

## GW Analysis Tools

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# Chapter 1

## Gravitational Waves Analysis Tools

A suite of analysis tools useful for gravitational wave science. All code is written in C++, with some of the interface classes wrapped in Cython to allow for python-access.

### 1.1 Compatibility

Known to work with gcc/g++-7

Known to work with gcc/g++-9

Need nvcc – known to work with v9.1 of CUDA

### 1.2 Required Software

Required non-standard C libraries: FFTW3 ADOL-C – (must be compiled with OpenMP option) GSL CUDA

Required non-standard Python packages: Cython

Required non-standard packages for documentation: Doxygen

### 1.3 Current Development

NOTE: currently using static parameters to share data between threads for [mcmc\\_gw.cpp](#). This could cause issues when running multiple samplers at the same time. Investigating further.

To do:

Change MCMC\_MH to use the more general threadPool class instead of a custom threadpool, incorporate job class and comparator

## 1.4 Installation

For proper compilation, update or create the environment variables CPATH, LIBRARY\_PATH, and LD\_LIBRARY\_PATH, which should point to header files and lib files, respectively. Specifically, these variables should point to the above libraries.

Also, the PYTHONPATH environment variables must point to /gw\_analysis\_tools\_py/src because I can't figure how to get this shit to work.

In the root directory of the project, run 'make' to compile source files, create the library file and create the cython modules, and create the documentation.

To just create C++/C files, run 'make c'.

Run 'make test' to build a test program that will create an executable.

## 1.5 Supported Functionality

### 1.5.1 Waveform Generation

IMRPhenomD, IMRPhenomPv2

### 1.5.2 Modified Gravity

ppE\_IMRPhenomD\_Inspiral ppE\_IMRPhenomD\_IMR ppE\_IMRPhenomPv2\_Inspiral ppE\_IMRPhenomPv2\_IMR

### 1.5.3 Fisher Analysis

utilizes the above waveform templates

### 1.5.4 MCMC Routines

Has a generic MCMC sampler, MCMC\_MH, that utilizes gaussian steps, differential evolution steps, and Fisher informed steps. Includes wrapping MCMC\_MH\_GW for GW specific sampling, currently only for one detector.

Includes log likelihood calculation for implementation in other samplers.

## 1.6 Usage

### 1.6.1 Environment variables

The environment variable PYTHONPATH should include the directory \$(PROJECT\_DIR)

### 1.6.2 Include

To include header files, use `-I$(PROJECT_DIRECTORY)/include`

### 1.6.3 Link

To link object files, use `-L$(PROJECT_DIRECTORY)/lib -lgwat` (the `-L` command is un-needed if you add `/lib` to the environment variable `CPATH`)

For dynamic linking, the following environment variables for Linux (MacOs) should be updated to include `/lib` – `LD_LIBRARY_PATH` (`DYLD_LIBRARY_PATH`)

For Cuda code: use `-lcuda -lcudart`

For Cuda, may need to link to `/usr/local/cuda/lib64/` (or wherever this library is on your machine)

### 1.6.4 Python Importable Code

Two modules currently available:

#### 1.6.4.1 `gw_analysis_tools_py.mcmc_routines_ext`

`mcmc_routines_ext.pyx` wraps the `log_likelihood` functions in `mcmc_routines.cpp`

#### 1.6.4.2 `gw_analysis_tools_py.waveform_generator_ext`

`waveform_generator_ext.pyx` wraps the `fourier_waveform` function in `waveform_generator.cpp`

Also contains the SNR calculation function

#### 1.6.4.3 Custom Waveforms

If adding waveforms and to have full accesibility:

Create class, using other waveforms as template – need interface to create full waveform (plus,cross polarization), and amplitude/phase

Add the option as a waveform to `waveform_generation.cpp`, including the header file at the top of the `waveform_↔ generation.cpp` file

For autodiff Fishers – write the class as a template with double and adouble types for all variables. Then write the necessary fisher subroutines (see fisher file to determine whats necessary)

For numerical Fishers – write finite difference method, following the template of the previous waveforms

For MCMC sampling – write `mcmc_fisher_wrapper` and `mcmc_likelihood_wrapper` options and write any necessary initialization in `MCMC_MH_GW`

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## Chapter 2

# gw\_analysis\_tools

A suite of tools useful for doing statistical studies on gravitational wave science, including routines useful in MC↔ MC studies, wave template generation, Fisher analysis, etc. Written in C++ and wrapped in Cython for access in Python.



## Chapter 3

# Namespace Index

### 3.1 Namespace List

Here is a list of all documented namespaces with brief descriptions:

<a href="#">waveform_generator_ext</a>	
Python wrapper for the waveform generation in <a href="#">waveform_generator.cpp</a>	13





## Chapter 4

# Class Index

### 4.1 Class List

Here are the classes, structs, unions and interfaces with brief descriptions:

<a href="#">Comparator</a>	
Class to facilitate the comparing of chains for priority	15
<a href="#">Comparatorswap</a>	15
<a href="#">mcmc_routines_ext.fft_w_outline_py</a>	16
<a href="#">waveform_generator_ext.gen_params_py</a>	
Python wrapper for the generation parameters structure, as defined in <a href="#">util.cpp</a>	16
<a href="#">ThreadPool</a>	16



## Chapter 5

# File Index

### 5.1 File List

Here is a list of all documented files with brief descriptions:

gw_analysis_tools_py/src/ <a href="#">mcmc_routines_ext.pyx</a>	
File that wraps the code in <a href="#">mcmc_gw.cpp</a> , <a href="#">mcmc_sampler.cpp</a> , <a href="#">mcmc_sampler_internals.cpp</a> , <a href="#">autocorrelation.cpp</a>	17
gw_analysis_tools_py/src/ <a href="#">waveform_generator_ext.pyx</a>	
File that contains cython code to wrap the c++ library	17
src/ <a href="#">autocorrelation.cpp</a>	18
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src/ <a href="#">detector_util.cpp</a>	29
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## Chapter 6

# Namespace Documentation

### 6.1 waveform\_generator\_ext Namespace Reference

Python wrapper for the waveform generation in [waveform\\_generator.cpp](#).

#### Classes

- class [gen\\_params\\_py](#)

*Python wrapper for the generation parameters structure, as defined in [util.cpp](#).*

#### Functions

- def **double** (self, double, mass1, double, mass2, double, DL, spin1, spin2, double, phic, double, tc, :1] bppe, double[:1] betappe, int Nmod, double theta, double phi, double incl\_angle, double f\_ref, double phiRef, bool NSflag):self.params.mass1=mass1 self.params.mass2=mass2 self.params.Luminosity←\_Distance=DL self.params.spin1=spin1 self.params.spin2=spin2 self.params.phic=phic self.params.tc=tc self.params.bppe=&bppe[0] self.params.betappe=&betappe[0] self.params.Nmod=Nmod self.params.incl←\_angle=incl\_angle self.params.theta=theta self.params.phi=phi self.params.f\_ref=f\_ref self.params.phi←\_Ref=phiRef self.params.NSflag=NSflag ##Computes the waveform in Fourier space # @param frequen-  
cies The array of frequencies to use # @param generation\_method Method to use for the waveform  
generation # @param [gen\\_params\\_py](#) Parameters of the binary def fourier\_waveform\_py(double[:1] fre-  
quencies, string generation\_method, [gen\\_params\\_py](#) parameters):cdef double[:1] waveform\_real=np.←  
ascontiguousarray(np.zeros((frequencies.size) int, dtype=np.float64)
- def **double** (:1] frequencies, string generation\_method, [gen\\_params\\_py](#) parameters):cdef double[:1]  
amplitude=np.ascontiguousarray(np.zeros((frequencies.size) double, dtype=np.float64, frequencies, frequen-  
cies, size, amplitude, generation\_method, parameters, :1] frequencies, string generation\_method,  
[gen\\_params\\_py](#) parameters):cdef double[:1] phase=np.ascontiguousarray(np.zeros((frequencies.size) dou-  
ble, dtype=np.float64, frequencies, frequencies, size, phase, generation\_method, parameters, :1]  
frequencies, string generation\_method, [gen\\_params\\_py](#) parameters):cdef double[:1] waveform\_plus\_←  
real=np.ascontiguousarray(np.zeros((frequencies.size) double, dtype=np.float64)

#### Variables

- **complex128\_t**
- **ndim**
- **waveform**
- **dtype**
- **i = i + 1**

#### 6.1.1 Detailed Description

Python wrapper for the waveform generation in [waveform\\_generator.cpp](#).



## Chapter 7

# Class Documentation

### 7.1 Comparator Class Reference

Class to facilitate the comparing of chains for priority.

#### Public Member Functions

- bool **operator()** (int i, int j)

#### 7.1.1 Detailed Description

Class to facilitate the comparing of chains for priority.

3 levels of priority: 0 (high) 1 (default) 2 (low)

The documentation for this class was generated from the following file:

- src/[mcmc\\_sampler.cpp](#)

### 7.2 Comparatorswap Class Reference

#### Public Member Functions

- bool **operator()** (int i, int j)

The documentation for this class was generated from the following file:

- src/[mcmc\\_sampler.cpp](#)

## 7.3 `mcmc_routines_ext.fft_w_outline_py` Class Reference

### Public Member Functions

- `def __init__ (self, N)`
- `def __reduce__ (self)`

### Public Attributes

- **N**

The documentation for this class was generated from the following file:

- `gw_analysis_tools_py/src/mcmc_routines_ext.pyx`

## 7.4 `waveform_generator_ext.gen_params_py` Class Reference

Python wrapper for the generation parameters structure, as defined in [util.cpp](#).

### 7.4.1 Detailed Description

Python wrapper for the generation parameters structure, as defined in [util.cpp](#).

The documentation for this class was generated from the following file:

- `gw_analysis_tools_py/src/waveform_generator_ext.pyx`

## 7.5 `ThreadPool` Class Reference

### Public Member Functions

- **ThreadPool** (`std::size_t numThreads`)
- void **enqueue** (`int i`)
- void **enqueue\_swap** (`int i`)
- void **public\_stop** ()

The documentation for this class was generated from the following file:

- `src/mcmc_sampler.cpp`



## Chapter 8

# File Documentation

### 8.1 `gw_analysis_tools_py/src/mcmc_routines_ext.pyx` File Reference

File that wraps the code in [mcmc\\_gw.cpp](#), [mcmc\\_sampler.cpp](#), [mcmc\\_sampler\\_internals.cpp](#), [autocorrelation.cpp](#).

#### Classes

- class [mcmc\\_routines\\_ext.fftw\\_outline\\_py](#)

#### Functions

- def **mcmc\_routines\_ext.write\_auto\_corr\_file\_from\_data\_file\_py** (string, autocorr\_filename, string, datafile, int, length, int, dimension, int, num\_segments, double, target\_corr, int, num\_threads)
- def **mcmc\_routines\_ext.arange** (string, autocorr\_filename, :1] data, int length, int dimension, int num\_↵ segments, double target\_corr, int num\_threads):#Not ideal -- have to wrap the memview in a real c++array  
cdef double \*\*temparr=< double \*\* >malloc(sizeof(double \*double, length)
- def **mcmc\_routines\_ext.allocate\_FFTW\_mem\_forward\_py** (fftw\_outline\_py, plan, int, length)
- def **mcmc\_routines\_ext.deallocate\_FFTW\_mem\_py** (fftw\_outline\_py, plan)

#### 8.1.1 Detailed Description

File that wraps the code in [mcmc\\_gw.cpp](#), [mcmc\\_sampler.cpp](#), [mcmc\\_sampler\\_internals.cpp](#), [autocorrelation.cpp](#).

### 8.2 `gw_analysis_tools_py/src/waveform_generator_ext.pyx` File Reference

File that contains cython code to wrap the c++ library.

#### Classes

- class [waveform\\_generator\\_ext.gen\\_params\\_py](#)  
*Python wrapper for the generation parameters structure, as defined in [util.cpp](#).*

## Namespaces

- [waveform\\_generator\\_ext](#)

Python wrapper for the waveform generation in [waveform\\_generator.cpp](#).

## Functions

- def **waveform\_generator\_ext.double** (self, double, mass1, double, mass2, double, DL, spin1, spin2, double, phic, double, tc, :1] bppe, double[:1] betappe, int Nmod, double theta, double phi, double incl\_angle, double f\_ref, double phiRef, bool NSflag):self.params.mass1=mass1 self.params.mass2=mass2 self.params.Luminosity\_Distance=DL self.params.spin1=spin1 self.params.spin2=spin2 self.params.phic=phic self.params.tc=tc self.params.bppe=&bppe[0] self.params.betappe=&betappe[0] self.params.Nmod=Nmod self.params.incl\_angle=incl\_angle self.params.theta=theta self.params.phi=phi self.params.f\_ref=f\_ref self.params.phiRef=phiRef self.params.NSflag=NSflag ##Computes the waveform in Fourier space # @param frequencies The array of frequencies to use # @param generation\_method Method to use for the waveform generation # @param gen\_params\_py Parameters of the binary def fourier\_waveform\_py(double[:1] frequencies, string generation\_method, gen\_params\_py parameters):cdef double[:1] waveform\_real=np.ascontiguousarray(np.zeros((frequencies.size) int, dtype=np.float64)
- def **waveform\_generator\_ext.double** (:1] frequencies, string generation\_method, gen\_params\_py parameters):cdef double[:1] amplitude=np.ascontiguousarray(np.zeros((frequencies.size) double, dtype=np.float64, frequencies, frequencies, size, amplitude, generation\_method, parameters, params, :1] frequencies, string generation\_method, gen\_params\_py parameters):cdef double[:1] phase=np.ascontiguousarray(np.zeros((frequencies.size) double, dtype=np.float64, frequencies, frequencies, size, phase, generation\_method, parameters, params, :1] frequencies, string generation\_method, gen\_params\_py parameters):cdef double[:1] waveform\_plus\_real=np.ascontiguousarray(np.zeros((frequencies.size) double, dtype=np.float64)

## Variables

- **waveform\_generator\_ext.complex128\_t**
- **waveform\_generator\_ext.ndim**
- **waveform\_generator\_ext.waveform**
- **waveform\_generator\_ext.dtype**
- **waveform\_generator\_ext.i = i + 1**

### 8.2.1 Detailed Description

File that contains cython code to wrap the c++ library.

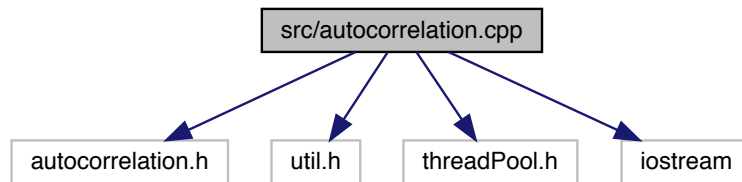
## 8.3 README.dox File Reference

## 8.4 src/autocorrelation.cpp File Reference

```
#include "autocorrelation.h"
#include "util.h"
#include "threadPool.h"
```

```
#include <iostream>
```

Include dependency graph for autocorrelation.cpp:



## Macros

- `#define MAX_SERIAL 200000`

## Functions

- void [write\\_auto\\_corr\\_file\\_from\\_data\\_file](#) (std::string autocorr\_filename, std::string datafile, int length, int dimension, int num\_segments, double target\_corr, int num\_threads)
- void [write\\_auto\\_corr\\_file\\_from\\_data](#) (std::string autocorr\_filename, double \*\*data, int length, int dimension, int num\_segments, double target\_corr, int num\_threads)
 

*Writes the autocorrelation file from a data array.*
- void [auto\\_corr\\_from\\_data](#) (double \*\*data, int length, int dimension, int \*\*output, int num\_segments, double target\_corr, int num\_threads)
 

*Calculates the autocorrelation length for a set of data for a number of segments for each dimension – completely host code, utilizes FFTW3 for longer chunks of the chains.*
- void [threaded\\_ac\\_spectral](#) (int thread, threaded\_ac\_jobs\_fft job)
 

*Internal routine to calculate an spectral autocorrelation job.*
- void [threaded\\_ac\\_serial](#) (int thread, threaded\_ac\_jobs\_serial job)
 

*Internal routine to calculate an serial autocorrelation job.*
- double [auto\\_correlation\\_serial](#) (double \*arr, int length, int start, double target)
 

*Calculates the autocorrelation of a chain with the brute force method.*
- void [auto\\_correlation\\_spectral](#) (double \*chain, int length, double \*autocorr, fftw\_outline \*plan\_forw, fftw\_outline \*plan\_rev)
 

*Wrapper function for convenience – assumes the data array starts at 0.*
- void [auto\\_correlation\\_spectral](#) (double \*chain, int length, int start, double \*autocorr, fftw\_outline \*plan\_forw, fftw\_outline \*plan\_rev)
 

*Faster approximation of the autocorrelation of a chain. Implements FFT/IFFT – accepts FFTW plan as argument for plan reuse and multi-threaded applications.*
- void [auto\\_correlation\\_spectral](#) (double \*chain, int length, double \*autocorr)
 

*Faster approximation of the autocorrelation of a chain. Implements FFT/IFFT.*
- double [auto\\_correlation](#) (double \*arr, int length, double tolerance)
 

*OUTDATED – numerically finds autocorrelation length – not reliable.*
- double [auto\\_correlation\\_serial\\_old](#) (double \*arr, int length)
 

*OUTDATED Calculates the autocorrelation – less general version.*
- double [auto\\_correlation\\_grid\\_search](#) (double \*arr, int length, int box\_num, int final\_length, double target\_length)

- OUTDATED – Grid search method of computing the autocorrelation – unreliable.*
- double [auto\\_correlation\\_internal](#) (double \*arr, int length, int lag, double ave)  
*Internal function to compute the auto correlation for a given lag.*
- void [auto\\_corr\\_intervals\\_outdated](#) (double \*data, int length, double \*output, int num\_segments, double accuracy)  
*Function that computes the autocorrelation length on an array of data at set intervals to help determine convergence.*
- void [write\\_auto\\_corr\\_file\\_from\\_data](#) (std::string auto\_corr\_filename, double \*\*output, int intervals, int dimension, int N\_steps)  
*OUTDATED – writes autocorrelation lengths for a data array, but only with the serial method and only for a target correlation of .01.*
- void [write\\_auto\\_corr\\_file\\_from\\_data\\_file](#) (std::string auto\_corr\_filename, std::string output\_file, int intervals, int dimension, int N\_steps)  
*OUTDATED – writes autocorrelation lengths for a data file, but only with the serial method and only for a target correlation of .01.*

### 8.4.1 Detailed Description

Turns out calculating the autocorrelation is more complicated if you want to do it fast, so it gets its own file now

### 8.4.2 Macro Definition Documentation

#### 8.4.2.1 MAX\_SERIAL

```
#define MAX_SERIAL 200000
```

Max length of array to use serial calculation

### 8.4.3 Function Documentation

#### 8.4.3.1 auto\_corr\_from\_data()

```
void auto_corr_from_data (
    double ** data,
    int length,
    int dimension,
    int ** output,
    int num_segments,
    double target_corr,
    int num_threads )
```

Calculates the autocorrelation length for a set of data for a number of segments for each dimension – completely host code, utilizes FFTW3 for longer chunks of the chains.

Takes in the data from a sampler, shape data[N\_steps][dimension]

Outputs lags that correspond to the target\_corr – shape output[dimension][num\_segments]

## Parameters

	<i>data</i>	Input data
	<i>length</i>	length of input data
	<i>dimension</i>	dimension of data
out	<i>output</i>	array that stores the auto-corr lengths – array[num_segments]
	<i>num_segments</i>	number of segments to compute the auto-corr length
	<i>target_corr</i>	Autocorrelation for which the autocorrelation length is defined (lag of autocorrelation for which it equals the target_corr)
	<i>num_threads</i>	Total number of threads to use

## 8.4.3.2 auto\_corr\_intervals\_outdated()

```
void auto_corr_intervals_outdated (
    double * data,
    int length,
    double * output,
    int num_segments,
    double accuracy )
```

Function that computes the autocorrelation length on an array of data at set intervals to help determine convergence.

outdated version – new version uses FFTs

## Parameters

	<i>data</i>	Input data
	<i>length</i>	length of input data
out	<i>output</i>	array that stores the auto-corr lengths – array[num_segments]
	<i>num_segments</i>	number of segments to compute the auto-corr length
	<i>accuracy</i>	longer chains are computed numerically, this specifies the tolerance

## 8.4.3.3 auto\_correlation\_grid\_search()

```
double auto_correlation_grid_search (
    double * arr,
    int length,
    int box_num,
    int final_length,
    double target_length )
```

OUTDATED – Grid search method of computing the autocorrelation – unreliable.

Hopefully more reliable than the box-search method, which can sometimes get caught in a recursive loop when the stepsize isn't tuned, but also faster than the basic linear, serial search

**Parameters**

<i>arr</i>	Input array to use for autocorrelation
<i>length</i>	Length of input array
<i>box_num</i>	number of boxes to use for each iteration, default is 10
<i>final_length</i>	number of elements per box at which the grid search ends and the serial calculation begins
<i>target_length</i>	target correlation that corresponds to the returned lag

**8.4.3.4 auto\_correlation\_internal()**

```
double auto_correlation_internal (
    double * arr,
    int length,
    int lag,
    double ave )
```

Internal function to compute the auto correlation for a given lag.

**8.4.3.5 auto\_correlation\_serial()**

```
double auto_correlation_serial (
    double * arr,
    int length,
    int start,
    double target )
```

Calculates the autocorrelation of a chain with the brute force method.

**Parameters**

<i>arr</i>	input array
<i>length</i>	Length of input array
<i>start</i>	starting index (probably 0)
<i>target</i>	Target autocorrelation for which "length" is defined

**8.4.3.6 auto\_correlation\_spectral()** [1/2]

```
void auto_correlation_spectral (
    double * chain,
    int length,
    int start,
    double * autocorr,
```

```
    fftw_outline * plan_forw,
    fftw_outline * plan_rev )
```

Faster approximation of the autocorrelation of a chain. Implements FFT/IFFT – accepts FFTW plan as argument for plan reuse and multi-threaded applications.

Based on the Wiener-Khinchin Theorem.

Algorithm used from <https://lingpipe-blog.com/2012/06/08/autocorrelation-fft-kiss-eigen/>

*NOTE* the length used in initializing the fftw plans should be  $L = \text{pow}(2, \text{std::ceil}(\text{std::log2}(\text{length})))$  – the plans are padded so the total length is a power of two

Option to provide starting index for multi-dimension arrays in collapsed to one dimension

length is the length of the segment to be analyzed, not necessarily the dimension of the chain

#### 8.4.3.7 auto\_correlation\_spectral() [2/2]

```
void auto_correlation_spectral (
    double * chain,
    int length,
    double * autocorr )
```

Faster approximation of the autocorrelation of a chain. Implements FFT/IFFT.

Based on the Wiener-Khinchin Theorem.

Algorithm used from <https://lingpipe-blog.com/2012/06/08/autocorrelation-fft-kiss-eigen/>

#### 8.4.3.8 threaded\_ac\_serial()

```
void threaded_ac_serial (
    int thread,
    threaded_ac_jobs_serial job )
```

Internal routine to calculate an serial autocorrelation job.

Allows for a more efficient use of the threadPool class

#### 8.4.3.9 threaded\_ac\_spectral()

```
void threaded_ac_spectral (
    int thread,
    threaded_ac_jobs_fft job )
```

Internal routine to calculate an spectral autocorrelation job.

