

## 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 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> | 15 |





## Chapter 4

# Hierarchical Index

### 4.1 Class Hierarchy

This inheritance list is sorted roughly, but not completely, alphabetically:

|  |    |
|--|----|
| alpha_coeffs< T > . . . . .                    | 17 |
| Comparator . . . . .                           | 17 |
| comparator_ac_fft . . . . .                    | 18 |
| comparator_ac_serial . . . . .                 | 18 |
| default_comp< jobtype > . . . . .              | 23 |
| epsilon_coeffs< T > . . . . .                  | 27 |
| fftw_outline . . . . .                         | 28 |
| mcmc_routines_ext.fftw_outline_py . . . . .    | 28 |
| gen_params . . . . .                           | 28 |
| waveform_generator_ext.gen_params_py . . . . . | 31 |
| GPUplan . . . . .                              | 31 |
| IMRPhenomD< T > . . . . .                      | 31 |
| IMRPhenomPv2< T > . . . . .                    | 45 |
| ppE_IMRPhenomD_Inspiral< T > . . . . .         | 53 |
| dCS_IMRPhenomD< T > . . . . .                  | 19 |
| dCS_IMRPhenomD_log< T > . . . . .              | 21 |
| EdGB_IMRPhenomD< T > . . . . .                 | 23 |
| EdGB_IMRPhenomD_log< T > . . . . .             | 25 |
| ppE_IMRPhenomD_IMR< T > . . . . .              | 48 |
| lambda_parameters< T > . . . . .               | 48 |
| sampler . . . . .                              | 56 |
| source_parameters< T > . . . . .               | 58 |
| sph_harm< T > . . . . .                        | 64 |
| threaded_ac_jobs_fft . . . . .                 | 64 |
| threaded_ac_jobs_serial . . . . .              | 66 |
| ThreadPool . . . . .                           | ?? |
| threadPool< jobtype, comparator > . . . . .    | 69 |
| useful_powers< T > . . . . .                   | 70 |



## Chapter 5

# Class Index

### 5.1 Class List

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

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| <a href="#">alpha_coeffs&lt; T &gt;</a>   | 17 |
| <a href="#">Comparator</a>  |    |
| Class to facilitate the comparing of chains for priority  | 17 |
| <a href="#">comparator_ac_fft</a>   |    |
| <a href="#">Comparator</a> to sort ac-jobs  | 18 |
| <a href="#">comparator_ac_serial</a>  |    |
| <a href="#">Comparator</a> to sort ac-jobs  | 18 |
| <a href="#">dCS_IMRPhenomD&lt; T &gt;</a>   | 19 |
| <a href="#">dCS_IMRPhenomD_log&lt; T &gt;</a>   | 21 |
| <a href="#">default_comp&lt; jobtype &gt;</a>   |    |
| Default comparator for priority_queue in <a href="#">threadPool</a> – no comparison   | 23 |
| <a href="#">EdGB_IMRPhenomD&lt; T &gt;</a>  | 23 |
| <a href="#">EdGB_IMRPhenomD_log&lt; T &gt;</a>  | 25 |
| <a href="#">epsilon_coeffs&lt; T &gt;</a>   | 27 |
| <a href="#">fftw_outline</a>  | 28 |
| <a href="#">mcmc_routines_ext.fftw_outline_py</a>   | 28 |
| <a href="#">gen_params</a>  | 28 |
| <a href="#">waveform_generator_ext.gen_params_py</a>  |    |
| Python wrapper for the generation parameters structure, as defined in <a href="#">util.cpp</a>  | 31 |
| <a href="#">GPUplan</a>   | 31 |
| <a href="#">IMRPhenomD&lt; T &gt;</a>   | 31 |
| <a href="#">IMRPhenomPv2&lt; T &gt;</a>   | 45 |
| <a href="#">lambda_parameters&lt; T &gt;</a>  | 48 |
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| <a href="#">ppE_IMRPhenomD_Inspiral&lt; T &gt;</a>  | 53 |
| <a href="#">sampler</a>   | 56 |
| <a href="#">source_parameters&lt; T &gt;</a>  | 58 |
| <a href="#">sph_harm&lt; T &gt;</a>   | 64 |
| <a href="#">threaded_ac_jobs_fft</a>  |    |
| Class to contain spectral method jobs   | 64 |
| <a href="#">threaded_ac_jobs_serial</a>   |    |
| Class to contain serial method jobs   | 66 |
| <a href="#">ThreadPool</a>  | ?? |
| <a href="#">threadPool&lt; jobtype, comparator &gt;</a>   |    |
| Class for creating a pool of threads to asynchronously distribute work  | 69 |
| <a href="#">useful_powers&lt; T &gt;</a>  |    |
| To speed up calculations within the for loops, we pre-calculate reoccurring powers of $M \cdot F$ and $P_i$ , since the <code>pow()</code> function is prohibitively slow | 70 |



## Chapter 6

# File Index

### 6.1 File List

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

|   |     |
|---|-----|
| gw_analysis_tools_py/src/mcmc_routines_ext.pyx  |     |
| 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> | 71  |
| gw_analysis_tools_py/src/waveform_generator_ext.pyx   |     |
| File that contains cython code to wrap the c++ library  | 71  |
| include/ <a href="#">autocorrelation.h</a>  | 72  |
| include/ <a href="#">autocorrelation_cuda.h</a>   | 78  |
| include/ <a href="#">autocorrelation_cuda.hu</a>  | 81  |
| include/ <b>D_Z_Config.h</b>  | ??  |
| include/ <a href="#">detector_util.h</a>  | 84  |
| include/ <a href="#">fisher.h</a>   | 89  |
| include/ <b>GWATConfig.h</b>  | ??  |
| include/ <a href="#">IMRPhenomD.h</a>   | 92  |
| include/ <a href="#">IMRPhenomP.h</a>   | 93  |
| include/ <a href="#">mcmc_gw.h</a>  | 94  |
| include/ <a href="#">mcmc_sampler.h</a>   | 103 |
| include/ <a href="#">mcmc_sampler_internals.h</a>   | 111 |
| include/ <a href="#">ppE_IMRPhenomD.h</a>   | 116 |
| include/ <a href="#">threadPool.h</a>   | 117 |
| include/ <a href="#">util.h</a>   | 118 |
| include/ <a href="#">waveform_generator.h</a>   | 132 |
| include/ <a href="#">waveform_generator_C.h</a>   | 133 |
| include/ <a href="#">waveform_util.h</a>  | 133 |
| src/ <a href="#">autocorrelation.cpp</a>  | 137 |
| src/ <a href="#">autocorrelation_cuda.cu</a>  | 143 |
| src/ <a href="#">detector_util.cpp</a>  | 148 |
| src/ <a href="#">fisher.cpp</a>   | 153 |
| src/ <a href="#">IMRPhenomD.cpp</a>   | 155 |
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| src/ <a href="#">mcmc_gw.cpp</a>  | 158 |
| src/ <a href="#">mcmc_sampler.cpp</a>   | 167 |
| src/ <a href="#">mcmc_sampler_internals.cpp</a>   | 175 |
| src/ <a href="#">ppE_IMRPhenomD.cpp</a>   | 179 |
| src/ <a href="#">util.cpp</a>   | 180 |
| src/ <a href="#">waveform_generator.cpp</a>   | 192 |
| src/ <a href="#">waveform_util.cpp</a>  | 196 |



