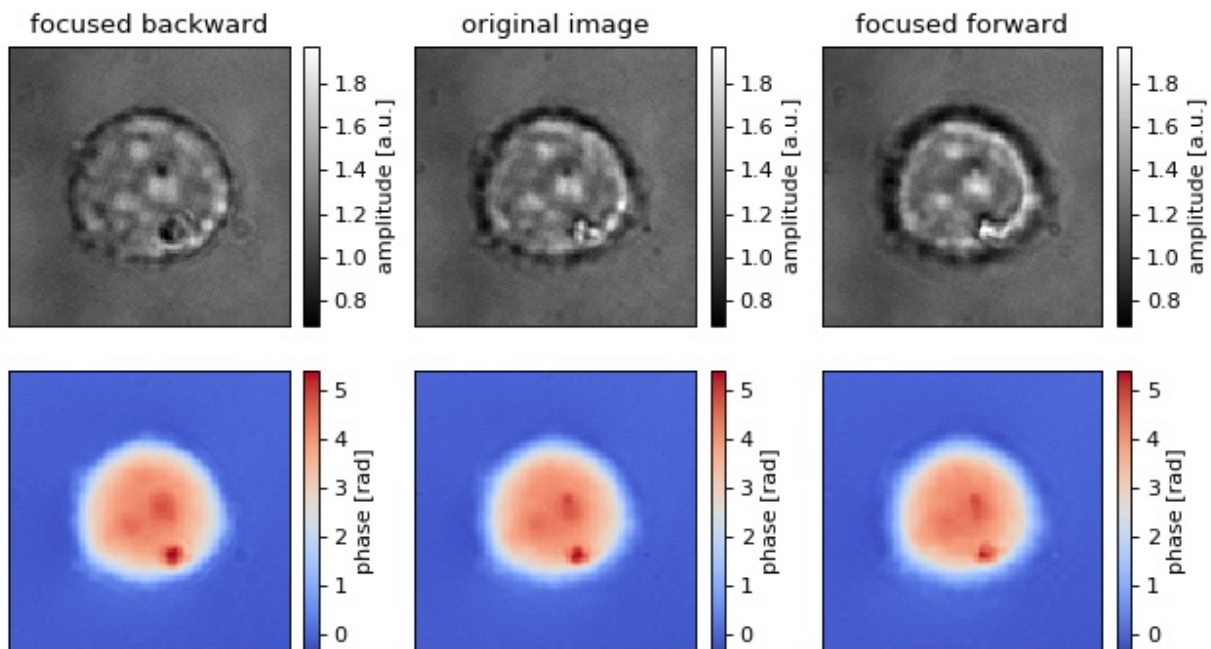
As a result, the transfer functions change to

$$\begin{aligned}\mathcal{H}_{\text{norm}}^{\text{Helmholtz}} &= e^{ik_{\text{m}}(M-1)d} = e^{id(\sqrt{k_{\text{m}}^2 - k_{\text{x}}^2 - k_{\text{y}}^2} - k_{\text{m}})} \\ \mathcal{H}_{\text{norm}}^{\text{Fresnel}} &= e^{-\frac{id(k_{\text{x}}^2 + k_{\text{y}}^2)}{2k_{\text{m}}}}.\end{aligned}$$

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 $20\mu\text{m}$.



refocus_cell.py

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 import unwrap
4
5 import nrefocus
6
7 from example_helper import load_cell
8
9 # load initial cell
10 cell1 = load_cell("HL60_field.zip")
```

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```

11
12 # refocus to two different positions
13 cell2 = nrefocus.refocus(cell1, 15, 1, 1) # forward
14 cell3 = nrefocus.refocus(cell1, -15, 1, 1) # backward
15
16 # amplitude range
17 vmina = np.min(np.abs(cell1))
18 vmaxa = np.max(np.abs(cell1))
19 ampkw = {"cmap": plt.get_cmap("gray"),
20         "vmin": vmina,
21         "vmax": vmaxa}
22
23 # phase range
24 cell1p = unwrap.unwrap(np.angle(cell1))
25 cell2p = unwrap.unwrap(np.angle(cell2))
26 cell3p = unwrap.unwrap(np.angle(cell3))
27 vminp = np.min(cell1p)
28 vmaxp = np.max(cell1p)
29 phakw = {"cmap": plt.get_cmap("coolwarm"),
30         "vmin": vminp,
31         "vmax": vmaxp}
32
33 # plots
34 fig, axes = plt.subplots(2, 3, figsize=(8, 4.5))
35 axes = axes.flatten()
36 for ax in axes:
37     ax.xaxis.set_major_locator(plt.NullLocator())
38     ax.yaxis.set_major_locator(plt.NullLocator())
39
40 # titles
41 axes[0].set_title("focused backward")
42 axes[1].set_title("original image")
43 axes[2].set_title("focused forward")
44
45 # data
46 mapamp = axes[0].imshow(np.abs(cell3), **ampkw)
47 axes[1].imshow(np.abs(cell1), **ampkw)
48 axes[2].imshow(np.abs(cell2), **ampkw)
49 mappha = axes[3].imshow(cell3p, **phakw)
50 axes[4].imshow(cell1p, **phakw)
51 axes[5].imshow(cell2p, **phakw)
52
53 # colobars
54 cbkwargs = {"fraction": 0.045}
55 plt.colorbar(mapamp, ax=axes[0], label="amplitude [a.u.]", **cbkwargs)
56 plt.colorbar(mapamp, ax=axes[1], label="amplitude [a.u.]", **cbkwargs)
57 plt.colorbar(mapamp, ax=axes[2], label="amplitude [a.u.]", **cbkwargs)
58 plt.colorbar(mappha, ax=axes[3], label="phase [rad]", **cbkwargs)
59 plt.colorbar(mappha, ax=axes[4], label="phase [rad]", **cbkwargs)
60 plt.colorbar(mappha, ax=axes[5], label="phase [rad]", **cbkwargs)
61
62 plt.tight_layout()

