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# **xrft Documentation**

*Release 0.1*

**xrft developers**

**Sep 11, 2021**



# GETTING STARTED

<b>1 Documentation</b>	<b>3</b>
<b>Python Module Index</b>	<b>39</b>
<b>Index</b>	<b>41</b>



**xrft** is a Python package for taking the discrete Fourier transform (DFT) on [xarray](#) and [dask](#) arrays. It is:

- **Powerful:** It keeps the metadata and coordinates of the original xarray dataset and provides a clean work flow of DFT.
- **Easy-to-use:** It uses the native arguments of numpy FFT and provides a simple, high-level API.
- **Fast:** It uses the dask API of FFT and `map_blocks` to allow parallelization of DFT.

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**Note:** `xrft` is at early stage of development and will keep improving in the future. The discrete Fourier transform API should be quite stable, but minor utilities could change in the next version. If you find any bugs or would like to request any enhancements, please [raise an issue on GitHub](#).

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## 1.1 Overview: Why xrft?

### 1.1.1 For robustness and efficiency

In the field of Earth Science, we often take Fourier transforms of the variable of interest. There has, however, not been an universal algorithm in which we calculate the transforms and our aim is to stream line this process.

We utilize the [dask](#) API to parallelize the computation to make it efficient for large data sets.

### 1.1.2 For usability and simplicity

The arguments in xrft rely on well-established standards ([dask](#) and [numpy](#)), so users don't need to learn a bunch of new syntaxes or even a new software stack.

xrft can track the metadata in `xarray.DataArray` (*example*), which makes it easy for large data sets.

The choice of Python and Anaconda also makes xrft *extremely easy to install*.

## 1.2 Current limitations

### 1.2.1 Discrete sinusoid transform

xrft currently only supports discrete fourier transforms. We plan to implement discrete sinusoid tranforms in the near future.

## 1.3 Installation

### 1.3.1 The quickest way

xrft is compatible both with Python 2 and 3. The major dependencies are [xarray](#) and [dask](#). The best way to install them is using [Anaconda](#):

```
$ conda install -c conda-forge xarray dask xrft .
```

It is also possible to install from [PyPI](#) by:

```
$ pip install xrft .
```

### 1.3.2 Install xrft from GitHub repo

To get the latest version:

```
$ git clone https://github.com/xgcm/xrft.git
$ cd xrft
$ python setup.py install .
```

Developers can track source code changes by:

```
$ git clone https://github.com/xgcm/xrft.git
$ cd xrft
$ python setup.py develop .
```

## 1.4 Contributor Guide

**xrft** is meant to be a community driven package and we welcome feedback and contributions.

Did you notice a bug? Are you missing a feature? A good first starting place is to open an issue in the [github issues page](#).

In order to contribute to xrft, please fork the repository and submit a pull request. A good step by step tutorial for this can be found in the [xarray contributor guide](#).

### 1.4.1 Environments

The easiest way to start developing xrft pull requests, is to install one of the conda environments provided in the `ci` folder:

```
conda env create -f ci/environment-py3.8.yml
```

Activate the environment with:

```
conda activate test_env_xrft
```

### 1.4.2 Code Formatting

We use `black` as code formatter and pull request will fail in the CI if not properly formatted.

All conda environments contain `black` and you can reformat code using:

```
black xrft
```

`pre-commit` provides an automated way to reformat your code prior to each commit. Simply install `pre-commit`:

```
pip install pre-commit
```

and install it in the xrft root directory with:



```
pre-commit install
```

and your code will be properly formatted before each commit.

### 1.4.3 How to release a new version of xrft (for maintainers only)

The process of releasing at this point is very easy.

We need only two things: A PR to update the documentation and and making a release on github.

1. Make sure that all the new features/bugfixes etc are appropriately documented in *doc/whats-new.rst*, add the date to the current release and make an empty (unreleased) entry for the next minor release as a PR.
2. Navigate to the ‘tags’ symbol on the repos main page, click on ‘Releases’ and on ‘Draft new release’ on the right. Add the version number and a short description and save the release.

From here the github actions take over and package things for [Pypi](#). The conda-forge package will be triggered by the Pypi release and you will have to approve a PR in [xrft-feedstock](#). This takes a while, usually a few hours to a day.

Thats it!

## 1.5 Example of discrete and inverse discrete Fourier transform

```
[1]: import numpy as np
import numpy.testing as npt
import xarray as xr
import xrft
import numpy.fft as npft
import scipy.signal as signal
import dask.array as dsar
import matplotlib.pyplot as plt
%matplotlib inline
```

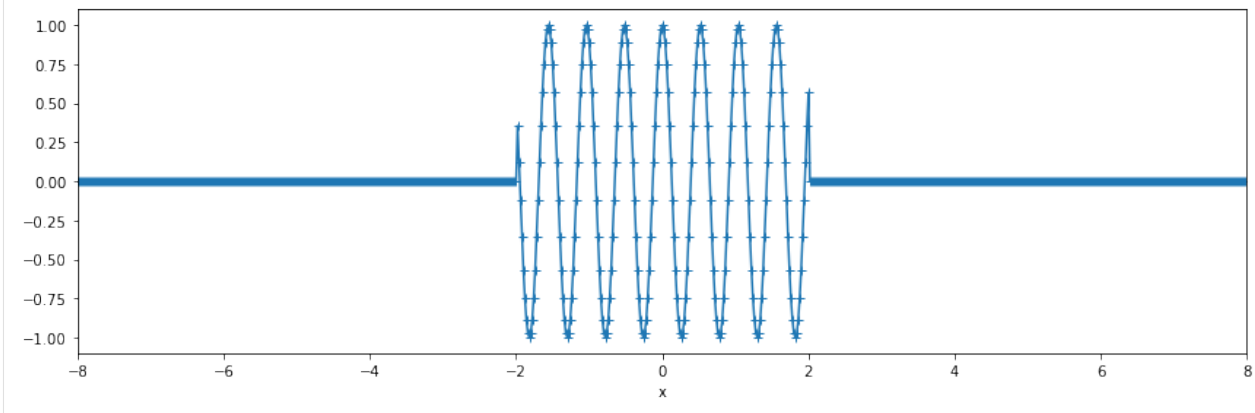
In this notebook, we provide examples of the discrete Fourier transform (DFT) and its inverse, and how `xrft` automatically harnesses the metadata. We compare the results to conventional `numpy.fft` (hereon `npft`) to highlight the strengths of `xrft`.

### 1.5.1 A case with synthetic data

Generate synthetic data centered around zero

```
[2]: k0 = 1/0.52
T = 4.
dx = 0.02
x = np.arange(-2*T, 2*T, dx)
y = np.cos(2*np.pi*k0*x)
y[np.abs(x)>T/2]=0.
da = xr.DataArray(y, dims=('x',), coords={'x':x})
```

```
[22]: fig, ax = plt.subplots(figsize=(12,4))
fig.set_tight_layout(True)
da.plot(ax=ax, marker='+', label='original signal')
ax.set_xlim([-8,8]);
```



### Let's take the Fourier transform

We will compare the Fourier transform with and without taking into consideration about the phase information.

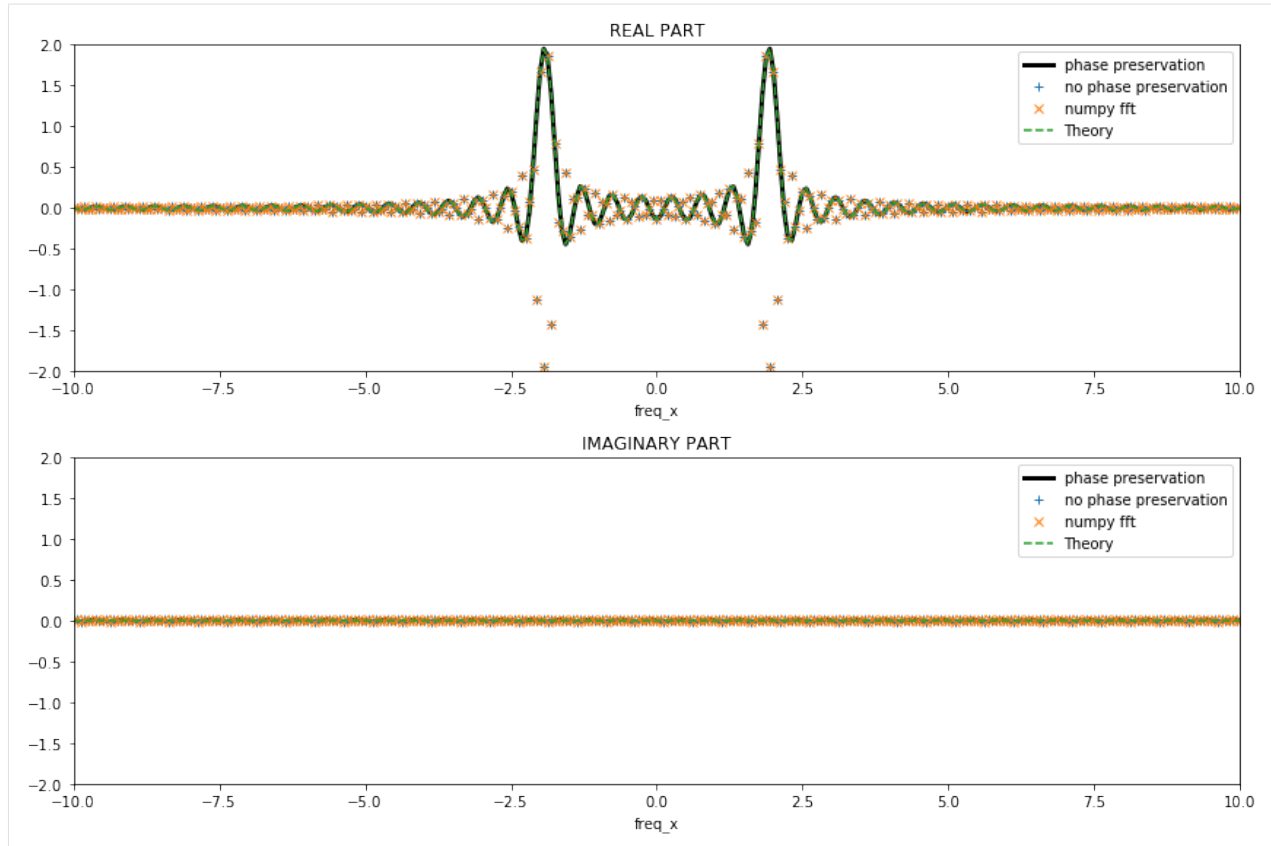
```
[3]: da_dft = xrft.dft(da, true_phase=True, true_amplitude=True) # Fourier Transform w/
↳ consideration of phase
da_fft = xrft.fft(da) # Fourier Transform w/ numpy.
↳ fft-like behavior
da_npft = npft.fft(da)
```

```
[4]: k = da_dft.freq_x # wavenumber axis
TF_s = T/2*(np.sinc(T*(k-k0)) + np.sinc(T*(k+k0))) # Theoretical result of the Fourier
↳ transform
```

```
[26]: fig, (ax1,ax2) = plt.subplots(figsize=(12,8), nrows=2, ncols=1)
fig.set_tight_layout(True)

(da_dft.real).plot(ax=ax1, linestyle='-', lw=3, c='k', label='phase preservation')
((da_fft*dx).real).plot(ax=ax1, linestyle='', marker='+', label='no phase preservation')
ax1.plot(k, (npft.fftshift(da_npft)*dx).real, linestyle='', marker='x', label='numpy fft')
ax1.plot(k, TF_s.real, linestyle='--', label='Theory')
ax1.set_xlim([-10,10])
ax1.set_ylim([-2,2])
ax1.legend()
ax1.set_title('REAL PART')

(da_dft.imag).plot(ax=ax2, linestyle='-', lw=3, c='k', label='phase preservation')
((da_fft*dx).imag).plot(ax=ax2, linestyle='', marker='+', label='no phase preservation')
ax2.plot(k, (npft.fftshift(da_npft)*dx).imag, linestyle='', marker='x', label='numpy fft')
ax2.plot(k, TF_s.imag, linestyle='--', label='Theory')
ax2.set_xlim([-10,10])
ax2.set_ylim([-2,2])
ax2.legend()
ax2.set_title('IMAGINARY PART');
```



