
LFPykit

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Team LFPy

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LFPYKIT

This Python module contains freestanding implementations of electrostatic forward models incorporated in LFPy (<https://github.com/LFPy/LFPy>, <https://LFPy.readthedocs.io>).

The aim of the `LFPykit` module is to provide electrostatic models in a manner that facilitates forward-model predictions of extracellular potentials and related measures from multicompartment neuron models, but without explicit dependencies on neural simulation software such as NEURON (<https://neuron.yale.edu>, <https://github.com/neuronsimulator/nrn>), Arbor (<https://arbor.readthedocs.io>, <https://github.com/arbor-sim/arbor>), or even LFPy. The `LFPykit` module can then be more easily incorporated with these simulators, or in various projects that utilize them such as LFPy (<https://LFPy.rtd.io>, <https://github.com/LFPy/LFPy>). BMTK (<https://alleninstitute.github.io/bmtk/>, <https://github.com/AllenInstitute/bmtk>), etc.

Its main functionality is providing class methods that return two-dimensional linear transformation matrices \mathbf{M} between transmembrane currents \mathbf{I} of multicompartment neuron models and some measurement \mathbf{Y} given by $\mathbf{Y}=\mathbf{MI}$.

The presently incorporated volume conductor models have been incorporated in LFPy (<https://LFPy.rtd.io>, <https://github.com/LFPy/LFPy>), as described in various papers and books:

1. Linden H, Hagen E, Leski S, Norheim ES, Pettersen KH, Einevoll GT (2014) LFPy: a tool for biophysical simulation of extracellular potentials generated by detailed model neurons. *Front. Neuroinform.* 7:41. doi: 10.3389/fninf.2013.00041
2. Hagen E, Næss S, Ness TV and Einevoll GT (2018) Multimodal Modeling of Neural Network Activity: Computing LFP, ECoG, EEG, and MEG Signals With LFPy 2.0. *Front. Neuroinform.* 12:92. doi: 10.3389/fninf.2018.00092
3. Ness, T. V., Chintaluri, C., Potworowski, J., Leski, S., Glabska, H., Wójcik, D. K., et al. (2015). Modelling and analysis of electrical potentials recorded in microelectrode arrays (MEAs). *Neuroinformatics* 13:403–426. doi: 10.1007/s12021-015-9265-6
4. Nunez and Srinivasan, Oxford University Press, 2006
5. Næss S, Chintaluri C, Ness TV, Dale AM, Einevoll GT and Wójcik DK (2017). Corrected Four-sphere Head Model for EEG Signals. *Front. Hum. Neurosci.* 11:490. doi: 10.3389/fnhum.2017.00490

1.1 Build Status

1.2 Features

LFPykit presently incorporates different electrostatic forward models for extracellular potentials and magnetic signals that has been derived using volume conductor theory. In volume-conductor theory the extracellular potentials can be calculated from a distance-weighted sum of contributions from transmembrane currents of neurons. Given the same transmembrane currents, the contributions to the magnetic field recorded both inside and outside the brain can also be computed.

The module presently incorporates different classes. To represent the geometry of a multicompartment neuron model we have:

- `CellGeometry`: Base class representing a multicompartment neuron geometry in terms of segment x-, y-, z-coordinates and diameter.

Different classes built to map transmembrane currents of `CellGeometry` like instances to different measurement modalities:

- `LinearModel`: Base class representing a generic forward model for subclassing
- `CurrentDipoleMoment`: Class for predicting current dipole moments
- `PointSourcePotential`: Class for predicting extracellular potentials assuming point sources and point contacts
- `LineSourcePotential`: Class for predicting extracellular potentials assuming line sources and point contacts
- `RecExtElectrode`: Class for simulations of extracellular potentials
- `RecMEAElectrode`: Class for simulations of in vitro (slice) extracellular potentials
- `OneSphereVolumeConductor`: For computing extracellular potentials within and outside a homogeneous sphere
- `LaminarCurrentSourceDensity`: For computing the ‘ground truth’ current source density across cylindrical volumes aligned with the z-axis
- `VolumetricCurrentSourceDensity`: For computing the ‘ground truth’ current source density on regularly spaced 3D grid

Different classes built to map current dipole moments (i.e., computed using `CurrentDipoleMoment`) to extracellular measurements:

- `eegmegcalc.FourSphereVolumeConductor`: For computing extracellular potentials in 4-sphere head model (brain, CSF, skull, scalp) from current dipole moment
- `eegmegcalc.InfiniteVolumeConductor`: To compute extracellular potentials in infinite volume conductor from current dipole moment

- `eegmegcalc.MEG`: Class for computing magnetic field from current dipole moments
- `eegmegcalc.NYHeadModel`: Class for computing extracellular potentials in detailed head volume conductor model (<https://www.parralab.org/nyhead>)

Each class (except `CellGeometry`) should have a public method `get_transformation_matrix()` that returns the linear map between the transmembrane currents or current dipole moment and corresponding measurements (see Usage below)

1.3 Usage

A basic usage example using a mock 3-segment stick-like neuron, treating each segment as a point source in a linear, isotropic and homogeneous volume conductor, computing the extracellular potential in ten different locations alongside the cell geometry:

```
>>> # imports
>>> import numpy as np
>>> from lfpykit import CellGeometry, PointSourcePotential
>>> n_seg = 3
>>> # instantiate class `CellGeometry`:
>>> cell = CellGeometry(x=np.array([[0.] * 2] * n_seg), # (μm)
                        y=np.array([[0.] * 2] * n_seg), # (μm)
                        z=np.array([[10. * x, 10. * (x + 1)]
                                   for x in range(n_seg)]), # (μm)
                        d=np.array([1.] * n_seg)) # (μm)
>>> # instantiate class `PointSourcePotential`:
>>> psp = PointSourcePotential(cell,
                               x=np.ones(10) * 10,
                               y=np.zeros(10),
                               z=np.arange(10) * 10,
                               sigma=0.3)
>>> # get linear response matrix mapping currents to measurements
>>> M = psp.get_transformation_matrix()
>>> # transmembrane currents (nA):
>>> imem = np.array([[ -1.,  1.],
                    [ 0.,  0.],
                    [ 1., -1.]])
>>> # compute extracellular potentials (mV)
>>> V_ex = M @ imem
>>> V_ex
array([[ -0.01387397,  0.01387397],
       [ -0.00901154,  0.00901154],
       [  0.00901154, -0.00901154],
       [  0.01387397, -0.01387397],
       [  0.00742668, -0.00742668],
       [  0.00409718, -0.00409718],
       [  0.00254212, -0.00254212],
       [  0.00172082, -0.00172082],
       [  0.00123933, -0.00123933],
       [  0.00093413, -0.00093413]])
```

A basic usage example using a mock 3-segment stick-like neuron, treating each segment as a point source, computing the current dipole moment and computing the potential in ten different remote locations away from the cell geometry:

```
>>> # imports
>>> import numpy as np
```

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```

>>> from lfpypykit import CellGeometry, CurrentDipoleMoment, \
>>>     eegmegcalc
>>> n_seg = 3
>>> # instantiate class `CellGeometry`:
>>> cell = CellGeometry(x=np.array([[0.] * 2] * n_seg), # ( $\mu\text{m}$ )
>>>                     y=np.array([[0.] * 2] * n_seg), # ( $\mu\text{m}$ )
>>>                     z=np.array([[10. * x, 10. * (x + 1)]
>>>                               for x in range(n_seg)]), # ( $\mu\text{m}$ )
>>>                     d=np.array([1.] * n_seg)) # ( $\mu\text{m}$ )
>>> # instantiate class `CurrentDipoleMoment`:
>>> cdp = CurrentDipoleMoment(cell)
>>> M_I_to_P = cdp.get_transformation_matrix()
>>> # instantiate class `eegmegcalc.InfiniteVolumeConductor` and map dipole moment to
>>> # extracellular potential at measurement sites
>>> ivc = eegmegcalc.InfiniteVolumeConductor(sigma=0.3)
>>> # compute linear response matrix between dipole moment and
>>> # extracellular potential
>>> M_P_to_V = ivc.get_transformation_matrix(np.c_[np.ones(10) * 1000,
>>>                                                np.zeros(10),
>>>                                                np.arange(10) * 100])