```

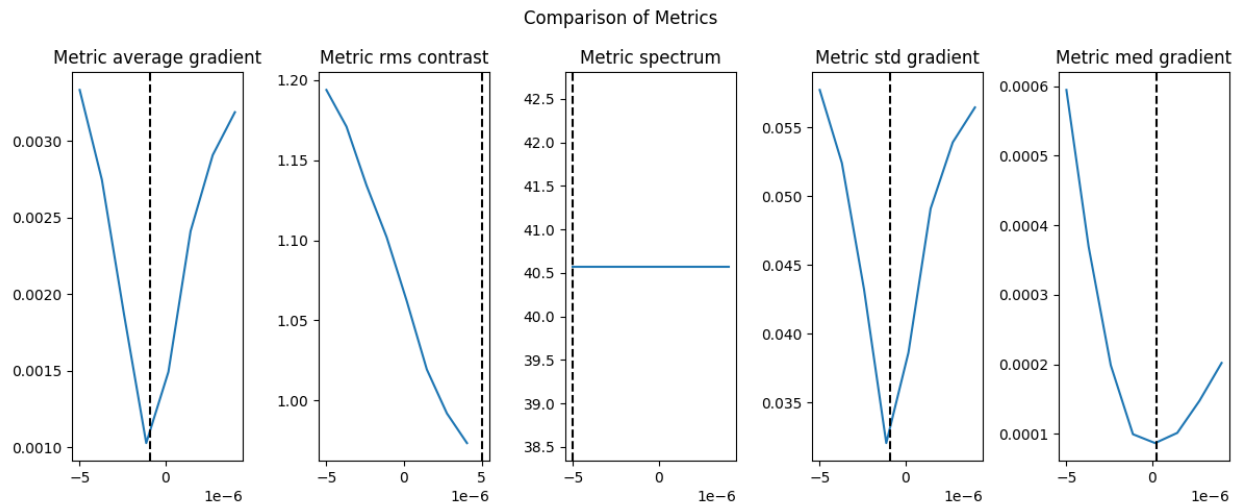
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63 `plt.show()`

3.2 Compare available Metrics for Refocusing

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



`compare_metrics.py`

```

1  import nrefocus
2  from nrefocus.metrics import METRICS
3  import matplotlib.pyplot as plt
4
5  from examples.example_helper import load_cell
6
7  # load initial cell and create rf object
8  rf = nrefocus.iface.RefocusNumpy(field=load_cell("HL60_field.zip"),
9                                   wavelength=647e-9,
10                                  pixel_size=0.139e-6,
11                                  kernel="helmholtz")
12
13  # autofocus the image for each metric
14  my_metrics = list(METRICS.keys())
15
16  fig, axes = plt.subplots(1, len(my_metrics), figsize=(12, 5))
17
18  for i, mt in enumerate(my_metrics):
19      af_vals = rf.autofocus(metric=mt,
20                             minimizer="lmfit",
21                             interval=(-5e-6, 5e-6),
22                             ret_field=True,
23                             ret_grid=True)
24      d, grid, field = af_vals
25

```

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```
26     axes[i].plot(grid[0], grid[1])
27     axes[i].axvline(d, color='k', ls='--')
28     axes[i].set_title(f"Metric {mt}")
29
30 fig.suptitle("Comparison of Metrics")
31 fig.tight_layout()
32 plt.show()
```

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 $\exp\left(id\left(\sqrt{k_m^2 - k_x^2 - k_y^2} - k_m\right)\right)$
 - "fresnel": paraxial approximation $\exp(-id(k_x^2 + k_y^2)/2k_m)$
- **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

The 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 $\exp\left(id\left(\sqrt{k_m^2 - k_x^2 - k_y^2} - k_m\right)\right)$
 - "fresnel": paraxial approximation $\exp(-id(k_x^2 + k_y^2)/2k_m)$
- **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

The 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 $\exp\left(id\left(\sqrt{k_m^2 - k_x^2} - k_m\right)\right)$

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

- **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 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*) – Wavelength in pixels
- **method** (*str*) – Defines the method of propagation; one of
 - “helmholtz” : the optical transfer function $\exp(ik(M-1))$
 - “fresnel” : paraxial approximation $\exp(ik^2/k)$
- **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*) – Wavelength in pixels
- **method** (*str*) – Defines the method of propagation; one of
 - “helmholtz” : the optical transfer function $\exp(ik(M-I))$
 - “fresnel” : paraxial approximation $\exp(ik^2/k)$
- **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. $\text{field} = \text{EX}/\text{BEx}$
 - **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

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 fail
- 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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