Allows for a more efficient use of the threadPool class

#### 8.4.3.10 write\_auto\_corr\_file\_from\_data()

```
void write_auto_corr_file_from_data (
    std::string autocorr_filename,
    double ** data,
    int length,
    int dimension,
    int num_segments,
    double target_corr,
    int num_threads )
```

Writes the autocorrelation file from a data array.

**Parameters**

<i>autocorr_filename</i>	Name of the file to write the autocorrelation to
<i>data</i>	Input chains
<i>length</i>	length of input data
<i>dimension</i>	dimension of data
<i>num_segments</i>	number of segments to compute the auto-corr length
<i>target_corr</i>	Autocorrelation for which the autocorrelation length is defined (lag of autocorrelation for which it equals the target_corr)
<i>num_threads</i>	Total number of threads to use

**8.4.3.11 write\_auto\_corr\_file\_from\_data\_file()**

```
void write_auto_corr_file_from_data_file (
    std::string autocorr_filename,
    std::string datafile,
    int length,
    int dimension,
    int num_segments,
    double target_corr,
    int num_threads )
```

**Parameters**

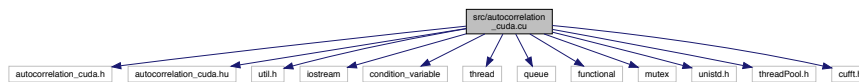
<i>length</i>	length of input data
<i>dimension</i>	dimension of data
<i>num_segments</i>	number of segments to compute the auto-corr length
<i>target_corr</i>	Autocorrelation for which the autocorrelation length is defined (lag of autocorrelation for which it equals the target_corr)
<i>num_threads</i>	Total number of threads to use

**8.5 src/autocorrelation\_cuda.cu File Reference**

```
#include "autocorrelation_cuda.h"
#include "autocorrelation_cuda.hu"
#include "util.h"
#include <iostream>
#include <condition_variable>
#include <thread>
#include <queue>
#include <functional>
#include <mutex>
#include <unistd.h>
#include <threadPool.h>
#include <cufft.h>
```



Include dependency graph for autocorrelation\_cuda.cu:



## Functions

- `__device__ __host__ void auto\_corr\_internal` (double \*arr, int length, int lag, double average, double \*corr, int start\_id)  
*Internal function to calculate the autocorrelation for a given lag Customized for the thread pool architecture, with extra arguments because of the way the memory is allocated.*
- `__global__ void auto\_corr\_internal\_kernel` (double \*arr, int length, double average, int \*rho\_index, double target\_corr, double var, int start\_id)  
*Internal function to launch the CUDA kernel for a range of autocorrelations.*
- void [write\\_file\\_auto\\_corr\\_from\\_data\\_file\\_accel](#) (std::string acfile, std::string chains\_file, int dimension, int N\_steps, int num\_segments, double target\_corr)  
*Write data file for autocorrelation lengths of the data given a data file name, as written by the mcmc\_sampler.*
- void [write\\_file\\_auto\\_corr\\_from\\_data\\_accel](#) (std::string acfile, double \*\*chains, int dimension, int N\_steps, int num\_segments, double target\_corr)  
*Write data file given output chains, as formatted by the mcmc\_sampler.*
- void [auto\\_corr\\_from\\_data\\_accel](#) (double \*\*output, int dimension, int N\_steps, int num\_segments, double target\_corr, double \*\*autocorr)  
*Find autocorrelation of data at different points in the chain length and output to autocorr.*
- void [ac\\_gpu\\_wrapper](#) (int thread, int job\_id)  
*Wrapper function for the thread pool.*
- void [launch\\_ac\\_gpu](#) (int device, int element, double \*\*data, int length, int dimension, double target\_corr, int num\_segments)  
*Launch the GPU kernel, formatted for the thread pool.*
- void [allocate\\_gpu\\_plan](#) (GPUplan \*plan, int data\_length, int dimension, int num\_segments)  
*Allocates memory for autocorrelation-GPU structure.*
- void [deallocate\\_gpu\\_plan](#) (GPUplan \*plan, int data\_length, int dimension, int num\_segments)  
*Deallocates memory for the autocorrelation-GPU structure.*
- void [copy\\_data\\_to\\_device](#) (GPUplan \*plan, double \*\*input\_data, int data\_length, int dimension, int num\_segments)  
*Copy data to device before starting kernels.*

## Variables

- GPUplan \* **plans\_global**

### 8.5.1 Function Documentation

#### 8.5.1.1 [ac\\_gpu\\_wrapper\(\)](#)

```
void ac_gpu_wrapper (
    int thread,
    int job_id )
```

Wrapper function for the thread pool.

## Parameters

<i>thread</i>	Host thread
<i>job↔ _id</i>	Job ID

8.5.1.2 `allocate_gpu_plan()`

```
void allocate_gpu_plan (
    GPUplan * plan,
    int data_length,
    int dimension,
    int num_segments )
```

Allocates memory for autocorrelation–GPU structure.

## Parameters

<i>plan</i>	Structure for GPU plan
<i>data_length</i>	Length of data
<i>dimension</i>	Dimension of the data
<i>num_segments</i>	Number of segments to calculate the autocorrelation length

8.5.1.3 `auto_corr_from_data_accel()`

```
void auto_corr_from_data_accel (
    double ** output,
    int dimension,
    int N_steps,
    int num_segments,
    double target_corr,
    double ** autocorr )
```

Find autocorrelation of data at different points in the chain length and output to autocorr.

## Parameters

	<i>output</i>	Chain data input
	<i>dimension</i>	Dimension of the data
	<i>N_steps</i>	Number of steps in the data
	<i>num_segments</i>	number of segments to calculate the autocorrelation length
	<i>target_corr</i>	Target correlation ratio
out	<i>autocorr</i>	Autocorrelation lengths for the different segments

## 8.5.1.4 auto\_corr\_internal()

```

__device__ __host__ void auto_corr_internal (
    double * arr,
    int length,
    int lag,
    double average,
    double * corr,
    int start_id )

```

Internal function to calculate the autocorrelation for a given lag Customized for the thread pool architecture, with extra arguments because of the way the memory is allocated.

## Parameters

	<i>arr</i>	Input array of data
	<i>length</i>	Length of input array
	<i>lag</i>	Lag to be used to calculate the correlation
	<i>average</i>	Average of the array arr
out	<i>corr</i>	output correlation
	<i>start_id</i>	ID of location to start calculation – input array arr is assumed to be contiguous for multiple dimensions

## 8.5.1.5 auto\_corr\_internal\_kernel()

```

__global__ void auto_corr_internal_kernel (
    double * arr,
    int length,
    double average,
    int * rho_index,
    double target_corr,
    double var,
    int start_id )

```

Internal function to launch the CUDA kernel for a range of autocorrelations.

Correlation function used:

$$\rho(\text{lag}) = 1 / (\text{length} - \text{lag}) \sum (\text{arr}[i+\text{lag}] - \text{average}) (\text{arr}[i] - \text{average})$$

$$\text{target\_corr} = \rho(\rho\_index) / \rho(0) = \rho(\rho\_index) / \text{var}$$

## Parameters

	<i>arr</i>	Input array of data
	<i>length</i>	Length of data array
	<i>average</i>	Average of input data
out	<i>rho_index</i>	Index of the lag that results in a correlation ratio target_corr
	<i>target_corr</i>	Target correlation ratio $\rho(\text{lag}) / \rho(0) = \text{target\_corr}$
	<i>var</i>	Variance $\rho(0)$
	<i>start_id</i>	Starting index to use for the data array arr

### 8.5.1.6 copy\_data\_to\_device()

```
void copy_data_to_device (
    GPUplan * plan,
    double ** input_data,
    int data_length,
    int dimension,
    int num_segments )
```

Copy data to device before starting kernels.

#### Parameters

<i>plan</i>	GPU plan
<i>input_data</i>	Input chain data
<i>data_length</i>	Length of data
<i>dimension</i>	Dimension of the data
<i>num_segments</i>	Number of segments to calculate the autocorrelation length

### 8.5.1.7 deallocate\_gpu\_plan()

```
void deallocate_gpu_plan (
    GPUplan * plan,
    int data_length,
    int dimension,
    int num_segments )
```

Deallocates memory for the autocorrelation-GPU structure.

#### Parameters

<i>plan</i>	Structure for the GPU plan
<i>data_length</i>	Length of data
<i>dimension</i>	Dimension of the data
<i>num_segments</i>	Number of segments to calculate the autocorrelation length

### 8.5.1.8 write\_file\_auto\_corr\_from\_data\_accel()

```
void write_file_auto_corr_from_data_accel (
    std::string acfile,
    double ** chains,
    int dimension,
    int N_steps,
```

```
int num_segments,
double target_corr )
```

Write data file given output chains, as formatted by the mcmc\_sampler.

#### Parameters

<i>acfile</i>	Output autocorrelation filename
<i>chains</i>	Chain data from MCMC_sampler
<i>dimension</i>	Dimension of the data
<i>N_steps</i>	Number of steps in the chain
<i>num_segments</i>	Number of segments to check the autocorrelation length for each dimension
<i>target_corr</i>	Target correlation ratio to use for the correlation length calculation

#### 8.5.1.9 write\_file\_auto\_corr\_from\_data\_file\_accel()

```
void write_file_auto_corr_from_data_file_accel (
    std::string acfile,
    std::string chains_file,
    int dimension,
    int N_steps,
    int num_segments,
    double target_corr )
```

Write data file for autocorrelation lengths of the data given a data file name, as written by the mcmc\_sampler.

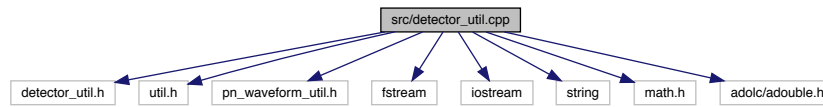
#### Parameters

<i>acfile</i>	Filename of the autocorrelation data
<i>chains_file</i>	Filename of the data file for the chains
<i>dimension</i>	Dimension of the data
<i>N_steps</i>	Number of steps in the chain
<i>num_segments</i>	Number of segments to check the autocorrelation length for each dimension
<i>target_corr</i>	Target correlation ratio to use for the correlation length calculation

## 8.6 src/detector\_util.cpp File Reference

```
#include "detector_util.h"
#include "util.h"
#include "pn_waveform_util.h"
#include <fstream>
#include <iostream>
#include <string>
#include <math.h>
#include <adolc/adouble.h>
```

Include dependency graph for detector\_util.cpp:



## Functions

- void [populate\\_noise](#) (double \*frequencies, std::string detector, double \*noise\_root, int length)  
*Function to populate the squareroot of the noise curve for various detectors.*
- double [aLIGO\\_analytic](#) (double f)  
*Analytic function approximating the PSD for aLIGO.*
- double [Hanford\\_O1\\_fitted](#) (double f)  
*Numerically fit PSD to the Hanford Detector's O1.*
- std::complex< double > [Q](#) (double theta, double phi, double iota, double psi)  
*Utility for the overall amplitude and phase shift for spin-aligned systems.*
- std::complex< double > [Q](#) (double theta, double phi, double iota)  
*Utility for the overall amplitude and phase shift for spin-aligned systems.*
- template<class T >  
T [right\\_interferometer\\_plus](#) (T theta, T phi)  
*Response function of a 90 deg interferometer for plus polarization.*
- template<class T >  
T [right\\_interferometer\\_cross](#) (T theta, T phi)  
*Response function of a 90 deg interferometer for cross polarization.*
- template<class T >  
void [celestial\\_horizon\\_transform](#) (T RA, T DEC, double gps\_time, std::string detector, T \*phi, T \*theta)  
*Transform from celestial coordinates to local horizontal coords.*
- void [derivative\\_celestial\\_horizon\\_transform](#) (double RA, double DEC, double gps\_time, std::string detector, double \*dphi\_dRA, double \*dtheta\_dRA, double \*dphi\_dDEC, double \*dtheta\_dDEC)  
*Numerical derivative of the transformation.*
- double [DTOA](#) (double theta1, double theta2, std::string detector1, std::string detector2)  
*calculate difference in time of arrival (DTOA) for a given source location and 2 different detectors*
- double [radius\\_at\\_lat](#) (double latitude, double elevation)
- template<class T >  
void [detector\\_response\\_functions\\_equatorial](#) (double D[3][3], T ra, T dec, T psi, double gmst, T \*Fplus, T \*Fcross)  
*Calculates the response coefficients for a detector with response tensor D for a source at RA, Dec, and psi.*
- template<class T >  
void [detector\\_response\\_functions\\_equatorial](#) (std::string detector, T ra, T dec, T psi, double gmst, T \*Fplus, T \*Fcross)  
*Wrapping of the equatorial detector response for terrestrial based detectors.*
- template<class T >  
void [detector\\_response\\_functions\\_equatorial](#) (std::string detector, T ra, T dec, T psi, double gmst, T \*times, int length, T LISA\_alpha0, T LISA\_phi0, T LISA\_theta\_I, T LISA\_phi\_I, double integration\_time, T \*Fplus, T \*Fcross)  
*Same as the other function, but for active and future detectors.*
- template<class T >  
T [LISA\\_response\\_plus](#) (source\_parameters< T > \*params, T theta\_s, T phi\_s, T theta\_I, T phi\_I, T alpha\_0, T phi\_0, T f, double integration\_time)

- `template<class T >`  
`T LISA_response_cross` (source\_parameters< T > \*params, T theta\_s, T phi\_s, T theta\_l, T phi\_l, T alpha\_0, T phi\_0, T f, double integration\_time)
- `template<class T >`  
`T LISA_response_plus_time` (T theta\_s, T phi\_s, T theta\_l, T phi\_l, T alpha\_0, T phi\_0, T t, double integration\_time)  
*Time dependent detector response of LISA for non-precessing waveforms.*
- `template<class T >`  
`T LISA_response_cross_time` (T theta\_s, T phi\_s, T theta\_l, T phi\_l, T alpha\_0, T phi\_0, T t, double integration\_time)
- `template double LISA_response_plus_time< double >` (double, double, double, double, double, double, double, double)
- `template adouble LISA_response_plus_time< adouble >` (adouble, adouble, adouble, adouble, adouble, adouble, adouble, double)
- `template double LISA_response_cross_time< double >` (double, double, double, double, double, double, double, double)
- `template adouble LISA_response_cross_time< adouble >` (adouble, adouble, adouble, adouble, adouble, adouble, adouble, double)
- `template double LISA_response_plus< double >` (source\_parameters< double > \*params, double, double, double, double, double, double, double)
- `template adouble LISA_response_plus< adouble >` (source\_parameters< adouble > \*params, adouble, adouble, adouble, adouble, adouble, adouble, double)
- `template double LISA_response_cross< double >` (source\_parameters< double > \*params, double, double, double, double, double, double, double)
- `template adouble LISA_response_cross< adouble >` (source\_parameters< adouble > \*params, adouble, adouble, adouble, adouble, adouble, adouble, double)
- `template double right_interferometer_cross< double >` (double, double)
- `template adouble right_interferometer_cross< adouble >` (adouble, adouble)
- `template double right_interferometer_plus< double >` (double, double)
- `template adouble right_interferometer_plus< adouble >` (adouble, adouble)
- `template void celestial_horizon_transform< double >` (double, double, double, std::string, double \*, double \*)
- `template void celestial_horizon_transform< adouble >` (adouble, adouble, double, std::string, adouble \*, adouble \*)
- `template void detector_response_functions_equatorial< double >` (double[3][3], double, double, double, double, double \*, double \*)
- `template void detector_response_functions_equatorial< adouble >` (double[3][3], adouble, adouble, adouble, adouble, double, adouble \*, adouble \*)
- `template void detector_response_functions_equatorial< double >` (std::string, double, double, double, double, double \*, int, double, double, double, double, double, double \*, double \*)
- `template void detector_response_functions_equatorial< adouble >` (std::string, adouble, adouble, adouble, adouble, double, adouble \*, int, adouble, adouble, adouble, adouble, double, adouble \*, adouble \*)
- `template void detector_response_functions_equatorial< double >` (std::string, double, double, double, double, double \*, double \*)
- `template void detector_response_functions_equatorial< adouble >` (std::string, adouble, adouble, adouble, adouble, double, adouble \*, double \*)

### 8.6.1 Detailed Description

Routines to construct noise curves for various detectors and for detector specific utilities for response functions and coordinate transformations

### 8.6.2 Function Documentation

### 8.6.2.1 aLIGO\_analytic()

```
double aLIGO_analytic (
    double f )
```

Analytic function approximating the PSD for aLIGO.

CITE (Will?)

### 8.6.2.2 celestial\_horizon\_transform()

```
template<class T >
void celestial_horizon_transform (
    T RA,
    T DEC,
    double gps_time,
    std::string detector,
    T * phi,
    T * theta )
```

Transform from celestial coordinates to local horizontal coords.

(RA,DEC) -> (altitude, azimuth)

Need *gps\_time* of transformation, as the horizontal coords change in time

*detector* is used to specify the lat and long of the local frame

#### Parameters

<i>RA</i>	in RAD
<i>DEC</i>	in RAD
<i>phi</i>	in RAD
<i>theta</i>	in RAD

### 8.6.2.3 derivative\_celestial\_horizon\_transform()

```
void derivative_celestial_horizon_transform (
    double RA,
    double DEC,
    double gps_time,
    std::string detector,
    double * dphi_dRA,
    double * dtheta_dRA,
    double * dphi_dDEC,
    double * dtheta_dDEC )
```

Numerical derivative of the transformation.

Planned for use in Fisher calculations, but not currently implemented anywhere



## Parameters

<i>RA</i>	in RAD
<i>DEC</i>	in RAD

## 8.6.2.4 detector\_response\_functions\_equatorial() [1/3]

```
template<class T >
void detector_response_functions_equatorial (
    double D[3][3],
    T ra,
    T dec,
    T psi,
    double gmst,
    T * Fplus,
    T * Fcross )
```

Calculates the response coefficients for a detector with response tensor D for a source at RA, Dec, and psi.

Taken from LALSuite

The response tensor for each of the operational detectors is precomputed in detector\_util.h, but to create a new tensor, follow the outline in Anderson et al 36 PRD 63 042003 (2001) Appendix B

For terrestrial detectors

## Parameters

	<i>D</i>	Detector Response tensor (3x3)
	<i>ra</i>	Right ascension in rad
	<i>dec</i>	Declination in rad
	<i>psi</i>	polarization angle in rad
	<i>gmst</i>	Greenwich mean sidereal time (rad)
out	<i>Fplus</i>	Fplus response coefficient
out	<i>Fcross</i>	Fcross response coefficient

## 8.6.2.5 detector\_response\_functions\_equatorial() [2/3]

```
template<class T >
void detector_response_functions_equatorial (
    std::string detector,
    T ra,
    T dec,
    T psi,
    double gmst,
    T * Fplus,
    T * Fcross )
```

Wrapping of the equatorial detector response for terrestrial based detectors.

For ground based detectors, the antenna pattern functions are not functions of time.

## Parameters

	<i>detector</i>	Detector
	<i>ra</i>	Right ascension in rad
	<i>dec</i>	Declination in rad
	<i>psi</i>	polarization angle in rad
	<i>gmst</i>	Greenwich mean sidereal time (rad)
out	<i>Fplus</i>	Fplus response coefficient
out	<i>Fcross</i>	Fcross response coefficient

## 8.6.2.6 detector\_response\_functions\_equatorial() [3/3]

```
template<class T >
void detector_response_functions_equatorial (
    std::string detector,
    T ra,
    T dec,
    T psi,
    double gmst,
    T * times,
    int length,
    T LISA_alpha0,
    T LISA_phi0,
    T LISA_theta_l,
    T LISA_phi_l,
    double integration_time,
    T * Fplus,
    T * Fcross )
```

Same as the other function, but for active and future detectors.

## Parameters

	<i>detector</i>	Detector
	<i>ra</i>	Right ascension in rad
	<i>dec</i>	Declination in rad
	<i>psi</i>	polarization angle in rad
	<i>gmst</i>	Greenwich mean sidereal time (rad)
	<i>times</i>	Times at which to evaluate Fplus and Fcross, in which case the Fplus and Fcross pointers are arrays
out	<i>Fplus</i>	Fplus response coefficient
out	<i>Fcross</i>	Fcross response coefficient

## 8.6.2.7 DTOA()

```
double DTOA (
    double theta_l,
```

```
double theta2,
std::string detector1,
std::string detector2 )
```

calculate difference in time of arrival (DTOA) for a given source location and 2 different detectors

#### Parameters

<i>theta1</i>	spherical polar angle for detector 1 in RAD
<i>theta2</i>	spherical polar angle for detector 2 in RAD
<i>detector1</i>	name of detector one
<i>detector2</i>	name of detector two

#### 8.6.2.8 Hanford\_O1\_fitted()

```
double Hanford_O1_fitted (
    double f )
```

Numerically fit PSD to the Hanford Detector's O1.

CITE (Yunes?)

#### 8.6.2.9 LISA\_response\_plus\_time()

```
template<class T >
T LISA_response_plus_time (
    T theta_s,
    T phi_s,
    T theta_l,
    T phi_l,
    T alpha_0,
    T phi_0,
    T t,
    double integration_time )
```

Time dependent detector response of LISA for non-precessing waveforms.

See <https://arxiv.org/abs/gr-qc/0411129> or <https://arxiv.org/abs/gr-qc/9703068>

All the arguments are ``barred'', using the notation in these two works. That is, they are relative to the solar system barycenter.

To get the second interferometer's response, evaluate with  $\phi_l - \pi/4$ .

#### 8.6.2.10 populate\_noise()

```
void populate_noise (
    double * frequencies,
    std::string detector,
    double * noise_root,
    int length )
```

Function to populate the squareroot of the noise curve for various detectors.

If frequencies are left as NULL, standard frequency spacing is applied and the frequencies are returned, in which case the frequencies argument becomes an output array

Detector names must be spelled exactly

Detectors include: aLIGO\_analytic, Hanford\_O1\_fitted

## Parameters

<i>frequencies</i>	double array of frquencies (NULL)
<i>detector</i>	String to designate the detector noise curve to be used
<i>noise_root</i>	ouptput double array for the square root of the PSD of the noise of the specified detector
<i>length</i>	integer length of the output and input arrays

8.6.2.11 `Q()` [1/2]

```
std::complex<double> Q (
    double theta,
    double phi,
    double iota,
    double psi )
```

Utility for the overall amplitude and phase shift for spin-aligned systems.

For spin aligned, all the extrinsic parameters have the effect of an overall amplitude modulation and phase shift

8.6.2.12 `Q()` [2/2]

```
std::complex<double> Q (
    double theta,
    double phi,
    double iota )
```

Utility for the overall amplitude and phase shift for spin-aligned systems.

For spin aligned, all the extrinsic parameters have the effect of an overall amplitude modulation and phase shift

8.6.2.13 `radius_at_lat()`

```
double radius_at_lat (
    double latitude,
    double elevation )
```

/brief Analytic approximation of the radius from the center of earth to a given location

Just the raidus as a function of angles, modelling an oblate spheroid

## Parameters

<i>latitude</i>	latitude in degrees
<i>elevation</i>	elevation in meters

#### 8.6.2.14 right\_interferometer\_cross()

```
template<class T >
T right_interferometer_cross (
    T theta,
    T phi )
```

Response function of a 90 deg interferometer for cross polarization.