>>> # transmembrane currents (nA):
>>> imem = np.array([[-1., 1.],
>>>                  [0., 0.],
>>>                  [1., -1.]])
>>> # compute extracellular potentials (mV)
>>> V_ex = M_P_to_V @ M_I_to_P @ imem
>>> V_ex
array([[ 0.00000000e+00,  0.00000000e+00],
       [ 5.22657054e-07, -5.22657054e-07],
       [ 1.00041193e-06, -1.00041193e-06],
       [ 1.39855769e-06, -1.39855769e-06],
       [ 1.69852477e-06, -1.69852477e-06],
       [ 1.89803345e-06, -1.89803345e-06],
       [ 2.00697409e-06, -2.00697409e-06],
       [ 2.04182029e-06, -2.04182029e-06],
       [ 2.02079888e-06, -2.02079888e-06],
       [ 1.96075587e-06, -1.96075587e-06]])

```

1.4 Physical units

Notes on physical units used in LFPykit:

- There are no explicit checks for physical units
- Transmembrane currents are assumed to be in units of (nA)
- Spatial information is assumed to be in units of (μm)
- Voltages are assumed to be in units of (mV)
- Extracellular conductivities are assumed to be in units of (S/m)
- current dipole moments are assumed to be in units of (nA μm)
- Magnetic fields are assumed to be in units of (nA/ μm)

1.5 Dimensionality

- Transmembrane currents are represented by arrays with shape `(n_seg, n_timesteps)` where `n_seg` is the number of segments of the neuron model.
- Current dipole moments are represented by arrays with shape `(3, n_timesteps)`
- Response matrices **M** have shape `(n_points, input.shape[0])` where `n_points` is for instance the number of extracellular recording sites and `input.shape[0]` the first dimension of the input; that is, the number of segments in case of transmembrane currents or 3 in case of current dipole moments.
- predicted signals (except magnetic fields using `eegmegcalc.MEG`) have shape `(n_points, n_timesteps)`

1.6 Documentation

The online Documentation of LFPykit can be found here: <https://lfpkit.readthedocs.io/en/latest>

1.7 Dependencies

LFPykit is implemented in Python and is written (and continuously tested) for Python ≥ 3.7 . The main LFPykit module depends on `numpy`, `scipy` and `MEAutility` (<https://github.com/alejoe91/MEAutility>, <https://meautility.readthedocs.io/en/latest/>).

Running all unit tests and example files may in addition require `py.test`, `matplotlib`, `neuron` (<https://www.neuron.yale.edu>), (arbor coming) and LFPy (<https://github.com/LFPy/LFPy>, <https://LFPy.readthedocs.io>).

1.8 Installation

1.8.1 From development sources (<https://github.com/LFPy/LFPykit>)

Install the current development version on <https://GitHub.com> using `git` (<https://git-scm.com>):

```
$ git clone https://github.com/LFPy/LFPykit.git
$ cd LFPykit
$ python setup.py install # --user optional
```

or using `pip`:

```
$ pip install . # --user optional
```

For active development, link the repository location

```
$ python setup.py develop # --user optional
```

1.8.2 Installation of stable releases on PyPI.org (<https://www.pypi.org>)

Installing from the Python Package Index (<https://www.pypi.org/project/lfpypykit>):

```
$ pip install lfpypykit # --user optional
```

To upgrade the installation using pip:

```
$ pip install --upgrade --no-deps lfpypykit
```

1.8.3 Installation of stable releases on conda-forge (<https://conda-forge.org>)

Installing lfpypykit from the conda-forge channel can be achieved by adding conda-forge to your channels with:

```
$ conda config --add channels conda-forge
```

Once the conda-forge channel has been enabled, lfpypykit can be installed with:

```
$ conda install lfpypykit
```

It is possible to list all of the versions of lfpypykit available on your platform with:

```
$ conda search lfpypykit --channel conda-forge
```

MODULE LFPYKIT

Initialization of LFPykit

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Classes

- **CellGeometry:** Base class representing a multicompartment neuron geometry for subclassing
- **LinearModel:** Base class representing a generic forward model for subclassing
- **CurrentDipoleMoment:** Class for predicting current dipole moments
- **PointSourcePotential:** Class for predicting extracellular potentials assuming point sources and contacts
- **LineSourcePotential:** Class for predicting extracellular potentials assuming line sources and point contacts
- **RecExtElectrode:** Class for simulations of extracellular potentials
- **RecMEAElectrode:** Class for simulations of in vitro (slice) extracellular potentials
- **OneSphereVolumeConductor:** For computing extracellular potentials within and outside a homogeneous sphere
- **LaminarCurrentSourceDensity:** For computing the ground truth current source density in cylindrical volumes aligned with the z-axis.
- **VolumetricCurrentSourceDensity:** For computing the ground truth current source density in cubic volumes with bin edges defined by x, y, z
- **eegmegcalc.FourSphereVolumeConductor:** For computing extracellular potentials in 4-sphere model (brain, CSF, skull, scalp) from current dipole moment
- **eegmegcalc.InfiniteVolumeConductor:** To compute extracellular potentials with current dipole moments in infinite volume conductor
- **eegmegcalc.MEG:** Class for computing magnetic field from current dipole moments
- **eegmegcalc.NYHeadModel:** Class for computing extracellular potentials in detailed head volume conductor model (<https://www.parralab.org/nyhead>)

Modules

- cellgeometry

- models
- eegmegcalc
- lfpcalc

CLASS CELLGEOMETRY

class `lfpykit.CellGeometry` (*x*, *y*, *z*, *d*)

Bases: `object`

Base class representing the geometry of multicompartment neuron models.

Assumptions

- each compartment is piecewise linear between their start and endpoints
- each compartment has a constant diameter
- the transmembrane current density is constant along the compartment axis

Parameters

- x: ndarray of floats** shape (n_seg x 2) array of start- and end-point coordinates of each compartment along x-axis in units of (μm)
- y: ndarray** shape (n_seg x 2) array of start- and end-point coordinates of each compartment along y-axis in units of (μm)
- z: ndarray** shape (n_seg x 2) array of start- and end-point coordinates of each compartment along z-axis in units of (μm)
- d: ndarray** shape (n_seg) or shape (n_seg x 2) array of compartment diameters in units of (μm). If the 2nd axis is equal to 2, conical frusta is assumed.

Attributes

- totnsegs: int** number of compartments
- x: ndarray of floats** shape (totnsegs x 2) array of start- and end-point coordinates of each compartment along x-axis in units of (μm)
- y: ndarray** shape (totnsegs x 2) array of start- and end-point coordinates of each compartment along y-axis in units of (μm)
- z: ndarray** shape (totnsegs x 2) array of start- and end-point coordinates of each compartment along z-axis in units of (μm)
- d: ndarray** shape (totnsegs) array of compartment diameters in units of (μm)
- length: ndarray** length of each compartment in units of μm
- area: ndarray** array of compartment surface areas in units of μm^2

MODULE `lfpykit.models`

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4.1 class `LinearModel`

class `lfpykit.LinearModel` (*cell*)

Bases: `object`

Base class that defines a 2D linear response matrix **M** between transmembrane currents **I** (nA) of a multicompartment neuron model and some measurement **Y** as

$$\mathbf{Y} = \mathbf{M}\mathbf{I}$$

`LinearModel` only creates a mapping that returns the currents themselves. The class is suitable as a base class for other linear model implementations, see for example class `CurrentDipoleMoment` or `PointSourcePotential`

Parameters

cell: `object` `lfpykit.CellGeometry` instance or similar. Can also be set to `None` which allows setting the attribute `cell` after class instantiation.

get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: `ndarray` shape (n_seg, n_seg) `ndarray`

Raises

AttributeError if `cell` is `None`

4.2 class CurrentDipoleMoment

class lfpypykit.**CurrentDipoleMoment** (*cell*)

Bases: lfpypykit.models.LinearModel

LinearModel subclass that defines a 2D linear response matrix **M** between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding current dipole moment **P** (nA μ m) [1] as

$$\mathbf{P} = \mathbf{M}\mathbf{I}$$

The current **I** is an ndarray of shape (n_seg, n_tsteps) with unit (nA), and the rows of **P** represent the *x*-, *y*- and *z*-components of the current dipole moment for every time step.

The current dipole moment can be used to compute distal measures of neural activity such as the EEG and MEG using lfpypykit.eegmegcalc.FourSphereVolumeConductor or lfpypykit.eegmegcalc.MEG, respectively

Parameters

cell: object CellGeometry instance or similar.

See also:

LinearModel

eegmegcalc.FourSphereVolumeConductor

eegmegcalc.MEG

eegmegcalc.NYHeadModel

References

[1]

Examples

Compute the current dipole moment of a 3-compartment neuron model:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, CurrentDipoleMoment
>>> n_seg = 3
>>> cell = CellGeometry(x=np.array([[0.]*2]*n_seg),
                        y=np.array([[0.]*2]*n_seg),
                        z=np.array([[1.*x, 1.*(x+1)]
                                    for x in range(n_seg)]),
                        d=np.array([1.]*n_seg))
>>> cdm = CurrentDipoleMoment(cell)
>>> M = cdm.get_transformation_matrix()
>>> imem = np.array([[-1., 1.],
                    [0., 0.],
                    [1., -1.]])
>>> P = M@imem
>>> P
array([[ 0.,  0.],
       [ 0.,  0.],
       [ 2., -2.]])
```


get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: ndarray shape (3, n_seg) ndarray

Raises

AttributeError if cell is None

4.3 class PointSourcePotential

class lfpypykit.PointSourcePotential (cell, x, y, z, sigma=0.3)

Bases: lfpypykit.models.LinearModel

LinearModel subclass that defines a 2D linear response matrix **M** between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding extracellular electric potential V_{ex} (mV) as

$$V_{ex} = \mathbf{M}\mathbf{I}$$

The current **I** is an ndarray of shape (n_seg, n_tsteps) with unit (nA), and each row indexed by j of V_{ex} represents the electric potential at each measurement site for every time step.

The elements of **M** are computed as

$$M_{ji} = 1/(4\pi\sigma|\mathbf{r}_i - \mathbf{r}_j|)$$

where σ is the electric conductivity of the extracellular medium, \mathbf{r}_i the midpoint coordinate of segment i and \mathbf{r}_j the coordinate of measurement site j [1], [2].