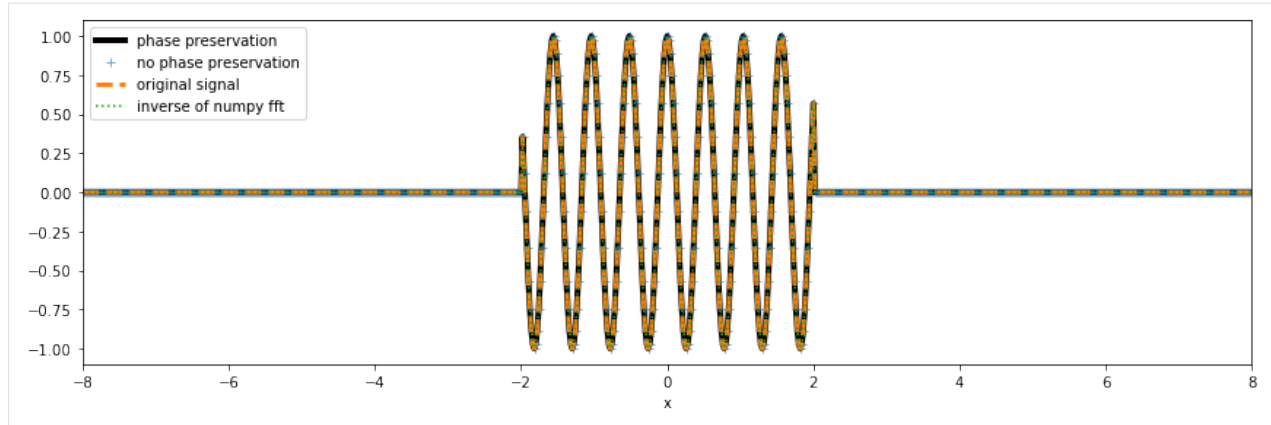
`xrft.dft`, `xrft.fft` (and `npft.fft` with careful `npft.fftshifting`) all give the same amplitudes as theory (as the coordinates of the original data was centered) but the latter two get the sign wrong due to losing the phase information. It is perhaps worth noting that the latter two (`xrft.fft` and `npft.fft`) require the amplitudes to be multiplied by  $dx$  to be consistent with theory while `xrft.dft` automatically takes care of this with the flag `true_amplitude=True`:

$$\mathcal{F}(da)(f) = \int_{-\infty}^{+\infty} da(x)e^{-2\pi ifx} dx \rightarrow \text{xrft.dft}(da)(f[m]) = \sum_n da(x[n])e^{-2\pi if[m]x[n]}\Delta x$$

### Perform the inverse transform

```
[5]: ida_dft = xrft.idft(da_dft, true_phase=True, true_amplitude=True) # Signal in direct_
     ↪ space
     ida_fft = xrft.ifft(da_fft)
```

```
[19]: fig, ax = plt.subplots(figsize=(12,4))
     fig.set_tight_layout(True)
     ida_dft.real.plot(ax=ax, linestyle='-', c='k', lw=4, label='phase preservation')
     ax.plot(x, ida_fft.real, linestyle='', marker='+', label='no phase preservation', alpha=.
     ↪ 6) # w/out the phase information, the coordinates are lost
     da.plot(ax=ax, ls='--', lw=3, label='original signal')
     ax.plot(x, npft.ifft(da_npft).real, ls=':', label='inverse of numpy fft')
     ax.set_xlim([-8,8])
     ax.legend(loc='upper left');
```



Although `xrft.ifft` misses the amplitude scaling (viz. resolution in wavenumber or frequency), since it is the inverse of the Fourier transform uncorrected for  $dx$ , the result becomes consistent with `xrft.idft`. In other words, `xrft.fft` (and `npft.fft`) misses the  $dx$  scaling and `xrft.ifft` (and `npft.ifft`) misses the  $df$  ( $= 1/(N \times dx)$ ) scaling. When applying the two operators in conjunction by doing `ifft(fft())`, there is a  $1/N$  ( $= dx \times df$ ) factor missing which is, in fact, *arbitrarily included in the `ifft` definition as a normalization factor* <https://numpy.org/doc/stable/reference/routines.fft.html#module-numpy.fft>. By incorporating the right scalings in `xrft.dft` and `xrft.idft`, there is no more consideration of the number of data points ( $N$ ):

$$\mathcal{F}^{-1}(\mathcal{F}(da))(x) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \mathcal{F}(da)(f) e^{2\pi i f x} df \rightarrow \text{xrft.idft}(\text{xrft.dft}(da))(x[n]) = \sum_m \text{xrft.dft}(da)(f[m]) e^{2\pi i f[m]x[n]} \Delta f$$

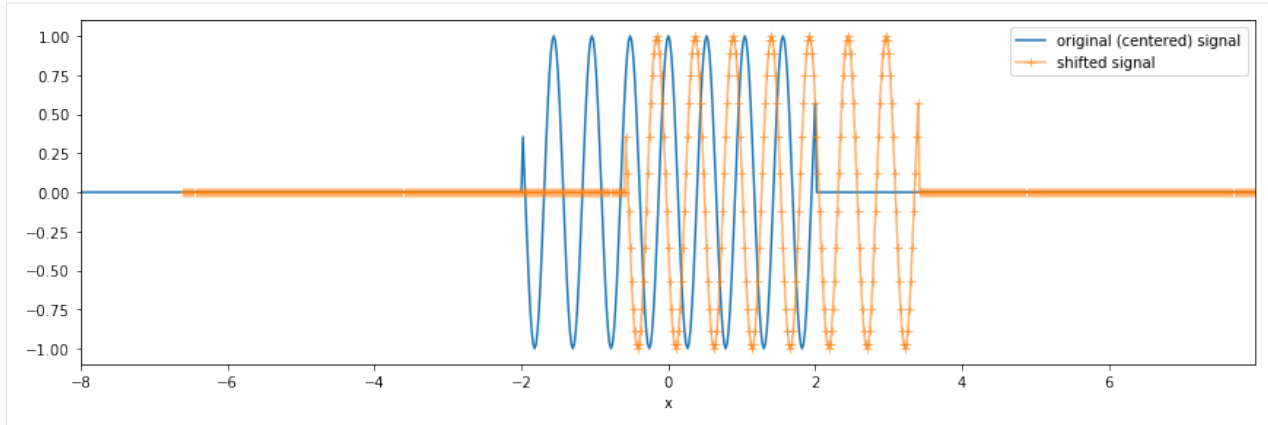
### Synthetic data not centered around zero

Now let's shift the coordinates so that they are not centered.

**This is where the `xrft` magic happens.** With the relevant flags, `xrft`'s `dft` can preserve information about the data's location in its original space. This information is not preserved in a `numpy` fourier transform. This section demonstrates how to preserve this information using the `true_phase=True`, `true_amplitude=True` flags.

```
[26]: nshift = 70 # defining a shift
      x0 = dx*nshift
      nda = da.shift(x=nshift).dropna('x')
```

```
[27]: fig, ax = plt.subplots(figsize=(12,4))
      fig.set_tight_layout(True)
      da.plot(ax=ax, label='original (centered) signal')
      nda.plot(ax=ax, marker='+', label='shifted signal', alpha=.6)
      ax.set_xlim([-8,nda.x.max()])
      ax.legend();
```



We consider again the Fourier transform.

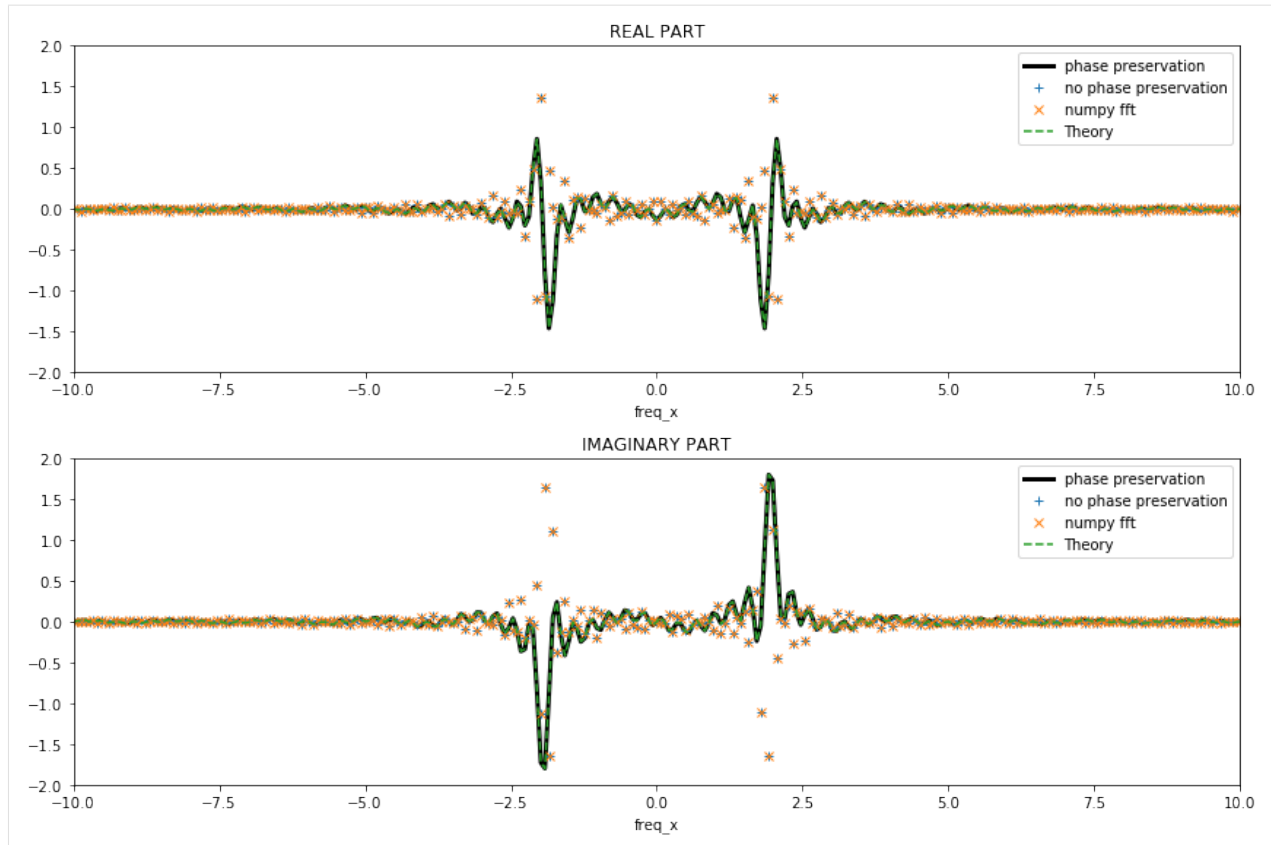
```
[28]: nda_dft = xrft.dft(nda, true_phase=True, true_amplitude=True) # Fourier Transform w/
      ↪ phase preservation
      nda_fft = xrft.fft(nda) # Fourier Transform w/out
      ↪ phase preservation
      nda_npft = npft.fft(nda)
```

```
[29]: nk = nda_dft.freq_x # wavenumber axis
      TF_ns = T/2*(np.sinc(T*(nk-k0)) + np.sinc(T*(nk+k0)))*np.exp(-2j*np.pi*nk*x0) #
      ↪ Theoretical FT (Note the additional phase)
```

```
[30]: fig, (ax1,ax2) = plt.subplots(figsize=(12,8), nrows=2, ncols=1)
      fig.set_tight_layout(True)

      (nda_dft.real).plot(ax=ax1, linestyle='-', lw=3, c='k', label='phase preservation')
      ((nda_fft*dx).real).plot(ax=ax1, linestyle='', marker='+', label='no phase preservation')
      ax1.plot(nk, (npft.fftshift(nda_npft)*dx).real, linestyle='', marker='x', label='numpy fft
      ↪')
      ax1.plot(nk, TF_ns.real, linestyle='--', label='Theory')
      ax1.set_xlim([-10,10])
      ax1.set_ylim([-2.,2])
      ax1.legend()
      ax1.set_title('REAL PART')

      (nda_dft.imag).plot(ax=ax2, linestyle='-', lw=3, c='k', label='phase preservation')
      ((nda_fft*dx).imag).plot(ax=ax2, linestyle='', marker='+', label='no phase preservation')
      ax2.plot(nk, (npft.fftshift(nda_npft)*dx).imag, linestyle='', marker='x', label='numpy fft
      ↪')
      ax2.plot(nk, TF_ns.imag, linestyle='--', label='Theory')
      ax2.set_xlim([-10,10])
      ax2.set_ylim([-2.,2.])
      ax2.legend()
      ax2.set_title('IMAGINARY PART');
```

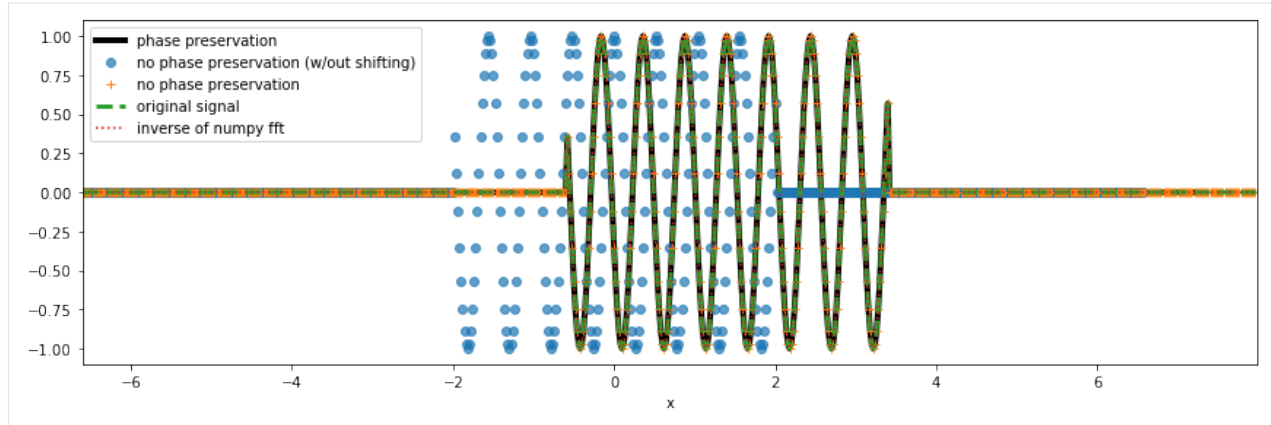


The expected additional phase (i.e. the complex term;  $e^{-i2\pi kx_0}$ ) that appears in theory is retrieved with `xrft.dft` but not with `xrft.fft` nor `npft.fft`. This is because in `npft.fft`, the input data is expected to be centered around zero. **In the current version of ``xrft``, the behavior of ``xrft.dft`` defaults to ``xrft.fft`` so set the flags ``true\_phase=True`` and ``true\_amplitude=True`` in order to have the results matching with theory.**

Now, let's take the inverse transform.

```
[31]: inda_dft = xrft.idft(nda_dft, true_phase=True, true_amplitude=True) # Signal in direct_
      ↪ space
      inda_fft = xrft.ifft(nda_fft)
```

```
[39]: fig, ax = plt.subplots(figsize=(12,4))
      fig.set_tight_layout(True)
      inda_dft.real.plot(ax=ax, linestyle='-', c='k', lw=4, label='phase preservation')
      ax.plot(x[:len(inda_fft.real)], inda_fft.real, linestyle='', marker='o', alpha=.7,
              label='no phase preservation (w/out shifting)')
      ax.plot(x[nshift:], inda_fft.real, linestyle='', marker='+', label='no phase preservation
      ↪ ')
      nda.plot(ax=ax, ls='--', lw=3, label='original signal')
      ax.plot(x[nshift:], npft.ifft(nda_npft).real, ls=':', label='inverse of numpy fft')
      ax.set_xlim([nda.x.min(),nda.x.max()])
      ax.legend(loc='upper left');
```



Note that we are only able to match the inverse transforms of `xrft.ifft` and `npft.ifft` to the data `nda` to it being Fourier transformed because we “know” the original data `da` was shifted by `nshift` datapoints as we see in `x[nshift:]` (compare the blue dots and orange crosses where without the knowledge of the shift, we may assume that the data were centered around zero). Using `xrft.ifft` along with `xrft.dft` with the flags `true_phase=True` and `true_amplitude=True` automatically takes care of the information of shifted coordinates.