## Chapter 7

# Namespace Documentation

### 7.1 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**

#### 7.1.1 Detailed Description

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





## Chapter 8

# Class Documentation

### 8.1 `alpha_coeffs< T >` Struct Template Reference

#### Public Attributes

- `T coeff1`
- `T coeff2`
- `T coeff3`
- `T coeff4`
- `T coeff5`

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

- `include/IMRPhenomP.h`

### 8.2 Comparator Class Reference

Class to facilitate the comparing of chains for priority.

#### Public Member Functions

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

#### 8.2.1 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`

## 8.3 comparator\_ac\_fft Class Reference

comparator to sort ac-jobs

```
#include <autocorrelation.h>
```

### Public Member Functions

- **bool operator()** ([threaded\\_ac\\_jobs\\_fft](#) t, [threaded\\_ac\\_jobs\\_fft](#) k)

#### 8.3.1 Detailed Description

comparator to sort ac-jobs

Starts with the longest jobs, then works down the list

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

- include/[autocorrelation.h](#)

## 8.4 comparator\_ac\_serial Class Reference

comparator to sort ac-jobs

```
#include <autocorrelation.h>
```

### Public Member Functions

- **bool operator()** ([threaded\\_ac\\_jobs\\_serial](#) t, [threaded\\_ac\\_jobs\\_serial](#) k)

#### 8.4.1 Detailed Description

comparator to sort ac-jobs

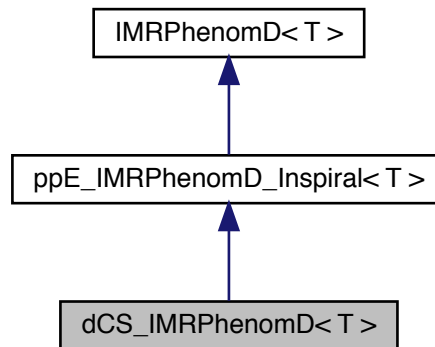
Starts with the longest jobs, then works down the list

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

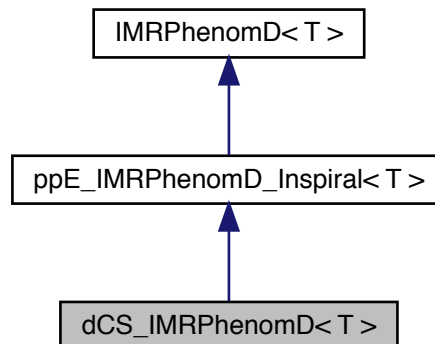
- include/[autocorrelation.h](#)

## 8.5 dCS\_IMRPhenomD< T > Class Template Reference

Inheritance diagram for dCS\_IMRPhenomD< T >:



Collaboration diagram for dCS\_IMRPhenomD< T >:



### Public Member Functions

- virtual int [construct\\_waveform](#) (T \*frequencies, int length, std::complex< T > \*waveform, [source\\_parameters](#)< T > \*params)  
Constructs the waveform as outlined by.
- virtual T [dCS\\_phase\\_mod](#) ([source\\_parameters](#)< T > \*param)
- virtual T [dCS\\_phase\\_factor](#) ([source\\_parameters](#)< T > \*param)
- virtual int [construct\\_amplitude](#) (T \*frequencies, int length, T \*amplitude, [source\\_parameters](#)< T > \*params)  
Constructs the Amplitude as outlined by [IMRPhenomD](#).
- virtual int [construct\\_phase](#) (T \*frequencies, int length, T \*phase, [source\\_parameters](#)< T > \*params)  
Constructs the Phase as outlined by [IMRPhenomD](#).

## 8.5.1 Member Function Documentation

### 8.5.1.1 `construct_amplitude()`

```
template<class T >
int dCS_IMRPhenomD< T >::construct_amplitude (
    T * frequencies,
    int length,
    T * amplitude,
    source_parameters< T > * params ) [virtual]
```

Constructs the Amplitude as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output amplitude, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

### 8.5.1.2 `construct_phase()`

```
template<class T >
int dCS_IMRPhenomD< T >::construct_phase (
    T * frequencies,
    int length,
    T * phase,
    source_parameters< T > * params ) [virtual]
```

Constructs the Phase as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output phase, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