Assumptions:

- the extracellular conductivity σ is infinite, homogeneous, frequency independent (linear) and isotropic.
- each segment is treated as a point source located at the midpoint between its start and end point coordinate.
- each measurement site $\mathbf{r}_j = (x_j, y_j, z_j)$ is treated as a point.
- $|\mathbf{r}_i - \mathbf{r}_j| \geq d_i/2$, where d_i is the segment diameter.

Parameters

cell: object CellGeometry instance or similar.

x: ndarray of floats x-position of measurement sites (μm)

y: ndarray of floats y-position of measurement sites (μm)

z: ndarray of floats z-position of measurement sites (μm)

sigma: float > 0 scalar extracellular conductivity (S/m)

See also:

[*LinearModel*](#)

[*LineSourcePotential*](#)

[*RecExtElectrode*](#)

References

[1], [2]

Examples

Compute the current dipole moment of a 3-compartment neuron model:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, PointSourcePotential
>>> n_seg = 3
>>> cell = CellGeometry(x=np.array([[0.]*2]*n_seg),
                        y=np.array([[0.]*2]*n_seg),
                        z=np.array([[10.*x, 10.*(x+1)]
                                   for x in range(n_seg)]),
                        d=np.array([1.]*n_seg))
>>> psp = PointSourcePotential(cell,
                               x=np.ones(10)*10,
                               y=np.zeros(10),
                               z=np.arange(10)*10,
                               sigma=0.3)
>>> M = psp.get_transformation_matrix()
>>> imem = np.array([[-1., 1.],
                    [0., 0.],
                    [1., -1.]])
>>> V_ex = M @ imem
>>> V_ex
array([[ -0.01387397,  0.01387397],
       [ -0.00901154,  0.00901154],
       [ 0.00901154, -0.00901154],
       [ 0.01387397, -0.01387397],
       [ 0.00742668, -0.00742668],
       [ 0.00409718, -0.00409718],
       [ 0.00254212, -0.00254212],
       [ 0.00172082, -0.00172082],
       [ 0.00123933, -0.00123933],
       [ 0.00093413, -0.00093413]])
```

get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: ndarray shape (n_coords, n_seg) ndarray

Raises

AttributeError if cell is None

4.4 class LineSourcePotential

class lfpypykit.LineSourcePotential (*cell*, *x*, *y*, *z*, *sigma*=0.3)

Bases: lfpypykit.models.LinearModel

LinearModel subclass that defines a 2D linear response matrix **M** between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding extracellular electric potential V_{ex} (mV) as

$$\mathbf{V}_{ex} = \mathbf{M}\mathbf{I}$$

The current **I** is an ndarray of shape (n_seg, n_tsteps) with unit (nA), and each row indexed by *j* of V_{ex} represents the electric potential at each measurement site for every time step.

The elements of **M** are computed as

$$M_{ji} = \frac{1}{4\pi\sigma L_i} \log \left| \frac{\sqrt{h_{ji}^2 + r_{ji}^2} - h_{ji}}{\sqrt{l_{ji}^2 + r_{ji}^2} - l_{ji}} \right|$$

Segment length is denoted L_i , perpendicular distance from the electrode point contact to the axis of the line segment is denoted r_{ji} , longitudinal distance measured from the start of the segment is denoted h_{ji} , and longitudinal distance from the other end of the segment is denoted $l_{ji} = L_i + h_{ji}$ [1], [2].

Assumptions:

- the extracellular conductivity σ is infinite, homogeneous, frequency independent (linear) and isotropic
- each segment is treated as a straight line source with homogeneous current density between its start and end point coordinate
- each measurement site $\mathbf{r}_j = (x_j, y_j, z_j)$ is treated as a point
- The minimum distance to a line source is set equal to segment radius.

Parameters

cell: object CellGeometry instance or similar.

x: ndarray of floats x-position of measurement sites (μm)

y: ndarray of floats y-position of measurement sites (μm)

z: ndarray of floats z-position of measurement sites (μm)

sigma: float > 0 scalar extracellular conductivity (S/m)

See also:

[*LinearModel*](#)

[*PointSourcePotential*](#)

[*RecExtElectrode*](#)

References

[1], [2]

Examples

Compute the current dipole moment of a 3-compartment neuron model:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, LineSourcePotential
>>> n_seg = 3
>>> cell = CellGeometry(x=np.array([[0.]*2]*n_seg),
                        y=np.array([[0.]*2]*n_seg),
                        z=np.array([[10.*x, 10.*(x+1)]
                                   for x in range(n_seg)]),
                        d=np.array([1.]*n_seg))
>>> lsp = LineSourcePotential(cell,
                              x=np.ones(10)*10,
                              y=np.zeros(10),
                              z=np.arange(10)*10,
                              sigma=0.3)
>>> M = lsp.get_transformation_matrix()
>>> imem = np.array([[-1., 1.],
                    [0., 0.],
                    [1., -1.]])
>>> V_ex = M @ imem
>>> V_ex
array([[ -0.01343699,  0.01343699],
       [ -0.0084647 ,  0.0084647 ],
       [  0.0084647 , -0.0084647 ],
       [  0.01343699, -0.01343699],
       [  0.00758627, -0.00758627],
       [  0.00416681, -0.00416681],
       [  0.002571  , -0.002571  ],
       [  0.00173439, -0.00173439],
       [  0.00124645, -0.00124645],
       [  0.0009382 , -0.0009382 ]])
```

get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: ndarray shape (n_coords, n_seg) ndarray

Raises

AttributeError if cell is None

4.5 class RecExtElectrode

```
class lfpypykit.RecExtElectrode(cell, sigma=0.3, probe=None, x=None, y=None, z=None,  
                                N=None, r=None, n=None, contact_shape='circle',  
                                method='linesource', verbose=False, seedvalue=None,  
                                **kwargs)
```

Bases: lfpypykit.models.LinearModel

class RecExtElectrode

Main class that represents an extracellular electric recording devices such as a laminar probe.

This class is a `LinearModel` subclass that defines a 2D linear response matrix \mathbf{M} between transmembrane current array \mathbf{I} (nA) of a multicompartment neuron model and the corresponding extracellular electric potential V_{ex} (mV) as

$$V_{ex} = \mathbf{M}\mathbf{I}$$

The current \mathbf{I} is an ndarray of shape (n_seg, n_tsteps) with unit (nA), and each row indexed by j of V_{ex} represents the electric potential at each measurement site for every time step.

The class differ from `PointSourcePotential` and `LineSourcePotential` by:

- supporting anisotropic volume conductors [1]
- supporting probe geometry specifications using `MEAutility` (<https://meautility.readthedocs.io/en/latest/>, <https://github.com/alejoe91/MEAutility>).
- supporting electrode contact points with finite extents [2], [3]
- switching between point- and linesources, and a combined method that assumes that the root element at segment index 0 is spherical.

Parameters

cell: **object** `CellGeometry` instance or similar.

sigma: **float or list/ndarray of floats** extracellular conductivity in units of (S/m). A scalar value implies an isotropic extracellular conductivity. If a length 3 list or array of floats is provided, these values corresponds to an anisotropic conductor with conductivities $[\sigma_x, \sigma_y, \sigma_z]$.

probe: **MEAutility MEA object or None** `MEAutility` probe object

x, y, z: **ndarray** coordinates or same length arrays of coordinates in units of (μm).

N: **None or list of lists** Normal vectors $[x, y, z]$ of each circular electrode contact surface, default `None`

r: **float** radius of each contact surface, default `None` (μm)

n: **int** if `N` is not `None` and $r > 0$, the number of discrete points used to compute the n-point average potential on each circular contact point.

contact_shape: **str** 'circle'/'square' (default 'circle') defines the contact point shape If 'circle' r is the radius, if 'square' r is the side length

method: **str** switch between the assumption of 'linesource', 'pointsource', 'root_as_point' to represent each compartment when computing extracellular potentials

verbose: **bool** Flag for verbose output, i.e., print more information

seedvalue: **int** random seed when finding random position on contact with $r > 0$

****kwargs:** Additional keyword arguments parsed to *RecExtElectrode.lfp_method()* which is determined by *method* parameter.