## 1.5.2 A case with real data

Load atmospheric temperature from the NMC reanalysis.

```
[4]: da = xr.tutorial.open_dataset("air_temperature").air
da
```

```
[4]: <xarray.DataArray 'air' (time: 2920, lat: 25, lon: 53)>
[3869000 values with dtype=float32]
Coordinates:
  * lat      (lat) float32 75.0 72.5 70.0 67.5 65.0 ... 25.0 22.5 20.0 17.5 15.0
  * lon      (lon) float32 200.0 202.5 205.0 207.5 ... 322.5 325.0 327.5 330.0
  * time      (time) datetime64[ns] 2013-01-01 ... 2014-12-31T18:00:00
Attributes:
  long_name:      4xDaily Air temperature at sigma level 995
  units:          degK
  precision:      2
  GRIB_id:        11
  GRIB_name:      TMP
  var_desc:       Air temperature
  dataset:        NMC Reanalysis
  level_desc:     Surface
  statistic:      Individual Obs
  parent_stat:    Other
  actual_range:   [185.16 322.1 ]
```

```
[6]: Fda = xrft.dft(da.isel(time=0), dim="lat", true_phase=True, true_amplitude=True)
Fda
```

```
[6]: <xarray.DataArray (freq_lat: 25, lon: 53)>
array([[ 55.72721061-46.86182115j,  54.88410513-45.81648436j,
         54.44861105-45.4792758j, ...,  63.78368643-52.78354988j,
         60.99712143-50.28091047j,  57.94756055-48.51852927j],
```

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```

[-38.90906614-66.9663849j , -38.90038095-67.92497252j,
 -38.544492 -68.17925905j, ..., -41.94737401-74.09175983j,
 -40.00936528-70.47655747j, -39.05651073-68.04032158j],
[-77.82019891+12.50876021j, -79.02288653+10.06164636j,
 -80.34175059 +9.81548668j, ..., -86.83039434+26.4819109j ,
 -84.02694401+23.31755583j, -81.26451369+21.4268003j ],
...,
[-77.82019891-12.50876021j, -79.02288653-10.06164636j,
 -80.34175059 -9.81548668j, ..., -86.83039434-26.4819109j ,
 -84.02694401-23.31755583j, -81.26451369-21.4268003j ],
[-38.90906614+66.9663849j , -38.90038095+67.92497252j,
 -38.544492 +68.17925905j, ..., -41.94737401+74.09175983j,
 -40.00936528+70.47655747j, -39.05651073+68.04032158j],
[ 55.72721061+46.86182115j,  54.88410513+45.81648436j,
  54.44861105+45.4792758j , ...,  63.78368643+52.78354988j,
  60.99712143+50.28091047j,  57.94756055+48.51852927j]])

```

Coordinates:

```

* lon      (lon) float32 200.0 202.5 205.0 207.5 ... 322.5 325.0 327.5 330.0
  time     datetime64[ns] 2013-01-01
* freq_lat (freq_lat) float64 -0.192 -0.176 -0.16 -0.144 ... 0.16 0.176 0.192

```

The coordinate metadata is lost during the DFT (or any Fourier transform) operation so we need to specify the lag to retrieve the latitudes back in the inverse transform. The original latitudes are centered around  $45^\circ$  so we set the lag to lag=45.

```
[8]: Fda_1 = xrft.idft(Fda, dim="freq_lat", true_phase=True, true_amplitude=True, lag=45)
      Fda_1
```

```
[8]: <xarray.DataArray (lat: 25, lon: 53)>
array([[296.29000854-7.01488818e-16j, 296.79000854-2.41028295e-15j,
       297.1000061 -1.08051561e-15j, ..., 296.8999939 +2.07870428e-15j,
       296.79000854+1.39068454e-15j, 296.6000061 +1.98243140e-15j],
       [295.8999939 -1.36617001e-16j, 296.19998169-3.08854147e-15j,
       296.79000854-2.27797690e-16j, ..., 295.8999939 -2.06120304e-15j,
       295.8999939 -7.63307736e-16j, 295.19998169+2.90958929e-15j],
       [296.6000061 +2.18513309e-15j, 296.19998169-5.34587573e-16j,
       296.3999939 -1.70159409e-15j, ..., 295.3999939 -9.67078004e-16j,
       295.1000061 -2.97325892e-15j, 294.69998169+2.84108954e-15j],
       ...,
       [250.      +1.32015223e-15j, 249.79998779+5.34587573e-16j,
       248.88999939-1.80369123e-15j, ..., 233.19999695+9.67078004e-16j,
       236.38999939+3.00722368e-17j, 241.69999695+3.04528382e-15j],
       [243.79998779-1.32169378e-16j, 244.5      -4.76080394e-15j,
       244.69999695-1.17678849e-15j, ..., 232.79998779+1.86297913e-15j,
       235.29998779-3.02882224e-16j, 239.29998779-9.67078004e-16j],
       [241.19999695+5.26510200e-16j, 242.5      -1.34198513e-15j,
       243.5      -3.83146461e-16j, ..., 232.79998779+2.46618241e-15j,
       235.5      +3.62856196e-16j, 238.59999084+4.17030299e-16j]])

```

Coordinates:

```

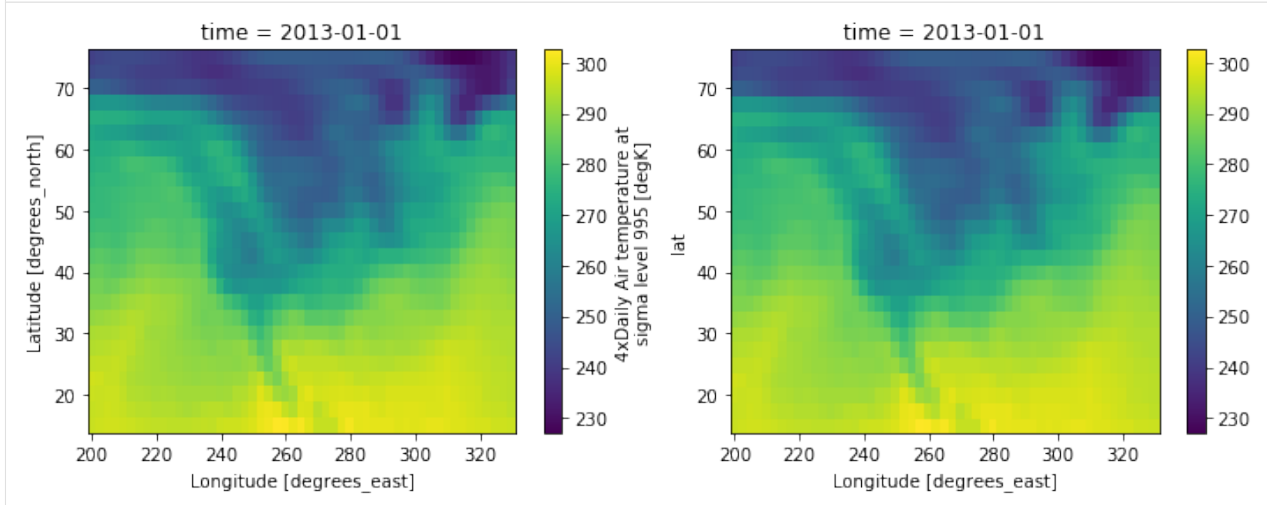
* lon      (lon) float32 200.0 202.5 205.0 207.5 ... 322.5 325.0 327.5 330.0
  time     datetime64[ns] 2013-01-01
* lat      (lat) float64 15.0 17.5 20.0 22.5 25.0 ... 65.0 67.5 70.0 72.5 75.0

```



```
[20]: fig, (ax1,ax2) = plt.subplots(figsize=(12,4), nrows=1, ncols=2)
da.isel(time=0).plot(ax=ax1)
Fda_1.real.plot(ax=ax2)
```

```
[20]: <matplotlib.collections.QuadMesh at 0x1226607f0>
```



We see the inverse DFT of the Fourier transformed original temperature data returns the original data.

```
[ ]:
```

## 1.6 Example of Parseval's theorem

```
[1]: import numpy as np
import numpy.testing as npt
import xarray as xr
import xrft
import numpy.fft as npft
import dask.array as dsar
import matplotlib.pyplot as plt
%matplotlib inline
```

First, we show that ``xrft.dft`` satisfies the Parseval's theorem exactly for a non-windowed signal

For one-dimensional data:

$$\sum_x (da)^2 \Delta x = \sum_k \mathcal{F}(da) [\mathcal{F}(da)]^* \Delta k.$$

Generate synthetic data

```
[10]: Nx = 40
dx = np.random.rand()
da = xr.DataArray(
    np.random.rand(Nx) + 1j * np.random.rand(Nx),
    dims="x",
    coords={"x": dx * (np.arange(-Nx // 2, -Nx // 2 + Nx)
        + np.random.randint(-Nx // 2, Nx // 2))
```

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```

    )
    },
)

```

```

[2]: #####
# Assert Parseval's using xrft.dft
#####
FT = xrft.dft(da, dim="x", true_phase=True, true_amplitude=True)
npt.assert_almost_equal(
    (np.abs(da) ** 2).sum() * dx, (np.abs(FT) ** 2).sum() * FT["freq_x"].spacing
)

#####
# Assert Parseval's using xrft.power_spectrum with scaling='density'
#####
ps = xrft.power_spectrum(da, dim="x")
npt.assert_almost_equal(
    ps.sum(),
    (np.abs(da) ** 2).sum() * dx
)

```

For two-dimensional data:

$$\sum_x \sum_y (da)^2 \Delta x \Delta y = \sum_k \sum_l \mathcal{F}(da) \mathcal{F}(da)^* \Delta k \Delta l.$$

### Generate synthetic data

```

[11]: Ny = 60
dx, dy = (np.random.rand(), np.random.rand())
da2 = xr.DataArray(
    np.random.rand(Nx, Ny) + 1j * np.random.rand(Nx, Ny),
    dims=["x", "y"],
    coords={"x": dx
            * (
                np.arange(-Nx // 2, -Nx // 2 + Nx)
                + np.random.randint(-Nx // 2, Nx // 2)
            ),
            "y": dy
            * (
                np.arange(-Ny // 2, -Ny // 2 + Ny)
                + np.random.randint(-Ny // 2, Ny // 2)
            ),
    },
)

```

```

[3]: #####
# Assert Parseval's using xrft.dft
#####
FT2 = xrft.dft(da2, dim=["x", "y"], true_phase=True, true_amplitude=True)
npt.assert_almost_equal(
    (np.abs(FT2) ** 2).sum() * FT2["freq_x"].spacing * FT2["freq_y"].spacing,

```

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```

        (np.abs(da2) ** 2).sum() * dx * dy,
        )

#####
# Assert Parseval's using xrft.power_spectrum with scaling='density'
#####
ps2 = xrft.power_spectrum(da2, dim=["x", "y"])
npt.assert_almost_equal(
    ps2.sum(),
    (np.abs(da2) ** 2).sum() * dx * dy
)