### 8.5.1.3 `construct_waveform()`

```
template<class T >
int dCS_IMRPhenomD< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform as outlined by.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

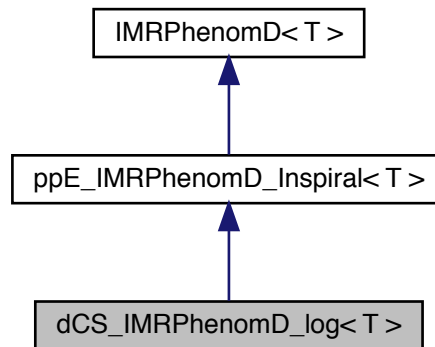
Reimplemented from [IMRPhenomD< T >](#).

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

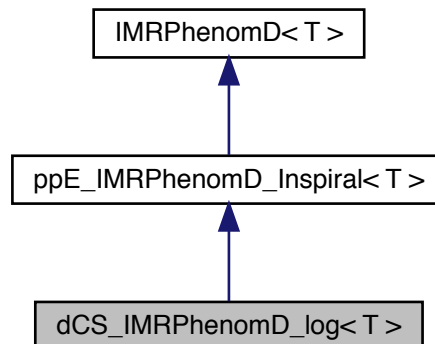
- [include/ppE\\_IMRPhenomD.h](#)
- [src/ppE\\_IMRPhenomD.cpp](#)

## 8.6 dCS\_IMRPhenomD\_log< T > Class Template Reference

Inheritance diagram for dCS\_IMRPhenomD\_log< T >:



Collaboration diagram for dCS\_IMRPhenomD\_log< T >:



### Public Member Functions

- virtual int [construct\\_waveform](#) (T \*frequencies, int length, std::complex< T > \*waveform, [source\\_parameters](#)< T > \*params)  
Constructs the waveform as outlined by.
- virtual T [dCS\\_phase\\_mod](#) ([source\\_parameters](#)< T > \*param)
- virtual T [dCS\\_phase\\_factor](#) ([source\\_parameters](#)< T > \*param)
- virtual int [construct\\_amplitude](#) (T \*frequencies, int length, T \*amplitude, [source\\_parameters](#)< T > \*params)  
Constructs the Amplitude as outlined by [IMRPhenomD](#).
- virtual int [construct\\_phase](#) (T \*frequencies, int length, T \*phase, [source\\_parameters](#)< T > \*params)  
Constructs the Phase as outlined by [IMRPhenomD](#).

## 8.6.1 Member Function Documentation

### 8.6.1.1 `construct_amplitude()`

```
template<class T >
int dCS_IMRPhenomD_log< T >::construct_amplitude (
    T * frequencies,
    int length,
    T * amplitude,
    source_parameters< T > * params ) [virtual]
```

Constructs the Amplitude as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output amplitude, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

### 8.6.1.2 `construct_phase()`

```
template<class T >
int dCS_IMRPhenomD_log< T >::construct_phase (
    T * frequencies,
    int length,
    T * phase,
    source_parameters< T > * params ) [virtual]
```

Constructs the Phase as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output phase, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

### 8.6.1.3 `construct_waveform()`

```
template<class T >
int dCS_IMRPhenomD_log< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform as outlined by.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

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

- [include/ppE\\_IMRPhenomD.h](#)
- [src/ppE\\_IMRPhenomD.cpp](#)

## 8.7 default\_comp< jobtype > Class Template Reference

Default comparator for priority\_queue in [threadPool](#) – no comparison.

```
#include <threadPool.h>
```

### Public Member Functions

- **bool operator()** (jobtype j, jobtype k)

#### 8.7.1 Detailed Description

```
template<class jobtype>  
class default_comp< jobtype >
```

Default comparator for priority\_queue in [threadPool](#) – no comparison.

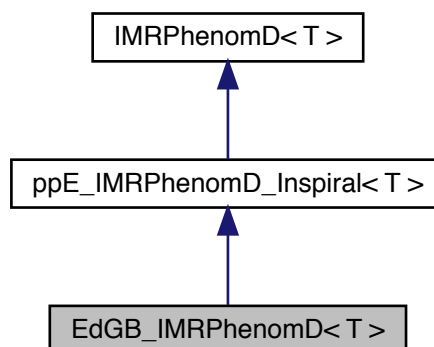
First in first out, not sorting

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

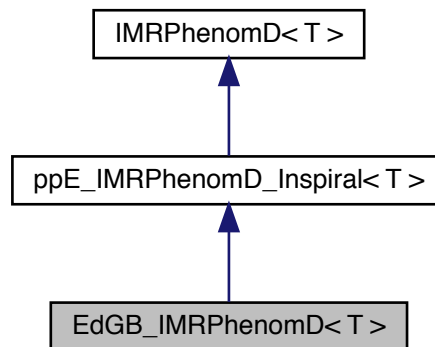
- include/[threadPool.h](#)

## 8.8 EdGB\_IMRPhenomD< T > Class Template Reference

Inheritance diagram for EdGB\_IMRPhenomD< T >:



Collaboration diagram for `EdGB_IMRPhenomD< T >`:



## Public Member Functions

- virtual int [construct\\_waveform](#) (T \*frequencies, int length, std::complex< T > \*waveform, [source\\_parameters](#)< T > \*params)  
Constructs the waveform as outlined by.
- virtual T [EdGB\\_phase\\_mod](#) ([source\\_parameters](#)< T > \*param)
- virtual T [EdGB\\_phase\\_factor](#) ([source\\_parameters](#)< T > \*param)
- virtual int [construct\\_amplitude](#) (T \*frequencies, int length, T \*amplitude, [source\\_parameters](#)< T > \*params)  
Constructs the Amplitude as outlined by [IMRPhenomD](#).
- virtual int [construct\\_phase](#) (T \*frequencies, int length, T \*phase, [source\\_parameters](#)< T > \*params)  
Constructs the Phase as outlined by [IMRPhenomD](#).

## 8.8.1 Member Function Documentation

### 8.8.1.1 `construct_amplitude()`

```

template<class T >
int EdGB_IMRPhenomD< T >::construct_amplitude (
    T * frequencies,
    int length,
    T * amplitude,
    source\_parameters< T > * params ) [virtual]
  
```

Constructs the Amplitude as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output amplitude, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).