Theta and phi are local, horizontal coordinates relative to the detector

#### 8.6.2.15 right\_interferometer\_plus()

```
template<class T >
T right_interferometer_plus (
    T theta,
    T phi )
```

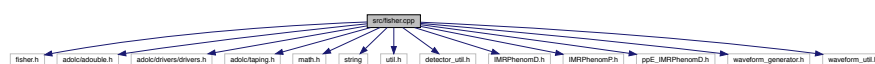
Response function of a 90 deg interferometer for plus polarization.

Theta and phi are local, horizontal coordinates relative to the detector

## 8.7 src/fisher.cpp File Reference

```
#include <fisher.h>
#include <adolc/adouble.h>
#include <adolc/drivers/drivers.h>
#include <adolc/taping.h>
#include <math.h>
#include <string>
#include "util.h"
#include "detector_util.h"
#include "IMRPhenomD.h"
#include "IMRPhenomP.h"
#include "ppE_IMRPhenomD.h"
#include "waveform_generator.h"
#include "waveform_util.h"
```

Include dependency graph for fisher.cpp:



## Functions

- void [fisher](#) (double \*frequency, int length, string generation\_method, string detector, double \*\*output, int dimension, gen\_params \*parameters, int \*amp\_tapes, int \*phase\_tapes, double \*noise)

*Calculates the fisher matrix for the given arguments.*

- void [calculate\\_derivatives](#) (double \*\*amplitude\_deriv, double \*\*phase\_deriv, double \*amplitude, double \*frequencies, int length, string detector, string gen\_method, gen\_params \*parameters)

*Abstraction layer for handling the case separation for the different waveforms.*

- void [fisher\\_autodiff](#) (double \*frequency, int length, std::string generation\_method, std::string detector, double \*\*output, int dimension, gen\_params \*parameters, int \*amp\_tapes, int \*phase\_tapes, double \*noise)

*Calculates the fisher matrix for the given arguments to within numerical error using automatic differentiation - slower than the numerical version.*

- void [calculate\\_derivatives\\_autodiff](#) (double \*frequency, int length, gen\_params \*parameters, std::complex<double> \*\*waveform\_deriv, int \*waveform\_tapes, std::string detector)

*Calculate the full fisher matrix for a precessing waveform.*

### 8.7.1 Detailed Description

All subroutines associated with waveform differentiation and Fisher analysis

### 8.7.2 Function Documentation

#### 8.7.2.1 [calculate\\_derivatives\(\)](#)

```
void calculate_derivatives (
    double ** amplitude_deriv,
    double ** phase_deriv,
    double * amplitude,
    double * frequencies,
    int length,
    string detector,
    string gen_method,
    gen_params * parameters )
```

Abstraction layer for handling the case separation for the different waveforms.

### 8.7.2.2 calculate\_derivatives\_autodiff()

```
void calculate_derivatives_autodiff (
    double * frequency,
    int length,
    gen_params * parameters,
    std::complex< double > ** waveform_deriv,
    int * waveform_tapes,
    std::string detector )
```

Calculate the full fisher matrix for a precessing waveform.

Calculates the fisher without maximizing the extrinsic parameters

15 dimensions:

cos \theta<sub>J</sub>

RA

DEC

DL

chirpmass

eta

spin1

spin2

theta1

theta2

phi1

phi2

phiRef

psi

all at reference frequency of 20hz

### 8.7.2.3 fisher()

```
void fisher (
    double * frequency,
    int length,
    string generation_method,
    string detector,
    double ** output,
    int dimension,
    gen_params * parameters,
    int * amp_tapes,
    int * phase_tapes,
    double * noise )
```

Calculates the fisher matrix for the given arguments.

Utilizes numerical derivatives



## Parameters

<i>length</i>	if 0, standard frequency range for the detector is used
<i>output</i>	double [dimension][dimension]
<i>amp_tapes</i>	if speed is required, precomputed tapes can be used - assumed the user knows what they're doing, no checks done here to make sure that the number of tapes matches the requirement by the generation_method – if using numerical derivatives or speed isn't that important, just set to NULL
<i>phase_tapes</i>	if speed is required, precomputed tapes can be used - assumed the user knows what they're doing, no checks done here to make sure that the number of tapes matches the requirement by the generation_method

## 8.7.2.4 fisher\_autodiff()

```
void fisher_autodiff (
    double * frequency,
    int length,
    std::string generation_method,
    std::string detector,
    double ** output,
    int dimension,
    gen_params * parameters,
    int * amp_tapes,
    int * phase_tapes,
    double * noise )
```

Calculates the fisher matrix for the given arguments to within numerical error using automatic differentiation - slower than the numerical version.

Build around ADOL-C

## Parameters

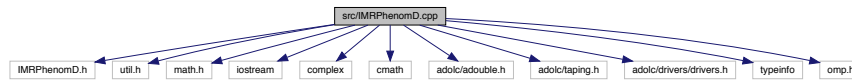
<i>length</i>	if 0, standard frequency range for the detector is used
<i>output</i>	double [dimension][dimension]
<i>amp_tapes</i>	if speed is required, precomputed tapes can be used - assumed the user knows what they're doing, no checks done here to make sure that the number of tapes matches the requirement by the generation_method
<i>phase_tapes</i>	if speed is required, precomputed tapes can be used - assumed the user knows what they're doing, no checks done here to make sure that the number of tapes matches the requirement by the generation_method

## 8.8 src/IMRPhenomD.cpp File Reference

```
#include "IMRPhenomD.h"
#include "util.h"
#include <math.h>
#include <iostream>
#include <complex>
```

```
#include <cmath>
#include <adolc/adouble.h>
#include <adolc/taping.h>
#include <adolc/drivers/drivers.h>
#include <typeinfo>
#include <omp.h>
```

Include dependency graph for IMRPhenomD.cpp:



## Macros

- `#define omp ignore`

## Variables

- `double log_64 = 4.15888308336`

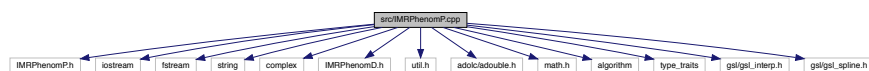
### 8.8.1 Detailed Description

File that includes all the low level functions that go into constructing the waveform

## 8.9 src/IMRPhenomP.cpp File Reference

```
#include "IMRPhenomP.h"
#include <iostream>
#include <fstream>
#include <string>
#include <complex>
#include "IMRPhenomD.h"
#include "util.h"
#include <adolc/adouble.h>
#include <math.h>
#include <algorithm>
#include <type_traits>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
```

Include dependency graph for IMRPhenomP.cpp:



## Macros

- #define **ROTATEZ**(angle, vx, vy, vz)
- #define **ROTATEY**(angle, vx, vy, vz)

## Variables

- const double **sqrt\_6** = 2.44948974278317788

### 8.9.1 Detailed Description

Source code for IMRPhenomP

### 8.9.2 Macro Definition Documentation

#### 8.9.2.1 ROTATEY

```
#define ROTATEY(  
    angle,  
    vx,  
    vy,  
    vz )
```

**Value:**

```
tmp1 = vx*cos(angle) + vz*sin(angle);\n tmp2 = - vx*sin(angle) + vz*cos(angle);\n vx = tmp1;\n vz = tmp2
```

#### 8.9.2.2 ROTATEZ

```
#define ROTATEZ(  
    angle,  
    vx,  
    vy,  
    vz )
```

**Value:**

```
tmp1 = vx*cos(angle) - vy*sin(angle);\n tmp2 = vx*sin(angle) + vy*cos(angle);\n vx = tmp1;\n vy = tmp2
```

## 8.10 src/mcmc\_gw.cpp File Reference

```
#include "mcmc_gw.h"
#include "waveform_generator.h"
#include "util.h"
#include "detector_util.h"
#include "waveform_util.h"
#include "fisher.h"
#include "mcmc_sampler.h"
#include <iostream>
#include <fstream>
#include <vector>
#include <complex>
#include <fftw3.h>
#include <algorithm>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
#include <gsl/gsl_errno.h>
#include <gsl/gsl_randist.h>
#include <gsl/gsl_rng.h>
```

Include dependency graph for mcmc\_gw.cpp:



## Functions

- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD](#) (double \*frequencies, int length, std::complex< double > \*data, double \*noise, double SNR, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, bool NSflag, fftw\_outline \*plan)

*Function to calculate the log Likelihood as defined by  $-1/2 (d-h|d-h)$  maximized over the extrinsic parameters  $\phi_{\text{hc}}$  and  $t_c$ .*

- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD](#) (double \*frequencies, size\_t length, double \*real\_data, double \*imag\_data, double \*noise, double SNR, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, bool NSflag)
- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD](#) (double \*frequencies, size\_t length, double \*real\_data, double \*imag\_data, double \*noise, double SNR, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, bool NSflag, fftw\_outline \*plan)
- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD\\_Full\\_Param](#) (double \*frequencies, int length, std::complex< double > \*data, double \*noise, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, double Luminosity\_Distance, double theta, double phi, double iota, bool NSflag, fftw\_outline \*plan)
- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD\\_Full\\_Param](#) (double \*frequencies, size\_t length, double \*real\_data, double \*imag\_data, double \*noise, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, double Luminosity\_Distance, double theta, double phi, double iota, bool NSflag)
- double [maximized\\_coal\\_log\\_likelihood\\_IMRPhenomD\\_Full\\_Param](#) (double \*frequencies, size\_t length, double \*real\_data, double \*imag\_data, double \*noise, double chirpmass, double symmetric\_mass\_ratio, double spin1, double spin2, double Luminosity\_Distance, double theta, double phi, double iota, bool NSflag, fftw\_outline \*plan)
- double [maximized\\_Log\\_Likelihood](#) (std::complex< double > \*data, double \*psd, double \*frequencies, size\_t length, gen\_params \*params, std::string detector, std::string generation\_method, fftw\_outline \*plan)

*routine to maximize over all extrinsic quantities and return the log likelihood*

- double **maximized\_Log\_Likelihood** (double \*data\_real, double \*data\_imag, double \*psd, double \*frequencies, size\_t length, gen\_params \*params, std::string detector, std::string generation\_method, fftw\_outline \*plan)
- double **maximized\_coal\_Log\_Likelihood** (std::complex< double > \*data, double \*psd, double \*frequencies, size\_t length, gen\_params \*params, std::string detector, std::string generation\_method, fftw\_outline \*plan, double \*tc, double \*phic)  
*Function to maximize only over coalescence variables tc and phic, returns the maximum values used.*
- double **maximized\_coal\_Log\_Likelihood\_internal** (std::complex< double > \*data, double \*psd, double \*frequencies, std::complex< double > \*detector\_response, size\_t length, fftw\_outline \*plan, double \*tc, double \*phic)
- double **Log\_Likelihood** (std::complex< double > \*data, double \*psd, double \*frequencies, size\_t length, gen\_params \*params, std::string detector, std::string generation\_method, fftw\_outline \*plan)  
*Unmarginalized log of the likelihood.*
- double **maximized\_Log\_Likelihood\_aligned\_spin\_internal** (std::complex< double > \*data, double \*psd, double \*frequencies, std::complex< double > \*detector\_response, size\_t length, fftw\_outline \*plan)  
*Maximized match over coalescence variables - returns log likelihood NOT NORMALIZED for aligned spins.*
- double **maximized\_Log\_Likelihood\_unaligned\_spin\_internal** (std::complex< double > \*data, double \*psd, double \*frequencies, std::complex< double > \*hplus, std::complex< double > \*hcross, size\_t length, fftw\_outline \*plan)  
*log likelihood function that maximizes over extrinsic parameters tc, phic, D, and phiRef, the reference frequency - for unaligned spins*
- double **Log\_Likelihood\_internal** (std::complex< double > \*data, double \*psd, double \*frequencies, std::complex< double > \*detector\_response, int length, fftw\_outline \*plan)  
*Internal function for the unmarginalized log of the likelihood.*
- void **continue\_RJPTMCMC\_MH\_GW** (std::string start\_checkpoint\_file, double \*\*\*output, int \*\*\*status, int max\_dim, int min\_dim, int N\_steps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int dimension, int chain\_id), void(\*RJ\_proposal)(double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int max\_dim, int chain\_id, double step\_width), int numThreads, bool pool, bool show\_prog, int num\_detectors, std::complex< double > \*\*data, double \*\*noise\_psd, double \*\*frequencies, int \*data\_length, double gps\_time, std::string \*detectors, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string final\_checkpoint\_filename)  
*Takes in an MCMC checkpoint file and continues the chain.*
- void **RJPTMCMC\_MH\_GW** (double \*\*\*output, int \*\*\*status, int max\_dim, int min\_dim, int N\_steps, int chain\_N, double \*initial\_pos, int \*initial\_status, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int dimension, int chain\_id), void(\*RJ\_proposal)(double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int max\_dim, int chain\_id, double step\_width), int numThreads, bool pool, bool show\_prog, int num\_detectors, std::complex< double > \*\*data, double \*\*noise\_psd, double \*\*frequencies, int \*data\_length, double gps\_time, std::string \*detectors, int Nmod\_max, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)  
*Wrapper for the RJPTMCMC\_MH function, specifically for GW analysis.*
- void **PTMCMC\_MH\_GW** (double \*\*\*output, int dimension, int N\_steps, int chain\_N, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int dimension, int chain\_id), int numThreads, bool pool, bool show\_prog, int num\_detectors, std::complex< double > \*\*data, double \*\*noise\_psd, double \*\*frequencies, int \*data\_length, double gps\_time, std::string \*detectors, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)  
*Wrapper for the MCMC\_MH function, specifically for GW analysis.*
- void **PTMCMC\_MH\_dynamic\_PT\_alloc\_GW** (double \*\*\*output, int dimension, int N\_steps, int chain\_N, int max\_chain\_N\_thermo\_ensemble, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, int t0, int nu, std::string chain\_distribution\_scheme, double(\*log\_prior)(double \*param, int dimension, int chain\_id), int numThreads, bool pool, bool show\_prog, int num\_detectors, std::complex< double > \*\*data, double \*\*noise\_psd, double \*\*frequencies, int \*data\_length, double gps\_time, std::string \*detectors, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_filename)

*Takes in an MCMC checkpoint file and continues the chain.*

- void `continue_PTMCMC_MH_GW` (std::string start\_checkpoint\_file, double \*\*\*output, int dimension, int N\_steps, int swp\_freq, double(\*log\_prior)(double \*param, int dimension, int chain\_id), int numThreads, bool pool, bool show\_prog, int num\_detectors, std::complex< double > \*\*data, double \*\*noise\_psd, double \*\*frequencies, int \*data\_length, double gps\_time, std::string \*detectors, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string final\_checkpoint\_filename)

*Takes in an MCMC checkpoint file and continues the chain.*

- void `RJPTMCMC_method_specific_prep` (std::string generation\_method, int max\_dim, int min\_dim, double \*seeding\_var, bool local\_seeding)

*Unpacks MCMC parameters for method specific initiation (RJ version)*

- void `PTMCMC_method_specific_prep` (std::string generation\_method, int dimension, double \*seeding\_var, bool local\_seeding)

*Unpacks MCMC parameters for method specific initiation.*

- void `MCMC_fisher_wrapper` (double \*param, int dimension, double \*\*output, int chain\_id)

*Fisher function for MCMC for GW.*

- double `MCMC_likelihood_extrinsic` (bool save\_waveform, gen\_params \*parameters, std::string generation\_method, int \*data\_length, double \*\*frequencies, std::complex< double > \*\*data, double \*\*psd, std::string \*detectors, fftw\_outline \*fftw\_plans, int num\_detectors, double RA, double DEC, double gps\_time)
- double `MCMC_likelihood_wrapper` (double \*param, int dimension, int chain\_id)

*log likelihood function for MCMC for GW*

- double `RJPTMCMC_likelihood_wrapper` (double \*param, int \*status, int max\_dim, int chain\_id)
- void `RJPTMCMC_RJ_proposal` (double \*current\_params, double \*proposed\_params, int \*current\_status, int \*proposed\_status, int max\_dim, int chain\_id, double step\_width)
- void `RJPTMCMC_fisher_wrapper` (double \*param, int \*status, int min\_dim, double \*\*output, int chain\_id)

### 8.10.1 Detailed Description

Routines for implementation in MCMC algorithms specific to GW CBC analysis

### 8.10.2 Function Documentation

#### 8.10.2.1 continue\_PTMCMC\_MH\_GW()

```
void continue_PTMCMC_MH_GW (
    std::string start_checkpoint_file,
    double *** output,
    int dimension,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    int numThreads,
    bool pool,
    bool show_prog,
    int num_detectors,
    std::complex< double > ** data,
    double ** noise_psd,
    double ** frequencies,
```

```

    int * data_length,
    double gps_time,
    std::string * detectors,
    int Nmod,
    int * bppe,
    std::string generation_method,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string final_checkpoint_filename )

```

Takes in an MCMC checkpoint file and continues the chain.

Obviously, the user must be sure to correctly match the dimension, number of chains, the generation\_method, the prior function, the data, psds, freqs, and the detectors (number and name), and the gps\_time to the previous run, otherwise the behavior of the sampler is undefined.

numThreads and pool do not necessarily have to be the same

#### 8.10.2.2 continue\_RJPTMCMC\_MH\_GW()

```

void continue_RJPTMCMC_MH_GW (
    std::string start_checkpoint_file,
    double *** output,
    int *** status,
    int max_dim,
    int min_dim,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int *status, int dimension, int chain_id) log_prior,
    void(*) (double *current_param, double *proposed_param, int *current_status, int
*proposed_status, int max_dim, int chain_id, double step_width) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    int num_detectors,
    std::complex< double > ** data,
    double ** noise_psd,
    double ** frequencies,
    int * data_length,
    double gps_time,
    std::string * detectors,
    int Nmod,
    int * bppe,
    std::string generation_method,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string final_checkpoint_filename )

```

Takes in an MCMC checkpoint file and continues the chain.

Obviously, the user must be sure to correctly match the dimension, number of chains, the generation\_method, the prior function, the data, psds, freqs, and the detectors (number and name), and the gps\_time to the previous run, otherwise the behavior of the sampler is undefined.

numThreads and pool do not necessarily have to be the same

### 8.10.2.3 Log\_Likelihood()

```
double Log_Likelihood (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    size_t length,
    gen_params * params,
    std::string detector,
    std::string generation_method,
    fftw_outline * plan )
```

Unmarginalized log of the likelihood.

### 8.10.2.4 Log\_Likelihood\_internal()

```
double Log_Likelihood_internal (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    std::complex< double > * detector_response,
    int length,
    fftw_outline * plan )
```

Internal function for the unmarginalized log of the likelihood.

$$.5 * ((h|h) - 2(D|h))$$

### 8.10.2.5 maximized\_coal\_Log\_Likelihood()

```
double maximized_coal_Log_Likelihood (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    size_t length,
    gen_params * params,
    std::string detector,
    std::string generation_method,
    fftw_outline * plan,
    double * tc,
    double * phic )
```

Function to maximize only over coalescence variables tc and phic, returns the maximum values used.



## 8.10.2.6 maximized\_coal\_log\_likelihood\_IMRPhenomD() [1/3]

```
double maximized_coal_log_likelihood_IMRPhenomD (
    double * frequencies,
    int length,
    std::complex< double > * data,
    double * noise,
    double SNR,
    double chirpmass,
    double symmetric_mass_ratio,
    double spin1,
    double spin2,
    bool NSflag,
    fftw_outline * plan )
```

Function to calculate the log Likelihood as defined by  $-1/2 (d-h|d-h)$  maximized over the extrinsic parameters  $\phi_{hc}$  and  $t_c$ .

frequency array must be uniform spacing - this shouldn't be a problem when working with real data as DFT return uniform spacing

## Parameters

<i>chirpmass</i>	in solar masses
------------------	-----------------

## 8.10.2.7 maximized\_coal\_log\_likelihood\_IMRPhenomD() [2/3]

```
double maximized_coal_log_likelihood_IMRPhenomD (
    double * frequencies,
    size_t length,
    double * real_data,
    double * imag_data,
    double * noise,
    double SNR,
    double chirpmass,
    double symmetric_mass_ratio,
    double spin1,
    double spin2,
    bool NSflag )
```

## Parameters

<i>chirpmass</i>	in solar masses
------------------	-----------------

## 8.10.2.8 maximized\_coal\_log\_likelihood\_IMRPhenomD() [3/3]

```
double maximized_coal_log_likelihood_IMRPhenomD (
    double * frequencies,
```

```

size_t length,
double * real_data,
double * imag_data,
double * noise,
double SNR,
double chirpmass,
double symmetric_mass_ratio,
double spin1,
double spin2,
bool NSflag,
fftw_outline * plan )

```

#### Parameters

<i>chirpmass</i>	in solar masses
------------------	-----------------

#### 8.10.2.9 maximized\_coal\_log\_likelihood\_IMRPhenomD\_Full\_Param() [1/3]

```

double maximized_coal_log_likelihood_IMRPhenomD_Full_Param (
    double * frequencies,
    int length,
    std::complex< double > * data,
    double * noise,
    double chirpmass,
    double symmetric_mass_ratio,
    double spin1,
    double spin2,
    double Luminosity_Distance,
    double theta,
    double phi,
    double iota,
    bool NSflag,
    fftw_outline * plan )

```

#### Parameters

<i>chirpmass</i>	in solar masses
------------------	-----------------

#### 8.10.2.10 maximized\_coal\_log\_likelihood\_IMRPhenomD\_Full\_Param() [2/3]

```

double maximized_coal_log_likelihood_IMRPhenomD_Full_Param (
    double * frequencies,
    size_t length,
    double * real_data,
    double * imag_data,
    double * noise,
    double chirpmass,
    double symmetric_mass_ratio,
    double spin1,

```

```
double spin2,
double Luminosity_Distance,
double theta,
double phi,
double iota,
bool NSflag )
```

**Parameters**

<i>chirpmass</i>	in solar masses
------------------	-----------------

**8.10.2.11 maximized\_coal\_log\_likelihood\_IMRPhenomD\_Full\_Param()** [3/3]

```
double maximized_coal_log_likelihood_IMRPhenomD_Full_Param (
    double * frequencies,
    size_t length,
    double * real_data,
    double * imag_data,
    double * noise,
    double chirpmass,
    double symmetric_mass_ratio,
    double spin1,
    double spin2,
    double Luminosity_Distance,
    double theta,
    double phi,
    double iota,
    bool NSflag,
    fftw_outline * plan )
```

**Parameters**

<i>chirpmass</i>	in solar masses
------------------	-----------------

**8.10.2.12 maximized\_Log\_Likelihood()**

```
double maximized_Log_Likelihood (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    size_t length,
    gen_params * params,
    std::string detector,
    std::string generation_method,
    fftw_outline * plan )
```

routine to maximize over all extrinsic quantities and return the log likelihood

IMRPhenomD – maximizes over DL, phic, tc, \iota, \phi, \theta IMRPhenomP – maximizes over DL, phic,tc, \psi, \phi, \theta

#### 8.10.2.13 `maximized_Log_Likelihood_aligned_spin_internal()`

```
double maximized_Log_Likelihood_aligned_spin_internal (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    std::complex< double > * detector_response,
    size_t length,
    fftw_outline * plan )
```

Maximized match over coalescence variables - returns log likelihood NOT NORMALIZED for aligned spins.