#####
# Assert Parseval's using xrft.power_spectrum with scaling='spectrum'
#####
ps2 = xrft.power_spectrum(da2, dim=["x", "y"], scaling='spectrum')
npt.assert_almost_equal(
    ps2.sum() / (ps2.freq_x.spacing * ps2.freq_y.spacing),
    (np.abs(da2) ** 2).sum() * dx * dy,
    )

```

Now, we show how Parseval's theorem is approximately satisfied for windowed data

$$\frac{1}{\langle w^2 \rangle} \sum_x (w da)^2 \Delta x = \sum_x (da)^2 \Delta x \approx \frac{1}{\langle w^2 \rangle} \sum_k \mathcal{F}(w) \circ \mathcal{F}(da) [\mathcal{F}(w) \circ \mathcal{F}(da)]^* \Delta k,$$

where  $w$  is the windowing function,  $\circ$  is the convolution operator and  $\langle \cdot \rangle$  is the area sum, namely,  $\sum_x$ .

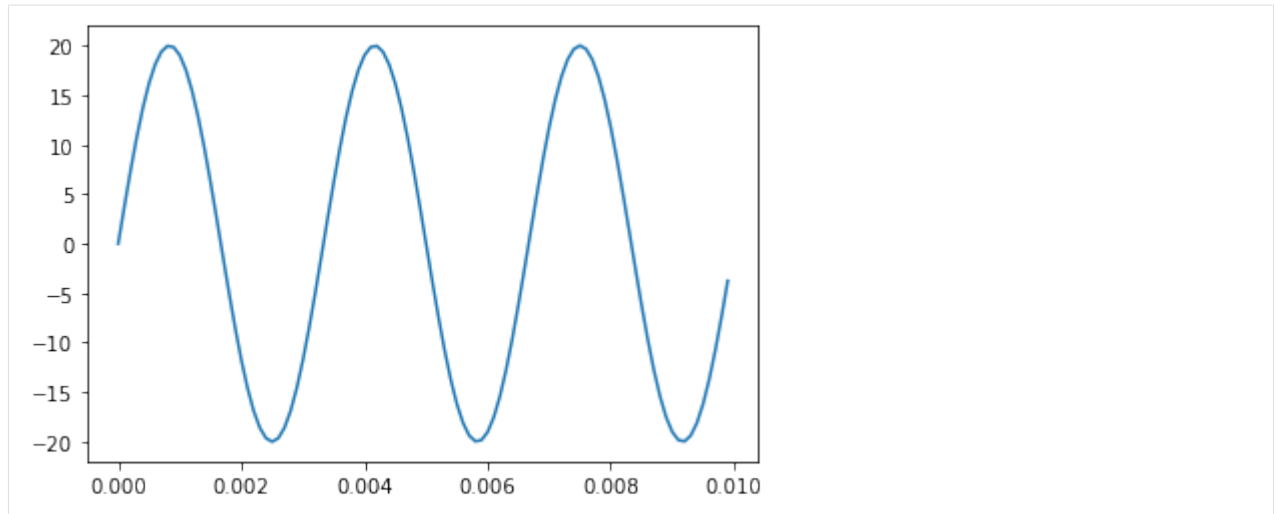
**Generate synthetic data:** A 300Hz sine wave with an RMS<sup>2</sup> of 200.

```

[3]: A = 20
     fs = 1e4
     n_segments = int(fs // 10)
     fsig = 300
     ii = int(fsig * n_segments // fs) # frequency index of fsig

     tt = np.arange(fs) / fs
     x = A * np.sin(2 * np.pi * fsig * tt)
     plt.plot(tt[:100], x[:100]);

```



### Assert Parseval's for different windowing functions

Depending on the scaling flag, a different correction is applied to the windowed spectrum:

- `scaling='density'`: **Energy correction** - this corrects for the energy (integral) of the spectrum. It is typically applied to the power spectral density (including cross power spectral density) and rescales the spectrum by  $1.0 / (\text{window}^{**2}).\text{mean}()$ . It ensures that the integral of the spectral density (approximately) matches the  $\text{RMS}^2$  of the signal (i.e. that Parseval's theorem is satisfied).
- `scaling='spectrum'`: **Amplitude correction** - this corrects the amplitude of peaks in the spectrum and rescales the spectrum by  $1.0 / \text{window}.\text{mean}()^{**2}$ . It is typically applied to the power spectrum (i.e. not density) and is most useful in strongly periodic signals. It ensures, for example, that the peak in the power spectrum of a 300 Hz sine wave with  $\text{RMS}^2 = 200$  has a magnitude of 200.

These scalings replicate the default behaviour of `scipy` spectral functions like `scipy.signal.periodogram` and `scipy.signal.welch` (cf. Section 11.5.2. of Bendat & Piersol, 2011; Section 10.3 of Brandt, 2011).

```
[4]: RMS = np.sqrt(np.mean((x**2)))

windows = np.array(["hann", "bartlett"], ["tukey", "flattop"]])
```

**Check the energy correction for `scaling='density'`:** With `window_correction=True`, the spectrum integrates to  $\text{RMS}^2$ .

```
[5]: fig, axes = plt.subplots(figsize=(13,10), nrows=2, ncols=2)
fig.set_tight_layout(True)

for window_type in windows.ravel():

    x_da = xr.DataArray(x, coords=[tt], dims=["x"]).chunk({"x": n_segments})

    ps = xrft.power_spectrum(
        x_da,
        dim="x",
        window=window_type,
        chunks_to_segments=True,
        window_correction=True,
    ).mean("x_segment")
```

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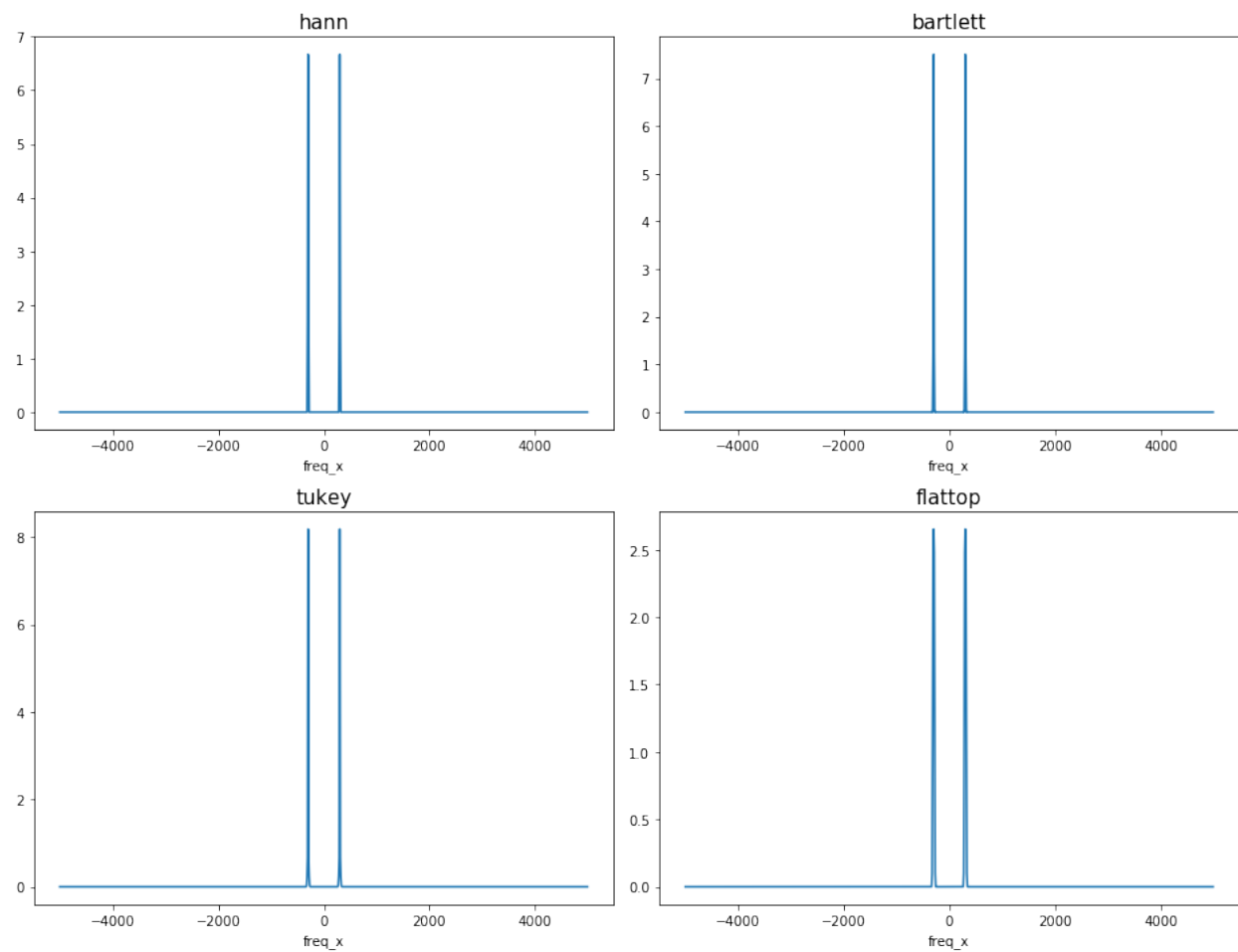
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```

ps.plot(ax=axes[np.where(windows==window_type)[0][0],np.where(windows==window_
↪type)[1][0]])
axes[np.where(windows==window_type)[0][0],np.where(windows==window_type)[1][0]].set_
↪title(window_type, fontsize=15)

npt.assert_allclose(
    np.trapz(ps.values, ps.freq_x.values),
    RMS**2,
    rtol=1e-3
)

```



The maximum amplitude differs amongst cases with different windows due to the difference in noise floor.

**Check the amplitude correction for ``scaling='spectrum'``:** With `window_correction=True`, the peak of the two-sided spectrum has a magnitude of  $\text{RMS}^2/2$ .

```

[6]: fig, axes = plt.subplots(figsize=(13,10), nrows=2, ncols=2)
fig.set_tight_layout(True)

```

```

for window_type in windows.ravel():

```

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```

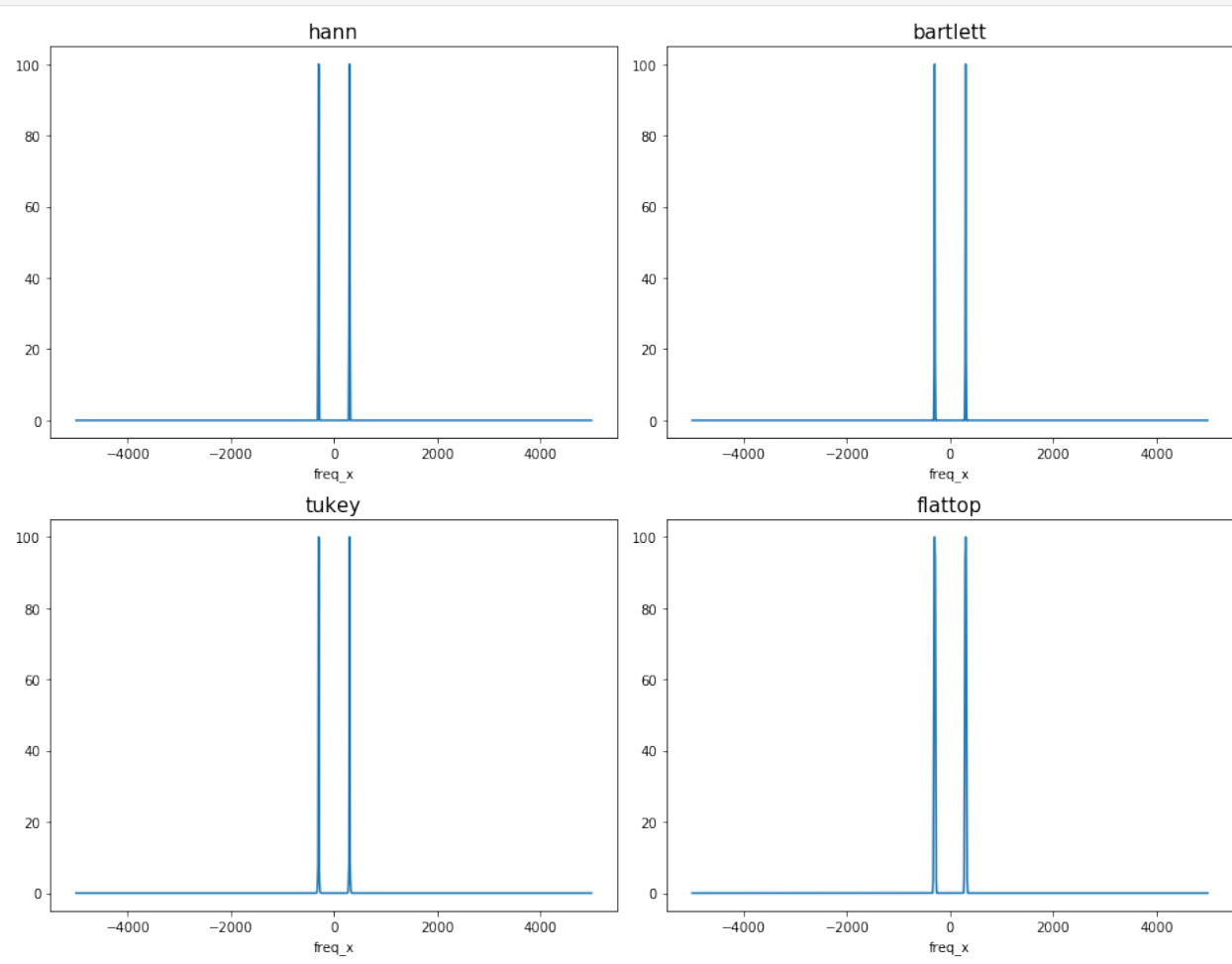
x_da = xr.DataArray(x, coords=[tt], dims=["x"]).chunk({"x": n_segments})

ps = xrft.power_spectrum(
    x_da,
    dim="x",
    window=window_type,
    chunks_to_segments=True,
    scaling="spectrum",
    window_correction=True,
).mean("x_segment")

ps.plot(ax=axes[np.where(windows==window_type)[0][0],np.where(windows==window_
↪ type)[1][0]])
axes[np.where(windows==window_type)[0][0],np.where(windows==window_type)[1][0]].set_
↪ title(window_type, fontsize=15)

# The factor of 0.5 is there because we're checking the two-sided spectrum
npt.assert_allclose(ps.sel(freq_x=fsig), 0.5 * RMS**2)

```



The maximum amplitudes are now all the same amongst different windows applied with the **amplitude correction**.

[ ]:

```
[1]: import numpy as np
import numpy.testing as npt
import xarray as xr
import xrft
import dask.array as dsar
from matplotlib import colors
import matplotlib.pyplot as plt
%matplotlib inline
```

## 1.7 Parallelized Bartlett's Method

For long data sets that have reached statistical equilibrium, it is useful to chunk the data, calculate the periodogram for each chunk and then take the average to reduce variance.