See also:

LinearModel

PointSourcePotential

LineSourcePotential

References

[1], [2], [3]

Examples

Mock cell geometry and transmembrane currents:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, RecExtElectrode
>>> # cell geometry with three segments (μm)
>>> cell = CellGeometry(x=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                      y=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                      z=np.array([[0, 10], [10, 20], [20, 30]]),
>>>                      d=np.array([1, 1, 1]))
>>> # transmembrane currents, three time steps (nA)
>>> I_m = np.array([[0., -1., 1.], [-1., 1., 0.], [1., 0., -1.]])
>>> # electrode locations (μm)
>>> r = np.array([[28.24653166, 8.97563241, 18.9492774, 3.47296614,
>>>                1.20517729, 9.59849603, 21.91956616, 29.84686727,
>>>                4.41045505, 3.61146625],
>>>                [24.4954352, 24.04977922, 22.41262238, 10.09702942,
>>>                3.28610789, 23.50277637, 8.14044367, 4.46909208,
>>>                10.93270117, 24.94698813],
>>>                [19.16644585, 15.20196335, 18.08924828, 24.22864702,
>>>                5.85216751, 14.8231048, 24.72666694, 17.77573431,
>>>                29.34508292, 9.28381892]])
>>> # instantiate electrode, get linear response matrix
>>> el = RecExtElectrode(cell=cell, x=r[0, ], y=r[1, ], z=r[2, ],
>>>                      sigma=0.3,
>>>                      method='pointsource')
>>> M = el.get_transformation_matrix()
>>> # compute extracellular potential
>>> M @ I_m
array([[ -4.11657148e-05,  4.16621950e-04, -3.75456235e-04],
       [ -6.79014892e-04,  7.30256301e-04, -5.12414088e-05],
       [ -1.90930536e-04,  7.34007655e-04, -5.43077119e-04],
       [ 5.98270144e-03,  6.73490846e-03, -1.27176099e-02],
       [ -1.34547752e-02, -4.65520036e-02,  6.00067788e-02],
       [ -7.49957880e-04,  7.03763787e-04,  4.61940938e-05],
       [ 8.69330232e-04,  1.80346156e-03, -2.67279180e-03],
       [ -2.04546513e-04,  6.58419628e-04, -4.53873115e-04],
       [ 6.82640209e-03,  4.47953560e-03, -1.13059377e-02],
       [ -1.33289553e-03, -1.11818140e-04,  1.44471367e-03]])
```

Compute extracellular potentials after simulating and storage of transmembrane currents with the LFPy.Cell class:

```
>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> import LFPy
>>> from lfpypykit import CellGeometry, RecExtElectrode
>>>
>>> cellParameters = {
>>>     'morphology': 'examples/morphologies/L5_Mainen96_LFPy.hoc',
>>>     'v_init': -65,                                     # initial voltage
>>>     'cm': 1.0,                                         # membrane capacitance
>>>     'Ra': 150,                                         # axial resistivity
>>>     'passive': True,                                   # insert passive channels
>>>     'passive_parameters': {"g_pas":1./3E4,
>>>                             "e_pas":-65}, # passive params
>>>     'dt': 2**-4,                                       # simulation time res
>>>     'tstart': 0.,                                     # start t of simulation
>>>     'tstop': 50.,                                     # end t of simulation
>>> }
>>> cell = LFPy.Cell(**cellParameters)
>>>
>>> synapseParameters = {
>>>     'idx': cell.get_closest_idx(x=0, y=0, z=800), # segment
>>>     'e': 0,                                         # reversal potential
>>>     'syntype': 'ExpSyn',                             # synapse type
>>>     'tau': 2,                                       # syn. time constant
>>>     'weight': 0.01,                                 # syn. weight
>>>     'record_current': True                           # syn. current record
>>> }
>>> synapse = LFPy.Synapse(cell, **synapseParameters)
>>> synapse.set_spike_times(np.array([10., 15., 20., 25.]))
>>>
>>> cell.simulate(rec_imem=True)
>>>
>>> N = np.empty((16, 3))
>>> for i in range(N.shape[0]): N[i,] = [1, 0, 0] # normal vectors
>>> electrodeParameters = {                               # parameters for RecExtElectrode class
>>>     'sigma': 0.3,                                     # Extracellular potential
>>>     'x': np.zeros(16)+25,                             # Coordinates of electrode contacts
>>>     'y': np.zeros(16),
>>>     'z': np.linspace(-500,1000,16),
>>>     'n': 20,
>>>     'r': 10,
>>>     'N': N,
>>> }
>>> cell_geometry = CellGeometry(
>>>     x=np.c_[cell.xstart, cell.xend],
>>>     y=np.c_[cell.ystart, cell.yend],
>>>     z=np.c_[cell.zstart, cell.zend],
>>>     d=cell.diam)
>>> electrode = RecExtElectrode(cell_geometry, **electrodeParameters)
>>> M = electrode.get_transformation_matrix()
>>> V_ex = M @ cell.imem
>>> plt.matshow(V_ex)
>>> plt.colorbar()
>>> plt.axis('tight')
>>> plt.show()
```

Compute extracellular potentials during simulation (recommended):

```
>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> import LFPy
>>> from lfpykit import CellGeometry, RecExtElectrode
>>>
>>> cellParameters = {
>>>     'morphology': 'examples/morphologies/L5_Mainen96_LFPy.hoc',
>>>     'v_init': -65,                                     # initial voltage
>>>     'cm': 1.0,                                         # membrane capacitance
>>>     'Ra': 150,                                         # axial resistivity
>>>     'passive': True,                                   # insert passive channels
>>>     'passive_parameters': {"g_pas":1./3E4,
>>>                             "e_pas":-65}, # passive params
>>>     'dt': 2**-4,                                       # simulation time res
>>>     'tstart': 0.,                                     # start t of simulation
>>>     'tstop': 50.,                                     # end t of simulation
>>> }
>>> cell = LFPy.Cell(**cellParameters)
>>>
>>> synapseParameters = {
>>>     'idx': cell.get_closest_idx(x=0, y=0, z=800), # compartment
>>>     'e': 0,                                         # reversal potential
>>>     'syntype': 'ExpSyn',                           # synapse type
>>>     'tau': 2,                                       # syn. time constant
>>>     'weight': 0.01,                                 # syn. weight
>>>     'record_current': True                         # syn. current record
>>> }
>>> synapse = LFPy.Synapse(cell, **synapseParameters)
>>> synapse.set_spike_times(np.array([10., 15., 20., 25.]))
>>>
>>> N = np.empty((16, 3))
>>> for i in range(N.shape[0]): N[i,] = [1, 0, 0] #normal vec. of contacts
>>> electrodeParameters = {                             # parameters for RecExtElectrode class
>>>     'sigma': 0.3,                                     # Extracellular potential
>>>     'x': np.zeros(16)+25,                             # Coordinates of electrode contacts
>>>     'y': np.zeros(16),
>>>     'z': np.linspace(-500,1000,16),
>>>     'n': 20,
>>>     'r': 10,
>>>     'N': N,
>>> }
>>> cell_geometry = CellGeometry(
>>>     x=np.c_[cell.xstart, cell.xend],
>>>     y=np.c_[cell.ystart, cell.yend],
>>>     z=np.c_[cell.zstart, cell.zend],
>>>     d=cell.diam)
>>> electrode = RecExtElectrode(cell_geometry, **electrodeParameters)
>>> M = electrode.get_transformation_matrix()
>>> cell.simulate(dotprodcoeffs=[M])
>>> V_ex = cell.dotprodresults[0]
>>> plt.matshow(V_ex)
>>> plt.colorbar()
>>> plt.axis('tight')
>>> plt.show()
```

Use MEAutility to to handle probes