Note: this function is not properly normalized for an absolute comparison. This is made for MCMC sampling, so to minimize time, constant terms like  $(Data|Data)$ , which would cancel in the Metropolis-Hasting ratio, are left out for efficiency

#### 8.10.2.14 `maximized_Log_Likelihood_unaligned_spin_internal()`

```
double maximized_Log_Likelihood_unaligned_spin_internal (
    std::complex< double > * data,
    double * psd,
    double * frequencies,
    std::complex< double > * hplus,
    std::complex< double > * hcross,
    size_t length,
    fftw_outline * plan )
```

log likelihood function that maximizes over extrinsic parameters  $tc$ ,  $\phi_{ic}$ ,  $D$ , and  $\phi_{iRef}$ , the reference frequency - for unaligned spins

Ref: arXiv 1603.02444v2

#### 8.10.2.15 `MCMC_fisher_wrapper()`

```
void MCMC_fisher_wrapper (
    double * param,
    int dimension,
    double ** output,
    int chain_id )
```

Fisher function for MCMC for GW.

Wraps the fisher calculation in [src/fisher.cpp](#) and unpacks parameters correctly for common GW analysis

Supports all the method/parameter combinations found in `MCMC_MH_GW`

#### 8.10.2.16 `MCMC_likelihood_wrapper()`

```
double MCMC_likelihood_wrapper (
    double * param,
    int dimension,
    int chain_id )
```

log likelihood function for MCMC for GW

Wraps the above likelihood functions and unpacks parameters correctly for common GW analysis

Supports all the method/parameter combinations found in `MCMC_MH_GW`

## 8.10.2.17 PTMCMC\_method\_specific\_prep()

```
void PTMCMC_method_specific_prep (
    std::string generation_method,
    int dimension,
    double * seeding_var,
    bool local_seeding )
```

Unpacks MCMC parameters for method specific initiation.

Populates seeding vector if non supplied, populates mcmc\_Nmod, populates mcmc\_log\_beta, populates mcmc\_↔intrinsic

## 8.10.2.18 PTMCMC\_MH\_dynamic\_PT\_alloc\_GW()

```
void PTMCMC_MH_dynamic_PT_alloc_GW (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    int max_chain_N_thermo_ensemble,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    int t0,
    int nu,
    std::string chain_distribution_scheme,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    int numThreads,
    bool pool,
    bool show_prog,
    int num_detectors,
    std::complex< double > ** data,
    double ** noise_psd,
    double ** frequencies,
    int * data_length,
    double gps_time,
    std::string * detectors,
    int Nmod,
    int * bppe,
    std::string generation_method,
    std::string statistics_filename,
    std::string chain_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_filename )
```

Takes in an MCMC checkpoint file and continues the chain.

Obviously, the user must be sure to correctly match the dimension, number of chains, the generation\_method, the prior function, the data, psds, freqs, and the detectors (number and name), and the gps\_time to the previous run, otherwise the behavior of the sampler is undefined.

numThreads and pool do not necessarily have to be the same

### 8.10.2.19 PTMCMC\_MH\_GW()

```
void PTMCMC_MH_GW (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    int numThreads,
    bool pool,
    bool show_prog,
    int num_detectors,
    std::complex< double > ** data,
    double ** noise_psd,
    double ** frequencies,
    int * data_length,
    double gps_time,
    std::string * detectors,
    int Nmod,
    int * bppe,
    std::string generation_method,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )
```

Wrapper for the MCMC\_MH function, specifically for GW analysis.

Handles the details of setting up the MCMC sampler and wraps the fisher and log likelihood to conform to the format of the sampler

**NOTE** – This sampler is NOT thread safe. There is global memory declared for each call to MCMC\_MH\_GW, so separate samplers should not be run in the same process space

Supported parameter combinations:

IMRPhenomD - 4 dimensions – ln chirpmass, eta, chi1, chi2

IMRPhenomD - 7 dimensions – ln D\_L, tc, phic, ln chirpmass, eta, chi1, chi2

IMRPhenomD - 9 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2, psi

dCS\_IMRPhenomD\_log - 8 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2, ln  $\alpha^2$  (the coupling parameter)

dCS\_IMRPhenomD - 8 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2,  $\alpha^2$  (the coupling parameter)

dCS\_IMRPhenomD\_root\_alpha - 8 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2,  $\sqrt{\alpha}$  (in km) (the coupling parameter)

IMRPhenomPv2 - 9 dimensions – cos J\_N, ln chirpmass, eta,  $|\chi_1|$ ,  $|\chi_1|$ , theta\_1, theta\_2, phi\_1, phi\_2

## Parameters

<i>statistics_filename</i>	Filename to output sampling statistics, if empty string, not output
<i>chain_filename</i>	Filename to output data (chain 0 only), if empty string, not output
<i>auto_corr_filename</i>	Filename to output auto correlation in some interval, if empty string, not output
<i>checkpoint_file</i>	Filename to output data for checkpoint, if empty string, not saved

## 8.10.2.20 RJPTMCMC\_method\_specific\_prep()

```
void RJPTMCMC_method_specific_prep (
    std::string generation_method,
    int max_dim,
    int min_dim,
    double * seeding_var,
    bool local_seeding )
```

Unpacks MCMC parameters for method specific initiation (RJ version)

Populates seeding vector if non supplied, populates mcmc\_Nmod, populates mcmc\_log\_beta, populates mcmc\_↔intrinsic

## 8.10.2.21 RJPTMCMC\_MH\_GW()

```
void RJPTMCMC_MH_GW (
    double *** output,
    int *** status,
    int max_dim,
    int min_dim,
    int N_steps,
    int chain_N,
    double * initial_pos,
    int * initial_status,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int *status, int dimension, int chain_id) log_prior,
    void(*) (double *current_param, double *proposed_param, int *current_status, int
*proposed_status, int max_dim, int chain_id, double step_width) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    int num_detectors,
    std::complex< double > ** data,
    double ** noise_psd,
    double ** frequencies,
    int * data_length,
    double gps_time,
    std::string * detectors,
    int Nmod_max,
    int * bppe,
    std::string generation_method,
```

```

std::string statistics_filename,
std::string chain_filename,
std::string auto_corr_filename,
std::string likelihood_log_filename,
std::string checkpoint_file )

```

Wrapper for the RJPTMCMC\_MH function, specifically for GW analysis.

Handles the details of setting up the MCMC sampler and wraps the fisher and log likelihood to conform to the format of the sampler

**NOTE** – This sampler as a whole is NOT thread safe. There is global memory declared for each call to MCMC\_MH\_GW, so separate samplers should not be run in the same process space.

Supported parameter combinations:

IMRPhenomD - 8 dimensions –

MIN DIMENSIONS – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2, TRANSDIMENSIONAL DIMENSIONS – ppE parameters for the bppe array specified

If RJ\_proposal is NULL, a default proposal is used.

#### Parameters

<i>statistics_filename</i>	Filename to output sampling statistics, if empty string, not output
<i>chain_filename</i>	Filename to output data (chain 0 only), if empty string, not output
<i>auto_corr_filename</i>	Filename to output auto correlation in some interval, if empty string, not output
<i>checkpoint_file</i>	Filename to output data for checkpoint, if empty string, not saved

## 8.11 src/mcmc\_sampler.cpp File Reference

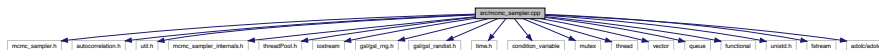
```

#include "mcmc_sampler.h"
#include "autocorrelation.h"
#include "util.h"
#include "mcmc_sampler_internals.h"
#include "threadPool.h"
#include <iostream>
#include <gsl/gsl_rng.h>
#include <gsl/gsl_randist.h>
#include <time.h>
#include <condition_variable>
#include <mutex>
#include <thread>
#include <vector>
#include <queue>
#include <functional>
#include <unistd.h>
#include <fstream>
#include "adolc/adolc.h"

```



Include dependency graph for mcmc\_sampler.cpp:



## Classes

- class [Comparator](#)  
*Class to facilitate the comparing of chains for priority.*
- class [Comparatorswap](#)
- class [ThreadPool](#)

## Macros

- `#define omp ignore`

## Functions

- void [continue\\_RJPTMCMC\\_MH\\_internal](#) (std::string start\_checkpoint\_file, double \*\*\*output, int \*\*\*status, int N\_steps, int swp\_freq, std::function< double(double \*, int \*, int, int)> log\_prior, std::function< double(double \*, int \*, int, int)> log\_likelihood, std::function< void(double \*, int \*, int, double \*\*, int)> [fisher](#), std::function< void(double \*, double \*, int \*, int \*, int, int, int)> RJ\_proposal, int numThreads, bool pool, bool show\_prog, bool update\_RJ\_width, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string end\_checkpoint\_file)

*Routine to take a checkpoint file and begin a new chain at said checkpoint.*

- void [RJPTMCMC\\_MH\\_internal](#) (double \*\*\*output, int \*\*\*parameter\_status, int max\_dimension, int min\_↵\_dimension, int N\_steps, int chain\_N, double \*initial\_pos, int \*initial\_status, double \*seeding\_var, double \*chain\_temps, int swp\_freq, std::function< double(double \*, int \*, int, int)> log\_prior, std::function< double(double \*, int \*, int, int)> log\_likelihood, std::function< void(double \*, int \*, int, double \*\*, int)> [fisher](#), std::function< void(double \*, double \*, int \*, int \*, int, int, int)> RJ\_proposal, int numThreads, bool pool, bool show\_prog, bool update\_RJ\_width, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)

*Generic reversible jump sampler, where the likelihood, prior, and reversible jump proposal are parameters supplied by the user.*

- void [PTMCMC\\_MH\\_dynamic\\_PT\\_alloc\\_internal](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_↵\_N, int max\_chain\_N, thermo\_ensemble, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, int t0, int nu, std::string chain\_distribution\_scheme, std::function< double(double \*, int \*, int, int)> log\_prior, std::function< double(double \*, int \*, int, int)> log\_likelihood, std::function< void(double \*, int \*, int, double \*\*, int)> [fisher](#), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)

*Dyanmically tunes an MCMC for optimal spacing. step width, and chain number.*

- void [PTMCMC\\_MH\\_internal](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_N, double \*initial\_↵\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, std::function< double(double \*, int \*, int, int)> log\_prior, std::function< double(double \*, int \*, int, int)> log\_likelihood, std::function< void(double \*, int \*, int, double \*\*, int)> [fisher](#), int numThreads, bool pool, bool show\_prog, std::string statistics\_↵\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std\_↵\_::string checkpoint\_file)

*Generic sampler, where the likelihood, prior are parameters supplied by the user.*

- void [continue\\_PTMMC\\_MH\\_internal](#) (std::string start\_checkpoint\_file, double \*\*\*output, int N\_steps, int swp\_freq, std::function< double(double \*, int \*, int, int)> log\_prior, std::function< double(double \*, int \*, int, int)> log\_likelihood, std::function< void(double \*, int \*, int, double \*\*, int)> [fisher](#), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_↵ filename, std::string likelihood\_log\_filename, std::string end\_checkpoint\_file)  
*Routine to take a checkpoint file and begin a new chain at said checkpoint.*
- void [PTMMC\\_MH\\_step\\_incremental](#) (sampler \*sampler, int increment)  
*Internal function that runs the actual loop for the sampler – increment version.*
- void [PTMMC\\_MH\\_loop](#) (sampler \*sampler)  
*Internal function that runs the actual loop for the sampler.*
- void [mcmc\\_step\\_threaded](#) (int j)
- void [mcmc\\_swap\\_threaded](#) (int i, int j)
- void [PTMMC\\_MH](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_N, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int dimension), double(\*log\_likelihood)(double \*param, int dimension), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#)), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_↵ filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)
- void [PTMMC\\_MH](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_N, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int dimension, int chain\_id), double(\*log\_likelihood)(double \*param, int dimension, int chain\_id), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#), int chain\_id), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_↵ filename, std::string checkpoint\_file)
- void [continue\\_PTMMC\\_MH](#) (std::string start\_checkpoint\_file, double \*\*\*output, int N\_steps, int swp\_↵ freq, double(\*log\_prior)(double \*param, int dimension, int chain\_id), double(\*log\_likelihood)(double \*param, int dimension, int chain\_id), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#), int chain\_id), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string end\_checkpoint\_file)
- void [continue\\_PTMMC\\_MH](#) (std::string start\_checkpoint\_file, double \*\*\*output, int N\_steps, int swp\_↵ freq, double(\*log\_prior)(double \*param, int dimension), double(\*log\_likelihood)(double \*param, int dimension), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#)), int numThreads, bool pool, bool show\_↵ \_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string end\_checkpoint\_file)
- void [PTMMC\\_MH\\_dynamic\\_PT\\_alloc](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_N, int max\_↵ \_chain\_N\_thermo\_ensemble, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_↵ freq, int t0, int nu, std::string chain\_distribution\_scheme, double(\*log\_prior)(double \*param, int dimension), double(\*log\_likelihood)(double \*param, int dimension), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#)), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_↵ filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)
- void [PTMMC\\_MH\\_dynamic\\_PT\\_alloc](#) (double \*\*\*output, int dimension, int N\_steps, int chain\_N, int max\_↵ \_chain\_N\_thermo\_ensemble, double \*initial\_pos, double \*seeding\_var, double \*chain\_temps, int swp\_↵ \_freq, int t0, int nu, std::string chain\_distribution\_scheme, double(\*log\_prior)(double \*param, int dimension, int chain\_id), double(\*log\_likelihood)(double \*param, int dimension, int chain\_id), void(\*[fisher](#))(double \*param, int dimension, double \*\*[fisher](#), int chain\_id), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)
- void [RJPTMMC\\_MH](#) (double \*\*\*output, int \*\*\*parameter\_status, int max\_dimension, int min\_dimension, int N\_steps, int chain\_N, double \*initial\_pos, int \*initial\_status, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int max\_dimension, int chain\_id), double(\*log\_↵ \_likelihood)(double \*param, int \*status, int max\_dimension, int chain\_id), void(\*[fisher](#))(double \*param, int \*status, int max\_dimension, double \*\*[fisher](#), int chain\_id), void(\*RJ\_proposal)(double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int max\_dimension, int chain\_id), int num\_↵ Threads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string checkpoint\_file)
- void [RJPTMMC\\_MH](#) (double \*\*\*output, int \*\*\*parameter\_status, int max\_dimension, int min\_dimension, int N\_steps, int chain\_N, double \*initial\_pos, int \*initial\_status, double \*seeding\_var, double \*chain\_temps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int max\_dimension, int chain\_id), double(\*log\_↵ \_likelihood)(double \*param, int \*status, int max\_dimension, int chain\_id), void(\*[fisher](#))(double \*param, int

- ```
*status, int max_dimension, double **fisher, int chain_id), void(*RJ_proposal)(double *current_param, double
*proposed_param, int *current_status, int *proposed_status, int max_dimension, int chain_id, double
gaussian_width), int numThreads, bool pool, bool show_prog, std::string statistics_filename, std::string
chain_filename, std::string auto_corr_filename, std::string likelihood_log_filename, std::string checkpoint_↵
file)
```
- void [continue\\_RJPTMCMC\\_MH](#) (std::string start\_checkpoint\_file, double \*\*\*output, int \*\*\*status, int N↵
\_steps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int max\_dimension, int chain\_id),
double(\*log\_likelihood)(double \*param, int \*status, int max\_dimension, int chain\_id), void(\*fisher)(double
\*param, int \*status, int max\_dimension, double \*\*fisher, int chain\_id), void(\*RJ\_proposal)(double \*current\_↵
\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int max\_dimension, int chain\_↵
\_id, double gaussian\_width), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std\_↵
::string chain\_filename, std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string end\_↵
\_checkpoint\_file)
  - void [continue\\_RJPTMCMC\\_MH](#) (std::string start\_checkpoint\_file, double \*\*\*output, int \*\*\*status, int N↵
\_steps, int swp\_freq, double(\*log\_prior)(double \*param, int \*status, int max\_dimension, int chain\_id),
double(\*log\_likelihood)(double \*param, int \*status, int max\_dimension, int chain\_id), void(\*fisher)(double
\*param, int \*status, int max\_dimension, double \*\*fisher, int chain\_id), void(\*RJ\_proposal)(double \*current\_↵
\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int max\_dimension, int chain\_↵
\_id), int numThreads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename,
std::string auto\_corr\_filename, std::string likelihood\_log\_filename, std::string end\_checkpoint\_file)

## Variables

- const gsl\_rng\_type \* **T**
- gsl\_rng \* **r**
- sampler \* **samplerptr**
- [ThreadPool](#) \* **poolptr**

### 8.11.1 Detailed Description

Source file for the sampler foundation

Source file for generic MCMC sampler. Sub routines that are application agnostic are housed in `mcmc_sampler_↵
internals`

### 8.11.2 Function Documentation

#### 8.11.2.1 `continue_PTMC_MH()` [1/2]

```
void continue_PTMC_MH (
    std::string start_checkpoint_file,
    double *** output,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    double(*) (double *param, int dimension, int chain_id) log_likelihood,
    void(*) (double *param, int dimension, double **fisher, int chain_id) fisher,
    int numThreads,
    bool pool,
```

```
bool show_prog,  
std::string statistics_filename,  
std::string chain_filename,  
std::string auto_corr_filename,  
std::string likelihood_log_filename,  
std::string end_checkpoint_file )
```

## Parameters

|     |                                |                                                                                                    |
|-----|--------------------------------|----------------------------------------------------------------------------------------------------|
|     | <i>start_checkpoint_file</i>   | File for starting checkpoint                                                                       |
| out | <i>output</i>                  | output array, dimensions: output[chain_N][N_steps][dimension]                                      |
|     | <i>N_steps</i>                 | Number of new steps to take                                                                        |
|     | <i>swp_freq</i>                | frequency of swap attempts between temperatures                                                    |
|     | <i>log_prior</i>               | Function pointer for the log_prior                                                                 |
|     | <i>log_likelihood</i>          | Function pointer for the log_likelihood                                                            |
|     | <i>fisher</i>                  | Function pointer for the fisher - if NULL, fisher steps are not used                               |
|     | <i>numThreads</i>              | Number of threads to use                                                                           |
|     | <i>pool</i>                    | Boolean for whether to use <code>deterministic</code> vs <code>stochastic</code> sampling          |
|     | <i>show_prog</i>               | Boolean for whether to show progress or not (turn off for cluster runs)                            |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                  |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip         |
|     | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

8.11.2.2 `continue_PTMMC_MH()` [2/2]

```

void continue_PTMMC_MH (
    std::string start_checkpoint_file,
    double *** output,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int dimension) log_prior,
    double(*) (double *param, int dimension) log_likelihood,
    void(*) (double *param, int dimension, double **fisher) fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string end_checkpoint_file )

```

## Parameters

|     |                              |                                                                      |
|-----|------------------------------|----------------------------------------------------------------------|
|     | <i>start_checkpoint_file</i> | File for starting checkpoint                                         |
| out | <i>output</i>                | output array, dimensions: output[chain_N][N_steps][dimension]        |
|     | <i>N_steps</i>               | Number of new steps to take                                          |
|     | <i>swp_freq</i>              | frequency of swap attempts between temperatures                      |
|     | <i>log_prior</i>             | Function pointer for the log_prior                                   |
|     | <i>log_likelihood</i>        | Function pointer for the log_likelihood                              |
|     | <i>fisher</i>                | Function pointer for the fisher - if NULL, fisher steps are not used |
|     | <i>numThreads</i>            | Number of threads to use                                             |

## Parameters

|  |                                |                                                                                                                      |
|--|--------------------------------|----------------------------------------------------------------------------------------------------------------------|
|  | <i>pool</i>                    | Boolean for whether to use <code>deterministic</code> vs <code>stochastic</code> sampling                            |
|  | <i>show_prog</i>               | Boolean for whether to show progress or not (turn off for cluster runs)                                              |
|  | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                  |
|  | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                                  |
|  | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                    |
|  | <i>likelihood_log_filename</i> | Filename to write the <code>log_likelihood</code> and <code>log_prior</code> at each step – use empty string to skip |
|  | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved                   |

8.11.2.3 `continue_PTMC_MH_internal()`

```
void continue_PTMC_MH_internal (
    std::string start_checkpoint_file,
    double *** output,
    int N_steps,
    int swp_freq,
    std::function< double(double *, int *, int, int)> log_prior,
    std::function< double(double *, int *, int, int)> log_likelihood,
    std::function< void(double *, int *, int, double **, int)> fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string end_checkpoint_file )
```

Routine to take a checkpoint file and begin a new chain at said checkpoint.