## 8.8.1.2 construct\_phase()

```
template<class T >
int EdGB_IMRPhenomD< T >::construct_phase (
    T * frequencies,
    int length,
    T * phase,
    source_parameters< T > * params ) [virtual]
```

Constructs the Phase as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output phase, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

## 8.8.1.3 construct\_waveform()

```
template<class T >
int EdGB_IMRPhenomD< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform as outlined by.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

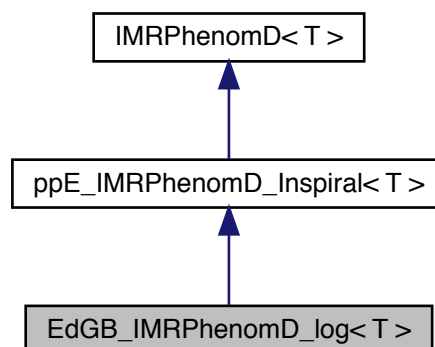
Reimplemented from [IMRPhenomD< T >](#).

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

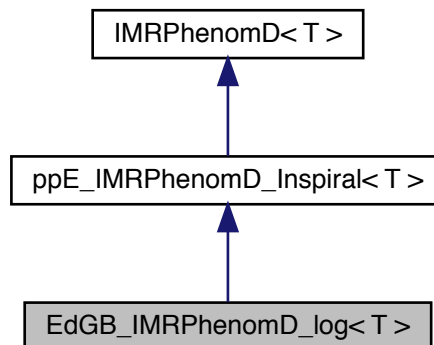
- include/[ppE\\_IMRPhenomD.h](#)
- src/[ppE\\_IMRPhenomD.cpp](#)

## 8.9 EdGB\_IMRPhenomD\_log&lt; T &gt; Class Template Reference

Inheritance diagram for EdGB\_IMRPhenomD\_log< T >:



Collaboration diagram for `EdGB_IMRPhenomD_log< T >`:



## Public Member Functions

- virtual int [construct\\_waveform](#) (T \*frequencies, int length, std::complex< T > \*waveform, [source\\_parameters](#)< T > \*params)  
Constructs the waveform as outlined by.
- virtual T [EdGB\\_phase\\_mod](#) ([source\\_parameters](#)< T > \*param)
- virtual T [EdGB\\_phase\\_factor](#) ([source\\_parameters](#)< T > \*param)
- virtual int [construct\\_amplitude](#) (T \*frequencies, int length, T \*amplitude, [source\\_parameters](#)< T > \*params)  
Constructs the Amplitude as outlined by [IMRPhenomD](#).
- virtual int [construct\\_phase](#) (T \*frequencies, int length, T \*phase, [source\\_parameters](#)< T > \*params)  
Constructs the Phase as outlined by [IMRPhenomD](#).

## 8.9.1 Member Function Documentation

### 8.9.1.1 [construct\\_amplitude\(\)](#)

```

template<class T >
int EdGB\_IMRPhenomD\_log< T >::construct_amplitude (
    T * frequencies,
    int length,
    T * amplitude,
    source\_parameters< T > * params ) [virtual]
  
```

Constructs the Amplitude as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output amplitude, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

8.9.1.2 `construct_phase()`

```
template<class T >
int EdGB_IMRPhenomD_log< T >::construct_phase (
    T * frequencies,
    int length,
    T * phase,
    source_parameters< T > * params ) [virtual]
```

Constructs the Phase as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output phase, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

8.9.1.3 `construct_waveform()`

```
template<class T >
int EdGB_IMRPhenomD_log< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform as outlined by.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

Reimplemented from [IMRPhenomD< T >](#).

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

- [include/ppE\\_IMRPhenomD.h](#)
- [src/ppE\\_IMRPhenomD.cpp](#)

8.10 `epsilon_coeffs< T >` Struct Template Reference

## Public Attributes

- `T coeff1`
- `T coeff2`
- `T coeff3`
- `T coeff4`
- `T coeff5`

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

- [include/IMRPhenomP.h](#)

## 8.11 fftw\_outline Struct Reference

### Public Attributes

- `fftw_complex * in`
- `fftw_complex * out`
- `fftw_plan p`

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

- `include/util.h`

## 8.12 mcmc\_routines\_ext.fftw\_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`

## 8.13 gen\_params Struct Reference

### Public Attributes

- double `mass1`
- double `mass2`
- double `Luminosity_Distance`
- double `spin1` [3]
- double `spin2` [3]
- double `phic` =0
- double `tc` =0
- int \* `bppe`
- double \* `betappe`
- int `Nmod`
- double `incl_angle`
- double `theta`
- double `phi`
- bool `NSflag`
- double `f_ref` =0
- double `phiRef` =0
- double `thetaJN` = -1
- double `alpha0` = 0
- double `zeta_polariz` = 0
- double `phi_aligned` = 0
- double `chil` = 0
- double `chip` = 0
- bool `sky_average`
- gsl\_spline \* `Z_DL_spline_ptr` =NULL
- gsl\_interp\_accel \* `Z_DL_accel_ptr` =NULL
- std::string `cosmology` ="PLANCK15"

### 8.13.1 Member Data Documentation

#### 8.13.1.1 betappe

double\* gen\_params::betappe

ppE coefficient for the phase modification - vector for multiple modifications

#### 8.13.1.2 bppe

int\* gen\_params::bppe

ppE b parameter (power of the frequency) - vector for multiple modifications

#### 8.13.1.3 f\_ref

double gen\_params::f\_ref =0

Reference frequency for PhenomPv2

#### 8.13.1.4 incl\_angle

double gen\_params::incl\_angle

\*angle between angular momentum and the total momentum

#### 8.13.1.5 Luminosity\_Distance

double gen\_params::Luminosity\_Distance

Luminosity distance to the source

#### 8.13.1.6 mass1

double gen\_params::mass1

mass of the larger body in Solar Masses

#### 8.13.1.7 mass2

double gen\_params::mass2

mass of the smaller body in Solar Masses

#### 8.13.1.8 Nmod

```
int gen_params::Nmod
```

Number of phase modificatinos

#### 8.13.1.9 NSflag

```
bool gen_params::NSflag
```

BOOL flag for early termination of NS binaries

#### 8.13.1.10 phic

```
double gen_params::phic =0
```

coalescence phase of the binary

#### 8.13.1.11 spin1

```
double gen_params::spin1[3]
```

Spin vector of the larger mass [Sx,Sy,Sz]

#### 8.13.1.12 spin2

```
double gen_params::spin2[3]
```

Spin vector of the smaller mass [Sx,Sy,Sz]

#### 8.13.1.13 tc

```
double gen_params::tc =0
```

coalescence time of the binary

#### 8.13.1.14 theta

```
double gen_params::theta
```

spherical angles for the source location relative to the detector

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

- [include/util.h](#)