```
[2]: n = int(2**8)
da = xr.DataArray(np.random.rand(n,int(n/2),int(n/2)), dims=['time','y','x'])
da
```

```
[2]: <xarray.DataArray (time: 256, y: 128, x: 128)>
array([[ [ 0.493341, 0.28303 , ..., 0.434256, 0.616031],
        [ 0.777314, 0.629644, ..., 0.152931, 0.445424],
        ...,
        [ 0.562456, 0.022227, ..., 0.88538 , 0.054687],
        [ 0.381456, 0.908454, ..., 0.843443, 0.706326]],

       [ [ 0.469143, 0.241104, ..., 0.249369, 0.830898],
        [ 0.283305, 0.438634, ..., 0.893666, 0.242556],
        ...,
        [ 0.897823, 0.187038, ..., 0.977466, 0.270899],
        [ 0.252733, 0.425873, ..., 0.228847, 0.954393]],

       ...,

       [ [ 0.936424, 0.793693, ..., 0.406293, 0.272336],
        [ 0.917752, 0.83908 , ..., 0.954489, 0.151129],
        ...,
        [ 0.081756, 0.016332, ..., 0.524886, 0.87095 ],
        [ 0.677224, 0.41488 , ..., 0.12199 , 0.689685]],

       [ [ 0.193302, 0.113419, ..., 0.083486, 0.784332],
        [ 0.695728, 0.376776, ..., 0.278004, 0.026373],
        ...,
        [ 0.677775, 0.255296, ..., 0.112851, 0.46325 ],
        [ 0.598086, 0.529324, ..., 0.267431, 0.65419 ]]])
Dimensions without coordinates: time, y, x
```

## 1.7.1 One dimension

### Discrete Fourier Transform

```
[3]: daft = xrft.dft(da.chunk({'time':int(n/4)}), dim=['time'], shift=False , chunks_to_
↳segments=True).compute()
daft
```

```
[3]: <xarray.DataArray 'fftn-917988d0ce7d7da01b5f7a3cf2bb9a26' (time_segment: 4, freq_time: 64, y: 128, x: 128)>
↳64, y: 128, x: 128)
array([[[[ 30.737014+0.j      , ...,  31.659135+0.j      ],
         ...,
         [ 31.308938+0.j      , ...,  31.768846+0.j      ]],
        ...,
        [[ 1.928097-0.118076j, ...,   0.732440+2.07656j ],
         ...,
         [ 0.225814+1.256083j, ...,   0.244113-1.276807j]]],
        ...,
        [[[ 37.777908+0.j      , ...,  30.996848+0.j      ],
         ...,
         [ 28.650088+0.j      , ...,  35.362874+0.j      ]],
        ...,
        [[ -1.780642+0.477772j, ...,   2.575858+1.71943j ],
         ...,
         [ 3.149759-2.664934j, ...,   1.872009-2.977565j]]]])
Coordinates:
  * time_segment      (time_segment) int64 0 1 2 3
  * freq_time         (freq_time) float64 0.0 0.01562 0.03125 0.04688 ...
  * y                 (y) int64 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...
  * x                 (x) int64 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...
  freq_time_spacing  float64 0.01562
```

```
[4]: data = da.chunk({'time':int(n/4)}).data
data_rs = data.reshape((4,int(n/4),int(n/2),int(n/2)))
da_rs = xr.DataArray(data_rs, dims=['time_segment','time','y','x'])
da1 = xr.DataArray(dsar.fft.fftn(data_rs, axes=[1]).compute(),
                  dims=['time_segment','freq_time','y','x'])
da1
```

```
[4]: <xarray.DataArray (time_segment: 4, freq_time: 64, y: 128, x: 128)>
array([[[[ 30.737014+0.j      , ...,  31.659135+0.j      ],
         ...,
         [ 31.308938+0.j      , ...,  31.768846+0.j      ]],
        ...,
        [[ 1.928097-0.118076j, ...,   0.732440+2.07656j ],
         ...,
         [ 0.225814+1.256083j, ...,   0.244113-1.276807j]]],
```

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```

...
[[[ 37.777908+0.j      , ...,  30.996848+0.j      ],
...
 [ 28.650088+0.j      , ...,  35.362874+0.j      ]],
...
[[ -1.780642+0.477772j, ...,   2.575858+1.71943j ],
...
 [  3.149759-2.664934j, ...,   1.872009-2.977565j]]]])
Dimensions without coordinates: time_segment, freq_time, y, x

```

We assert that our calculations give equal results.

```
[5]: npt.assert_almost_equal(da1, daft.values)
```

## Power Spectrum

```
[6]: ps = xrft.power_spectrum(da.chunk({'time':int(n/4)}), dim=['time'], chunks_to_
↳segments=True)
ps
```

```
[6]: <xarray.DataArray 'concatenate-183433100cd82e429170a4fe2f9c4cbb' (time_segment: 4, freq_
↳time: 64, y: 128, x: 128)>
dask.array<truediv, shape=(4, 64, 128, 128), dtype=float64, chunksize=(1, 32, 128, 128)>
Coordinates:
  * time_segment      (time_segment) int64 0 1 2 3
  * freq_time         (freq_time) float64 -0.5 -0.4844 -0.4688 -0.4531 ...
  * y                 (y) int64 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...
  * x                 (x) int64 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...
  freq_time_spacing  float64 0.01562
```

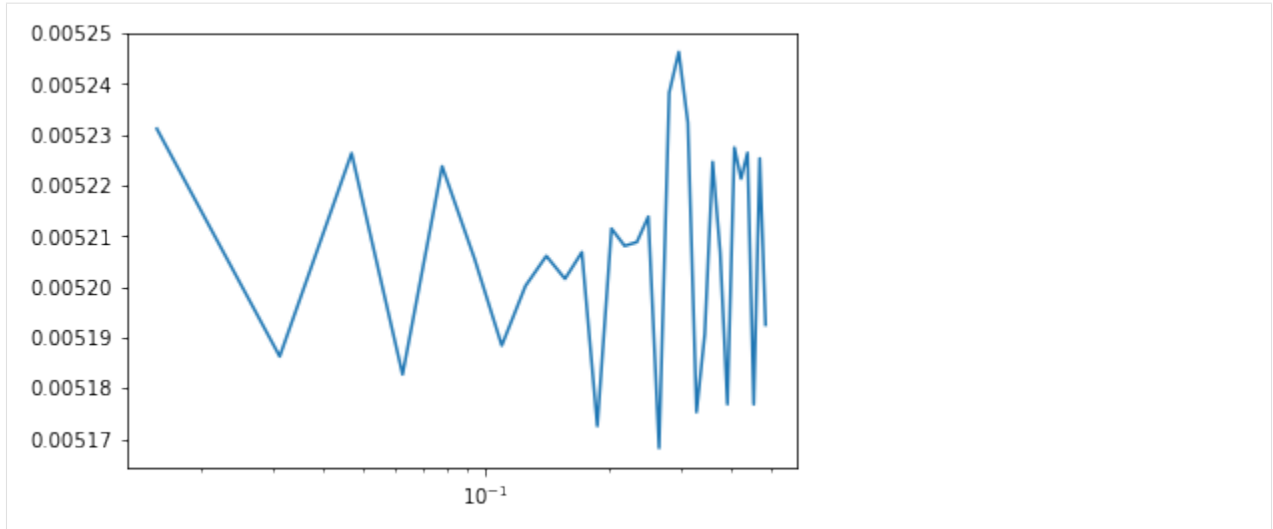
Taking the mean over the segments gives the Barlett's estimate.

```
[7]: ps = ps.mean(['time_segment', 'y', 'x'])
ps
```

```
[7]: <xarray.DataArray 'concatenate-183433100cd82e429170a4fe2f9c4cbb' (freq_time: 64)>
dask.array<mean_agg-aggregate, shape=(64,), dtype=float64, chunksize=(32,)>
Coordinates:
  * freq_time         (freq_time) float64 -0.5 -0.4844 -0.4688 -0.4531 ...
  freq_time_spacing  float64 0.01562
```

```
[8]: fig, ax = plt.subplots()
ax.semilogx(ps.freq_time[int(n/8)+1:], ps[int(n/8)+1:])
```

```
[8]: [<matplotlib.lines.Line2D at 0x10ebc9518>]
```



## 1.7.2 Two dimension

### Discrete Fourier Transform

```
[9]: daft = xrft.dft(da.chunk({'y':32,'x':32}), dim=['y','x'], shift=False , chunks_to_
↳segments=True).compute()
daft
```

```
[9]: <xarray.DataArray 'fftn-8077935acd6b48b40d6593c688c326b2' (time: 256, y_segment: 4, freq_
↳y: 32, x_segment: 4, freq_x: 32)>
array([[[[ 505.090962 +0.j          , ...,      3.673241 +2.033024j],
        ...,
        [ 506.979486 +0.j          , ...,      2.672219 +8.645102j]],
        ...,
        [[ -1.746757 -1.347122j, ...,     -2.183099+17.472835j],
        ...,
        [   3.450049 +3.832201j, ...,     -4.072164 -7.279733j]]],
        ...,
        [[[ 504.971751 +0.j          , ...,     -6.610465-12.385931j],
        ...,
        [ 512.756185 +0.j          , ...,     -4.344255 -8.458134j]],
        ...,
        [[ -7.979198 -7.454325j, ...,     -2.962019 +6.43059j ],
        ...,
        [   4.024805 +3.72519j , ...,     -8.242673 -8.259182j]]],
        ...,
        [[[[ 518.573138 +0.j          , ...,      0.573928-10.006888j],
```

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```

    ...,
    [ 520.423164 +0.j      , ...,  -1.110088 +0.141936j]],
    ...,
    [[ 2.043005 -3.116515j, ...,  8.697924 -5.116488j],
    ...,
    [ 3.702009 -7.202762j, ...,  -12.007770 +3.514272j]]],
    ...,
    [[[ 523.615806 +0.j      , ...,  -9.301065 +4.935474j],
    ...,
    [ 521.535950 +0.j      , ...,  6.826755 +1.688166j]],
    ...,
    [[ 2.157400-14.676636j, ...,  -1.865237-11.408717j],
    ...,
    [ 0.651302 +0.531716j, ...,  5.861882 +5.968681j]]]]])
Coordinates:
* time          (time) int64 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 ...
* y_segment     (y_segment) int64 0 1 2 3
* freq_y        (freq_y) float64 0.0 0.03125 0.0625 0.09375 0.125 0.1562 ...
* x_segment     (x_segment) int64 0 1 2 3
* freq_x        (freq_x) float64 0.0 0.03125 0.0625 0.09375 0.125 0.1562 ...
freq_y_spacing float64 0.03125
freq_x_spacing float64 0.03125

```

```

[10]: data = da.chunk({'y':32,'x':32}).data
data_rs = data.reshape((256,4,32,4,32))
da_rs = xr.DataArray(data_rs, dims=['time','y_segment','y','x_segment','x'])
da2 = xr.DataArray(dsar.fft.fftn(data_rs, axes=[2,4]).compute(),
                  dims=['time','y_segment','freq_y','x_segment','freq_x'])
da2

```

```

[10]: <xarray.DataArray (time: 256, y_segment: 4, freq_y: 32, x_segment: 4, freq_x: 32)>
array([[[[[[ 505.090962 +0.j      , ...,  3.673241 +2.033024j],
    ...,
    [ 506.979486 +0.j      , ...,  2.672219 +8.645102j]],
    ...,
    [[ -1.746757 -1.347122j, ...,  -2.183099+17.472835j],
    ...,
    [ 3.450049 +3.832201j, ...,  -4.072164 -7.279733j]]]],
    ...,
    [[[ 504.971751 +0.j      , ...,  -6.610465-12.385931j],
    ...,
    [ 512.756185 +0.j      , ...,  -4.344255 -8.458134j]],
    ...,
    [[ -7.979198 -7.454325j, ...,  -2.962019 +6.43059j ],

```

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```

    ...,
    [ 4.024805 +3.72519j , ..., -8.242673 -8.259182j]]]],
    ...,
    [[[[ 518.573138 +0.j      , ...,  0.573928-10.006888j],
        ...,
        [ 520.423164 +0.j      , ..., -1.110088 +0.141936j]],
    ...,
    [[ 2.043005 -3.116515j, ...,  8.697924 -5.116488j],
    ...,
    [ 3.702009 -7.202762j, ..., -12.007770 +3.514272j]]],
    ...,
    [[[[ 523.615806 +0.j      , ..., -9.301065 +4.935474j],
        ...,
        [ 521.535950 +0.j      , ...,  6.826755 +1.688166j]],
    ...,
    [[ 2.157400-14.676636j, ..., -1.865237-11.408717j],
    ...,
    [ 0.651302 +0.531716j, ...,  5.861882 +5.968681j]]]])
Dimensions without coordinates: time, y_segment, freq_y, x_segment, freq_x

```

We assert that our calculations give equal results.

```
[11]: npt.assert_almost_equal(da2, daft.values)
```