```

>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> import MEAutility as mu
>>> import LFPy
>>> from lfpykit import CellGeometry, RecExtElectrode
>>>
>>> cellParameters = {
>>>     'morphology': 'examples/morphologies/L5_Mainen96_LFPy.hoc',
>>>     'v_init': -65,                      # initial voltage
>>>     'cm': 1.0,                          # membrane capacitance
>>>     'Ra': 150,                          # axial resistivity
>>>     'passive': True,                   # insert passive channels
>>>     'passive_parameters': {"g_pas":1./3E4,
>>>                             "e_pas":-65}, # passive params
>>>     'dt': 2**-4,                      # simulation time res
>>>     'tstart': 0.,                     # start t of simulation
>>>     'tstop': 50.,                     # end t of simulation
>>> }
>>> cell = LFPy.Cell(**cellParameters)
>>>
>>> synapseParameters = {
>>>     'idx': cell.get_closest_idx(x=0, y=0, z=800), # compartment
>>>     'e': 0,                                     # reversal potential
>>>     'syntype': 'ExpSyn',                       # synapse type
>>>     'tau': 2,                                  # syn. time constant
>>>     'weight': 0.01,                            # syn. weight
>>>     'record_current': True                     # syn. current record
>>> }
>>> synapse = LFPy.Synapse(cell, **synapseParameters)
>>> synapse.set_spike_times(np.array([10., 15., 20., 25.]))
>>>
>>> cell.simulate(rec_imem=True)
>>>
>>> probe = mu.return_mea('Neuropixels-128')
>>> cell_geometry = CellGeometry(
>>>     x=np.c_[cell.xstart, cell.xend],
>>>     y=np.c_[cell.ystart, cell.yend],
>>>     z=np.c_[cell.zstart, cell.zend],
>>>     d=cell.diam)
>>> electrode = RecExtElectrode(cell_geometry, probe=probe)
>>> V_ex = electrode.get_transformation_matrix() @ cell.imem
>>> mu.plot_mea_recording(V_ex, probe)
>>> plt.axis('tight')
>>> plt.show()

```

get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: ndarray shape (n_contacts, n_seg) ndarray

Raises

AttributeError if cell is None

4.6 class RecMEAElectrode

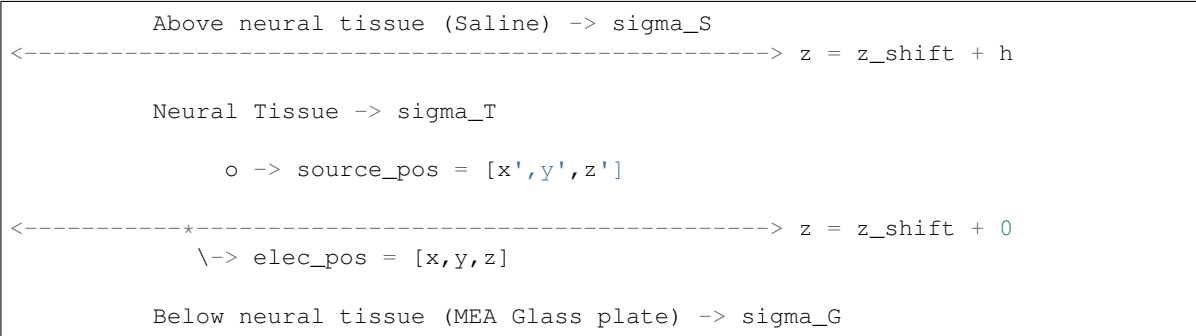
```
class lfpypykit.RecMEAElectrode(cell, sigma_T=0.3, sigma_S=1.5, sigma_G=0.0, h=300.0,  
                                z_shift=0.0, steps=20, probe=None, x=array([0]), y=array([0]),  
                                z=array([0]), N=None, r=None, n=None, method='linesource',  
                                verbose=False, seedvalue=None, squeeze_cell_factor=None,  
                                **kwargs)
```

Bases: lfpypykit.models.RecExtElectrode

class RecMEAElectrode

Electrode class that represents an extracellular in vitro slice recording as a Microelectrode Array (MEA). Inherits RecExtElectrode class

Illustration:



For further details, see reference [1].

Parameters

cell: **object** GeometryCell instance or similar.

sigma_T: **float** extracellular conductivity of neural tissue in unit (S/m)

sigma_S: **float** conductivity of saline bath that the neural slice is immersed in [1.5] (S/m)

sigma_G: **float** conductivity of MEA glass electrode plate. Most commonly assumed non-conducting [0.0] (S/m)

h: **float, int** Thickness in um of neural tissue layer containing current the current sources (i.e., in vitro slice or cortex)

z_shift: **float, int** Height in um of neural tissue layer bottom. If e.g., top of neural tissue layer should be $z=0$, use $z_shift=-h$. Defaults to $z_shift = 0$, so that the neural tissue layer extends from $z=0$ to $z=h$.

squeeze_cell_factor: **float or None** Factor to squeeze the cell in the z-direction. This is needed for large cells that are thicker than the slice, since no part of the cell is allowed to be outside the slice. The squeeze is done after the neural simulation, and therefore does not affect neuronal simulation, only calculation of extracellular potentials.

probe: **MEAutility MEA object or None** MEAutility probe object

x, y, z: **np.ndarray** coordinates or arrays of coordinates in units of (um). Must be same length

N: **None or list of lists** Normal vectors [x, y, z] of each circular electrode contact surface, default None

r: **float** radius of each contact surface, default None

n: int if N is not None and $r > 0$, the number of discrete points used to compute the n-point average potential on each circular contact point.

contact_shape: str 'circle'/'square' (default 'circle') defines the contact point shape If 'circle' r is the radius, if 'square' r is the side length

method: str switch between the assumption of 'linesource', 'pointsource', 'root_as_point' to represent each compartment when computing extracellular potentials

verbose: bool Flag for verbose output, i.e., print more information

seedvalue: int random seed when finding random position on contact with $r > 0$

See also:

[*LinearModel*](#)

[*PointSourcePotential*](#)

[*LineSourcePotential*](#)

[*RecExtElectrode*](#)

References

[1]

Examples

Mock cell geometry and transmembrane currents:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, RecMEAElectrode
>>> # cell geometry with four segments (μm)
>>> cell = CellGeometry(
>>>     x=np.array([[0, 10], [10, 20], [20, 30], [30, 40]]),
>>>     y=np.array([[0, 0], [0, 0], [0, 0], [0, 0]]),
>>>     z=np.array([[0, 0], [0, 0], [0, 0], [0, 0]]) + 10,
>>>     d=np.array([1, 1, 1, 1]))
>>> # transmembrane currents, three time steps (nA)
>>> I_m = np.array([[0.25, -1., 1.],
>>>                  [-1., 1., -0.25],
>>>                  [1., -0.25, -1.],
>>>                  [-0.25, 0.25, 0.25]])
>>> # electrode locations (μm)
>>> r = np.stack([np.arange(10)*4 + 2, np.zeros(10), np.zeros(10)])
>>> # instantiate electrode, get linear response matrix
>>> el = RecMEAElectrode(cell=cell,
>>>                        sigma_T=0.3, sigma_S=1.5, sigma_G=0.0,
>>>                        x=r[0, :], y=r[1, :], z=r[2, :],
>>>                        method='pointsource')
>>> M = el.get_transformation_matrix()
>>> # compute extracellular potential
>>> M @ I_m
array([[ -0.00233572, -0.01990957,  0.02542055],
       [ -0.00585075, -0.01520865,  0.02254483],
       [ -0.01108601, -0.00243107,  0.01108601],
       [ -0.01294584,  0.01013595, -0.00374823],
```

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```

[-0.00599067, 0.01432711, -0.01709416],
[ 0.00599067, 0.01194602, -0.0266944 ],
[ 0.01294584, 0.00953841, -0.02904238],
[ 0.01108601, 0.00972426, -0.02324134],
[ 0.00585075, 0.01075236, -0.01511768],
[ 0.00233572, 0.01038382, -0.00954429]]

```

See also <LFPy>/examples/example_MEA.py

```

>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> import LFPy
>>> from lfpykit import CellGeometry, RecMEAElectrode
>>>
>>> cellParameters = {
>>>     'morphology': 'examples/morphologies/L5_Mainen96_LFPy.hoc',
>>>     'v_init': -65,                                     # initial voltage
>>>     'cm': 1.0,                                         # membrane capacitance
>>>     'Ra': 150,                                         # axial resistivity
>>>     'passive': True,                                   # insert passive channels
>>>     'passive_parameters': {"g_pas":1./3E4,
>>>                             "e_pas":-65}, # passive params
>>>     'dt': 2**-4,                                       # simulation time res
>>>     'tstart': 0.,                                     # start t of simulation
>>>     'tstop': 50.,                                     # end t of simulation
>>> }
>>> lfpy_cell = LFPy.Cell(**cellParameters)
>>> lfpy_cell.set_rotation(x=np.pi/2, z=np.pi/2)
>>> lfpy_cell.set_pos(z=100)
>>> synapseParameters = {
>>>     'idx': lfpy_cell.get_closest_idx(x=800, y=0, z=100), # segment
>>>     'e': 0,                                             # reversal potential
>>>     'syntype': 'ExpSyn',                               # synapse type
>>>     'tau': 2,                                           # syn. time constant
>>>     'weight': 0.01,                                     # syn. weight
>>>     'record_current': True                             # syn. current record
>>> }
>>> synapse = LFPy.Synapse(lfpy_cell, **synapseParameters)
>>> synapse.set_spike_times(np.array([10., 15., 20., 25.]))
>>>
>>> MEA_electrode_parameters = {
>>>     'sigma_T': 0.3,                                     # extracellular conductivity
>>>     'sigma_G': 0.0,                                     # MEA glass electrode plate conductivity
>>>     'sigma_S': 1.5,                                     # Saline bath conductivity
>>>     'x': np.linspace(0, 1200, 16), # 1d vector of positions
>>>     'y': np.zeros(16),
>>>     'z': np.zeros(16),
>>>     "method": "pointsource",
>>>     "h": 300,
>>>     "squeeze_cell_factor": 0.5,
>>> }
>>> lfpy_cell.simulate(rec_imem=True)
>>>
>>> cell = CellGeometry(
>>>     x=np.c_[lfpy_cell.xstart, lfpy_cell.xend],
>>>     y=np.c_[lfpy_cell.ystart, lfpy_cell.yend],
>>>     z=np.c_[lfpy_cell.zstart, lfpy_cell.zend],

```

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```

>>> d=lfpypy_cell.diam)
>>> MEA = RecMEAElectrode(cell, **MEA_electrode_parameters)
>>> V_ext = MEA.get_transformation_matrix() @ lfpypy_cell.imem
>>>
>>> plt.matshow(V_ext)
>>> plt.colorbar()
>>> plt.axis('tight')
>>> plt.show()

```

distort_cell_geometry (*axis='z', nu=0.0*)

Distorts cellular morphology with a relative squeeze_cell_factor along a chosen axis preserving Poisson's ratio. A ratio nu=0.5 assumes uncompressible and isotropic media that embeds the cell. A ratio nu=0 will only affect geometry along the chosen axis. A ratio nu=-1 will isometrically scale the neuron geometry along each axis. This method does not affect the underlying cable properties of the cell, only predictions of extracellular measurements (by affecting the relative locations of sources representing the compartments).

Parameters

axis: **str** which axis to apply compression/stretching. Default is “z”.

nu: **float** Poisson's ratio. Ratio between axial and transversal compression/stretching. Default is 0.

get_transformation_matrix ()

Get linear response matrix

Returns

response_matrix: **ndarray** shape (n_contacts, n_seg) **ndarray**

Raises

AttributeError if cell is None

4.7 class OneSphereVolumeConductor

class lfpypykit.OneSphereVolumeConductor (*cell, r, R=10000.0, sigma_i=0.3, sigma_o=0.03*)

Bases: lfpypykit.models.LinearModel

Computes extracellular potentials within and outside a spherical volume- conductor model that assumes homogeneous, isotropic, linear (frequency independent) conductivity in and outside the sphere with a radius R. The conductivity in and outside the sphere must be greater than 0, and the current source(s) must be located within the radius R.