See `MCMC_MH_internal` for more details of parameters (pretty much all the same)

## Parameters

|     |                              |                                                                                                                                                                                                      |
|-----|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|     | <i>start_checkpoint_file</i> | File for starting checkpoint                                                                                                                                                                         |
| out | <i>output</i>                | output array, dimensions: <code>output[chain_N][N_steps][dimension]</code>                                                                                                                           |
|     | <i>N_steps</i>               | Number of new steps to take                                                                                                                                                                          |
|     | <i>swp_freq</i>              | frequency of swap attempts between temperatures                                                                                                                                                      |
|     | <i>log_prior</i>             | <code>std::function</code> for the <code>log_prior</code> function – takes <code>double *position</code> , <code>int dimension</code> , <code>int chain_id</code>                                    |
|     | <i>log_likelihood</i>        | <code>std::function</code> for the <code>log_likelihood</code> function – takes <code>double *position</code> , <code>int dimension</code> , <code>int chain_id</code>                               |
|     | <i>fisher</i>                | <code>std::function</code> for the <code>fisher</code> function – takes <code>double *position</code> , <code>int dimension</code> , <code>double **output_fisher</code> , <code>int chain_id</code> |
|     | <i>numThreads</i>            | Number of threads to use                                                                                                                                                                             |
|     | <i>pool</i>                  | Boolean for whether to use <code>deterministic</code> vs <code>stochastic</code> sampling                                                                                                            |
|     | <i>show_prog</i>             | Boolean for whether to show progress or not (turn off for cluster runs)                                                                                                                              |

## Parameters

|  |                                |                                                                                                    |
|--|--------------------------------|----------------------------------------------------------------------------------------------------|
|  | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                |
|  | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                |
|  | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                  |
|  | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip         |
|  | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

## 8.11.2.4 continue\_RJPTMCMC\_MH() [1/2]

```

void continue_RJPTMCMC_MH (
    std::string start_checkpoint_file,
    double *** output,
    int *** status,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_prior,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_↵
likelihood,
    void(*) (double *param, int *status, int max_dimension, double **fisher, int chain↵
_id) fisher,
    void(*) (double *current_param, double *proposed_param, int *current_status, int
*proposed_status, int max_dimension, int chain_id, double gaussian_width) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string end_checkpoint_file )

```

## Parameters

|     |                              |                                                                                                                        |
|-----|------------------------------|------------------------------------------------------------------------------------------------------------------------|
|     | <i>start_checkpoint_file</i> | File for starting checkpoint                                                                                           |
| out | <i>output</i>                | output array, dimensions: output[chain_N][N_steps][dimension]                                                          |
| out | <i>status</i>                | output parameter status array, dimensions: status[chain_N][N_steps][dimension]                                         |
|     | <i>N_steps</i>               | Number of new steps to take                                                                                            |
|     | <i>swp_freq</i>              | frequency of swap attempts between temperatures                                                                        |
|     | <i>RJ_proposal</i>           | std::function for the log_likelihood function – takes double *position, int *param_status, int dimension, int chain_id |
|     | <i>numThreads</i>            | Number of threads to use                                                                                               |
|     | <i>pool</i>                  | Boolean for whether to use deterministic'' vsstochastic" sampling                                                      |
|     | <i>show_prog</i>             | Boolean for whether to show progress or not (turn off for cluster runs                                                 |
|     | <i>statistics_filename</i>   | Filename to output sampling statistics, if empty string, not output                                                    |
|     | <i>chain_filename</i>        | Filename to output data (chain 0 only), if empty string, not output                                                    |
|     | <i>auto_corr_filename</i>    | Filename to output auto correlation in some interval, if empty string, not output                                      |

## Parameters

|  |                                |                                                                                                    |
|--|--------------------------------|----------------------------------------------------------------------------------------------------|
|  | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip         |
|  | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

## 8.11.2.5 continue\_RJPTCMC\_MH() [2/2]

```

void continue_RJPTCMC_MH (
    std::string start_checkpoint_file,
    double *** output,
    int *** status,
    int N_steps,
    int swp_freq,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_prior,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_↵
likelihood,
    void(*) (double *param, int *status, int max_dimension, double **fisher, int chain↵
_id) fisher,
    void(*) (double *current_param, double *proposed_param, int *current_status, int
*proposed_status, int max_dimension, int chain_id) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string end_checkpoint_file )

```

## Parameters

|     |                                |                                                                                                                        |
|-----|--------------------------------|------------------------------------------------------------------------------------------------------------------------|
|     | <i>start_checkpoint_file</i>   | File for starting checkpoint                                                                                           |
| out | <i>output</i>                  | output array, dimensions: output[chain_N][N_steps][dimension]                                                          |
| out | <i>status</i>                  | output parameter status array, dimensions: status[chain_N][N_steps][dimension]                                         |
|     | <i>N_steps</i>                 | Number of new steps to take                                                                                            |
|     | <i>swp_freq</i>                | frequency of swap attempts between temperatures                                                                        |
|     | <i>RJ_proposal</i>             | std::function for the log_likelihood function – takes double *position, int *param_status, int dimension, int chain_id |
|     | <i>numThreads</i>              | Number of threads to use                                                                                               |
|     | <i>pool</i>                    | Boolean for whether to use <code>deterministic</code> vs <code>stochastic</code> sampling                              |
|     | <i>show_prog</i>               | Boolean for whether to show progress or not (turn off for cluster runs)                                                |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                    |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                                    |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                      |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                             |
|     | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved                     |



## 8.11.2.6 continue\_RJPTMCMC\_MH\_internal()

```

void continue_RJPTMCMC_MH_internal (
    std::string start_checkpoint_file,
    double *** output,
    int *** status,
    int N_steps,
    int swp_freq,
    std::function< double(double *, int *, int, int)> log_prior,
    std::function< double(double *, int *, int, int)> log_likelihood,
    std::function< void(double *, int *, int, double **, int)> fisher,
    std::function< void(double *, double *, int *, int *, int, int, int)> RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    bool update_RJ_width,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string end_checkpoint_file )

```

Routine to take a checkpoint file and begin a new chain at said checkpoint.

See MCMC\_MH\_internal for more details of parameters (pretty much all the same)

## Parameters

|                      |                                |                                                                                                                                                                 |
|----------------------|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                      | <i>start_checkpoint_file</i>   | File for starting checkpoint                                                                                                                                    |
| out                  | <i>output</i>                  | output array, dimensions: output[chain_N][N_steps][dimension]                                                                                                   |
| out                  | <i>status</i>                  | output parameter status array, dimensions: status[chain_N][N_steps][dimension]                                                                                  |
|                      | <i>N_steps</i>                 | Number of new steps to take                                                                                                                                     |
|                      | <i>swp_freq</i>                | frequency of swap attempts between temperatures                                                                                                                 |
|                      | <i>log_prior</i>               | std::function for the log_prior function – takes double *position, int *param_status, int dimension, int chain_id                                               |
|                      | <i>log_likelihood</i>          | std::function for the log_likelihood function – takes double *position, int *param_status, int dimension, int chain_id                                          |
|                      | <i>fisher</i>                  | std::function for the fisher function – takes double *position, int *param_status, int dimension, double **output_fisher, int chain_id                          |
|                      | <i>RJ_proposal</i>             | std::function for the log_likelihood function – takes double *position, int *param_status, int dimension, int chain_id                                          |
|                      | <i>numThreads</i>              | Number of threads to use                                                                                                                                        |
|                      | <i>pool</i>                    | Boolean for whether to use <code>deterministic</code> vs <code>stochastic</code> sampling                                                                       |
|                      | <i>show_prog</i>               | Boolean for whether to show progress or not (turn off for cluster runs)                                                                                         |
|                      | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                                                             |
|                      | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output – if multiple cold chains, it will append each output to the other, and write out the total |
|                      | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                                                               |
|                      | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                                                                      |
| Generated by Doxygen | <i>end_checkpoint_file</i>     | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved                                                              |

## 8.11.2.7 PTMCMC\_MH() [1/2]

```

void PTMCMC_MH (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int dimension) log_prior,
    double(*) (double *param, int dimension) log_likelihood,
    void(*) (double *param, int dimension, double **fisher) fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )

```

## Parameters

|     |                                |                                                                                                          |
|-----|--------------------------------|----------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                  | Output chains, shape is double[chain_N, N_steps,dimension]                                               |
|     | <i>dimension</i>               | dimension of the parameter space being explored                                                          |
|     | <i>N_steps</i>                 | Number of total steps to be taken, per chain                                                             |
|     | <i>chain_N</i>                 | Number of chains                                                                                         |
|     | <i>initial_pos</i>             | Initial position in parameter space - shape double[dimension]                                            |
|     | <i>seeding_var</i>             | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension]      |
|     | <i>chain_temps</i>             | Double array of temperatures for the chains                                                              |
|     | <i>swp_freq</i>                | the frequency with which chains are swapped                                                              |
|     | <i>log_prior</i>               | Function pointer for the log_prior                                                                       |
|     | <i>log_likelihood</i>          | Function pointer for the log_likelihood                                                                  |
|     | <i>fisher</i>                  | Function pointer for the fisher - if NULL, fisher steps are not used                                     |
|     | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                         |
|     | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have >2 threads)                                          |
|     | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to "false" if submitting to a cluster) |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                      |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                      |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                        |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip               |
|     | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                       |

## 8.11.2.8 PTMCMC\_MH() [2/2]

```

void PTMCMC_MH (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    double(*) (double *param, int dimension, int chain_id) log_likelihood,
    void(*) (double *param, int dimension, double **fisher, int chain_id) fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )

```

## Parameters

|     |                                |                                                                                                          |
|-----|--------------------------------|----------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                  | Output chains, shape is double[chain_N, N_steps,dimension]                                               |
|     | <i>dimension</i>               | dimension of the parameter space being explored                                                          |
|     | <i>N_steps</i>                 | Number of total steps to be taken, per chain                                                             |
|     | <i>chain_N</i>                 | Number of chains                                                                                         |
|     | <i>initial_pos</i>             | Initial position in parameter space - shape double[dimension]                                            |
|     | <i>seeding_var</i>             | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension]      |
|     | <i>chain_temps</i>             | Double array of temperatures for the chains                                                              |
|     | <i>swp_freq</i>                | the frequency with which chains are swapped                                                              |
|     | <i>log_prior</i>               | Function pointer for the log_prior                                                                       |
|     | <i>log_likelihood</i>          | Function pointer for the log_likelihood                                                                  |
|     | <i>fisher</i>                  | Function pointer for the fisher - if NULL, fisher steps are not used                                     |
|     | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                         |
|     | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have >2 threads)                                          |
|     | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to "false" if submitting to a cluster) |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                      |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                      |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                        |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip               |
|     | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                       |

## 8.11.2.9 PTMCMC\_MH\_dynamic\_PT\_alloc() [1/2]

```

void PTMCMC_MH_dynamic_PT_alloc (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    int max_chain_N_thermo_ensemble,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    int t0,
    int nu,
    std::string chain_distribution_scheme,
    double(*) (double *param, int dimension) log_prior,
    double(*) (double *param, int dimension) log_likelihood,
    void(*) (double *param, int dimension, double **fisher) fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )

```

## Parameters

|     |                                    |                                                                                                          |
|-----|------------------------------------|----------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                      | Output chains, shape is double[max_chain_N, N_steps,dimension]                                           |
|     | <i>dimension</i>                   | dimension of the parameter space being explored                                                          |
|     | <i>N_steps</i>                     | Number of total steps to be taken, per chain AFTER chain allocation                                      |
|     | <i>chain_N</i>                     | Maximum number of chains to use                                                                          |
|     | <i>max_chain_N_thermo_ensemble</i> | Maximum number of chains to use in the thermodynamic ensemble (may use less)                             |
|     | <i>initial_pos</i>                 | Initial position in parameter space - shape double[dimension]                                            |
|     | <i>seeding_var</i>                 | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension]      |
|     | <i>chain_temps</i>                 | Final chain temperatures used – should be shape double[chain_N]                                          |
|     | <i>swp_freq</i>                    | the frequency with which chains are swapped                                                              |
|     | <i>t0</i>                          | Time constant of the decay of the chain dynamics (~1000)                                                 |
|     | <i>nu</i>                          | Initial amplitude of the dynamics (~100)                                                                 |
|     | <i>log_prior</i>                   | Function pointer for the log_prior                                                                       |
|     | <i>log_likelihood</i>              | Function pointer for the log_likelihood                                                                  |
|     | <i>fisher</i>                      | Function pointer for the fisher - if NULL, fisher steps are not used                                     |
|     | <i>numThreads</i>                  | Number of threads to use (=1 is single threaded)                                                         |
|     | <i>pool</i>                        | boolean to use stochastic chain swapping (MUST have >2 threads)                                          |
|     | <i>show_prog</i>                   | boolean whether to print out progress (for example, should be set to "false" if submitting to a cluster) |
|     | <i>statistics_filename</i>         | Filename to output sampling statistics, if empty string, not output                                      |
|     | <i>chain_filename</i>              | Filename to output data (chain 0 only), if empty string, not output                                      |

## Parameters

|  |                                |                                                                                            |
|--|--------------------------------|--------------------------------------------------------------------------------------------|
|  | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip |
|  | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                         |

## 8.11.2.10 PTMCMC\_MH\_dynamic\_PT\_alloc() [2/2]

```
void PTMCMC_MH_dynamic_PT_alloc (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    int max_chain_N_thermo_ensemble,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    int t0,
    int nu,
    std::string chain_distribution_scheme,
    double(*) (double *param, int dimension, int chain_id) log_prior,
    double(*) (double *param, int dimension, int chain_id) log_likelihood,
    void(*) (double *param, int dimension, double **fisher, int chain_id) fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )
```

## Parameters

|     |                                    |                                                                                                     |
|-----|------------------------------------|-----------------------------------------------------------------------------------------------------|
| out | <i>output</i>                      | Output chains, shape is double[max_chain_N, N_steps,dimension]                                      |
|     | <i>dimension</i>                   | dimension of the parameter space being explored                                                     |
|     | <i>N_steps</i>                     | Number of total steps to be taken, per chain AFTER chain allocation                                 |
|     | <i>chain_N</i>                     | Maximum number of chains to use                                                                     |
|     | <i>max_chain_N_thermo_ensemble</i> | Maximum number of chains to use in the thermodynamic ensemble (may use less)                        |
|     | <i>initial_pos</i>                 | Initial position in parameter space - shape double[dimension]                                       |
|     | <i>seeding_var</i>                 | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension] |
|     | <i>chain_temps</i>                 | Final chain temperatures used – should be shape double[chain_N]                                     |
|     | <i>swp_freq</i>                    | the frequency with which chains are swapped                                                         |
|     | <i>t0</i>                          | Time constant of the decay of the chain dynamics (~1000)                                            |
|     | <i>nu</i>                          | Initial amplitude of the dynamics (~100)                                                            |
|     | <i>log_prior</i>                   | Function pointer for the log_prior                                                                  |
|     | <i>log_likelihood</i>              | Function pointer for the log_likelihood                                                             |

## Parameters

|  |                                |                                                                                                          |
|--|--------------------------------|----------------------------------------------------------------------------------------------------------|
|  | <i>fisher</i>                  | Function pointer for the fisher - if NULL, fisher steps are not used                                     |
|  | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                         |
|  | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have >2 threads)                                          |
|  | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to `false` if submitting to a cluster) |
|  | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                      |
|  | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                      |
|  | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip               |
|  | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                       |

## 8.11.2.11 PTMCMC\_MH\_dynamic\_PT\_alloc\_internal()

```

void PTMCMC_MH_dynamic_PT_alloc_internal (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    int max_chain_N_thermo_ensemble,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    int t0,
    int nu,
    std::string chain_distribution_scheme,
    std::function< double(double *, int *, int, int)> log_prior,
    std::function< double(double *, int *, int, int)> log_likelihood,
    std::function< void(double *, int *, int, double **, int)> fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )

```

Dyanmically tunes an MCMC for optimal spacing. step width, and chain number.

NOTE: nu, and t0 parameters determine the dynamics, so these are important quantities. nu is related to how many swap attempts it takes to substantially change the temperature ladder, why t0 determines the length of the total dyanimcally period. Moderate initial choices would be 10 and 1000, respectively.

Based on arXiv:1501.05823v3

Currently, Chain number is fixed

max\_chain\_N\_thermo\_ensemble sets the maximum number of chains to use to in successively hotter chains to cover the likelihood surface while targeting an optimal swap acceptance target\_swp\_acc.

max\_chain\_N determines the total number of chains to run once thermodynamic equilibrium has been reached. This results in chains being added after the initial PT dynamics have finished according to chain\_distribution\_scheme.

If no preference, set max\_chain\_N\_thermo\_ensemble = max\_chain\_N = numThreads = (number of cores (number of threads if hyperthreaded))– this will most likely be the most optimal configuration. If the number of cores on the system is low, you may want to use n\*numThreads for some integer n instead, depending on the system.

chain\_distribution\_scheme:

"cold": All chains are added at T=1 (untempered)

"refine": Chains are added between the optimal temps geometrically – this may be a good option as it will be a good approximation of the ideal distribution of chains, while keeping the initial dynamical time low

"double": Chains are added in order of rising temperature that mimic the distribution achieved by the earlier PT dynamics

"half\_ensemble": For every cold chain added, half of the ensemble is added again. Effectively, two cold chains for every ensemble

#### Parameters

|     |                                    |                                                                                                                     |
|-----|------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                      | Output chains, shape is double[max_chain_N, N_steps,dimension]                                                      |
|     | <i>dimension</i>                   | dimension of the parameter space being explored                                                                     |
|     | <i>N_steps</i>                     | Number of total steps to be taken, per chain AFTER chain allocation                                                 |
|     | <i>chain_N</i>                     | Maximum number of chains to use                                                                                     |
|     | <i>max_chain_N_thermo_ensemble</i> | Maximum number of chains to use in the thermodynamic ensemble (may use less)                                        |
|     | <i>initial_pos</i>                 | Initial position in parameter space - shape double[dimension]                                                       |
|     | <i>seeding_var</i>                 | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension]                 |
| out | <i>chain_temps</i>                 | Final chain temperatures used – should be shape double[chain_N]                                                     |
|     | <i>swp_freq</i>                    | the frequency with which chains are swapped                                                                         |
|     | <i>t0</i>                          | Time constant of the decay of the chain dynamics (~1000)                                                            |
|     | <i>nu</i>                          | Initial amplitude of the dynamics (~100)                                                                            |
|     | <i>log_prior</i>                   | std::function for the log_prior function – takes double *position, int dimension, int chain_id                      |
|     | <i>log_likelihood</i>              | std::function for the log_likelihood function – takes double *position, int dimension, int chain_id                 |
|     | <i>fisher</i>                      | std::function for the fisher function – takes double *position, int dimension, double **output_fisher, int chain_id |
|     | <i>numThreads</i>                  | Number of threads to use (=1 is single threaded)                                                                    |
|     | <i>pool</i>                        | boolean to use stochastic chain swapping (MUST have >2 threads)                                                     |
|     | <i>show_prog</i>                   | boolean whether to print out progress (for example, should be set to "false" if submitting to a cluster)            |
|     | <i>statistics_filename</i>         | Filename to output sampling statistics, if empty string, not output                                                 |
|     | <i>chain_filename</i>              | Filename to output data (chain 0 only), if empty string, not output                                                 |
|     | <i>likelihood_log_filename</i>     | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                          |
|     | <i>checkpoint_file</i>             | Filename to output data for checkpoint, if empty string, not saved                                                  |

### 8.11.2.12 PTMCMC\_MH\_internal()

```
void PTMCMC_MH_internal (
    double *** output,
    int dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    std::function< double(double *, int *, int, int)> log_prior,
    std::function< double(double *, int *, int, int)> log_likelihood,
    std::function< void(double *, int *, int, double **, int)> fisher,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )
```

Generic sampler, where the likelihood, prior are parameters supplied by the user.

Base of the sampler, generic, with user supplied quantities for most of the samplers properties

Uses the Metropolis-Hastings method, with the option for Fisher/MALA steps if the Fisher routine is supplied.

3 modes to use -

single threaded (numThreads = 1) runs single threaded

multi-threaded "deterministic" (numThreads>1 ; pool = false) progresses each chain in parallel for swp\_freq steps, then waits for all threads to complete before swapping temperatures in sequential order (j, j+1) then (j+1, j+2) etc (sequentially)

multi-threaded "stochastic" (numThreads>2 ; pool = true) progresses each chain in parallel by queueing each temperature and evaluating them in the order they were submitted. Once finished, the threads are queued to swap, where they swapped in the order they are submitted. This means the chains are swapped randomly, and the chains do NOT finish at the same time. The sampler runs until the the 0th chain reaches the step number

Note on limits: In the prior function, if a set of parameters should be disallowed, return -std::numeric\_limits<double>::infinity() – (this is in the <limits> file in std)

Format for the auto\_corr file (compatible with csv, dat, txt extensions): each row is a dimension of the cold chain, with the first row being the lengths used for the auto-corr calculation:

lengths: length1 , length2 ...

dim1: length1 , length2 ...

Format for the chain file (compatible with csv, dat, txt extensions): each row is a step, each column a dimension:

Step1: dim1 , dim2 , ...



Step2: dim1 , dim2 , ...

Statistics\_filename : should be txt extension

checkpoint\_file : This file saves the final position of all the chains, as well as other metadata, and can be loaded by the function <FUNCTION> to continue the chain from the point it left off. Not meant to be read by humans, the data order is custom to this software library. An empty string ("") means no checkpoint will be saved. For developers, the contents are:

dimension, # of chains

temps of chains

Stepping widths of all chains

Final position of all chains

#### Parameters

|     |                                |                                                                                                                     |
|-----|--------------------------------|---------------------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                  | Output chains, shape is double[chain_N, N_steps,dimension]                                                          |
|     | <i>dimension</i>               | dimension of the parameter space being explored                                                                     |
|     | <i>N_steps</i>                 | Number of total steps to be taken, per chain                                                                        |
|     | <i>chain_N</i>                 | Number of chains                                                                                                    |
|     | <i>initial_pos</i>             | Initial position in parameter space - shape double[dimension]                                                       |
|     | <i>seeding_var</i>             | Variance of the normal distribution used to seed each chain higher than 0 - shape double[dimension]                 |
|     | <i>chain_temps</i>             | Double array of temperatures for the chains                                                                         |
|     | <i>swp_freq</i>                | the frequency with which chains are swapped                                                                         |
|     | <i>log_prior</i>               | std::function for the log_prior function – takes double *position, int dimension, int chain_id                      |
|     | <i>log_likelihood</i>          | std::function for the log_likelihood function – takes double *position, int dimension, int chain_id                 |
|     | <i>fisher</i>                  | std::function for the fisher function – takes double *position, int dimension, double **output_fisher, int chain_id |
|     | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                                    |
|     | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have >2 threads)                                                     |
|     | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to "false" if submitting to a cluster)            |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                 |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                                 |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                   |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                          |
|     | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                                  |

#### 8.11.2.13 PTMCMC\_MH\_loop()

```
void PTMCMC_MH_loop (
    sampler * sampler )
```

Internal function that runs the actual loop for the sampler.

#### 8.11.2.14 PTMCMC\_MH\_step\_incremental()

```
void PTMCMC_MH_step_incremental (
    sampler * sampler,
    int increment )
```

Internal function that runs the actual loop for the sampler – increment version.