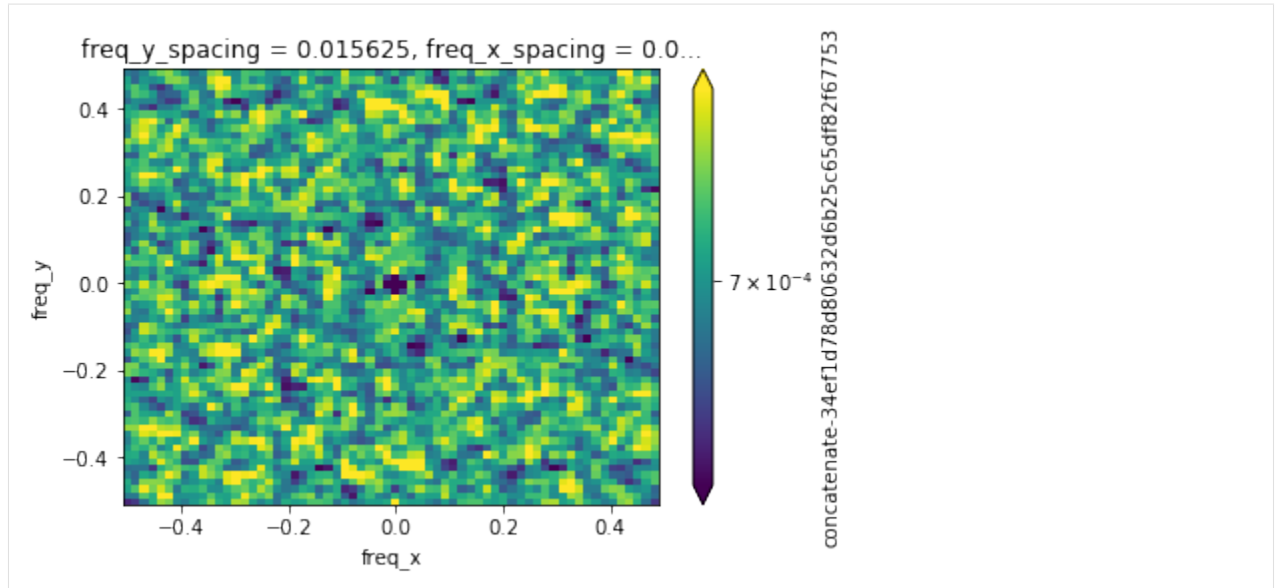
## Power Spectrum

```
[14]: ps = xrft.power_spectrum(da.chunk({'time':1,'y':64,'x':64}), dim=['y','x'],
                               chunks_to_segments=True, window=True, detrend='linear')
ps = ps.mean(['time','y_segment','x_segment'])
ps
```

```
[14]: <xarray.DataArray 'concatenate-34ef1d78d80632d6b25c65df82f67753' (freq_y: 64, freq_x:
→64)>
dask.array<mean_agg-aggregate, shape=(64, 64), dtype=float64, chunksize=(32, 32)>
Coordinates:
  * freq_y      (freq_y) float64 -0.5 -0.4844 -0.4688 -0.4531 -0.4375 ...
  * freq_x      (freq_x) float64 -0.5 -0.4844 -0.4688 -0.4531 -0.4375 ...
  freq_y_spacing float64 0.01562
  freq_x_spacing float64 0.01562
```

```
[19]: fig, ax = plt.subplots()
ps.plot(ax=ax, norm=colors.LogNorm(), vmin=6.5e-4, vmax=7.5e-4)
```

```
[19]: <matplotlib.collections.QuadMesh at 0x1210117b8>
```



```
[ ]:
```

## 1.8 Realistic example using outputs from MITgcm

This example requires the understanding of `xgcm.grid` and `xmitgcm.open_mdssdataset`.

```
[1]: import numpy as np
import xarray as xr
import os.path as op
import xrft
from dask.diagnostics import ProgressBar
from xmitgcm import open_mdssdataset
from xgcm.grid import Grid
from matplotlib import colors, ticker
import matplotlib.pyplot as plt
%matplotlib inline
```

```
[2]: ddir = '/swot/SUM05/takaya/MITgcm/channel/runs/'
```

One year of daily-averaged output from MITgcm.

```
[3]: ys20, dy20 = (60,1)
dt = 8e2
df = 108
ts = int(360*86400*ys20/dt+df)
te = int(360*86400*(ys20+dy20)/dt+df)
ds = open_mdssdataset(op.join(ddir, 'zerores_20km_MOMbgc'), grid_dir=op.join(ddir, '20km_
↳grid'),
                    iters=range(ts,te,df), prefix=['MOMtave'], delta_t=dt
                    ).sel(YC=slice(5e5,15e5), YG=slice(5e5,15e5))
ds
```

```

/home/takaya/xmitgcm/xmitgcm/utils.py:314: UserWarning: Not sure what to do with rlev = L
  warnings.warn("Not sure what to do with rlev = " + rlev)
/home/takaya/xmitgcm/xmitgcm/mds_store.py:235: FutureWarning: iteration over an xarray.
↳ Dataset will change in xarray v0.11 to only include data variables, not coordinates.↳
↳ Iterate over the Dataset.variables property instead to preserve existing behavior in a
↳ forwards compatible manner.
  for vname in ds:

```

```

[3]: <xarray.Dataset>
Dimensions: (XC: 50, XG: 50, YC: 50, YG: 51, Z: 40, Zl: 40, Zp1: 41, Zu: 40, time: 360)
Coordinates:
  * XC      (XC) >f4 10000.0 30000.0 50000.0 70000.0 90000.0 110000.0 ...
  * YC      (YC) >f4 510000.0 530000.0 550000.0 570000.0 590000.0 610000.0 ...
  * XG      (XG) >f4 0.0 20000.0 40000.0 60000.0 80000.0 100000.0 120000.0 ...
  * YG      (YG) >f4 500000.0 520000.0 540000.0 560000.0 580000.0 600000.0 ...
  * Z       (Z) >f4 -5.0 -15.0 -25.0 -36.0 -49.0 -64.0 -81.5 -102.0 -126.0 ...
  * Zp1     (Zp1) >f4 0.0 -10.0 -20.0 -30.0 -42.0 -56.0 -72.0 -91.0 -113.0 ...
  * Zu      (Zu) >f4 -10.0 -20.0 -30.0 -42.0 -56.0 -72.0 -91.0 -113.0 ...
  * Zl      (Zl) >f4 0.0 -10.0 -20.0 -30.0 -42.0 -56.0 -72.0 -91.0 -113.0 ...
  rA       (YC, XC) >f4 dask.array<shape=(50, 50), chunksize=(50, 50)>
  dxG      (YG, XC) >f4 dask.array<shape=(51, 50), chunksize=(51, 50)>
  dyG      (YC, XG) >f4 dask.array<shape=(50, 50), chunksize=(50, 50)>
  Depth    (YC, XC) >f4 dask.array<shape=(50, 50), chunksize=(50, 50)>
  rAz      (YG, XG) >f4 dask.array<shape=(51, 50), chunksize=(51, 50)>
  dxC      (YC, XG) >f4 dask.array<shape=(50, 50), chunksize=(50, 50)>
  dyC      (YG, XC) >f4 dask.array<shape=(51, 50), chunksize=(51, 50)>
  rAw      (YC, XG) >f4 dask.array<shape=(50, 50), chunksize=(50, 50)>
  rAs      (YG, XC) >f4 dask.array<shape=(51, 50), chunksize=(51, 50)>
  drC      (Zp1) >f4 dask.array<shape=(41,), chunksize=(41,)>
  drF      (Z) >f4 dask.array<shape=(40,), chunksize=(40,)>
  PHrefC   (Z) >f4 dask.array<shape=(40,), chunksize=(40,)>
  PHrefF   (Zp1) >f4 dask.array<shape=(41,), chunksize=(41,)>
  hFacC    (Z, YC, XC) >f4 dask.array<shape=(40, 50, 50), chunksize=(40, 50, 50)>
  hFacW    (Z, YC, XG) >f4 dask.array<shape=(40, 50, 50), chunksize=(40, 50, 50)>
  hFacS    (Z, YG, XC) >f4 dask.array<shape=(40, 51, 50), chunksize=(40, 51, 50)>
  iter     (time) int64 dask.array<shape=(360,), chunksize=(1,)>
  * time    (time) float64 1.866e+09 1.866e+09 1.866e+09 1.867e+09 ...
Data variables:
  UVEL     (time, Z, YC, XG) float32 dask.array<shape=(360, 40, 50, 50), chunksize=(1,
↳ 40, 50, 50)>
  VVEL     (time, Z, YG, XC) float32 dask.array<shape=(360, 40, 51, 50), chunksize=(1,
↳ 40, 51, 50)>
  WVVEL    (time, Zl, YC, XC) float32 dask.array<shape=(360, 40, 50, 50), chunksize=(1,
↳ 40, 50, 50)>
  PHIHYD   (time, Z, YC, XC) float32 dask.array<shape=(360, 40, 50, 50), chunksize=(1,
↳ 40, 50, 50)>
  THETA    (time, Z, YC, XC) float32 dask.array<shape=(360, 40, 50, 50), chunksize=(1,
↳ 40, 50, 50)>

```

```
[4]: grid = Grid(ds, periodic=['X'])
```

```
[5]: u = ds.UVEL      #zonal velocity
     v = ds.VVEL     #meridional velocity
```

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```
w = ds.WVEL      #vertical velocity
phi = ds.PHIHYD #hydrostatic pressure
```

## 1.8.1 Discrete Fourier Transform

We chunk the data along the time and Z axes to allow parallelized computation and detrend and window the data before taking the DFT along the horizontal axes.

```
[6]: b = grid.diff(phi, 'Z', boundary='fill')/grid.diff(phi.Z, 'Z', boundary='fill')
with ProgressBar():
    what = xrft.dft(w.chunk({'time':1, 'Zl':1}),
                    dim=['XC', 'YC'], detrend='linear', window=True).compute()
    bhat = xrft.dft(b.chunk({'time':1, 'Zl':1}),
                    dim=['XC', 'YC'], detrend='linear', window=True).compute()
bhat
```

```
/home/takaya/xrft/xrft/xrft.py:272: FutureWarning: xarray.DataArray.__contains__
→currently checks membership in DataArray.coords, but in xarray v0.11 will change to
→check membership in array values.
elif d in da:
```

```
[#####] | 100% Completed | 3min 18.9s
[#####] | 100% Completed | 3min 20.1s
```

```
[6]: <xarray.DataArray 'rechunk-merge-20d2920474ad47b75b05955c0456f69d' (time: 360, Zl: 40,
→freq_YC: 50, freq_XC: 50)>
array([[[[ 2.801601e-03+8.771196e-17j, ..., -1.076925e-03-1.451031e-03j],
        ...,
        [-6.912831e-04-1.127047e-03j, ..., -1.114039e-03+8.825552e-04j]],
        ...,
        [[ 3.786092e-07-9.317362e-21j, ..., -7.612376e-07-3.355050e-07j],
        ...,
        [ 1.314610e-06+7.461259e-07j, ..., -1.471702e-06-5.475275e-07j]]],
        ...,
        [[[-3.941056e-04-1.888680e-16j, ..., -6.151166e-04+1.212955e-03j],
        ...,
        [-3.724654e-04+6.164418e-04j, ..., 1.445227e-03-2.389259e-04j]],
        ...,
        [[ 3.398755e-07-5.251604e-20j, ..., -7.561893e-07-1.006210e-06j],
        ...,
        [ 3.863488e-07+5.592156e-07j, ..., 1.252672e-06+1.153922e-06j]]]])
Coordinates:
  * time          (time) float64 1.866e+09 1.866e+09 1.866e+09 1.867e+09 ...
  * Zl           (Zl) >f4 0.0 -10.0 -20.0 -30.0 -42.0 -56.0 -72.0 -91.0 ...
```

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```
* freq_YC      (freq_YC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
* freq_XC      (freq_XC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
freq_XC_spacing float64 1e-06
freq_YC_spacing float64 1e-06
```

## 1.8.2 Power spectrum

We compute the surface eddy kinetic energy spectrum.

```
[8]: with ProgressBar():
      uhat2 = xrft.power_spectrum(grid.interp(u, 'X')[:,0].chunk({'time':1}),
                                dim=['XC', 'YC'], detrend='linear', window=True).compute()
      vhat2 = xrft.power_spectrum(grid.interp(v, 'Y', boundary='fill')[:,0].chunk({'time':1}
      ↪),
                                dim=['XC', 'YC'], detrend='linear', window=True).compute()
      ekehat = .5*(uhat2 + vhat2)
      ekehat
```

```
/home/takaya/xrft/xrft/xrft.py:272: FutureWarning: xarray.DataArray.__contains__
↪currently checks membership in DataArray.coords, but in xarray v0.11 will change to
↪check membership in array values.
      elif d in da:
```

```
[#####] | 100% Completed | 6.7s
```

```
[#####] | 100% Completed | 6.4s
```

```
[8]: <xarray.DataArray (time: 360, freq_YC: 50, freq_XC: 50)>
array([[0.656013, 0.634131, ..., 0.373603, 0.634131],
       [0.420887, 0.593453, ..., 1.585473, 1.477422],
       ...,
       [1.743543, 0.468147, ..., 2.274391, 3.250841],
       [0.420887, 1.477422, ..., 1.285897, 0.593453]],

       [[0.005765, 0.126508, ..., 0.363493, 0.126508],
       [0.099985, 0.140124, ..., 0.49843 , 0.109594],
       ...,
       [1.436623, 0.598675, ..., 1.692357, 0.797681],
       [0.099985, 0.109594, ..., 0.497809, 0.140124]],

       ...,

       [[0.063022, 0.463507, ..., 0.839914, 0.463507],
       [0.161973, 0.310822, ..., 1.181991, 0.372522],
       ...,
       [0.122832, 0.415118, ..., 0.231018, 0.244315],
       [0.161973, 0.372522, ..., 0.500013, 0.310822]],

       [[0.140999, 0.475876, ..., 1.034042, 0.475876],
       [0.032224, 0.080152, ..., 1.088543, 0.660645],
       ...,
       [0.545666, 0.291697, ..., 4.745674, 1.533154],
       [0.032224, 0.660645, ..., 0.817556, 0.080152]]])
```