## 8.14 waveform\_generator\_ext.gen\_params\_py Class Reference

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

### 8.14.1 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](#)

## 8.15 GPUplan Struct Reference

### Public Attributes

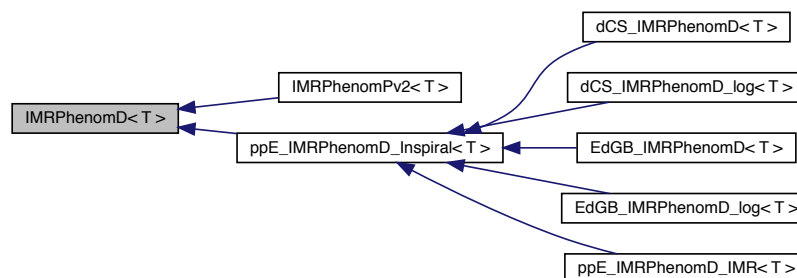
- int **device\_id**
- double \* **device\_data**
- double \* **host\_data**
- int \* **host\_lag**
- int \* **device\_lag**
- int \* **device\_lags**
- int \* **initial\_lag**
- cudaStream\_t **stream**

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

- [include/autocorrelation\\_cuda.hu](#)

## 8.16 IMRPhenomD< T > Class Template Reference

Inheritance diagram for IMRPhenomD< T >:



## Public Member Functions

- virtual void **fisher\_calculation** (double \*frequency, int length, [gen\\_params](#) \*parameters, double \*\*amplitude\_deriv, double \*\*phase\_deriv, double \*amplitude, int \*amp\_tapes, int \*phase\_tapes)
- virtual void **change\_parameter\_basis** (T \*old\_param, T \*new\_param, bool sky\_average)
 

*Convenience method to change parameter basis between common Fisher parameters and the intrinsic parameters of [IMRPhenomD](#).*
- virtual void **construct\_amplitude\_derivative** (double \*frequencies, int length, int dimension, double \*\*amplitude\_derivative, [source\\_parameters](#)< double > \*input\_params, int \*tapes=NULL)
 

*Construct the derivative of the amplitude for a given source evaluated by the given frequency.*
- virtual void **construct\_phase\_derivative** (double \*frequencies, int length, int dimension, double \*\*phase\_derivative, [source\\_parameters](#)< double > \*input\_params, int \*tapes=NULL)
 

*Construct the derivative of the phase for a given source evaluated by the given frequency.*
- virtual void **amplitude\_tape** ([source\\_parameters](#)< double > \*input\_params, int \*tape)
 

*Creates the tapes for derivatives of the amplitude.*
- virtual void **phase\_tape** ([source\\_parameters](#)< double > \*input\_params, int \*tape)
 

*Creates the tapes for derivatives of phase.*
- virtual int **construct\_waveform** (T \*frequencies, int length, std::complex< T > \*waveform, [source\\_parameters](#)< T > \*params)
 

*Constructs the waveform as outlined by.*
- virtual std::complex< T > **construct\_waveform** (T frequency, [source\\_parameters](#)< T > \*params)
 

*overloaded method to evaluate the waveform for one frequency instead of an array*
- virtual int **construct\_amplitude** (T \*frequencies, int length, T \*amplitude, [source\\_parameters](#)< T > \*params)
 

*Constructs the Amplitude as outlined by [IMRPhenomD](#).*
- virtual int **construct\_phase** (T \*frequencies, int length, T \*phase, [source\\_parameters](#)< T > \*params)
 

*Constructs the Phase as outlined by [IMRPhenomD](#).*
- virtual T **build\_amp** (T f, [lambda\\_parameters](#)< T > \*lambda, [source\\_parameters](#)< T > \*params, [useful\\_powers](#)< T > \*pows, T \*amp\_coeff, T \*deltas)
 

*constructs the [IMRPhenomD](#) amplitude for frequency f*
- virtual T **build\_phase** (T f, [lambda\\_parameters](#)< T > \*lambda, [source\\_parameters](#)< T > \*params, [useful\\_powers](#)< T > \*pows, T \*phase\_coeff)
 

*constructs the [IMRPhenomD](#) phase for frequency f*
- virtual T **assign\_lambda\_param\_element** ([source\\_parameters](#)< T > \*source\_param, int i)
 

*Calculate the lambda parameters from Khan et al for element i.*
- virtual void **assign\_lambda\_param** ([source\\_parameters](#)< T > \*source\_param, [lambda\\_parameters](#)< T > \*lambda)
 

*Wrapper for the Lambda parameter assignment that handles the looping.*
- virtual void **precalc\_powers\_ins** (T f, T M, [useful\\_powers](#)< T > \*Mf\_pows)
 

*Pre-calculate powers of Mf, to speed up calculations for the inspiral waveform (both amplitude and phase).*
- virtual void **precalc\_powers\_PI** ([useful\\_powers](#)< T > \*PI\_pows)
 

*Pre-calculate powers of pi, to speed up calculations for the inspiral phase.*
- virtual void **precalc\_powers\_ins\_phase** (T f, T M, [useful\\_powers](#)< T > \*Mf\_pows)
 

*Pre-calculate powers of Mf, to speed up calculations for the inspiral phase.*
- virtual void **precalc\_powers\_ins\_amp** (T f, T M, [useful\\_powers](#)< T > \*Mf\_pows)
 

*Pre-calculate powers of Mf, to speed up calculations for the inspiral amplitude.*
- virtual void **assign\_pn\_amplitude\_coeff** ([source\\_parameters](#)< T > \*source\_param, T \*coeff)
 

*Calculates the static PN coefficients for the amplitude.*
- virtual void **assign\_static\_pn\_phase\_coeff** ([source\\_parameters](#)< T > \*source\_param, T \*coeff)
 

*Calculates the static PN coefficients for the phase - coefficients 0,1,2,3,4,7.*
- virtual void **assign\_nonstatic\_pn\_phase\_coeff** ([source\\_parameters](#)< T > \*source\_param, T \*coeff, T f)
 