The regular loop function runs for the entire range, this increment version will only step `increment` steps – asynchronous: steps are measured by the cold chains NEEDS TO CHANGE

#### 8.11.2.15 RJPTMCMC\_MH() [1/2]

```
void RJPTMCMC_MH (
    double *** output,
    int *** parameter_status,
    int max_dimension,
    int min_dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    int * initial_status,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_prior,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_likelihoood,
    void(*) (double *param, int *status, int max_dimension, double **fisher, int chain_id) fisher,
    void(*) (double *current_param, double *proposed_param, int *current_status, int *proposed_status, int max_dimension, int chain_id) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,
    std::string auto_corr_filename,
    std::string likelihood_log_filename,
    std::string checkpoint_file )
```

#### Parameters

|     |                         |                                                                                                                                                                                     |
|-----|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| out | <i>output</i>           | Output chains, shape is double[chain_N, N_steps,dimension]                                                                                                                          |
| out | <i>parameter_status</i> | Parameter status for each step corresponding to the output chains, shape is double[chain_N, N_steps,dimension]                                                                      |
|     | <i>max_dimension</i>    | maximum dimension of the parameter space being explored – only consideration is memory, as memory scales with dimension. Keep this reasonable, unless memory is REALLY not an issue |
|     | <i>min_dimension</i>    | minimum dimension of the parameter space being explored $\geq 1$                                                                                                                    |
|     | <i>N_steps</i>          | Number of total steps to be taken, per chain                                                                                                                                        |

## Parameters

|  |                                |                                                                                                                                                                                     |
|--|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <i>chain_N</i>                 | Number of chains                                                                                                                                                                    |
|  | <i>initial_pos</i>             | Initial position in parameter space - shape double[dimension]                                                                                                                       |
|  | <i>initial_status</i>          | Initial status of the parameters in the initial position in parameter space - shape int[max_dim]                                                                                    |
|  | <i>seeding_var</i>             | Variance of the normal distribution used to seed each chain higher than 0 - shape double[max_dimension] – initial seeding of zero corresponds to the dimension turned off initially |
|  | <i>chain_temps</i>             | Double array of temperatures for the chains                                                                                                                                         |
|  | <i>swp_freq</i>                | the frequency with which chains are swapped                                                                                                                                         |
|  | <i>RJ_proposal</i>             | std::function for the log_likelihood function – takes double *position, int *param_status, int dimension, int chain_id                                                              |
|  | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                                                                                                    |
|  | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have >2 threads)                                                                                                                     |
|  | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to “false” if submitting to a cluster)                                                                            |
|  | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                                                                                 |
|  | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                                                                                                 |
|  | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                                                                                   |
|  | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                                                                                          |
|  | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                                                                                                  |

## 8.11.2.16 RJPTMCMC\_MH() [2/2]

```

void RJPTMCMC_MH (
    double *** output,
    int *** parameter_status,
    int max_dimension,
    int min_dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    int * initial_status,
    double * seeding_var,
    double * chain_temps,
    int swp_freq,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_prior,
    double(*) (double *param, int *status, int max_dimension, int chain_id) log_↵
likelihood,
    void(*) (double *param, int *status, int max_dimension, double **fisher, int chain↵
_id) fisher,
    void(*) (double *current_param, double *proposed_param, int *current_status, int
*proposed_status, int max_dimension, int chain_id, double gaussian_width) RJ_proposal,
    int numThreads,
    bool pool,
    bool show_prog,
    std::string statistics_filename,
    std::string chain_filename,

```

```

std::string auto_corr_filename,
std::string likelihood_log_filename,
std::string checkpoint_file )

```

#### Parameters

|     |                                |                                                                                                                                                                                     |
|-----|--------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| out | <i>output</i>                  | Output chains, shape is double[chain_N, N_steps,dimension]                                                                                                                          |
| out | <i>parameter_status</i>        | Parameter status for each step corresponding to the output chains, shape is double[chain_N, N_steps,dimension]                                                                      |
|     | <i>max_dimension</i>           | maximum dimension of the parameter space being explored – only consideration is memory, as memory scales with dimension. Keep this reasonable, unless memory is REALLY not an issue |
|     | <i>min_dimension</i>           | minimum dimension of the parameter space being explored $\geq 1$                                                                                                                    |
|     | <i>N_steps</i>                 | Number of total steps to be taken, per chain                                                                                                                                        |
|     | <i>chain_N</i>                 | Number of chains                                                                                                                                                                    |
|     | <i>initial_pos</i>             | Initial position in parameter space - shape double[dimension]                                                                                                                       |
|     | <i>initial_status</i>          | Initial status of the parameters in the initial position in parameter space - shape int[max_dim]                                                                                    |
|     | <i>seeding_var</i>             | Variance of the normal distribution used to seed each chain higher than 0 - shape double[max_dimension] – initial seeding of zero corresponds to the dimension turned off initially |
|     | <i>chain_temps</i>             | Double array of temperatures for the chains                                                                                                                                         |
|     | <i>swp_freq</i>                | the frequency with which chains are swapped                                                                                                                                         |
|     | <i>RJ_proposal</i>             | std::function for the log_likelihood function – takes double *position, int *param_status,int dimension, int chain_id                                                               |
|     | <i>numThreads</i>              | Number of threads to use (=1 is single threaded)                                                                                                                                    |
|     | <i>pool</i>                    | boolean to use stochastic chain swapping (MUST have $>2$ threads)                                                                                                                   |
|     | <i>show_prog</i>               | boolean whether to print out progress (for example, should be set to “false” if submitting to a cluster)                                                                            |
|     | <i>statistics_filename</i>     | Filename to output sampling statistics, if empty string, not output                                                                                                                 |
|     | <i>chain_filename</i>          | Filename to output data (chain 0 only), if empty string, not output                                                                                                                 |
|     | <i>auto_corr_filename</i>      | Filename to output auto correlation in some interval, if empty string, not output                                                                                                   |
|     | <i>likelihood_log_filename</i> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                                                                                          |
|     | <i>checkpoint_file</i>         | Filename to output data for checkpoint, if empty string, not saved                                                                                                                  |

#### 8.11.2.17 RJPTMCMC\_MH\_internal()

```

void RJPTMCMC_MH_internal (
    double *** output,
    int *** parameter_status,
    int max_dimension,
    int min_dimension,
    int N_steps,
    int chain_N,
    double * initial_pos,
    int * initial_status,
    double * seeding_var,
    double * chain_temps,

```

```

int swp_freq,
std::function< double(double *, int *, int, int)> log_prior,
std::function< double(double *, int *, int, int)> log_likelihood,
std::function< void(double *, int *, int, double **, int)> fisher,
std::function< void(double *, double *, int *, int *, int, int, int)> RJ_proposal,
int numThreads,
bool pool,
bool show_prog,
bool update_RJ_width,
std::string statistics_filename,
std::string chain_filename,
std::string auto_corr_filename,
std::string likelihood_log_filename,
std::string checkpoint_file )

```

Generic reversible jump sampler, where the likelihood, prior, and reversible jump proposal are parameters supplied by the user.

Note: Using a `min_dimension` tells the sampler that there is a base model'', and that the dimensions from `min_dim` to `max_dim` are small'' corrections to that model. This helps inform some of the proposal algorithms and speeds up computation. If using discrete models with no overlap of variables (ie model A or model B), set `min_dim` to 0. Even if reusing certain parameters, if the extra dimensions don't describe small'' deviations, it's probably best to set `min_dim` to 0. Since the RJ proposal is user specified, even if there are parameters that should never be removed, it's up to the user to dictate that. Using `min_dim` will not affect that aspect of the sampler. If there's a base-model'', the fisher function should produce a fisher matrix for the base model only. The modifications are then normally distributed around the last parameter value. Then the fisher function should take the minimum dimension instead of the maximum, like the other functions.

Currently, no dynamic PT option, as it would be too many free parameters for the sampler to converge to a reasonable temperature distribution in a reasonable amount of time. Best use case, use the PTMCMC\_MH\_dynamic for the ``base'' dimension space, and use that temperature ladder.

Base of the sampler, generic, with user supplied quantities for most of the samplers properties

Uses the Metropolis-Hastings method, with the option for Fisher/MALA steps if the Fisher routine is supplied.

3 modes to use -

single threaded (`numThreads = 1`) runs single threaded

multi-threaded ``deterministic'' (`numThreads > 1` ; `pool = false`) progresses each chain in parallel for `swp_freq` steps, then waits for all threads to complete before swapping temperatures in sequential order (`j, j+1`) then (`j+1, j+2`) etc (sequentially)

multi-threaded ``stochastic'' (`numThreads > 2` ; `pool = true`) progresses each chain in parallel by queueing each temperature and evaluating them in the order they were submitted. Once finished, the threads are queued to swap, where they swapped in the order they are submitted. This means the chains are swapped randomly, and the chains do NOT finish at the same time. The sampler runs until the the 0th chain reaches the step number

Note on limits: In the prior function, if a set of parameters should be disallowed, return `-std::numeric_limits<double>::infinity()` – (this is in the `<limits>` file in std)

The parameter array uses the dimensions `[0,min_dim]` always, and `[min_dim, max_dim]` in RJPTMCMC fashion

Format for the `auto_corr` file (compatible with csv, dat, txt extensions): each row is a dimension of the cold chain, with the first row being the lengths used for the auto-corr calculation:

lengths: length1 , length2 ...

dim1: length1 , length2 ...

Format for the chain file (compatible with csv, dat, txt extensions): each row is a step, each column a dimension:

Step1: dim1 , dim2 , ..., max\_dim, param\_status1, param\_status2, ...

Step2: dim1 , dim2 , ..., max\_dim, param\_status1, param\_status2, ...

Statistics\_filename : should be txt extension

checkpoint\_file : This file saves the final position of all the chains, as well as other metadata, and can be loaded by the function <FUNCTION> to continue the chain from the point it left off. Not meant to be read by humans, the data order is custom to this software library. An empty string ("") means no checkpoint will be saved. For developers, the contents are:

dimension, # of chains

temps of chains

Stepping widths of all chains

Final position of all chains

#### Parameters

|     |                         |                                                                                                                                                                                     |
|-----|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| out | <i>output</i>           | Output chains, shape is double[chain_N, N_steps,dimension]                                                                                                                          |
| out | <i>parameter_status</i> | Parameter status for each step corresponding to the output chains, shape is double[chain_N, N_steps,dimension]                                                                      |
|     | <i>max_dimension</i>    | maximum dimension of the parameter space being explored – only consideration is memory, as memory scales with dimension. Keep this reasonable, unless memory is REALLY not an issue |
|     | <i>min_dimension</i>    | minimum dimension of the parameter space being explored >=1                                                                                                                         |
|     | <i>N_steps</i>          | Number of total steps to be taken, per chain                                                                                                                                        |
|     | <i>chain_N</i>          | Number of chains                                                                                                                                                                    |
|     | <i>initial_pos</i>      | Initial position in parameter space - shape double[dimension]                                                                                                                       |
|     | <i>initial_status</i>   | Initial status of the parameters in the initial position in parameter space - shape int[max_dim]                                                                                    |
|     | <i>seeding_var</i>      | Variance of the normal distribution used to seed each chain higher than 0 - shape double[max_dimension] – initial seeding of zero corresponds to the dimension turned off initially |
|     | <i>chain_temps</i>      | Double array of temperatures for the chains                                                                                                                                         |
|     | <i>swp_freq</i>         | the frequency with which chains are swapped                                                                                                                                         |
|     | <i>log_prior</i>        | std::function for the log_prior function – takes double *position, int *param_status, int dimension, int chain_id                                                                   |
|     | <i>log_likelihood</i>   | std::function for the log_likelihood function – takes double *position, int *param_status,int dimension, int chain_id                                                               |
|     | <i>fisher</i>           | std::function for the fisher function – takes double *position, int *param_status,int dimension, double **output_fisher, int chain_id                                               |
|     | <i>RJ_proposal</i>      | std::function for the log_likelihood function – takes double *position, int *param_status,int dimension, int chain_id                                                               |
|     | <i>numThreads</i>       | Number of threads to use (=1 is single threaded)                                                                                                                                    |
|     | <i>pool</i>             | boolean to use stochastic chain swapping (MUST have >2 threads)                                                                                                                     |
|     | <i>show_prog</i>        | boolean whether to print out progress (for example, should be set to 'false' if submitting to a cluster)                                                                            |

## Parameters

|  |                                      |                                                                                                                                                                 |
|--|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
|  | <code>update_RJ_width</code>         | boolean whether to print out progress (for example, should be set to ``false'' if submitting to a cluster)                                                      |
|  | <code>statistics_filename</code>     | Filename to output sampling statistics, if empty string, not output                                                                                             |
|  | <code>chain_filename</code>          | Filename to output data (chain 0 only), if empty string, not output – if multiple cold chains, it will append each output to the other, and write out the total |
|  | <code>auto_corr_filename</code>      | Filename to output auto correlation in some interval, if empty string, not output                                                                               |
|  | <code>likelihood_log_filename</code> | Filename to write the log_likelihood and log_prior at each step – use empty string to skip                                                                      |
|  | <code>checkpoint_file</code>         | Filename to output data for checkpoint, if empty string, not saved                                                                                              |

## 8.12 src/mcmc\_sampler\_internals.cpp File Reference

```
#include "mcmc_sampler_internals.h"
#include "autocorrelation.h"
#include "util.h"
#include <iostream>
#include <fstream>
#include <string>
#include <math.h>
#include <gsl/gsl_randist.h>
#include <gsl/gsl_rng.h>
#include <eigen3/Eigen/Eigen>
#include <limits>
#include <iomanip>
#include <fftw3.h>
#include <stdio.h>
```

Include dependency graph for mcmc\_sampler\_internals.cpp:



## Functions

- int [mcmc\\_step](#) (sampler \*sampler, double \*current\_param, double \*next\_param, int \*current\_status, int \*next\_status, int chain\_number)  
*interface function between the sampler and the internal step functions*
- void [gaussian\\_step](#) (sampler \*sampler, double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int chain\_id)  
*Straight gaussian step.*
- void [fisher\\_step](#) (sampler \*sampler, double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int chain\_index)  
*Fisher informed gaussian step.*
- void [update\\_fisher](#) (sampler \*sampler, double \*current\_param, int \*param\_status, int chain\_index)
- void [mmala\\_step](#) (sampler \*sampler, double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status)

- MMALA informed step – Currently not supported.*
- void [diff\\_ev\\_step](#) (sampler \*sampler, double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int chain\_id)
- differential evolution informed step*
- void [RJ\\_smooth\\_history](#) (sampler \*sampler, double \*current\_param, int \*current\_param\_status, int base\_↵ history\_id, double \*eff\_history\_coord, int \*eff\_history\_status, int chain\_id)
- void [RJ\\_step](#) (sampler \*sampler, double \*current\_param, double \*proposed\_param, int \*current\_status, int \*proposed\_status, int chain\_number)
- RJ-proposal step for trans-dimensional MCMCs.*
- void [chain\\_swap](#) (sampler \*sampler, double \*\*\*output, int \*\*\*param\_status, int step\_num, int \*swp\_↵ accepted, int \*swp\_rejected)
- subroutine to perform chain comparison for parallel tempering*
- int [single\\_chain\\_swap](#) (sampler \*sampler, double \*chain1, double \*chain2, int \*chain1\_status, int \*chain2\_↵ \_status, int T1\_index, int T2\_index)
- subroutine to actually swap two chains*
- void [assign\\_probabilities](#) (sampler \*sampler, int chain\_index)
- update and initiate probabilities for each variety of step*
- void [transfer\\_chain](#) (sampler \*samplerptr\_dest, sampler \*samplerptr\_source, int id\_dest, int id\_source, bool transfer\_output)
- Copies contents of one chain to another.*
- bool [check\\_sampler\\_status](#) (sampler \*samplerptr)
- Checks the status of a sampler for the stochastic sampling.*
- void [update\\_step\\_widths](#) (sampler \*samplerptr, int chain\_id)
- Updates the step widths, shooting for 20% acceptance ratios for each type of step.*
- void [allocate\\_sampler\\_mem](#) (sampler \*sampler)
- void [deallocate\\_sampler\\_mem](#) (sampler \*sampler)
- void [update\\_history](#) (sampler \*sampler, double \*new\_params, int \*new\_param\_status, int chain\_index)
- void [write\\_stat\\_file](#) (sampler \*sampler, std::string filename)
- void [write\\_checkpoint\\_file](#) (sampler \*sampler, std::string filename)
- Routine that writes metadata and final positions of a sampler to a checkpoint file.*
- void [load\\_temps\\_checkpoint\\_file](#) (std::string check\_file, double \*temps, int chain\_N)
- load temperatures from checkpoint file*
- void [load\\_checkpoint\\_file](#) (std::string check\_file, sampler \*sampler)
- load checkpoint file into sampler struct*
- void [assign\\_ct\\_p](#) (sampler \*sampler, int step, int chain\_index)
- void [assign\\_ct\\_m](#) (sampler \*sampler, int step, int chain\_index)
- void [assign\\_initial\\_pos](#) (sampler \*samplerptr, double \*initial\_pos, int \*initial\_status, double \*seeding\_var)
- double [PT\\_dynamical\\_timescale](#) (int t0, int nu, int t)
- Timescale of the PT dynamics.*
- void [update\\_temperatures](#) (sampler \*samplerptr, int t0, int nu, int t)
- updates the temperatures for a sampler such that all acceptance rates are equal*
- void [initiate\\_full\\_sampler](#) (sampler \*sampler\_new, sampler \*sampler\_old, int chain\_N\_thermo\_ensemble, int chain\_N, std::string chain\_allocation\_scheme)
- For the dynamic PT sampler, this is the function that starts the full sampler with the max number of chains.*
- void [write\\_output\\_file](#) (std::string file, int step\_num, int max\_dimension, double \*\*output, int \*\*status)
- Utility to write out the parameters and status of a sampler to a file.*

## 8.12.1 Detailed Description

File containing definitions for all the internal, generic mcmc subroutines



## 8.12.2 Function Documentation

### 8.12.2.1 assign\_probabilities()

```
void assign_probabilities (
    sampler * sampler,
    int chain_index )
```

update and initiate probabilities for each variety of step

Type 0: Gaussian step

Type 1: Differential Evolution step

Type 2: MMALA step (currently not supported)

Type 3: Fisher step

### 8.12.2.2 chain\_swap()

```
void chain_swap (
    sampler * sampler,
    double *** output,
    int *** param_status,
    int step_num,
    int * swp_accepted,
    int * swp_rejected )
```

subroutine to perform chain comparison for parallel tempering

The total output file is passed, and the chains are swapped sequentially

This is the routine for "Deterministic" sampling (parallel or sequential, but not pooled)

#### Parameters

|                     |                                 |
|---------------------|---------------------------------|
| <i>sampler</i>      | sampler struct                  |
| <i>output</i>       | output vector containing chains |
| <i>param_status</i> | Parameter status                |
| <i>step_num</i>     | current step number             |

### 8.12.2.3 check\_sampler\_status()

```
bool check_sampler_status (
    sampler * samplerptr )
```

Checks the status of a sampler for the stochastic sampling.

Just loops through the ref\_chain\_status variables

#### 8.12.2.4 `diff_ev_step()`

```
void diff_ev_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    int * current_status,
    int * proposed_status,
    int chain_id )
```

differential evolution informed step

Differential evolution uses the past history of the chain to inform the proposed step:

Take the difference of two random, accepted previous steps and step along that with some step size, determined by a gaussian

##### Parameters

|     |                       |                                      |
|-----|-----------------------|--------------------------------------|
|     | <i>sampler</i>        | Sampler struct                       |
|     | <i>current_param</i>  | current position in parameter space  |
| out | <i>proposed_param</i> | Proposed position in parameter space |

#### 8.12.2.5 `fisher_step()`

```
void fisher_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    int * current_status,
    int * proposed_status,
    int chain_index )
```

Fisher informed gaussian step.

##### Parameters

|     |                       |                                      |
|-----|-----------------------|--------------------------------------|
|     | <i>sampler</i>        | Sampler struct                       |
|     | <i>current_param</i>  | current position in parameter space  |
| out | <i>proposed_param</i> | Proposed position in parameter space |

#### 8.12.2.6 `gaussian_step()`

```
void gaussian_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
```

```
int * current_status,
int * proposed_status,
int chain_id )
```

Straight gaussian step.

#### Parameters

|     |                       |                                      |
|-----|-----------------------|--------------------------------------|
|     | <i>sampler</i>        | Sampler struct                       |
|     | <i>current_param</i>  | current position in parameter space  |
| out | <i>proposed_param</i> | Proposed position in parameter space |

#### 8.12.2.7 initiate\_full\_sampler()

```
void initiate_full_sampler (
    sampler * sampler_new,
    sampler * sampler_old,
    int chain_N_thermo_ensemble,
    int chain_N,
    std::string chain_allocation_scheme )
```

For the dynamic PT sampler, this is the function that starts the full sampler with the max number of chains.

The output file will be reused, but the positions are set back to zero (copying the current position to position zero)

Assumes the output, chain\_temps have been allocated in memory for the final number of chains chain\_N and steps N\_steps

Allocates memory for the new sampler sampler\_new -> it's the user's responsibility to deallocate with deallocate\_sampler\_mem

#### Parameters

|                                |                                                     |
|--------------------------------|-----------------------------------------------------|
| <i>sampler_old</i>             | Dynamic sampler                                     |
| <i>chain_N_thermo_ensemble</i> | Number of chains used in the thermodynamic ensemble |
| <i>chain_N</i>                 | Number of chains to use in the static sampler       |
| <i>chain_allocation_scheme</i> | Scheme to use to allocate any remaining chains      |

#### 8.12.2.8 load\_checkpoint\_file()

```
void load_checkpoint_file (
    std::string check_file,
    sampler * sampler )
```

load checkpoint file into sampler struct

**NOTE** – allocate\_sampler called in function – MUST deallocate manually

**NOTE** – sampler->chain\_temps allocated internally – MUST free manually

### 8.12.2.9 load\_temps\_checkpoint\_file()

```
void load_temps_checkpoint_file (
    std::string check_file,
    double * temps,
    int chain_N )
```

load temperatures from checkpoint file

Assumed the temps array is already allocated in memory for the correct number of chains

Just a utility routine to read temperatures from checkpoint file

It would be easy to read in the chain number and allocate memory in the function, but I prefer to leave allocation/deallocation up to the client

### 8.12.2.10 mmala\_step()

```
void mmala_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    int * current_status,
    int * proposed_status )
```

MMALA informed step – Currently not supported.

#### Parameters

|     |                       |                                      |
|-----|-----------------------|--------------------------------------|
|     | <i>sampler</i>        | Sampler struct                       |
|     | <i>current_param</i>  | current position in parameter space  |
| out | <i>proposed_param</i> | Proposed position in parameter space |

### 8.12.2.11 PT\_dynamical\_timescale()

```
double PT_dynamical_timescale (
    int t0,
    int nu,
    int t )
```

Timescale of the PT dynamics.

kappa in the the language of arXiv:1501.05823v3

#### Parameters

|           |                                                         |
|-----------|---------------------------------------------------------|
| <i>t0</i> | Timescale of the dyanmics                               |
| <i>nu</i> | Initial amplitude (number of steps to base dynamics on) |
| <i>t</i>  | current time                                            |

## 8.12.2.12 RJ\_smooth\_history()

```
void RJ_smooth_history (
    sampler * sampler,
    double * current_param,
    int * current_param_status,
    int base_history_id,
    double * eff_history_coord,
    int * eff_history_status,
    int chain_id )
```

## Parameters

|     |                             |                               |
|-----|-----------------------------|-------------------------------|
|     | <i>sampler</i>              | Current sampler               |
|     | <i>current_param</i>        | Current parameters to match   |
|     | <i>current_param_status</i> | Current parameters to match   |
|     | <i>base_history_id</i>      | Original history element      |
| out | <i>eff_history_coord</i>    | Modified history coord        |
| out | <i>eff_history_status</i>   | Modified History status       |
|     | <i>chain_id</i>             | Chain ID of the current chain |

## 8.12.2.13 RJ\_step()

```
void RJ_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    int * current_status,
    int * proposed_status,
    int chain_number )
```

RJ-proposal step for trans-dimensional MCMCs.

This extra step may seem unnecessary, I'm just adding it in in case the extra flexibility is useful in the future for preprocessing of the chain before sending it to the user's RJ\_proposal

## Parameters

|     |                        |                                         |
|-----|------------------------|-----------------------------------------|
|     | <i>sampler</i>         | sampler                                 |
|     | <i>current_param</i>   | current coordinates in parameter space  |
| out | <i>proposed_param</i>  | Proposed coordinates in parameter space |
|     | <i>current_status</i>  | Current status of parameters            |
| out | <i>proposed_status</i> | Proposed status of parameters           |
|     | <i>chain_number</i>    | chain number                            |

#### 8.12.2.14 single\_chain\_swap()

```
int single_chain_swap (
    sampler * sampler,
    double * chain1,
    double * chain2,
    int * chain1_status,
    int * chain2_status,
    int T1_index,
    int T2_index )
```

subroutine to actually swap two chains

This is the more general subroutine, which just swaps the two chains passed to the function

##### Parameters

|                      |                                                                                     |
|----------------------|-------------------------------------------------------------------------------------|
| <i>sampler</i>       | sampler structure                                                                   |
| <i>chain1</i>        | parameter position of chain that could be changed                                   |
| <i>chain2</i>        | chain that is not swapped, but provides parameters to be swapped by the other chain |
| <i>chain1_status</i> | Parameter status array for chain1                                                   |
| <i>chain2_status</i> | Parameter status array for chain2                                                   |
| <i>T1_index</i>      | number of chain swape in chain_temps                                                |
| <i>T2_index</i>      | number of chain swapper in chain_temps                                              |

#### 8.12.2.15 transfer\_chain()

```
void transfer_chain (
    sampler * samplerptr_dest,
    sampler * samplerptr_source,
    int id_dest,
    int id_source,
    bool transfer_output )
```

Copies contents of one chain to another.