The implementation is based on the description of electric potentials of point charge in an dielectric sphere embedded in dielectric media [1], which is mathematically equivalent to a current source in conductive media.

This class is a `LinearModel` subclass that defines a 2D linear response matrix **M** between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding extracellular electric potential **V_{ex}** (mV) as

$$\mathbf{V}_{ex} = \mathbf{M}\mathbf{I}$$

The current **I** is an **ndarray** of shape (n_seg, n_tsteps) with unit (nA), and each row indexed by *j* of **V_{ex}** represents the electric potential at each measurement site for every time step.

Parameters

cell: **object or None** `CellGeometry` instance or similar.

r: ndarray, dtype=float shape(3, n_points) observation points in space in spherical coordinates (radius, theta, phi) relative to the center of the sphere.

R: float sphere radius (μm)

sigma_i: float electric conductivity for radius $r \leq R$ (S/m)

sigma_o: float electric conductivity for radius $r > R$ (S/m)

References

[1]

Examples

Compute the potential for a single monopole along the x-axis:

```
>>> # import modules
>>> from lfpypykit import OneSphereVolumeConductor
>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> # observation points in spherical coordinates (flattened)
>>> X, Y = np.mgrid[-15000:15100:1000., -15000:15100:1000.]
>>> r = np.array([np.sqrt(X**2 + Y**2).flatten(),
>>>               np.arctan2(Y, X).flatten(),
>>>               np.zeros(X.size)])
>>> # set up class object and compute electric potential in all locations
>>> sphere = OneSphereVolumeConductor(r, R=10000.,
>>>                                   sigma_i=0.3, sigma_o=0.03)
>>> Phi = sphere.calc_potential(rs=8000, current=1.).reshape(X.shape)
>>> # plot
>>> fig, ax = plt.subplots(1,1)
>>> im=ax.contourf(X, Y, Phi,
>>>               levels=np.linspace(Phi.min(),
>>>               np.median(Phi[np.isfinite(Phi)]) * 4, 30))
>>> circle = plt.Circle(xy=(0,0), radius=sphere.R, fc='none', ec='k')
>>> ax.add_patch(circle)
>>> fig.colorbar(im, ax=ax)
>>> plt.show()
```

calc_potential (rs, current, min_distance=1.0, n_max=1000)

Return the electric potential at observation points for source current as function of time.

Parameters

rs: float monopole source location along the horizontal x-axis (μm)

current: float or ndarray, dtype float float or shape (n_tsteps,) array containing source current (nA)

min_distance: None or float minimum distance between source location and observation point (μm) (in order to avoid singularities)

n_max: int Number of elements in polynomial expansion to sum over (see [1]).

Returns

Phi: ndarray shape (n-points,) ndarray of floats if I is float like. If I is an 1D ndarray, and shape (n-points, I.size) ndarray is returned. Unit (mV).

References

[1]

get_transformation_matrix (*n_max=1000*)

Compute linear mapping between transmembrane currents of `CellGeometry` like object instance and extracellular potential in and outside of sphere.

Parameters

n_max: int Number of elements in polynomial expansion to sum over (see [1]).

Returns

ndarray Shape (*n_points*, *n_compartments*) mapping between individual segments and extracellular potential in extracellular locations

Raises

AttributeError if `cell` is `None`

Notes

Each segment is treated as a point source in space. The minimum source to measurement site distance will be set to the diameter of each segment

References

[1]

Examples

Compute extracellular potential in one-sphere volume conductor model from `LFPy.Cell` object:

```
>>> # import modules
>>> import LFPy
>>> from lfpypykit import CellGeometry, >>> OneSphereVolumeConductor
>>> import os
>>> import numpy as np
>>> import matplotlib.pyplot as plt
>>> from matplotlib.collections import PolyCollection
>>> # create cell
>>> cell = LFPy.Cell(morphology=os.path.join(LFPy.__path__[0], 'test',
>>>                                         'ball_and_sticks.hoc'),
>>>                  tstop=10.)
>>> cell.set_pos(z=9800.)
>>> # stimulus
>>> syn = LFPy.Synapse(cell, idx=cell.totnsegs-1, syntype='Exp2Syn',
>>>                    weight=0.01)
>>> syn.set_spike_times(np.array([1.]))
>>> # simulate
>>> cell.simulate(rec_imem=True)
>>> # observation points in spherical coordinates (flattened)
>>> X, Z = np.mgrid[-500:501:10., 9500:10501:10.]
>>> Y = np.zeros(X.shape)
>>> r = np.array([np.sqrt(X**2 + Z**2).flatten(),
>>>               np.arccos(Z / np.sqrt(X**2 + Z**2)).flatten(),
```

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```

>>> np.arctan2(Y, X).flatten())
>>> # instantiate CellGeometry class with cell's geometry
>>> cell_geometry = CellGeometry(x=np.c_[cell.xstart, cell.xend],
>>>                             y=np.c_[cell.ystart, cell.yend],
>>>                             z=np.c_[cell.zstart, cell.zend],
>>>                             d=cell.diam)
>>> # set up class object and compute mapping between segment currents
>>> # and electric potential in space
>>> sphere = OneSphereVolumeConductor(cell_geometry, r=r, R=10000.,
>>>                                   sigma_i=0.3, sigma_o=0.03)
>>> M = sphere.get_transformation_matrix(n_max=1000)
>>> # pick out some time index for the potential and compute potential
>>> ind = cell.tvec==2.
>>> V_ex = (M @ cell.imem)[: , ind].reshape(X.shape)
>>> # plot potential
>>> fig, ax = plt.subplots(1,1)
>>> zips = []
>>> for x, z in cell.get_idx_polygons(projection=('x', 'z')):
>>>     zips.append(list(zip(x, z)))
>>> polycol = PolyCollection(zips,
>>>                          edgecolors='none',
>>>                          facecolors='gray')
>>> vrange = 1E-3 # limits for color contour plot
>>> im=ax.contour(X, Z, V_ex,
>>>               levels=np.linspace(-vrange, vrange, 41))
>>> circle = plt.Circle(xy=(0,0), radius=sphere.R, fc='none', ec='k')
>>> ax.add_collection(polycol)
>>> ax.add_patch(circle)
>>> ax.axis(ax.axis('equal'))
>>> ax.set_xlim(X.min(), X.max())
>>> ax.set_ylim(Z.min(), Z.max())
>>> fig.colorbar(im, ax=ax)
>>> plt.show()

```

4.8 class LaminarCurrentSourceDensity

class lfpypykit.LaminarCurrentSourceDensity (cell, z, r)

Bases: lfpypykit.models.LinearModel

Facilitates calculations of the ground truth Current Source Density (CSD) in cylindrical volumes aligned with the z-axis based on [1] and [2].

The implementation assumes piecewise linear current sources similar to LineSourcePotential, and accounts for the fraction of each segment's length within each volume, see Eq. 11 in [2].

This class is a LinearModel subclass that defines a 2D linear response matrix **M** between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding CSD **C** (nA/μm³) as

$$\mathbf{C} = \mathbf{M}\mathbf{I}$$

The current **I** is an ndarray of shape (n_seg, n_tsteps) with unit (nA), and each row indexed by *j* of **C** represents the CSD in each volume for every time step as the sum of currents divided by the volume.

Parameters

cell: object or None CellGeometry instance or similar.

z: ndarray, dtype=float shape (n_volumes, 2) array of lower and upper edges of each volume along the z-axis in units of (μm). The lower edge value must be below the upper edge value.

r: ndarray, dtype=float shape (n_volumes,) array with assumed radius of each cylindrical volume. Each radius must be greater than zero, and in units of (μm)

Raises

AttributeError inputs z and r must be ndarrays of correct shape etc.

See also:

[*LinearModel*](#)

[*VolumetricCurrentSourceDensity*](#)

References

[1], [2]

Examples

Mock cell geometry and transmembrane currents:

```
>>> import numpy as np
>>> from lfpykit import CellGeometry, LaminarCurrentSourceDensity
>>> # cell geometry with three segments ( $\mu\text{m}$ )
>>> cell = CellGeometry(x=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                    y=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                    z=np.array([[0, 10], [10, 20], [20, 30]]),
>>>                    d=np.array([1, 1, 1]))
>>> # transmembrane currents, three time steps (nA)
>>> I_m = np.array([[0., -1., 1.], [-1., 1., 0.], [1., 0., -1.]])
>>> # define geometry (z - upper and lower boundary; r - radius)
>>> # of cylindrical volumes aligned with the z-axis ( $\mu\text{m}$ )
>>> z = np.array([[-10., 0.], [0., 10.], [10., 20.],
>>>               [20., 30.], [30., 40.]])
>>> r = np.array([100., 100., 100., 100., 100.])
>>> # instantiate electrode, get linear response matrix
>>> csd = LaminarCurrentSourceDensity(cell=cell, z=z, r=r)
>>> M = csd.get_transformation_matrix()
>>> # compute current source density [ $\text{nA}/\mu\text{m}^3$ ]
>>> M @ I_m
array([[ 0.00000000e+00,  0.00000000e+00,  0.00000000e+00],
       [ 0.00000000e+00, -3.18309886e-06,  3.18309886e-06],
       [-3.18309886e-06,  3.18309886e-06,  0.00000000e+00],
       [ 3.18309886e-06,  0.00000000e+00, -3.18309886e-06],
       [ 0.00000000e+00,  0.00000000e+00,  0.00000000e+00]])
```

get_transformation_matrix()

Get linear response matrix

Returns

response_matrix: ndarray shape (n_volumes, n_seg) ndarray

Raises

AttributeError if cell is None

4.9 class VolumetricCurrentSourceDensity

class lfpypykit.VolumetricCurrentSourceDensity (*cell, x=None, y=None, z=None, dl=1.0*)

Bases: lfpypykit.models.LinearModel

Facilitates calculations of the ground truth Current Source Density (CSD) across 3D volumetric grid with bin edges defined by parameters *x*, *y* and *z*.

The implementation assumes piecewise constant current sources similar to `LineSourcePotential`, and accounts for the fraction of each segment's length within each volume by counting the number of points representing partial segments with max length *dl* divided by the number of partial segments.

This class is a `LinearModel` subclass that defines a 4D linear response matrix **M** of shape (*x.size-1*, *y.size-1*, *z.size-1*, *n_seg*) between transmembrane current array **I** (nA) of a multicompartment neuron model and the corresponding CSD **C** (nA/μm³) as

$$\mathbf{C} = \mathbf{M}\mathbf{I}$$

The current **I** is an ndarray of shape (*n_seg*, *n_tsteps*) with unit (nA), and each row indexed by *j* of **C** represents the CSD in each bin for every time step as the sum of currents divided by the volume.

Parameters

cell: object or None `CellGeometry` instance or similar.

x, y, z: ndarray, dtype=float shape (n,) array of bin edges of each volume along each axis in units of (μm). Must be monotonously increasing.

dl: float discretization length of compartments before binning (μm). Default=1. Lower values will result in more accurate estimates as each line source gets split into more points.

See also:

[`LinearModel`](#)

[`LaminarCurrentSourceDensity`](#)

Notes

The resulting mapping **M** may be very sparse (i.e., mostly made up by zeros) and can be converted into a sparse array for more efficient multiplication for the same result:

```
>>> import scipy.sparse as ss
>>> M_csc = ss.csc_matrix(M.reshape((-1, M.shape[-1])))
>>> C = M_csc @ I_m
>>> np.all(C.reshape((M.shape[:-1] + (-1,))) == (M @ I_m))
True
```

Examples

Mock cell geometry and transmembrane currents:

```
>>> import numpy as np
>>> from lfpypykit import CellGeometry, VolumetricCurrentSourceDensity
>>> # cell geometry with three segments ( $\mu\text{m}$ )
>>> cell = CellGeometry(x=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                      y=np.array([[0, 0], [0, 0], [0, 0]]),
>>>                      z=np.array([[0, 10], [10, 20], [20, 30]]),
>>>                      d=np.array([1, 1, 1]))
>>> # transmembrane currents, three time steps (nA)
>>> I_m = np.array([[0., -1., 1.], [-1., 1., 0.], [1., 0., -1.]])
>>> # instantiate probe, get linear response matrix
>>> csd = VolumetricCurrentSourceDensity(cell=cell,
>>>                                       x=np.linspace(-20, 20, 5),
>>>                                       y=np.linspace(-20, 20, 5),
>>>                                       z=np.linspace(-20, 20, 5), dl=1.)
>>> M = csd.get_transformation_matrix()
>>> # compute current source density [ $\text{nA}/\mu\text{m}^3$ ]
>>> M @ I_m
array([[[[ 0.,  0.,  0.],
          [ 0.,  0.,  0.],
          [ 0.,  0.,  0.],
          [ 0.,  0.,  0.]],
        ...
```

`get_transformation_matrix()`

Get linear response matrix

Returns

response_matrix: ndarray shape (x.size-1, y.size-1, z.size-1, n_seg) ndarray

Raises

AttributeError if cell is None

MODULE `lfpykit.eegmegcalc`

Collection of classes defining forward models applicable with current dipole moment predictions.

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5.1 class `eegmegcalc.FourSphereVolumeConductor`

```
class lfpykit.eegmegcalc.FourSphereVolumeConductor(r_electrodes,      radii=[79000.0,  
                                           80000.0, 85000.0, 90000.0],  
                                           sigmas=[0.3, 1.5, 0.015, 0.3],  
                                           iter_factor=2.02020202020204e-  
                                           08)
```

Bases: `object`

Main class for computing extracellular potentials in a four-sphere volume conductor model that assumes homogeneous, isotropic, linear (frequency independent) conductivity within the inner sphere and outer shells. The conductance outside the outer shell is 0 (air).

This class implements the corrected 4-sphere model described in [1], [2]

Parameters

`r_electrodes`: `ndarray, dtype=float` Shape (n_contacts, 3) array containing n_contacts electrode locations in cartesian coordinates in units of (μm). All `r_el` in `r_electrodes` must be less than or equal to scalp radius and larger than the distance between dipole and sphere center: $|r_z| < r_{el} \leq radii[3]$.

`radii`: `list, dtype=float` Len 4 list with the outer radii in units of (μm) for the 4 concentric shells in the four-sphere model: brain, csf, skull and scalp, respectively.

`sigmas`: `list, dtype=float` Len 4 list with the electrical conductivity in units of (S/m) of the four shells in the four-sphere model: brain, csf, skull and scalp, respectively.

`iter_factor`: `float` iteration-stop factor

See also:

[`InfiniteVolumeConductor`](#)

[`MEG`](#)

References

[1], [2]

Examples

Compute extracellular potential from current dipole moment in four-sphere head model:

```
>>> from lfpypykit.eegmegcalc import FourSphereVolumeConductor
>>> import numpy as np
>>> radii = [79000., 80000., 85000., 90000.] # ( $\mu\text{m}$ )
>>> sigmas = [0.3, 1.5, 0.015, 0.3] # (S/m)
>>> r_electrodes = np.array([[0., 0., 90000.], [0., 85000., 0.]]) # ( $\mu\text{m}$ )
>>> sphere_model = FourSphereVolumeConductor(r_electrodes, radii,
>>>                                         sigmas)
>>> # current dipole moment
>>> p = np.array([[10.]*10, [10.]*10, [10.]*10]) # 10 timesteps (nA  $\mu\text{m}$ )
>>> dipole_location = np.array([0., 0., 78000.]) # ( $\mu\text{m}$ )
>>> # compute potential
>>> sphere_model.calc_potential(p, dipole_location) # (mV)
array([[1.06247669e-08, 1.06247669e-08, 1.06247669e-08, 1.06247669e-08,
        1.06247669e-08, 1.06247669e-08, 1.06247669e-08, 1.06247669e-08,
        1.06247669e-08, 1.06247669e-08],
       [2.39290752e-10, 2.39290752e-10, 2.39290752e-10, 2.39290752e-10,
        2.39290752e-10, 2.39290752e-10, 2.39290752e-10, 2.39290752e-10,
        2.39290752e-10, 2.39290752e-10]])
```

get_dipole_potential (*p*, *dipole_location*)

Return electric potential from current dipole moment *p* in location *dipole_location* in locations *r_electrodes*

Parameters

p: **ndarray, dtype=float** Shape (3, *n_timesteps*) array containing the x,y,z components of the current dipole moment in units of (nA* μm) for all timesteps.

dipole_location: **ndarray, dtype=float** Shape (3,) array containing the position of the current dipole in cartesian coordinates. Units of (μm).

Returns

potential: **ndarray, dtype=float** Shape (*n_contacts*, *n_timesteps*) array containing the electric potential at contact point(s) *FourSphereVolumeConductor.r* in units of (mV) for all timesteps of current dipole moment *p*.

get_transformation_matrix (*dipole_location*)

Get linear response matrix mapping current dipole moment in (nA μm) located in location *r_z* to extracellular potential in (mV) at recording sites *FourSphereVolumeConductor.r*. (μm)

Parameters

dipole_location: **ndarray, dtype=float** Shape (3,) array containing the position of the current dipole in cartesian coordinates. Units of (μm).

Returns

response_matrix: **ndarray** shape (*n_contacts*, 3) ndarray

5.2 class `eegmegcalc.InfiniteVolumeConductor`

class `lfpypykit.eegmegcalc.InfiniteVolumeConductor` (*sigma=0.3*)

Bases: `object`

Main class for computing extracellular potentials with current dipole moment \mathbf{P} in an infinite 3D volume conductor model that assumes homogeneous, isotropic, linear (frequency independent) conductivity σ . The potential V is computed as [1]:

$$V = \frac{\mathbf{P} \cdot \mathbf{r}}{4\pi\sigma r^3}$$

Parameters

sigma: float Electrical conductivity in extracellular space in units of (S/cm)

See also:

`FourSphereVolumeConductor`

MEG

References

[1]

Examples

Computing the potential from dipole moment valid in the far field limit.