*Calculates the dynamic PN phase coefficients 5,6.*



- virtual void [assign\\_nonstatic\\_pn\\_phase\\_coeff\\_deriv](#) (source\_parameters< T > \*source\_param, T \*Dcoeff, T f)  
*Calculates the derivative of the dynamic PN phase coefficients 5,6.*
- virtual void [post\\_merger\\_variables](#) (source\_parameters< T > \*source\_param)  
*Calculates the post-merger ringdown frequency and dampening frequency.*
- virtual T [fpeak](#) (source\_parameters< T > \*params, lambda\_parameters< T > \*lambda)  
*Solves for the peak frequency, where the waveform transitions from intermediate to merger-ringdown.*
- virtual T [amp\\_ins](#) (T f, source\_parameters< T > \*param, T \*pn\_coeff, lambda\_parameters< T > \*lambda, useful\_powers< T > \*pow)  
*Calculates the scaled inspiral amplitude A/A0 for frequency f with precomputed powers of MF and PI.*
- virtual T [Damp\\_ins](#) (T f, source\_parameters< T > \*param, T \*pn\_coeff, lambda\_parameters< T > \*lambda)  
*Calculates the derivative wrt frequency for the scaled inspiral amplitude A/A0 for frequency f.*
- virtual T [phase\\_ins](#) (T f, source\_parameters< T > \*param, T \*pn\_coeff, lambda\_parameters< T > \*lambda, useful\_powers< T > \*pow)  
*Calculates the inspiral phase for frequency f with precomputed powers of MF and PI for speed.*
- virtual T [Dphase\\_ins](#) (T f, source\_parameters< T > \*param, T \*pn\_coeff, lambda\_parameters< T > \*lambda)  
*Calculates the derivative of the inspiral phase for frequency f.*
- virtual T [amp\\_mr](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the scaled merger-ringdown amplitude A/A0 for frequency f.*
- virtual T [phase\\_mr](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the merger-ringdown phase for frequency f.*
- virtual T [Damp\\_mr](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the derivative wrt frequency for the scaled merger-ringdown amplitude A/A0 for frequency f.*
- virtual T [Dphase\\_mr](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the derivative of the merger-ringdown phase for frequency f.*
- virtual T [amp\\_int](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda, T \*deltas)  
*Calculates the scaled intermediate range amplitude A/A0 for frequency f.*
- virtual T [phase\\_int](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the intermediate phase for frequency f.*
- virtual T [Dphase\\_int](#) (T f, source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)  
*Calculates the derivative of the intermediate phase for frequency f.*
- virtual void [phase\\_connection\\_coefficients](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda, T \*pn\_coeffs)  
*Calculates the phase connection coefficients  $\alpha_{0,1}$  and  $\beta_{0,1}$ .*
- virtual T [calculate\\_beta1](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda, T \*pn\_coeffs)
- virtual T [calculate\\_beta0](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda, T \*pn\_coeffs)
- virtual T [calculate\\_alpha1](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)
- virtual T [calculate\\_alpha0](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda)
- virtual void [amp\\_connection\\_coeffs](#) (source\_parameters< T > \*param, lambda\_parameters< T > \*lambda, T \*pn\_coeffs, T \*coeffs)  
*Solves for the connection coefficients to ensure the transition from inspiral to merger ringdown is continuous and smooth.*
- virtual T [calculate\\_delta\\_parameter\\_0](#) (T f1, T f2, T f3, T v1, T v2, T v3, T dd1, T dd3, T M)  
*Calculates the delta\_0 component.*
- virtual T [calculate\\_delta\\_parameter\\_1](#) (T f1, T f2, T f3, T v1, T v2, T v3, T dd1, T dd3, T M)  
*Calculates the delta\_1 component.*
- virtual T [calculate\\_delta\\_parameter\\_2](#) (T f1, T f2, T f3, T v1, T v2, T v3, T dd1, T dd3, T M)  
*Calculates the delta\_2 component.*
- virtual T [calculate\\_delta\\_parameter\\_3](#) (T f1, T f2, T f3, T v1, T v2, T v3, T dd1, T dd3, T M)  
*Calculates the delta\_3 component.*
- virtual T [calculate\\_delta\\_parameter\\_4](#) (T f1, T f2, T f3, T v1, T v2, T v3, T dd1, T dd3, T M)  
*Calculates the delta\_4 component.*

## 8.16.1 Member Function Documentation

### 8.16.1.1 amp\_ins()

```
template<class T >
T IMRPhenomD< T >::amp_ins (
    T f,
    source_parameters< T > * param,
    T * pn_coeff,
    lambda_parameters< T > * lambda,
    useful_powers< T > * pow ) [virtual]
```

Calculates the scaled inspiral amplitude  $A/A_0$  for frequency  $f$  with precomputed powers of MF and PI.

return a T

additional argument contains useful powers of MF and PI in structure useful\_powers

### 8.16.1.2 amp\_int()

```
template<class T >
T IMRPhenomD< T >::amp_int (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda,
    T * deltas ) [virtual]
```

Calculates the scaled intermediate range amplitude  $A/A_0$  for frequency  $f$ .

return a T

### 8.16.1.3 amp\_mr()

```
template<class T >
T IMRPhenomD< T >::amp_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the scaled merger-ringdown amplitude  $A/A_0$  for frequency  $f$ .

return a T

### 8.16.1.4 amplitude\_tape()

```
template<class T >
void IMRPhenomD< T >::amplitude_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of the amplitude.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

## Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#), and [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

## 8.16.1.5 assign\_nonstatic\_pn\_phase\_coeff()

```
template<class T >
void IMRPhenomD< T >::assign_nonstatic_pn_phase_coeff (
    source_parameters< T > * source_param,
    T * coeff,
    T f ) [virtual]
```

Calculates the dynamic PN phase coefficients 5,6.

f is in Hz

## 8.16.1.6 assign\_nonstatic\_pn\_phase\_coeff\_deriv()

```
template<class T >
void IMRPhenomD< T >::assign_nonstatic_pn_phase_coeff_deriv (
    source_parameters< T > * source_param,
    T * Dcoeff,
    T f ) [virtual]
```

Calculates the derivative of the dynamic PN phase coefficients 5,6.

f is in Hz

## 8.16.1.7 build\_amp()

```
template<class T >
T IMRPhenomD< T >::build_amp (
    T f,
    lambda_parameters< T > * lambda,
    source_parameters< T > * params,
    useful_powers< T > * pows,
    T * amp_coeff,
    T * deltas ) [virtual]
```

constructs the [IMRPhenomD](#) amplitude for frequency f

arguments: numerical parameters from Khan et al [lambda\\_parameters](#) structure, [source\\_parameters](#) structure, [useful\\_powers<T>](#) structure, PN parameters for the inspiral portions of the waveform, and the delta parameters for the intermediate region, numerically solved for using the [amp\\_connection\\_coeffs](#) function

### 8.16.1.8 build\_phase()

```
template<class T >
T IMRPhenomD< T >::build_phase (
    T f,
    lambda_parameters< T > * lambda,
    source_parameters< T > * params,
    useful_powers< T > * pows,
    T * phase_coeff ) [virtual]
```

constructs the [IMRPhenomD](#) phase for frequency  $f$

arguments: numerical parameters from Khan et al [lambda\\_parameters](#) structure, [source\\_parameters](#) structure, [useful\\_powers](#) structure, PN parameters for the inspiral portions of the waveform

### 8.16.1.9 calculate\_delta\_parameter\_0()

```
template<class T >
T IMRPhenomD< T >::calculate_delta_parameter_0 (
    T f1,
    T f2,
    T f3,
    T v1,
    T v2,
    T v3,
    T dd1,
    T dd3,
    T M ) [virtual]
```

Calculates the  $\delta_0$  component.