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Coordinates:

```
* time          (time) float64 1.866e+09 1.866e+09 1.866e+09 1.867e+09 ...
* freq_YC       (freq_YC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
* freq_XC       (freq_XC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
freq_XC_spacing float64 1e-06
freq_YC_spacing float64 1e-06
```

### 1.8.3 Isotropic wavenumber spectrum

We now isotropize the spectrum:

```
[11]: with ProgressBar():
      uiso2 = xrft.isotropic_powerspectrum(grid.interp(u,'X')[0,0],
      dim=['XC','YC'], detrend='linear', window=True).
      ↪compute()
      viso2 = xrft.isotropic_powerspectrum(grid.interp(v,'Y',boundary='fill')[0,0],
      dim=['XC','YC'], detrend='linear', window=True).
      ↪compute()
      ekeiso = .5*(uiso2 + viso2)
      ekeiso
```

```
[#####] | 100% Completed | 0.1s
```

```
/home/takaya/xrft/xrft/xrft.py:428: RuntimeWarning: invalid value encountered in true_
      ↪divide
```

```
kr = np.bincount(kidx, weights=K.ravel()) / area
/home/takaya/xrft/xrft/xrft.py:433: RuntimeWarning: invalid value encountered in true_
      ↪divide
      / area) * kr
```

```
[#####] | 100% Completed | 0.1s
```

```
[11]: <xarray.DataArray (freq_r: 13)>
      array([          nan, 6.735224e+01, 1.488857e+02, 4.130706e+01, 1.541406e+01,
      9.217845e+00, 5.425922e+00, 1.887154e+00, 5.665645e-01, 2.813448e-01,
      6.721589e-02, 2.577505e-02, 7.507335e-03])
      Coordinates:
      * freq_r      (freq_r) float64 nan 1.358e-06 3.36e-06 5.571e-06 7.73e-06 ...
```

We plot  $u$ ,  $v$ ,  $\hat{u}^2 +$

```
[22]: fig, axes = plt.subplots(nrows=1, ncols=4, figsize=(20,4))
      fig.set_tight_layout(True)
      u[0,0].plot(ax=axes[0])
      v[0,0].plot(ax=axes[1])
      im = axes[2].pcolormesh(ekehat.freq_XC*1e3, ekehat.freq_YC*1e3, ekehat[0],
      norm=colors.LogNorm())
      axes[3].plot(ekeiso.freq_r*1e3, ekeiso)
      cbar = fig.colorbar(im, ax=axes[2])
      cbar.set_label(r'[m$^2$ s$^{-2}$]')
      axes[3].set_xscale('log')
      axes[3].set_yscale('log')
      axes[2].set_xlabel(r'k [cpkm]')
```

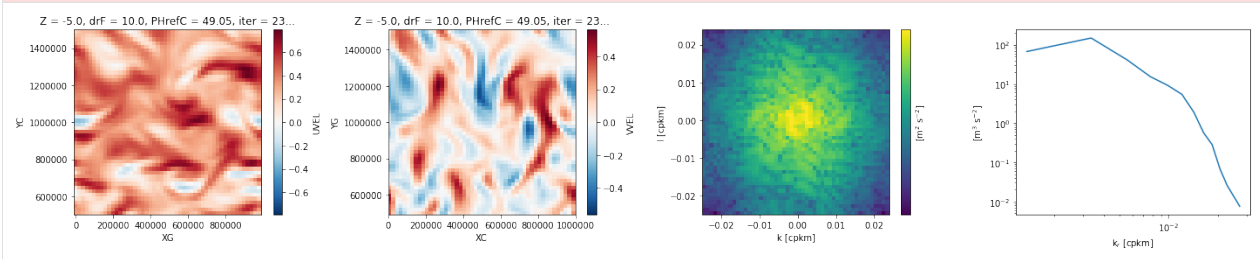
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```
axes[2].set_ylabel(r'l [cpkm]')
axes[3].set_xlabel(r'k$_r$ [cpkm]')
axes[3].set_ylabel(r'$s^{\{-2\}}$')
```

[22]: `Text(0,0.5, '[m$^3$ s$^{-2}$']')`

```
/home/takaya/miniconda3/envs/uptodate/lib/python3.6/site-packages/matplotlib/scale.py:
↳111: RuntimeWarning: invalid value encountered in less_equal
    out[a <= 0] = -1000
/home/takaya/miniconda3/envs/uptodate/lib/python3.6/site-packages/matplotlib/figure.py:
↳2022: UserWarning: This figure includes Axes that are not compatible with tight_layout,
↳ so results might be incorrect.
warnings.warn("This figure includes Axes that are not compatible "
```



### 1.8.4 Cross Spectrum

We calculate the cross correlation between vertical velocity ( $w$ ) and buoyancy ( $b$ ):

```
[31]: with ProgressBar():
    whatbhat = xrft.cross_spectrum(w.chunk({'time':1, 'Zl':1}), b.chunk({'time':1, 'Zl':1}
↳),
                                  dim=['XC', 'YC'], detrend='linear', window=True,
↳density=False).compute()
whatbhat
```

```
/home/takaya/xrft/xrft/xrft.py:272: FutureWarning: xarray.DataArray.__contains__
↳currently checks membership in DataArray.coords, but in xarray v0.11 will change to
↳check membership in array values.
    elif d in da:
```

[#####] | 100% Completed | 7min 48.4s

```
[31]: <xarray.DataArray (time: 360, Zl: 40, freq_YC: 50, freq_XC: 50)>
array([[[[ 6.217574e-11, ..., 5.227157e-11],
        ...,
        [-1.960930e-12, ..., 1.145311e-11]],
        ...,
        [[ 2.433719e-11, ..., 4.670022e-11],
        ...,
        [-9.319683e-11, ..., -7.301667e-11]]],
        ...,
        ...])
```

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```

[[[-8.180808e-12, ..., 1.913746e-11],
 ...,
 [ 4.396894e-12, ..., -1.844566e-12]],
 ...,
 [[-1.291420e-11, ..., 2.346000e-11],
 ...,
 [ 2.565280e-11, ..., 4.489265e-11]]])
Coordinates:
* time          (time) float64 1.866e+09 1.866e+09 1.866e+09 1.867e+09 ...
* Zl            (Zl) >f4 0.0 -10.0 -20.0 -30.0 -42.0 -56.0 -72.0 -91.0 ...
* freq_YC      (freq_YC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
* freq_XC      (freq_XC) float64 -2.5e-05 -2.4e-05 -2.3e-05 -2.2e-05 ...
freq_XC_spacing float64 1e-06
freq_YC_spacing float64 1e-06

```

```

[32]: fig, (ax1, ax2) = plt.subplots(nrows=1, ncols=2, figsize=(11,4))
fig.set_tight_layout(True)
(what*np.conjugate(bhat)).real[:, :8].mean(['time', 'Zl']).plot(ax=ax1)
whatbhat[:, :8].mean(['time', 'Zl']).plot(ax=ax2)

```

```

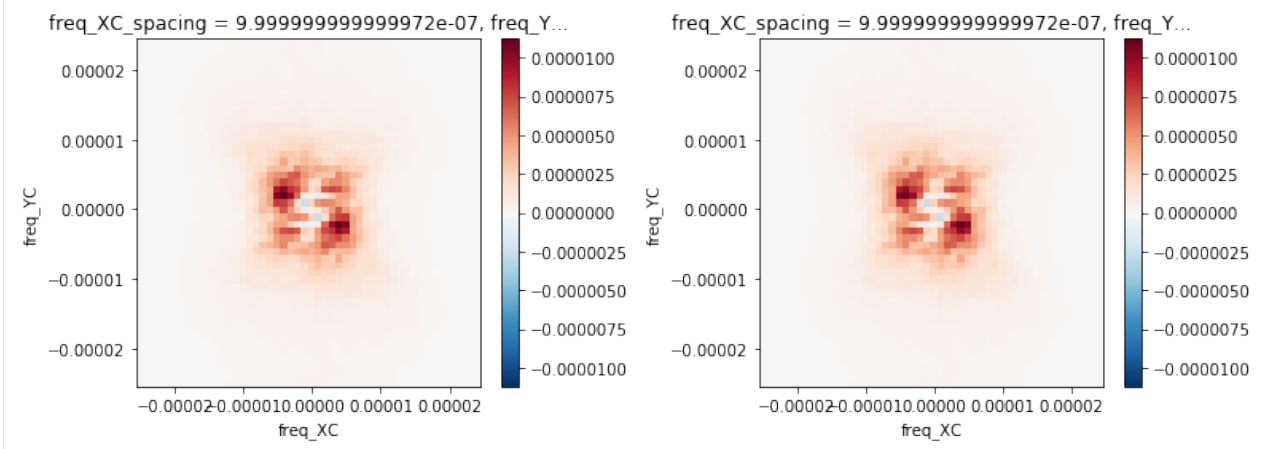
[32]: <matplotlib.collections.QuadMesh at 0x7f10409c7ba8>

```

```

/home/takaya/miniconda3/envs/uptodate/lib/python3.6/site-packages/matplotlib/figure.py:
↳ 2022: UserWarning: This figure includes Axes that are not compatible with tight_layout,
↳ so results might be incorrect.
warnings.warn("This figure includes Axes that are not compatible ")

```



We see that  $\hat{w}\hat{b}^*$  and `xrft.cross_spectrum(w, b)` are equivalent.

```

[ ]:

```

## 1.9 What's New

### 1.9.1 v0.3.0 (18 February 2021)

#### Enhancements

- Implemented the inverse discrete Fourier transform `idft`. By [Frederic Nougquier](#)
- Allowed windowing other than the Hann function. By [Takaya Uchida](#)
- Allowed parallelization of isotropizing the spectrum via `numpy_groupies`. By [Takaya Uchida](#)
- Implemented proper amplitude correction for real Fourier transform and windowed data. By [Dougie Squire](#)

### 1.9.2 v0.2.0 (10 April 2019)

#### Enhancements

- Allowed `dft` and `power_spectrum` functions to support real Fourier transforms. ([:issue:`57`](#)) By [Takaya Uchida](#) and [Tom Nicholas](#).
- Implemented `cross_phase` function to calculate the phase difference between two signals as a function of frequency. By [Tom Nicholas](#).
- Allowed `isotropic_powerspectrum` function to support arrays with up to four dimensions. ([:issue:`9`](#)) By [Takaya Uchida](#)

**Warning:** Python 2.7 is no longer supported in `xrft`. For the more details, see:

- [Python 3 Statement](#)
- [Tips on porting to Python 3](#)

## 1.10 API reference

This page provides an auto-generated summary of `xrft`'s API. For more details and examples, refer to the relevant chapters in the main part of the documentation.

---

**Note:** None of `xrft`'s functions will work correctly in the presence of NaNs or missing data. It's the user's responsibility to ensure data are free of NaN or that NaNs have been filled somehow.

---

### 1.10.1 xrft

`xrft.xrft.cross_phase(da1, da2, dim=None, true_phase=False, **kwargs)`

Calculates the cross-phase between da1 and da2.

Returned values are in  $[-\pi, \pi]$ .

$$da1' = da1 - \overline{da1}; \quad da2' = da2 - \overline{da2}$$

$$cp = \text{extArg}[\mathbb{F}(da1')^*, \mathbb{F}(da2')]$$

#### Parameters

**da1** [*xarray.DataArray*] The data to be transformed

**da2** [*xarray.DataArray*] The data to be transformed

**kwargs** [dict]

`xrft.xrft.cross_spectrum(da1, da2, dim=None, real_dim=None, scaling='density', window_correction=False, true_phase=False, **kwargs)`

Calculates the cross spectra of da1 and da2.

$$da1' = da1 - \overline{da1}; \quad da2' = da2 - \overline{da2}$$

$$cs = \mathbb{F}(da1')\mathbb{F}(da2')^*$$

#### Parameters

**da1** [*xarray.DataArray*] The data to be transformed

**da2** [*xarray.DataArray*] The data to be transformed

**dim** [str or sequence of str, optional] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed.

**real\_dim** [str, optional] Real Fourier transform will be taken along this dimension.

**scaling** [str, optional] If 'density', it will normalize the output to power spectral density. If 'spectrum', it will normalize the output to power spectrum.

**window\_correction** [boolean] If True, it will correct for the energy reduction resulting from applying a non-uniform window. This is the default behaviour of many tools for computing power spectrum (e.g. `scipy.signal.welch` and `scipy.signal.periodogram`). If `scaling = 'spectrum'`, correct the amplitude of peaks in the spectrum. This ensures, for example, that the peak in the one-sided power spectrum of a 10 Hz sine wave with  $\text{RMS}^2 = 10$  has a magnitude of 10. If `scaling = 'density'`, correct for the energy (integral) of the spectrum. This ensures, for example, that the power spectral density integrates to the square of the RMS of the signal (ie that Parseval's theorem is satisfied). Note that in most cases, Parseval's theorem will only be approximately satisfied with this correction as it assumes that the signal being windowed is independent of the window. The correction becomes more accurate as the width of the window gets large in comparison with any noticeable period in the signal. If False, the spectrum gives a representation of the power in the windowed signal. Note that when True, Parseval's theorem may only be approximately satisfied.