Transfers *id\_source* in *samplerptr\_source* to *id\_dest* *samplerptr\_dest*

NOTE: This copies the VALUE, not the reference. This could be expensive, so use with caution

*id\_dest* is ERASED

*samplerptr\_dest* and *samplerptr\_source* MUST have the same dimension, the same sampling details (like having or not having a fisher) etc

*samplerptr\_dest* must be previously allocated properly

As output is the largest transfer by far, the *transfer\_output* flag can be used to allow the user to handle that manually.

#### 8.12.2.16 update\_temperatures()

```
void update_temperatures (
    sampler * samplerptr,
    int t0,
    int nu,
    int t )
```

updates the temperatures for a sampler such that all acceptance rates are equal

Follows the algorithm outlined in arXiv:1501.05823v3

Fixed temperatures for the first and last chain

used in MCMC\_MH\_dynamic\_PT\_alloc\_internal

For defined results, this should be used while the sampler is using non-pooling methods

#### 8.12.2.17 write\_checkpoint\_file()

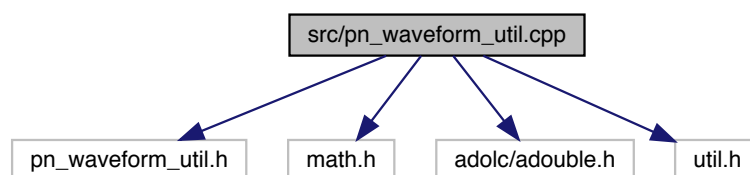
```
void write_checkpoint_file (
    sampler * sampler,
    std::string filename )
```

Routine that writes metadata and final positions of a sampler to a checkpoint file.

## 8.13 src/pn\_waveform\_util.cpp File Reference

```
#include "pn_waveform_util.h"
#include <math.h>
#include <adolc/adouble.h>
#include "util.h"
```

Include dependency graph for pn\_waveform\_util.cpp:



## Functions

- `template<class T >`  
`T t_2PN` (T f, T eta, T chirpmass, T chi1, T chi2, T tc)  
*Time t as a function of f up to 2nd PN order.*
- `template<class T >`  
`T FISCO` (T mass)  
*Utility function for the frequency at the innermost stable circular orbit (ISCO)*
- `template double t_2PN< double >` (double, double, double, double, double, double)
- `template adouble t_2PN< adouble >` (adouble, adouble, adouble, adouble, adouble, adouble)
- `template adouble FISCO` (adouble mass)
- `template double FISCO` (double mass)

### 8.13.1 Detailed Description

PN waveform utilities

### 8.13.2 Function Documentation

#### 8.13.2.1 FISCO()

```
template<class T >
T FISCO (
    T mass )
```

Utility function for the frequency at the innermost stable circular orbit (ISCO)

#### 8.13.2.2 t\_2PN()

```
template<class T >
T t_2PN (
    T f,
    T eta,
    T chirpmass,
    T chi1,
    T chi2,
    T tc )
```

Time t as a function of f up to 2nd PN order.

Taken from <https://arxiv.org/pdf/gr-qc/0411129.pdf>

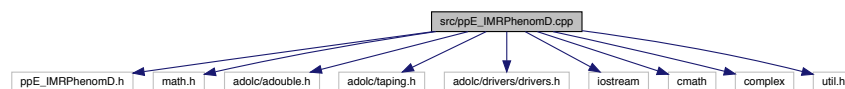
Non-precressing for now



## 8.14 src/ppE\_IMRPhenomD.cpp File Reference

```
#include "ppE_IMRPhenomD.h"
#include <math.h>
#include <adolc/adouble.h>
#include <adolc/taping.h>
#include <adolc/drivers/drivers.h>
#include <iostream>
#include <cmath>
#include <complex>
#include "util.h"
```

Include dependency graph for ppE\_IMRPhenomD.cpp:



### 8.14.1 Detailed Description

File for the implementation of the ppE formalism for testing GR

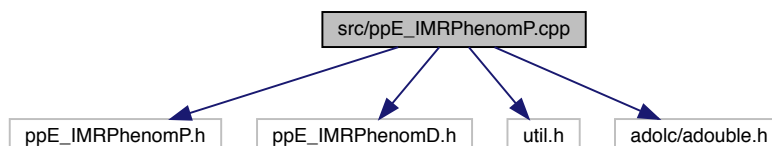
Extends the IMRPhenomD template to include non-GR phase terms

Supported waveforms: ppE Inspiral, ppE IMR, dCS, EdGB

## 8.15 src/ppE\_IMRPhenomP.cpp File Reference

```
#include "ppE_IMRPhenomP.h"
#include "ppE_IMRPhenomD.h"
#include "util.h"
#include <adolc/adouble.h>
```

Include dependency graph for ppE\_IMRPhenomP.cpp:



### Macros

- #define **ROTATEZ**(angle, vx, vy, vz)
- #define **ROTATEY**(angle, vx, vy, vz)

## Variables

- const double **sqrt\_6** = 2.44948974278317788

### 8.15.1 Detailed Description

Source code file for parameterized post Einsteinian Modifications to the precessing waveform model IMRPhenomP

### 8.15.2 Macro Definition Documentation

#### 8.15.2.1 ROTATEY

```
#define ROTATEY(  
    angle,  
    vx,  
    vy,  
    vz )
```

**Value:**

```
tmp1 = vx*cos(angle) + vz*sin(angle);\n tmp2 = - vx*sin(angle) + vz*cos(angle);\n vx = tmp1;\n vz = tmp2
```

#### 8.15.2.2 ROTATEZ

```
#define ROTATEZ(  
    angle,  
    vx,  
    vy,  
    vz )
```

**Value:**

```
tmp1 = vx*cos(angle) - vy*sin(angle);\n tmp2 = vx*sin(angle) + vy*cos(angle);\n vx = tmp1;\n vy = tmp2
```

## 8.16 src/util.cpp File Reference

```
#include "util.h"
#include "GWATConfig.h"
#include "D_Z_Config.h"
#include <math.h>
#include <string>
#include <string.h>
#include <complex>
#include <iostream>
#include <stdio.h>
#include <fstream>
#include <adolc/adouble.h>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
#include <gsl/gsl_errno.h>
```

Include dependency graph for util.cpp:



### Functions

- void [initiate\\_LumD\\_Z\\_interp](#) (gsl\_interp\_accel \*\*Z\_DL\_accel\_ptr, gsl\_spline \*\*Z\_DL\_spline\_ptr)  
*Function that uses the GSL libraries to interpolate pre-calculated Z-D\_L data.*
- void [free\\_LumD\\_Z\\_interp](#) (gsl\_interp\_accel \*\*Z\_DL\_accel\_ptr, gsl\_spline \*\*Z\_DL\_spline\_ptr)  
*Frees the allocated interpolation function.*
- adouble [Z\\_from\\_DL\\_interp](#) (adouble DL, gsl\_interp\_accel \*Z\_DL\_accel\_ptr, gsl\_spline \*Z\_DL\_spline\_ptr)
- double [Z\\_from\\_DL\\_interp](#) (double DL, gsl\_interp\_accel \*Z\_DL\_accel\_ptr, gsl\_spline \*Z\_DL\_spline\_ptr)
- double [Z\\_from\\_DL](#) (double DL, std::string cosmology)  
*Calculates the redshift given the luminosity distance.*
- adouble [Z\\_from\\_DL](#) (adouble DL, std::string cosmology)  
*Calculates the redshift given the luminosity distance adouble version for ADOL-C implementation.*
- double [DL\\_from\\_Z](#) (double Z, std::string cosmology)  
*Calculates the luminosity distance given the redshift.*
- adouble [DL\\_from\\_Z](#) (adouble Z, std::string cosmology)  
*Calculates the luminosity distance given the redshift adouble version for ADOL-C implementation.*
- double [cosmology\\_interpolation\\_function](#) (double x, double \*coeffs, int interp\_degree)  
*Custom interpolation function used in the cosmology calculations.*
- adouble [cosmology\\_interpolation\\_function](#) (adouble x, double \*coeffs, int interp\_degree)  
*Custom interpolation function used in the cosmology calculations adouble version for ADOL-C.*
- double [cosmology\\_lookup](#) (std::string cosmology)  
*Helper function for mapping cosmology name to an internal index.*
- void [printProgress](#) (double percentage)  
*routine to print the progress of a process to the terminal as a progress bar*
- void [allocate\\_FFTW\\_mem\\_forward](#) (fftw\_outline \*plan, int length)  
*Allocate memory for FFTW3 methods used in a lot of inner products input is a locally defined structure that houses all the pertinent data.*
- void [allocate\\_FFTW\\_mem\\_reverse](#) (fftw\_outline \*plan, int length)

Allocate memory for FFTW3 methods used in a lot of inner products –INVERSE input is a locally defined structure that houses all the pertinent data.

- void `deallocate_FFTW_mem` (fftw\_outline \*plan)  
*deallocates the memory used for FFTW routines*
- double `calculate_chirpmass` (double mass1, double mass2)  
*Calculates the chirp mass from the two component masses.*
- adouble `calculate_chirpmass` (adouble mass1, adouble mass2)
- double `calculate_eta` (double mass1, double mass2)  
*Calculates the symmetric mass ration from the two component masses.*
- adouble `calculate_eta` (adouble mass1, adouble mass2)
- double `calculate_mass1` (double chirpmass, double eta)  
*Calculates the larger mass given a chirp mass and symmetric mass ratio.*
- adouble `calculate_mass1` (adouble chirpmass, adouble eta)
- double `calculate_mass2` (double chirpmass, double eta)  
*Calculates the smaller mass given a chirp mass and symmetric mass ratio.*
- adouble `calculate_mass2` (adouble chirpmass, adouble eta)
- long `factorial` (long num)  
*Local function to calculate a factorial.*
- double `pow_int` (double base, int power)  
*Local power function, specifically for integer powers.*
- adouble `pow_int` (adouble base, int power)
- double `cbrt_internal` (double base)  
*Fucntion that just returns the cuberoot.*
- adouble `cbrt_internal` (adouble base)  
*Fucntion that just returns the cuberoot ADOL-C doesn't have the cbrt function (which is faster), so have to use the power function.*
- double \*\* `allocate_2D_array` (int dim1, int dim2)  
*Utility to malloc 2D array.*
- int \*\* `allocate_2D_array_int` (int dim1, int dim2)
- void `deallocate_2D_array` (double \*\*array, int dim1, int dim2)  
*Utility to free malloc'd 2D array.*
- void `deallocate_2D_array` (int \*\*array, int dim1, int dim2)
- double \*\*\* `allocate_3D_array` (int dim1, int dim2, int dim3)  
*Utility to malloc 3D array.*
- int \*\*\* `allocate_3D_array_int` (int dim1, int dim2, int dim3)
- void `deallocate_3D_array` (double \*\*\*array, int dim1, int dim2, int dim3)  
*Utility to free malloc'd 2D array.*
- void `deallocate_3D_array` (int \*\*\*array, int dim1, int dim2, int dim3)  
*Utility to free malloc'd 2D array.*
- void `read_file` (std::string filename, double \*\*output, int rows, int cols)  
*Utility to read in data.*
- void `read_file` (std::string filename, double \*output)  
*Utility to read in data (single dimension vector)*
- void `read_LOSC_data_file` (std::string filename, double \*output, double \*data\_start\_time, double \*duration, double \*fs)  
*Read data file from LIGO Open Science Center.*
- void `read_LOSC_PSD_file` (std::string filename, double \*\*output, int rows, int cols)  
*Read PSD file from LIGO Open Science Center.*
- void `allocate_LOSC_data` (std::string \*data\_files, std::string psd\_file, int num\_detectors, int psd\_length, int data\_file\_length, double trigger\_time, std::complex< double > \*\*data, double \*\*psds, double \*\*freqs)  
*Prepare data for MCMC directly from LIGO Open Science Center.*

- void `free_LOSC_data` (std::complex< double > \*\*data, double \*\*psds, double \*\*freqs, int num\_detectors, int length)
- void `tukey_window` (double \*window, int length, double alpha)  
*Tukey window function for FFTs.*
- void `write_file` (std::string filename, double \*\*input, int rows, int cols)  
*Utility to write 2D array to file.*
- void `write_file` (std::string filename, double \*input, int length)  
*Utility to write 1D array to file.*
- template<class T >  
void `celestial_horizon_transform` (T RA, T DEC, double gps\_time, T LONG, T LAT, T \*phi, T \*theta)  
*Utility to transform from celestial coord RA and DEC to local horizon coord for detector response functions.*
- template void `celestial_horizon_transform`< double > (double, double, double, double, double, double \*, double \*)
- template void `celestial_horizon_transform`< adouble > (adouble, adouble, double, adouble, adouble, adouble \*, adouble \*)
- template<class T >  
T `gps_to_GMST` (T gps\_time)  
*Utility to transform from gps time to GMST <https://aa.usno.navy.mil/faq/docs/GAST.php>.*
- template double `gps_to_GMST`< double > (double)
- template<class T >  
T `gps_to_JD` (T gps\_time)  
*Utility to transform from gps to JD.*
- template double `gps_to_JD`< double > (double)
- template adouble `gps_to_JD`< adouble > (adouble)
- void `transform_cart_sph` (double \*cartvec, double \*sphvec)  
*utility to transform a vector from cartesian to spherical (radian)*
- void `transform_sph_cart` (double \*sphvec, double \*cartvec)  
*utility to transform a vector from spherical (radian) to cartesian*
- template<class T >  
std::complex< T > `cpolar` (T mag, T phase)
- template<class T >  
std::complex< T > `XLALSpinWeightedSphericalHarmonic` (T theta, T phi, int s, int l, int m)
- template std::complex< double > `XLALSpinWeightedSphericalHarmonic`< double > (double, double, int, int, int)
- template std::complex< adouble > `XLALSpinWeightedSphericalHarmonic`< adouble > (adouble, adouble, int, int, int)
- template std::complex< double > `cpolar`< double > (double, double)
- template std::complex< adouble > `cpolar`< adouble > (adouble, adouble)

### 8.16.1 Detailed Description

General utilities that are not necessarily specific to any part of the project at large

### 8.16.2 Function Documentation

**8.16.2.1 allocate\_2D\_array()**

```
double** allocate_2D_array (
    int dim1,
    int dim2 )
```

Utility to malloc 2D array.

**8.16.2.2 allocate\_3D\_array()**

```
double*** allocate_3D_array (
    int dim1,
    int dim2,
    int dim3 )
```

Utility to malloc 3D array.

**8.16.2.3 allocate\_LOSC\_data()**

```
void allocate_LOSC_data (
    std::string * data_files,
    std::string psd_file,
    int num_detectors,
    int psd_length,
    int data_file_length,
    double trigger_time,
    std::complex< double > ** data,
    double ** psds,
    double ** freqs )
```

Prepare data for MCMC directly from LIGO Open Science Center.

Trims data for Tobs (determined by PSD file)  $3/4 * T_{obs}$  in front of trigger, and  $1/4 * T_{obs}$  behind

Currently, default to sampling frequency and observation time set by PSD – cannot be customized

Output is in order of PSD columns – string vector of detectos MUST match order of PSD cols

Output shapes– psds = [num\_detectors][psd\_length] data = [num\_detectors][psd\_length]

freqs = [num\_detectors][psd\_length]

Total observation time =  $1 / ( \text{freq}[i] - \text{freq}[i-1] )$  (from PSD file)

Sampling frequency fs = max frequency from PSD file

ALLOCATES MEMORY – must be freed to prevent memory leak

## Parameters

|     |                         |                                                    |
|-----|-------------------------|----------------------------------------------------|
|     | <i>data_files</i>       | Vector of strings for each detector file from LOSC |
|     | <i>psd_file</i>         | String of psd file from LOSC                       |
|     | <i>num_detectors</i>    | Number of detectors to use                         |
|     | <i>psd_length</i>       | Length of the PSD file (number of rows of DATA)    |
|     | <i>data_file_length</i> | Length of the data file (number of rows of DATA)   |
|     | <i>trigger_time</i>     | Time for the signal trigger (GPS)                  |
| out | <i>data</i>             | Output array of data for each detector             |
| out | <i>psds</i>             | Output array of psds for each detector             |
| out | <i>freqs</i>            | Output array of freqs for each detector            |

## 8.16.2.4 calculate\_chirpmass()

```
double calculate_chirpmass (
    double mass1,
    double mass2 )
```

Calculates the chirp mass from the two component masses.

The output units are whatever units the input masses are

## 8.16.2.5 calculate\_mass1()

```
double calculate_mass1 (
    double chirpmass,
    double eta )
```

Calculates the larger mass given a chirp mass and symmetric mass ratio.

Units of the output match the units of the input chirp mass

## 8.16.2.6 calculate\_mass2()

```
double calculate_mass2 (
    double chirpmass,
    double eta )
```

Calculates the smaller mass given a chirp mass and symmetric mass ratio.

Units of the output match the units of the input chirp mass

#### 8.16.2.7 celestial\_horizon\_transform()

```
template<class T >
void celestial_horizon_transform (
    T RA,
    T DEC,
    double gps_time,
    T LONG,
    T LAT,
    T * phi,
    T * theta )
```

Utility to transform from celestial coord RA and DEC to local horizon coord for detector response functions.

Outputs are the spherical polar angles defined by North as 0 degrees azimuth and the normal to the earth as 0 degree polar



## Parameters

|     |                 |                               |
|-----|-----------------|-------------------------------|
|     | <i>RA</i>       | Right ascension (rad)         |
|     | <i>DEC</i>      | Declination (rad)             |
|     | <i>gps_time</i> | GPS time                      |
|     | <i>LONG</i>     | Longitude (rad)               |
|     | <i>LAT</i>      | Latitude (rad)                |
| out | <i>phi</i>      | horizon azimuthal angle (rad) |
| out | <i>theta</i>    | horizon polar angle (rad)     |

## 8.16.2.8 cosmology\_interpolation\_function()

```
double cosmology_interpolation_function (
    double x,
    double * coeffs,
    int interp_degree )
```

Custom interpolation function used in the cosmology calculations.

Power series in half power increments of x, up to 11/2. powers of x

## 8.16.2.9 deallocate\_2D\_array()

```
void deallocate_2D_array (
    double ** array,
    int dim1,
    int dim2 )
```

Utility to free malloc'd 2D array.

## 8.16.2.10 deallocate\_3D\_array() [1/2]

```
void deallocate_3D_array (
    double *** array,
    int dim1,
    int dim2,
    int dim3 )
```

Utility to free malloc'd 2D array.

**8.16.2.11 deallocate\_3D\_array()** [2/2]

```
void deallocate_3D_array (
    int *** array,
    int dim1,
    int dim2,
    int dim3 )
```

Utility to free malloc'd 2D array.

**8.16.2.12 DL\_from\_Z()**

```
double DL_from_Z (
    double Z,
    std::string cosmology )
```

Calculates the luminosity distance given the redshift.

Based on Astropy.cosmology calculations – see python script in the ./data folder of the project – numerically calculated given astropy.cosmology's definitions ( <http://docs.astropy.org/en/stable/cosmology/>) and used scipy.optimize to fit to a power series, stepping in half powers of Z. These coefficients are then output to a header file (D\_Z\_config.h) which are used here to calculate distance. Custom cosmologies etc can easily be achieved by editing the python script D\_Z\_config.py, the c++ functions do not need modification. They use whatever data is available in the header file. If the functional form of the fitting function changes, these functions DO need to change.

5 cosmological models are available (this argument must be spelled exactly):

PLANCK15, PLANCK13, WMAP9, WMAP7, WMAP5

**8.16.2.13 free\_LOSC\_data()**

```
void free_LOSC_data (
    std::complex< double > ** data,
    double ** psds,
    double ** freqs,
    int num_detectors,
    int length )
```

/brief Free data allocated by prep\_LOSC\_data function

**8.16.2.14 initiate\_LumD\_Z\_interp()**

```
void initiate_LumD_Z_interp (
    gsl_interp_accel ** Z_DL_accel_ptr,
    gsl_spline ** Z_DL_spline_ptr )
```

Function that uses the GSL libraries to interpolate pre-calculated Z-D\_L data.

Initiates the required functions – GSL interpolation requires allocating memory before hand

**8.16.2.15 pow\_int()**

```
double pow_int (
    double base,
    int power )
```

Local power function, specifically for integer powers.

Much faster than the std version, because this is only for integer powers

**8.16.2.16 printProgress()**

```
void printProgress (
    double percentage )
```

routine to print the progress of a process to the terminal as a progress bar

Call everytime you want the progress printed

**8.16.2.17 read\_file()** [1/2]

```
void read_file (
    std::string filename,
    double ** output,
    int rows,
    int cols )
```

Utility to read in data.

Takes filename, and assigns to output[rows][cols]

File must be comma separated doubles

**Parameters**

|     |                 |                                                 |
|-----|-----------------|-------------------------------------------------|
|     | <i>filename</i> | input filename, relative to execution directory |
| out | <i>output</i>   | array to store output, dimensions rowsXcols     |
|     | <i>rows</i>     | first dimension                                 |
|     | <i>cols</i>     | second dimension                                |

**8.16.2.18 read\_file()** [2/2]

```
void read_file (
    std::string filename,
    double * output )
```

Utility to read in data (single dimension vector)

Takes filename, and assigns to output[i\*rows + cols]

Output vector must be long enough, no check is done for the length

File must be comma separated doubles

## Parameters

|     |                 |                                                                |
|-----|-----------------|----------------------------------------------------------------|
|     | <i>filename</i> | input filename, relative to execution directory                |
| out | <i>output</i>   | output array, assumed to have the proper length of total items |

## 8.16.2.19 read\_LOSC\_data\_file()

```
void read_LOSC_data_file (
    std::string filename,
    double * output,
    double * data_start_time,
    double * duration,
    double * fs )
```

Read data file from LIGO Open Science Center.

Convenience function for cutting off the first few lines of text

## Parameters

|     |                        |                                    |
|-----|------------------------|------------------------------------|
|     | <i>filename</i>        | input filename                     |
| out | <i>output</i>          | Output data                        |
| out | <i>data_start_time</i> | GPS start time of the data in file |
| out | <i>duration</i>        | Duration of the signal             |
| out | <i>fs</i>              | Sampling frequency of the data     |

## 8.16.2.20 read\_LOSC\_PSD\_file()

```
void read_LOSC_PSD_file (
    std::string filename,
    double ** output,
    int rows,
    int cols )
```

Read PSD file from LIGO Open Science Center.

Convenience function for cutting off the first few lines of text

## 8.16.2.21 transform\_cart\_sph()

```
void transform_cart_sph (
    double * cartvec,
    double * sphvec )
```

utility to transform a vector from cartesian to spherical (radian)

order:

cart: x, y, z

spherical: r, polar, azimuthal

**8.16.2.22 transform\_sph\_cart()**

```
void transform_sph_cart (
    double * sphvec,
    double * cartvec )
```

utility to transform a vector from spherical (radian) to cartesian

order:

cart: x, y, z

spherical: r, polar, azimuthal

**8.16.2.23 tukey\_window()**

```
void tukey_window (
    double * window,
    int length,
    double alpha )
```

Tukey window function for FFTs.