Solved in Mathematica and imported to C

### 8.16.1.10 calculate\_delta\_parameter\_1()

```
template<class T >
T IMRPhenomD< T >::calculate_delta_parameter_1 (
    T f1,
    T f2,
    T f3,
    T v1,
    T v2,
    T v3,
    T dd1,
    T dd3,
    T M ) [virtual]
```

Calculates the  $\delta_1$  component.

Solved in Mathematica and imported to C

**8.16.1.11 calculate\_delta\_parameter\_2()**

```
template<class T >
T IMRPhenomD< T >::calculate_delta_parameter_2 (
    T f1,
    T f2,
    T f3,
    T v1,
    T v2,
    T v3,
    T dd1,
    T dd3,
    T M ) [virtual]
```

Calculates the delta\_2 component.

Solved in Mathematica and imported to C

**8.16.1.12 calculate\_delta\_parameter\_3()**

```
template<class T >
T IMRPhenomD< T >::calculate_delta_parameter_3 (
    T f1,
    T f2,
    T f3,
    T v1,
    T v2,
    T v3,
    T dd1,
    T dd3,
    T M ) [virtual]
```

Calculates the delta\_3 component.

Solved in Mathematica and imported to C

**8.16.1.13 calculate\_delta\_parameter\_4()**

```
template<class T >
T IMRPhenomD< T >::calculate_delta_parameter_4 (
    T f1,
    T f2,
    T f3,
    T v1,
    T v2,
    T v3,
    T dd1,
    T dd3,
    T M ) [virtual]
```

Calculates the delta\_4 component.

Solved in Mathematica and imported to C

#### 8.16.1.14 `change_parameter_basis()`

```
template<class T >
void IMRPhenomD< T >::change_parameter_basis (
    T * old_param,
    T * new_param,
    bool sky_average ) [virtual]
```

Convenience method to change parameter basis between common Fisher parameters and the intrinsic parameters of [IMRPhenomD](#).

Takes input array of old parameters and outputs array of transformed parameters

##### Parameters

|                  |   |
|------------------|---|
| <i>old_param</i> | array of old params, order {A0, tc, phic, chirpmass, eta, spin1, spin2} |
| <i>new_param</i> | output new array: order {m1,m2,DL, spin1,spin2,phic,tc}                 |

#### 8.16.1.15 `construct_amplitude()`

```
template<class T >
int IMRPhenomD< T >::construct_amplitude (
    T * frequencies,
    int length,
    T * amplitude,
    source\_parameters< T > * params ) [virtual]
```

Constructs the Amplitude as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output amplitude, and a [source\\_parameters](#) structure

##### Parameters

|                    |   |
|--------------------|---|
| <i>frequencies</i> | T array of frequencies the waveform is to be evaluated at             |
| <i>length</i>      | integer length of the input array of frequencies and the output array |
| <i>amplitude</i>   | output T array for the amplitude                                      |
| <i>params</i>      | Structure of source parameters to be initialized before computation   |

Reimplemented in [EdGB\\_IMRPhenomD< T >](#), [EdGB\\_IMRPhenomD\\_log< T >](#), [dCS\\_IMRPhenomD< T >](#), and [dCS\\_IMRPhenomD\\_log< T >](#).

#### 8.16.1.16 `construct_amplitude_derivative()`

```
template<class T >
void IMRPhenomD< T >::construct_amplitude_derivative (
    double * frequencies,
```

```

    int length,
    int dimension,
    double ** amplitude_derivative,
    source_parameters< double > * input_params,
    int * tapes = NULL ) [virtual]

```

Construct the derivative of the amplitude for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta$  :  $\theta$  {A0,tc, phic, chirp mass, eta, symmetric spin, antisymmetric spin}

#### Parameters

|                             |  |
|-----------------------------|--|
| <i>frequencies</i>          | input array of frequency   |
| <i>length</i>               | length of the frequency array  |
| <i>amplitude_derivative</i> | < dimension of the fisher output array for all the derivatives double[dimension][length] |
| <i>input_params</i>         | Source parameters structure for the source   |
| <i>tapes</i>                | int array of tape ids, if NULL, these will be calculated                                 |

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#), and [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

#### 8.16.1.17 construct\_phase()

```

template<class T >
int IMRPhenomD< T >::construct_phase (
    T * frequencies,
    int length,
    T * phase,
    source_parameters< T > * params ) [virtual]

```

Constructs the Phase as outlined by [IMRPhenomD](#).

arguments: array of frequencies, length of that array, T array for the output phase, and a [source\\_parameters](#) structure

#### Parameters

|                    |  |
|--------------------|--|
| <i>frequencies</i> | T array of frequencies the waveform is to be evaluated at          |
| <i>length</i>      | integer length of the input and output arrays                      |
| <i>phase</i>       | output T array for the phase                                       |
| <i>params</i>      | structure of source parameters to be calculated before computation |

Reimplemented in [EdGB\\_IMRPhenomD< T >](#), [EdGB\\_IMRPhenomD\\_log< T >](#), [dCS\\_IMRPhenomD< T >](#), and [dCS\\_IMRPhenomD\\_log< T >](#).