**kwargs** [dict]

`xrft.xrft.dft(da, dim=None, true_phase=False, true_amplitude=False, **kwargs)`

Deprecated function. See `fft doc`

`xrft.xrft.fft(da, spacing_tol=0.001, dim=None, real_dim=None, shift=True, detrend=None, window=None, true_phase=False, true_amplitude=False, chunks_to_segments=False, prefix='freq_', **kwargs)`  
Perform discrete Fourier transform of xarray data-array *da* along the specified dimensions.

$$da.ft = \mathbb{F}(da - \overline{da})$$

### Parameters

- da** [*xarray.DataArray*] The data to be transformed
- spacing\_tol: float, optional** Spacing tolerance. Fourier transform should not be applied to uneven grid but this restriction can be relaxed with this setting. Use caution.
- dim** [str or sequence of str, optional] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed. If the inputs are dask arrays, the arrays must not be chunked along these dimensions.
- real\_dim** [str, optional] Real Fourier transform will be taken along this dimension.
- shift** [bool, default] Whether to shift the fft output. Default is *True*, unless *real\_dim* is not *None*, in which case shift will be set to *False* always.
- detrend** [{*None*, 'constant', 'linear' }] If *constant*, the mean across the transform dimensions will be subtracted before calculating the Fourier transform (FT). If *linear*, the linear least-square fit will be subtracted before the FT. For *linear*, only dims of length 1 and 2 are supported.
- window** [str, optional] Whether to apply a window to the data before the Fourier transform is taken. A window will be applied to all the dimensions in *dim*. Please follow *scipy.signal.windows*' naming convention.
- true\_phase** [bool, optional] If set to *False*, standard fft algorithm is applied on signal without consideration of coordinates. If set to *True*, coordinates location are correctly taken into account to evaluate Fourier Transform phase and *fftshift* is applied on input signal prior to *fft* (*fft* algorithm intrinsically considers that input signal is on *fftshifted* grid).
- true\_amplitude** [bool, optional] If set to *True*, output is multiplied by the spacing of the transformed variables to match theoretical FT amplitude. If set to *False*, amplitude regularisation by spacing is not applied (as in *numpy.fft*)
- chunks\_to\_segments** [bool, optional] Whether the data is chunked along the axis to take FFT.
- prefix** [str] The prefix for the new transformed dimensions.

### Returns

- daft** [*xarray.DataArray*] The output of the Fourier transformation, with appropriate dimensions.

`xrft.xrft.fit_loglog(x, y)`  
Fit a line to isotropic spectra in log-log space

### Parameters

- x** [*numpy.array*] Coordinate of the data
- y** [*numpy.array*] data

### Returns

- y\_fit** [*numpy.array*] The linear fit
- a** [float64] Slope of the fit
- b** [float64] Intercept of the fit

`xrft.xrft.idft` (*daft*, *dim=None*, *true\_phase=False*, *true\_amplitude=False*, *\*\*kwargs*)  
 Deprecated function. See `ifft` doc

`xrft.xrft.ifft` (*daft*, *spacing\_tol=0.001*, *dim=None*, *real\_dim=None*, *shift=True*, *true\_phase=False*,  
*true\_amplitude=False*, *chunks\_to\_segments=False*, *prefix='freq\_'*, *lag=None*, *\*\*kwargs*)  
 Perform inverse discrete Fourier transform of `xarray` data-array *daft* along the specified dimensions.

$$da = \mathbb{F}(daft - \overline{daft})$$

### Parameters

- daft** [`xarray.DataArray`] The data to be transformed
- spacing\_tol: float, optional** Spacing tolerance. Fourier transform should not be applied to uneven grid but this restriction can be relaxed with this setting. Use caution.
- dim** [str or sequence of str, optional] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed.
- real\_dim** [str, optional] Real Fourier transform will be taken along this dimension.
- shift** [bool, default] Whether to shift the fft output. Default is *True*.
- chunks\_to\_segments** [bool, optional] Whether the data is chunked along the axis to take FFT.
- prefix** [str] The prefix for the new transformed dimensions.
- true\_phase** [bool, optional] If set to *False*, standard `ifft` algorithm is applied on signal without consideration of coordinates order. If set to *True*, coordinates are correctly taken into account to evaluate Inverse Fourier Transform phase and `fftshift` is applied on input signal prior to `ifft` (`ifft` algorithm intrinsically considers that input signal is on `fftshifted` grid).
- true\_amplitude** [bool, optional] If set to *True*, output is divided by the spacing of the transformed variables to match theoretical IFT amplitude. If set to *False*, amplitude regularisation by spacing is not applied (as in `numpy.ifft`)
- lag** [*None*, float or sequence of float and/or *None*, optional] Output coordinates of transformed dimensions will be shifted by corresponding lag values and correct signal phasing will be preserved if *true\_phase* is set to *True*. If lag is *None* (default), 'direct\_lag' attributes of each dimension is used (or set to zero if not found). If defined, lag must have same length as dim. If lag is a sequence, a *None* element means that 'direct\_lag' attribute will be used for the corresponding dimension Manually set lag to zero to get output coordinates centered on zero.

### Returns

- da** [`xarray.DataArray`] The output of the Inverse Fourier transformation, with appropriate dimensions.

`xrft.xrft.isotropic_cross_spectrum` (*da1*, *da2*, *spacing\_tol=0.001*, *dim=None*, *shift=True*, *detrend=None*,  
*scaling='density'*, *window=None*, *window\_correction=False*,  
*nfactor=4*, *truncate=False*, *\*\*kwargs*)

Calculates the isotropic spectrum from the two-dimensional power spectrum by taking the azimuthal average.

$$extiso_{cs} = k_r N^{-1} \sum_N (\mathbb{F}(da1') \mathbb{F}(da2')^*)$$

where *N* is the number of azimuthal bins.

Note: the method is not lazy does trigger computations.

### Parameters

- da1** [*xarray.DataArray*] The data to be transformed
- da2** [*xarray.DataArray*] The data to be transformed
- spacing\_tol: float (default)** Spacing tolerance. Fourier transform should not be applied to uneven grid but this restriction can be relaxed with this setting. Use caution.
- dim** [list (optional)] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed.
- shift** [bool (optional)] Whether to shift the fft output.
- detrend** [str (optional)] If *constant*, the mean across the transform dimensions will be subtracted before calculating the Fourier transform (FT). If *linear*, the linear least-square fit will be subtracted before the FT.
- density** [list (optional)] If true, it will normalize the spectrum to spectral density
- window** [str (optional)] Whether to apply a window to the data before the Fourier transform is taken. Please adhere to `scipy.signal.windows` for naming convention.
- nfactor** [int (optional)] Ratio of number of bins to take the azimuthal averaging with the data size. Default is 4.
- truncate** [bool, optional] If True, the spectrum will be truncated for wavenumbers larger than the Nyquist wavenumber.

### Returns

**iso\_cs** [*xarray.DataArray*] Isotropic cross spectrum

`xrft.xrft.isotropic_crossspectrum(*args, **kwargs)`

Deprecated function. See `isotropic_cross_spectrum` doc

`xrft.xrft.isotropic_power_spectrum(da, spacing_tol=0.001, dim=None, shift=True, detrend=None, scaling='density', window=None, window_correction=False, nfactor=4, truncate=False, **kwargs)`

Calculates the isotropic spectrum from the two-dimensional power spectrum by taking the azimuthal average.

$$extiso_{ps} = k_r N^{-1} \sum_N |\mathbb{F}(da')|^2$$

where  $N$  is the number of azimuthal bins.

Note: the method is not lazy does trigger computations.

### Parameters

- da** [*xarray.DataArray*] The data to be transformed
- spacing\_tol: float, optional** Spacing tolerance. Fourier transform should not be applied to uneven grid but this restriction can be relaxed with this setting. Use caution.
- dim** [list, optional] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed.
- shift** [bool, optional] Whether to shift the fft output.
- detrend** [str, optional] If *constant*, the mean across the transform dimensions will be subtracted before calculating the Fourier transform (FT). If *linear*, the linear least-square fit will be subtracted before the FT.
- density** [list, optional] If true, it will normalize the spectrum to spectral density
- window** [str, optional] Whether to apply a window to the data before the Fourier transform is taken. Please adhere to `scipy.signal.windows` for naming convention.



**nfactor** [int, optional] Ratio of number of bins to take the azimuthal averaging with the data size. Default is 4.

**truncate** [bool, optional] If True, the spectrum will be truncated for wavenumbers larger than the Nyquist wavenumber.

### Returns

**iso\_ps** [*xarray.DataArray*] Isotropic power spectrum

`xrft.xrft.isotropic_powerspectrum(*args, **kwargs)`  
 Deprecated function. See `isotropic_power_spectrum` doc

`xrft.xrft.isotropize(ps, fftdim, nfactor=4, truncate=False)`  
 Isotropize a 2D power spectrum or cross spectrum by taking an azimuthal average.

$$extiso_{ps} = k_r N^{-1} \sum_N |\mathbb{F}(da')|^2$$

where  $N$  is the number of azimuthal bins.

### Parameters

**ps** [*xarray.DataArray*] The power spectrum or cross spectrum to be isotropized.

**fftdim** [list] The fft dimensions overwhich the isotropization must be performed.

**nfactor** [int, optional] Ratio of number of bins to take the azimuthal averaging with the data size. Default is 4.

**truncate** [bool, optional] If True, the spectrum will be truncated for wavenumbers larger than the Nyquist wavenumber.

`xrft.xrft.power_spectrum(da, dim=None, real_dim=None, scaling='density', window_correction=False, **kwargs)`

Calculates the power spectrum of da.

$da' = da - \overline{da}$  ..  $ps = \mathbb{F}(da') \{\mathbb{F}(da')\}^*$

### Parameters

**da** [*xarray.DataArray*] The data to be transformed

**dim** [str or sequence of str, optional] The dimensions along which to take the transformation. If *None*, all dimensions will be transformed.

**real\_dim** [str, optional] Real Fourier transform will be taken along this dimension.

**scaling** [str, optional] If 'density', it will normalize the output to power spectral density. If 'spectrum', it will normalize the output to power spectrum.

**window\_correction** [boolean] If True, it will correct for the energy reduction resulting from applying a non-uniform window. This is the default behaviour of many tools for computing power spectrum (e.g `scipy.signal.welch` and `scipy.signal.periodogram`). If `scaling = 'spectrum'`, correct the amplitude of peaks in the spectrum. This ensures, for example, that the peak in the one-sided power spectrum of a 10 Hz sine wave with  $RMS^2 = 10$  has a magnitude of 10. If `scaling = 'density'`, correct for the energy (integral) of the spectrum. This ensures, for example, that the power spectral density integrates to the square of the RMS of the signal (ie that Parseval's theorem is satisfied). Note that in most cases, Parseval's theorem will only be approximately satisfied with this correction as it assumes that the signal being windowed is independent of the window. The correction becomes more accurate as the width of the window gets large in comparison with any noticeable period in the signal. If False, the spectrum gives a representation of the power in the windowed signal. Note that when True, Parseval's theorem may only be approximately satisfied.

**kwargs** [dict]

## 1.10.2 detrend

You also may wish to use xrft's detrend function on its own.

Functions for detrending xarray data.

`xrft.detrend.detrend(da, dim, detrend_type='constant')`  
Detrend a DataArray

### Parameters

**da** [xarray.DataArray] The data to detrend

**dim** [str or list] Dimensions along which to apply detrend. Can be either one dimension or a list with two dimensions. Higher-dimensional detrending is not supported. If dask data are passed, the data must be chunked along dim.

**detrend\_type** [{ 'constant', 'linear' }] If `constant`, a constant offset will be removed from each dim. If `linear`, a linear least-squares fit will be estimated and removed from the data.

### Returns

**da** [xarray.DataArray] The detrended data.

### Notes

This function will act lazily in the presence of dask arrays on the input.

## PYTHON MODULE INDEX

### X

`xrft.detrend`, 38

`xrft.xrft`, 33



## INDEX

### C

`cross_phase()` (in module `xrft.xrft`), 33  
`cross_spectrum()` (in module `xrft.xrft`), 33

### D

`detrend()` (in module `xrft.detrend`), 38  
`dft()` (in module `xrft.xrft`), 33

### F

`fft()` (in module `xrft.xrft`), 33  
`fit_loglog()` (in module `xrft.xrft`), 34

### I

`idft()` (in module `xrft.xrft`), 34  
`ifft()` (in module `xrft.xrft`), 35  
`isotropic_cross_spectrum()` (in module `xrft.xrft`),  
35  
`isotropic_crossspectrum()` (in module `xrft.xrft`), 36  
`isotropic_power_spectrum()` (in module `xrft.xrft`),  
36  
`isotropic_powerspectrum()` (in module `xrft.xrft`), 37  
`isotropize()` (in module `xrft.xrft`), 37

### M

module  
    `xrft.detrend`, 38  
    `xrft.xrft`, 33

### P

`power_spectrum()` (in module `xrft.xrft`), 37

### X

`xrft.detrend`  
    module, 38  
`xrft.xrft`  
    module, 33