```
>>> from lfpypykit.eegmegcalc import InfiniteVolumeConductor
>>> import numpy as np
>>> inf_model = InfiniteVolumeConductor(sigma=0.3)
>>> p = np.array([[10.], [10.], [10.]]) # (nA * μm)
>>> r = np.array([[1000., 0., 5000.]]) # (μm)
>>> inf_model.get_dipole_potential(p, r) # (mV)
array([[1.20049432e-07]])
```

get_dipole_potential (*p*, *r*)

Return electric potential from current dipole moment *p* in locations *r* relative to dipole

Parameters

p: ndarray, dtype=float Shape (3, *n_timesteps*) array containing the x,y,z components of the current dipole moment in units of (nA*μm) for all timesteps

r: ndarray, dtype=float Shape (*n_contacts*, 3) array containing the displacement vectors from dipole location to measurement location

Returns

potential: ndarray, dtype=float Shape (*n_contacts*, *n_timesteps*) array containing the electric potential at contact point(s) *r* in units of (mV) for all timesteps of current dipole moment *p*

get_transformation_matrix (*r*)

Get linear response matrix mapping current dipole moment in (nA μm) to extracellular potential in (mV) at recording sites *r* (μm)

Parameters

r: `ndarray, dtype=float` Shape (n_contacts, 3) array containing the displacement vectors from dipole location to measurement location (μm)

Returns

response_matrix: `ndarray` shape (n_contacts, 3) `ndarray`

5.3 class `eegmegcalc.MEG`

class `lfpypykit.eegmegcalc.MEG`(*sensor_locations*, *mu*=`1.2566370614359173e-06`)

Bases: `object`

Basic class for computing magnetic field from current dipole moment. For this purpose we use the Biot-Savart law derived from Maxwell's equations under the assumption of negligible magnetic induction effects [1]:

$$\mathbf{H} = \frac{\mathbf{p} \times \mathbf{R}}{4\pi R^3}$$

where \mathbf{p} is the current dipole moment, \mathbf{R} the vector between dipole source location and measurement location, and $R = |\mathbf{R}|$

Note that the magnetic field \mathbf{H} is related to the magnetic field \mathbf{B} as

$$\mu_0 \mathbf{H} = \mathbf{B} - \mathbf{M}$$

where μ_0 is the permeability of free space (very close to permeability of biological tissues). \mathbf{M} denotes material magnetization (also ignored)

Parameters

sensor_locations: `ndarray, dtype=float` shape (n_locations x 3) array with x,y,z-locations of measurement devices where magnetic field of current dipole moments is calculated. In unit of (μm)

mu: `float` Permeability. Default is permeability of vacuum ($\mu_0 = 4 * \pi * 10^{-7} \text{ T}\cdot\text{m/A}$)

Raises

AssertionError If dimensionality of `sensor_locations` is wrong

See also:

`FourSphereVolumeConductor`

`InfiniteVolumeConductor`

References

[1]

Examples

Define cell object, create synapse, compute current dipole moment:

```
>>> import LFPy, os, numpy as np, matplotlib.pyplot as plt
>>> from lfpypykit import CurrentDipoleMoment
>>> from lfpypykit.eegmegcalc import MEG
>>> # create LFPy.Cell object
>>> cell = LFPy.Cell(morphology=os.path.join(LFPy.__path__[0], 'test',
>>>                                         'ball_and_sticks.hoc'),
>>>                  passive=True)
>>> cell.set_pos(0., 0., 0.)
>>> # create single synaptic stimuli at soma (idx=0)
>>> syn = LFPy.Synapse(cell, idx=0, syntype='ExpSyn', weight=0.01, tau=5,
>>>                  record_current=True)
>>> syn.set_spike_times_w_netstim()
>>> # simulate, record current dipole moment
>>> cell.simulate(rec_imem=True)
>>> # Compute current dipole moment
>>> cdp = CurrentDipoleMoment(cell=cell)
>>> M_cdp = cdp.get_transformation_matrix()
>>> current_dipole_moment = M_cdp @ cell.imem
>>> # Compute the dipole location as an average of segment locations
>>> # weighted by membrane area:
>>> dipole_location = (cell.area * np.c_[cell.x.mean(axis=-1),
>>>                                     cell.y.mean(axis=-1),
>>>                                     cell.z.mean(axis=-1)].T
>>>                  / cell.area.sum()).sum(axis=1)
>>> # Define sensor site, instantiate MEG object, get transformation matrix
>>> sensor_locations = np.array([[1E4, 0, 0]])
>>> meg = MEG(sensor_locations)
>>> M = meg.get_transformation_matrix(dipole_location)
>>> # compute the magnetic signal in a single sensor location:
>>> H = M @ current_dipole_moment
>>> # plot output
>>> plt.figure(figsize=(12, 8), dpi=120)
>>> plt.subplot(311)
>>> plt.plot(cell.tvec, cell.somav)
>>> plt.ylabel(r'$V_{soma}$ (mV)')
>>> plt.subplot(312)
>>> plt.plot(cell.tvec, syn.i)
>>> plt.ylabel(r'$I_{syn}$ (nA)')
>>> plt.subplot(313)
>>> plt.plot(cell.tvec, H[0].T)
>>> plt.ylabel(r'$H$ (nA/um)')
>>> plt.xlabel('$t$ (ms)')
>>> plt.legend(['$H_x$', '$H_y$', '$H_z$'])
>>> plt.show()
```

calculate_H(current_dipole_moment, dipole_location)

Compute magnetic field H from single current-dipole moment localized somewhere in space

Parameters

current_dipole_moment: ndarray, dtype=float shape (3, n_timesteps) array with x,y,z-components of current- dipole moment time series data in units of (nA μm)

dipole_location: ndarray, dtype=float shape (3,) array with x,y,z-location of dipole in units of (μm)

Returns

ndarray, dtype=float shape (n_locations x 3 x n_timesteps) array with x,y,z-components of the magnetic field **H** in units of (nA/μm)

Raises

AssertionError If dimensionality of current_dipole_moment and/or dipole_location is wrong

get_transformation_matrix(dipole_location)

Get linear response matrix mapping current dipole moment in (nA μm) located in location dipole_location to magnetic field **H** in units of (nA/μm) at sensor_locations

Parameters

dipole_location: ndarray, dtype=float shape (3,) array with x,y,z-location of dipole in units of (μm)

Returns

response_matrix: ndarray shape (n_contacts, 3, 3) ndarray

5.4 class eegmegcalc.NYHeadModel

class lfpypykit.eegmegcalc.NYHeadModel (nyhead_file=None)

Bases: object

Main class for computing EEG signals from current dipole moment **P** in New York Head Model [1], [2]

Assumes units of nA * um for current dipole moment, and mV for the EEG

Parameters

nyhead_file: str [optional] Location of file containing New York Head Model. If empty (or None), it will be looked for in the main LFPykit folder. If not present the user is asked if it should be downloaded from https://www.parralab.org/nyhead/sa_nyhead.mat

See also:

FourSphereVolumeConductor

MEG

Notes

The original unit of the New York model current dipole moment is (probably?) mA*m, and the EEG output unit is V. LFPykit's current dipole moments have units nA*um, and EEGs from the NYhead model is here recomputed in units of mV.

References

[1], [2]

Examples

Computing EEG from dipole moment.

```
>>> from lfpypykit.eegmegcalc import NYHeadModel
```

```
>>> nyhead = NYHeadModel()
```

```
>>> nyhead.set_dipole_pos('parietal_lobe') # predefined example location
>>> M = nyhead.get_transformation_matrix()
```

```
>>> # Rotate to be along normal vector of cortex
>>> p = nyhead.rotate_dipole_to_surface_normal([[0.], [0.], [1.]])
>>> eeg = M @ p # (mV)
```

find_closest_electrode()

Returns minimal distance (mm) and closest electrode idx to dipole location specified in self.dipole_pos.

get_transformation_matrix()

Get linear response matrix mapping from current dipole moment (nA μ m) to EEG signal (mV) at EEG electrodes (n=231)

Returns

response_matrix: ndarray shape (231, 3) ndarray

return_closest_idx(pos)

Returns the index of the closest vertex in the brain to a given position (in mm).

Parameters

pos [array of length (3)] [x, y, z] of a location in the brain, given in mm, and not in μ m which is the default position unit in LFPy

Returns

idx [int] Index of the vertex in the brain that is closest to the given location

rotate_dipole_to_surface_normal(p, orig_ax_vec=[0, 0, 1])

Returns rotated dipole moment, p_rot, oriented along the normal vector of the cortex at the dipole location

Parameters

p [np.ndarray of size (3, num_timesteps)] Current dipole moment from neural simulation, [p_x(t), p_y(t), p_z(t)]. If z-axis is the depth axis of cortex in the original neural simulation p_x(t) and p_y(t) will typically be small, and orig_ax_vec = [0, 0, 1].

orig_ax_vec [np.ndarray or list of length (3)] Original surface vector of cortex in the neural simulation. If depth axis of cortex is the z-axis, orig_ax_vec = [0, 0, 1].

Returns

p_rot [np.ndarray of size (3, num_timesteps)] Rotated current dipole moment, oriented along cortex normal vector at the dipole location

References

See: https://en.wikipedia.org/wiki/Rotation_matrix under “Rotation matrix from axis and angle”

set_dipole_pos (*dipole_pos=None*)

Sets the dipole location in the brain

Parameters

dipole_pos: None, str or array of length (3) [x, y, z] (mm) Location of the dipole. If no argument is given (or `dipole_pos=None`), a location, ‘`motorsensory_cortex`’, from `self.dipole_pos_dict` is used. If `dipole_pos` is an array of length 3, the closest vertex in the brain will be set as the dipole location.

INDICES AND TABLES

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