As defined by [https://en.wikipedia.org/wiki/Window\\_function](https://en.wikipedia.org/wiki/Window_function)

**8.16.2.24 write\_file()** [1/2]

```
void write_file (
    std::string filename,
    double ** input,
    int rows,
    int cols )
```

Utility to write 2D array to file.

Grid of data, comma separated

Grid has rows rows and cols columns

**Parameters**

|                 |                                                          |
|-----------------|----------------------------------------------------------|
| <i>filename</i> | Filename of output file, relative to execution directory |
| <i>input</i>    | Input 2D array pointer array[rows][cols]                 |
| <i>rows</i>     | First dimension of array                                 |
| <i>cols</i>     | second dimension of array                                |

**8.16.2.25 write\_file()** [2/2]

```
void write_file (
    std::string filename,
```

```
double * input,
int length )
```

Utility to write 1D array to file.

Single column of data

#### Parameters

|                 |                                                          |
|-----------------|----------------------------------------------------------|
| <i>filename</i> | Filename of output file, relative to execution directory |
| <i>input</i>    | input 1D array pointer array[length]                     |
| <i>length</i>   | length of array                                          |

#### 8.16.2.26 XLALSpinWeightedSphericalHarmonic()

```
template<class T >
std::complex<T> XLALSpinWeightedSphericalHarmonic (
    T theta,
    T phi,
    int s,
    int l,
    int m )
```

Shamelessly stolen from LALsuite

#### Parameters

|              |                       |
|--------------|-----------------------|
| <i>theta</i> | polar angle (rad)     |
| <i>phi</i>   | azimuthal angle (rad) |
| <i>s</i>     | spin weight           |
| <i>l</i>     | mode number l         |
| <i>m</i>     | mode number m         |

#### 8.16.2.27 Z\_from\_DL()

```
double Z_from_DL (
    double DL,
    std::string cosmology )
```

Calculates the redshift given the luminosity distance.

Based on Astropy.cosmology calculations – see python script in the ./data folder of the project – numerically calculated given astropy.cosmology's definitions ( <http://docs.astropy.org/en/stable/cosmology/>) and used scipy.optimize to fit to a power series, stepping in half powers of DL. These coefficients are then output to a header file (D\_Z\_config.h) which are used here to calculate redshift. Custom cosmologies etc can easily be achieved by editing the python script D\_Z\_config.py, the c++ functions do not need modification. They use whatever data is available in the header file.

5 cosmological models are available (this argument must be spelled exactly, although case insensitive):

PLANCK15, PLANCK13, WMAP9, WMAP7, WMAP5

### 8.16.2.28 Z\_from\_DL\_interp() [1/2]

```
adouble Z_from_DL_interp (
    adouble DL,
    gsl_interp_accel * Z_DL_accel_ptr,
    gsl_spline * Z_DL_spline_ptr )
```

Function that returns Z from a given luminosity Distance – only Planck15

adouble version for ADOL-C calculations

### 8.16.2.29 Z\_from\_DL\_interp() [2/2]

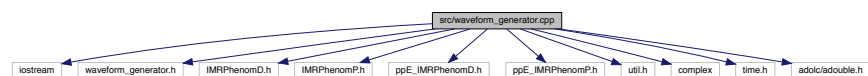
```
double Z_from_DL_interp (
    double DL,
    gsl_interp_accel * Z_DL_accel_ptr,
    gsl_spline * Z_DL_spline_ptr )
```

Function that returns Z from a given luminosity Distance – only Planck15

## 8.17 src/waveform\_generator.cpp File Reference

```
#include <iostream>
#include "waveform_generator.h"
#include "IMRPhenomD.h"
#include "IMRPhenomP.h"
#include "ppE_IMRPhenomD.h"
#include "ppE_IMRPhenomP.h"
#include "util.h"
#include <complex>
#include <time.h>
#include <adolc/adouble.h>
```

Include dependency graph for waveform\_generator.cpp:



## Functions

- `template<class T >`  
`int fourier\_waveform (T *frequencies, int length, std::complex< T > *waveform_plus, std::complex< T > *waveform_cross, string generation_method, gen_params_base< T > *parameters)`  
*Function to produce the plus/cross polarizations of an quasi-circular binary.*
- `int fourier\_waveform (double *frequencies, int length, double *waveform_plus_real, double *waveform_plus_imag, double *waveform_cross_real, double *waveform_cross_imag, string generation_method, gen_params_base *parameters)`
- `int fourier\_waveform (double *frequencies, int length, std::complex< double > *waveform, string generation_method, gen_params_base *parameters)`



*Function to produce the (2,2) mode of an quasi-circular binary.*

- int `fourier_waveform` (double \*frequencies, int length, double \*waveform\_real, double \*waveform\_imag, string generation\_method, gen\_params \*parameters)
- int `fourier_amplitude` (double \*frequencies, int length, double \*amplitude, string generation\_method, gen\_params \*parameters)

*Function to produce the amplitude of the (2,2) mode of an quasi-circular binary.*

- int `fourier_phase` (double \*frequencies, int length, double \*phase, string generation\_method, gen\_params \*parameters)

*Function to produce the phase of the (2,2) mode of an quasi-circular binary.*

- template int `fourier_waveform`< double > (double \*, int, std::complex< double > \*, std::complex< double > \*, std::string, gen\_params\_base< double > \*)
- template int `fourier_waveform`< adouble > (adouble \*, int, std::complex< adouble > \*, std::complex< adouble > \*, std::string, gen\_params\_base< adouble > \*)

### 8.17.1 Detailed Description

File that handles the construction of the (2,2) waveform as described by IMRPhenomD by Khan et. al.

Builds a waveform for given DETECTOR FRAME parameters

### 8.17.2 Function Documentation

#### 8.17.2.1 `fourier_amplitude()`

```
int fourier_amplitude (
    double * frequencies,
    int length,
    double * amplitude,
    string generation_method,
    gen_params * parameters )
```

Function to produce the amplitude of the (2,2) mode of an quasi-circular binary.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

#### Parameters

|                          |                                                                            |
|--------------------------|----------------------------------------------------------------------------|
| <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
| <i>length</i>            | integer length of all the arrays                                           |
| <i>amplitude</i>         | output array for the amplitude                                             |
| <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |

#### 8.17.2.2 `fourier_phase()`

```
int fourier_phase (
```

```
double * frequencies,
int length,
double * phase,
string generation_method,
gen_params * parameters )
```

Function to produce the phase of the (2,2) mode of an quasi-circular binary.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

#### Parameters

|                          |                                                                            |
|--------------------------|----------------------------------------------------------------------------|
| <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
| <i>length</i>            | integer length of all the arrays                                           |
| <i>phase</i>             | output array for the phase                                                 |
| <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |

#### 8.17.2.3 `fourier_waveform()` [1/4]

```
template<class T >
int fourier_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform_plus,
    std::complex< T > * waveform_cross,
    string generation_method,
    gen_params_base< T > * parameters )
```

Function to produce the plus/cross polarizations of an quasi-circular binary.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

This puts the responsibility on the user to pass the necessary parameters

*NEED TO OUTLINE OPTIONS FOR EACH METHOD IN DEPTH*

NEW PHASE OPTIONS for

PHENOMD ONLY:

If `phic` is assigned, the reference frequency and reference phase are IGNORED.

If `Phic` is unassigned, a reference phase AND a reference frequency are looked for. If no options are found, both are set to 0.

If `tc` is assigned, it is used.

If `tc` is unassigned, the waveform is shifted so the merger happens at 0.

PhenomPv2:

`PhiRef` and `f_ref` are required, `phic` is not an option.

`tc`, if specified, is used with the use of interpolation. If not, `tc` is set such that coalescence happens at  $t=0$

## Parameters

|     |                          |                                                                            |
|-----|--------------------------|----------------------------------------------------------------------------|
|     | <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
|     | <i>length</i>            | integer length of all the arrays                                           |
| out | <i>waveform_plus</i>     | complex array for the output plus polarization waveform                    |
| out | <i>waveform_cross</i>    | complex array for the output cross polarization waveform                   |
|     | <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
|     | <i>parameters</i>        | structure containing all the source parameters                             |

8.17.2.4 `fourier_waveform()` [2/4]

```
int fourier_waveform (
    double * frequencies,
    int length,
    double * waveform_plus_real,
    double * waveform_plus_imag,
    double * waveform_cross_real,
    double * waveform_cross_imag,
    string generation_method,
    gen_params * parameters )
```

## Parameters

|                            |                                                                            |
|----------------------------|----------------------------------------------------------------------------|
| <i>frequencies</i>         | double array of frequencies for the waveform to be evaluated at            |
| <i>length</i>              | integer length of all the arrays                                           |
| <i>waveform_plus_real</i>  | complex array for the output waveform                                      |
| <i>waveform_plus_imag</i>  | complex array for the output waveform                                      |
| <i>waveform_cross_real</i> | complex array for the output waveform                                      |
| <i>waveform_cross_imag</i> | complex array for the output waveform                                      |
| <i>generation_method</i>   | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
| <i>parameters</i>          | structure containing all the source parameters                             |

8.17.2.5 `fourier_waveform()` [3/4]

```
int fourier_waveform (
    double * frequencies,
    int length,
    std::complex< double > * waveform,
    string generation_method,
    gen_params * parameters )
```

Function to produce the (2,2) mode of an quasi-circular binary.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

**Parameters**

|                          |                                                                            |
|--------------------------|----------------------------------------------------------------------------|
| <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
| <i>length</i>            | integer length of all the arrays                                           |
| <i>waveform</i>          | complex array for the output waveform                                      |
| <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
| <i>parameters</i>        | structure containing all the source parameters                             |

**8.17.2.6 `fourier_waveform()`** [4/4]

```
int fourier_waveform (
    double * frequencies,
    int length,
    double * waveform_real,
    double * waveform_imag,
    string generation_method,
    gen_params * parameters )
```

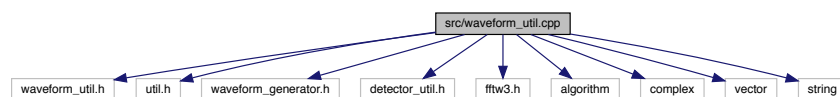
**Parameters**

|                          |                                                                            |
|--------------------------|----------------------------------------------------------------------------|
| <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
| <i>length</i>            | integer length of all the arrays                                           |
| <i>waveform_real</i>     | complex array for the output waveform                                      |
| <i>waveform_imag</i>     | complex array for the output waveform                                      |
| <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
| <i>parameters</i>        | structure containing all the source parameters                             |

**8.18 `src/waveform_util.cpp` File Reference**

```
#include "waveform_util.h"
#include "util.h"
#include "waveform_generator.h"
#include "detector_util.h"
#include <fftw3.h>
#include <algorithm>
#include <complex>
#include <vector>
#include <string>
```

Include dependency graph for `waveform_util.cpp`:



## Functions

- double [data\\_snr\\_maximized\\_extrinsic](#) (double \*frequencies, int length, std::complex< double > \*data, double \*psd, std::string detector, std::string generation\_method, gen\_params \*param)  
*Utility to calculate the snr of a fourier transformed data stream while maximizing over the coalescence parameters phic and tc.*
- double [data\\_snr\\_maximized\\_extrinsic](#) (double \*frequencies, int length, double \*data\_real, double \*data\_imag, double \*psd, std::string detector, std::string generation\_method, gen\_params \*param)  
*Light wrapper for the data\_snr\_maximized\_extrinsic method.*
- double [calculate\\_snr](#) (std::string detector, std::complex< double > \*waveform, double \*frequencies, int length)  
*Caclulates the snr given a detector and waveform (complex) and frequencies.*
- template<class T >  
int [fourier\\_detector\\_response](#) (T \*frequencies, int length, std::complex< T > \*hplus, std::complex< T > \*hcross, std::complex< T > \*detector\_response, T theta, T phi, std::string detector)
- template<class T >  
int [fourier\\_detector\\_response](#) (T \*frequencies, int length, std::complex< T > \*hplus, std::complex< T > \*hcross, std::complex< T > \*detector\_response, T theta, T phi, T psi, std::string detector)
- template<class T >  
int [fourier\\_detector\\_response\\_equatorial](#) (T \*frequencies, int length, std::complex< T > \*hplus, std::complex< T > \*hcross, std::complex< T > \*detector\_response, T ra, T dec, T psi, double gmst, std::string detector)
- template<class T >  
int [fourier\\_detector\\_response](#) (T \*frequencies, int length, std::complex< T > \*response, std::string detector, std::string generation\_method, gen\_params\_base< T > \*parameters)  
*Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary.*
- template<class T >  
int [fourier\\_detector\\_response\\_equatorial](#) (T \*frequencies, int length, std::complex< T > \*response, std::string detector, std::string generation\_method, gen\_params\_base< T > \*parameters)  
*Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary for equatorial coordinates.*
- int [fourier\\_detector\\_amplitude\\_phase](#) (double \*frequencies, int length, double \*amplitude, double \*phase, std::string detector, std::string generation\_method, gen\_params \*parameters)  
*Calculates the amplitude (magnitude) and phase (argument) of the response of a given detector.*
- template int [fourier\\_detector\\_response< double >](#) (double \*, int, std::complex< double > \*, std::complex< double > \*, std::complex< double > \*, double, double, std::string)
- template int [fourier\\_detector\\_response< adouble >](#) (adouble \*, int, std::complex< adouble > \*, std::complex< adouble > \*, std::complex< adouble > \*, adouble, adouble, std::string)
- template int [fourier\\_detector\\_response< double >](#) (double \*, int, std::complex< double > \*, std::complex< double > \*, std::complex< double > \*, double, double, double, std::string)
- template int [fourier\\_detector\\_response< adouble >](#) (adouble \*, int, std::complex< adouble > \*, std::complex< adouble > \*, std::complex< adouble > \*, adouble, adouble, adouble, std::string)
- template int [fourier\\_detector\\_response\\_equatorial< double >](#) (double \*, int, std::complex< double > \*, std::string, std::string, gen\_params\_base< double > \*)
- template int [fourier\\_detector\\_response\\_equatorial< adouble >](#) (adouble \*, int, std::complex< adouble > \*, std::string, std::string, gen\_params\_base< adouble > \*)
- template int [fourier\\_detector\\_response< double >](#) (double \*, int, std::complex< double > \*, std::string, std::string, gen\_params\_base< double > \*)
- template int [fourier\\_detector\\_response< adouble >](#) (adouble \*, int, std::complex< adouble > \*, std::string, std::string, gen\_params\_base< adouble > \*)
- template int [fourier\\_detector\\_response\\_equatorial< double >](#) (double \*, int, std::complex< double > \*, std::complex< double > \*, std::complex< double > \*, double, double, double, double, std::string)
- template int [fourier\\_detector\\_response\\_equatorial< adouble >](#) (adouble \*, int, std::complex< adouble > \*, std::complex< adouble > \*, std::complex< adouble > \*, adouble, adouble, adouble, double, std::string)

### 8.18.1 Detailed Description

Utilities for waveforms - SNR calculation and detector response

includes snr and detector response

### 8.18.2 Function Documentation

#### 8.18.2.1 calculate\_snr()

```
double calculate_snr (
    std::string detector,
    std::complex< double > * waveform,
    double * frequencies,
    int length )
```

Caclulates the snr given a detector and waveform (complex) and frequencies.

This function computes the un-normalized snr:  $\sqrt{H | H}$

##### Parameters

|                    |                                                                   |
|--------------------|-------------------------------------------------------------------|
| <i>detector</i>    | detector name - must match the string of populate_noise precisely |
| <i>waveform</i>    | complex waveform                                                  |
| <i>frequencies</i> | double array of frequencies that the waveform is evaluated at     |
| <i>length</i>      | length of the above two arrays                                    |

#### 8.18.2.2 data\_snr\_maximized\_extrinsic() [1/2]

```
double data_snr_maximized_extrinsic (
    double * frequencies,
    int length,
    std::complex< double > * data,
    double * psd,
    std::string detector,
    std::string generation_method,
    gen_params * param )
```

Utility to calculate the snr of a fourier transformed data stream while maximizing over the coalescence parameters phic and tc.

The gen\_params structure holds the parameters for the template to be used (the maximum likelihood parameters)

##### Parameters

|                    |                          |
|--------------------|--------------------------|
| <i>frequencies</i> | Frequencies used by data |
|--------------------|--------------------------|

## Parameters

|                          |                                                                              |
|--------------------------|------------------------------------------------------------------------------|
| <i>length</i>            | length of the data                                                           |
| <i>data</i>              | input data in the fourier domain                                             |
| <i>psd</i>               | PSD for the detector that created the data                                   |
| <i>detector</i>          | Name of the detector –See noise_util for options                             |
| <i>generation_method</i> | Generation method for the template – See waveform_generation.cpp for options |
| <i>param</i>             | gen_params structure for the template                                        |

## 8.18.2.3 data\_snr\_maximized\_extrinsic() [2/2]

```
double data_snr_maximized_extrinsic (
    double * frequencies,
    int length,
    double * data_real,
    double * data_imag,
    double * psd,
    std::string detector,
    std::string generation_method,
    gen_params * param )
```

Light wrapper for the data\_snr\_maximized\_extrinsic method.

Splits the data into real and imaginary, so all the arguments are C-safe

## Parameters

|                          |                                                                              |
|--------------------------|------------------------------------------------------------------------------|
| <i>frequencies</i>       | Frequencies used by data                                                     |
| <i>length</i>            | length of the data                                                           |
| <i>data_real</i>         | input data in the fourier domain – real part                                 |
| <i>data_imag</i>         | input data in the fourier domain – imaginary part                            |
| <i>psd</i>               | PSD for the detector that created the data                                   |
| <i>detector</i>          | Name of the detector –See noise_util for options                             |
| <i>generation_method</i> | Generation method for the template – See waveform_generation.cpp for options |
| <i>param</i>             | gen_params structure for the template                                        |

## 8.18.2.4 fourier\_detector\_amplitude\_phase()

```
int fourier_detector_amplitude_phase (
    double * frequencies,
    int length,
    double * amplitude,
    double * phase,
    std::string detector,
    std::string generation_method,
    gen_params * parameters )
```

Calculates the amplitude (magnitude) and phase (argument) of the response of a given detector.

This is for general waveforms, and will work for precessing waveforms

Not as fast as non-precessing, but that can't be helped. MUST include plus/cross polarizations

#### 8.18.2.5 `fourier_detector_response()` [1/3]

```
template<class T >
int fourier_detector_response (
    T * frequencies,
    int length,
    std::complex< T > * hplus,
    std::complex< T > * hcross,
    std::complex< T > * detector_response,
    T theta,
    T phi,
    std::string detector )
```

##### Parameters

|     |                          |                                                      |
|-----|--------------------------|------------------------------------------------------|
|     | <i>frequencies</i>       | array of frequencies corresponding to waveform       |
|     | <i>length</i>            | length of frequency/waveform arrays                  |
|     | <i>hcross</i>            | precomputed cross polarization of the waveform       |
| out | <i>detector_response</i> | detector response                                    |
|     | <i>theta</i>             | polar angle (rad) theta in detector frame            |
|     | <i>phi</i>               | azimuthal angle (rad) phi in detector frame          |
|     | <i>detector</i>          | detector - list of supported detectors in noise_util |

#### 8.18.2.6 `fourier_detector_response()` [2/3]

```
template<class T >
int fourier_detector_response (
    T * frequencies,
    int length,
    std::complex< T > * hplus,
    std::complex< T > * hcross,
    std::complex< T > * detector_response,
    T theta,
    T phi,
    T psi,
    std::string detector )
```

##### Parameters

|     |                          |                                                |
|-----|--------------------------|------------------------------------------------|
|     | <i>frequencies</i>       | array of frequencies corresponding to waveform |
|     | <i>length</i>            | length of frequency/waveform arrays            |
|     | <i>hcross</i>            | precomputed cross polarization of the waveform |
| out | <i>detector_response</i> | detector response                              |
|     | <i>theta</i>             | polar angle (rad) theta in detector frame      |



## Parameters

|  |                 |                                                      |
|--|-----------------|------------------------------------------------------|
|  | <i>phi</i>      | azimuthal angle (rad) phi in detector frame          |
|  | <i>psi</i>      | polarization angle (rad) phi in detector frame       |
|  | <i>detector</i> | detector - list of supported detectors in noise_util |

8.18.2.7 `fourier_detector_response()` [3/3]

```
template<class T >
int fourier_detector_response (
    T * frequencies,
    int length,
    std::complex< T > * response,
    std::string detector,
    std::string generation_method,
    gen_params_base< T > * parameters )
```

Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

This puts the responsibility on the user to pass the necessary parameters

Detector options include classic interferometers like LIGO/VIRGO (coming soon: ET and LISA)

This is a wrapper that combines generation with response functions: if producing multiple responses for one waveform (ie stacking Hanford, Livingston, and VIRGO), it will be considerably more efficient to calculate the waveform once, then combine each response manually

## Parameters

|     |                          |                                                                            |
|-----|--------------------------|----------------------------------------------------------------------------|
|     | <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
|     | <i>length</i>            | integer length of all the arrays                                           |
| out | <i>response</i>          | complex array for the output plus polarization waveform                    |
|     | <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
|     | <i>parameters</i>        | structure containing all the source parameters                             |

8.18.2.8 `fourier_detector_response_equatorial()` [1/2]

```
template<class T >
int fourier_detector_response_equatorial (
    T * frequencies,
    int length,
    std::complex< T > * hplus,
    std::complex< T > * hcross,
    std::complex< T > * detector_response,
```

```

T ra,
T dec,
T psi,
double gmst,
std::string detector )

```

#### Parameters

|     |                          |                                                      |
|-----|--------------------------|------------------------------------------------------|
|     | <i>frequencies</i>       | array of frequencies corresponding to waveform       |
|     | <i>length</i>            | length of frequency/waveform arrays                  |
|     | <i>hcross</i>            | precomputed cross polarization of the waveform       |
| out | <i>detector_response</i> | detector response                                    |
|     | <i>ra</i>                | Right Ascension in rad                               |
|     | <i>dec</i>               | Declination in rad                                   |
|     | <i>psi</i>               | polarization angle (rad)                             |
|     | <i>gmst</i>              | greenwich mean sidereal time                         |
|     | <i>detector</i>          | detector - list of supported detectors in noise_util |

#### 8.18.2.9 `fourier_detector_response_equatorial()` [2/2]

```

template<class T >
int fourier_detector_response_equatorial (
    T * frequencies,
    int length,
    std::complex< T > * response,
    std::string detector,
    std::string generation_method,
    gen_params_base< T > * parameters )

```

Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary for equatorial coordinates.

By using the structure parameter, the function is allowed to be more flexible in using different method of waveform generation - not all methods use the same parameters

This puts the responsibility on the user to pass the necessary parameters

Detector options include classic interferometers like LIGO/VIRGO (coming soon: ET and LISA)

This is a wrapper that combines generation with response functions: if producing multiple responses for one waveform (ie stacking Hanford, Livingston, and VIRGO), it will be considerably more efficient to calculate the waveform once, then combine each response manually

#### Parameters

|     |                          |                                                                            |
|-----|--------------------------|----------------------------------------------------------------------------|
|     | <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
|     | <i>length</i>            | integer length of all the arrays                                           |
| out | <i>response</i>          | complex array for the output plus polarization waveform                    |
|     | <i>generation_method</i> | String that corresponds to the generation method - MUST BE SPELLED EXACTLY |
|     | <i>parameters</i>        | structure containing all the source parameters                             |

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