#### 8.16.1.18 construct\_phase\_derivative()

```

template<class T >
void IMRPhenomD< T >::construct_phase_derivative (

```

```
double * frequencies,
int length,
int dimension,
double ** phase_derivative,
source_parameters< double > * input_params,
int * tapes = NULL ) [virtual]
```

Construct the derivative of the phase for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta$  :  $\theta$  {A0,tc, phic, chirp mass, eta, symmetric spin, antisymmetric spin}

#### Parameters

|                         |  |
|-------------------------|--|
| <i>frequencies</i>      | input array of frequency   |
| <i>length</i>           | length of the frequency array  |
| <i>phase_derivative</i> | < dimension of the fisher output array for all the derivatives double[dimension][length] |
| <i>input_params</i>     | Source parameters structure for the source   |
| <i>tapes</i>            | int array of tape ids, if NULL, these will be calculated                                 |

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#), and [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

#### 8.16.1.19 construct\_waveform() [1/2]

```
template<class T >
int IMRPhenomD< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform as outlined by.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

#### Parameters

|                    |   |
|--------------------|---|
| <i>frequencies</i> | T array of frequencies the waveform is to be evaluated at   |
| <i>length</i>      | integer length of the array of frequencies and the waveform |
| <i>waveform</i>    | complex T array for the waveform to be output               |

Reimplemented in [EdGB\\_IMRPhenomD< T >](#), [EdGB\\_IMRPhenomD\\_log< T >](#), [dCS\\_IMRPhenomD< T >](#), and [dCS\\_IMRPhenomD\\_log< T >](#).

#### 8.16.1.20 construct\_waveform() [2/2]

```
template<class T >
std::complex< T > IMRPhenomD< T >::construct_waveform (
```



```

T frequency,
source_parameters< T > * params ) [virtual]

```

overloaded method to evaluate the waveform for one frequency instead of an array

#### Parameters

|                  |   |
|------------------|---|
| <i>frequency</i> | T array of frequencies the waveform is to be evaluated at |
|------------------|---|

##### 8.16.1.21 Damp\_ins()

```

template<class T >
T IMRPhenomD< T >::Damp_ins (
    T f,
    source_parameters< T > * param,
    T * pn_coeff,
    lambda_parameters< T > * lambda ) [virtual]

```

Calculates the derivative wrt frequency for the scaled inspiral amplitude A/A0 for frequency f.

This is an analytic derivative for the smoothness condition on the amplitude connection

return a T

##### 8.16.1.22 Damp\_mr()

```

template<class T >
T IMRPhenomD< T >::Damp_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]

```

Calculates the derivative wrt frequency for the scaled merger-ringdown amplitude A/A0 for frequency f.

This is an analytic derivative for the smoothness condition on the amplitude connection

The analytic expression was obtained from Mathematica - See the mathematica folder for code

return a T

##### 8.16.1.23 Dphase\_ins()

```

template<class T >
T IMRPhenomD< T >::Dphase_ins (
    T f,
    source_parameters< T > * param,
    T * pn_coeff,
    lambda_parameters< T > * lambda ) [virtual]

```

Calculates the derivative of the inspiral phase for frequency f.

For phase continuity and smoothness return a T

Reimplemented in [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

**8.16.1.24 Dphase\_int()**

```
template<class T >
T IMRPhenomD< T >::Dphase_int (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the derivative of the intermediate phase for frequency f.

For phase continuity and smoothness return a T

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

**8.16.1.25 Dphase\_mr()**

```
template<class T >
T IMRPhenomD< T >::Dphase_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the derivative of the merger-ringdown phase for frequency f.

For phase continuity and smoothness return a T

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

**8.16.1.26 fpeak()**

```
template<class T >
T IMRPhenomD< T >::fpeak (
    source_parameters< T > * params,
    lambda_parameters< T > * lambda ) [virtual]
```

Solves for the peak frequency, where the waveform transitions from intermediate to merger-ringdown.

returns Hz

**8.16.1.27 phase\_connection\_coefficients()**

```
template<class T >
void IMRPhenomD< T >::phase_connection_coefficients (
    source_parameters< T > * param,
    lambda_parameters< T > * lambda,
    T * pn_coeffs ) [virtual]
```

Calculates the phase connection coefficients  $\alpha_{0,1}$  and  $\beta_{0,1}$ .

Note: these coefficients are stored in the lambda parameter structure, not a separate array

## 8.16.1.28 phase\_ins()

```
template<class T >
T IMRPhenomD< T >::phase_ins (
    T f,
    source_parameters< T > * param,
    T * pn_coeff,
    lambda_parameters< T > * lambda,
    useful_powers< T > * pow ) [virtual]
```

Calculates the inspiral phase for frequency  $f$  with precomputed powers of MF and PI for speed.

return a T

extra argument of precomputed powers of MF and pi, contained in the structure `useful_powers<T>`

Reimplemented in [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

## 8.16.1.29 phase\_int()

```
template<class T >
T IMRPhenomD< T >::phase_int (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the intermediate phase for frequency  $f$ .

return a T

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

## 8.16.1.30 phase\_mr()

```
template<class T >
T IMRPhenomD< T >::phase_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the merger-ringdown phase for frequency  $f$ .

return a T

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

## 8.16.1.31 phase\_tape()

```
template<class T >
void IMRPhenomD< T >::phase_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of phase.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

## Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#), and [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

8.16.1.32 `post_merger_variables()`

```
template<class T >
void IMRPhenomD< T >::post_merger_variables (
    source_parameters< T > * source_param ) [virtual]
```

Calculates the post-merger ringdown frequency and dampening frequency.

Returns in Hz - assigns fRD to var[0] and fdamp to var[1]

8.16.1.33 `precalc_powers_ins()`

```
template<class T >
void IMRPhenomD< T >::precalc_powers_ins (
    T f,
    T M,
    useful_powers< T > * Mf_pows ) [virtual]
```

Pre-calculate powers of Mf, to speed up calculations for the inspiral waveform (both amplitude and phase.

It seems the pow() function is very slow, so to speed things up, powers of Mf will be precomputed and passed to the functions within the frequency loops

8.16.1.34 `precalc_powers_ins_amp()`

```
template<class T >
void IMRPhenomD< T >::precalc_powers_ins_amp (
    T f,
    T M,
    useful_powers< T > * Mf_pows ) [virtual]
```

Pre-calculate powers of Mf, to speed up calculations for the inspiral amplitude.

It seems the pow() function is very slow, so to speed things up, powers of Mf will be precomputed and passed to the functions within the frequency loops

## 8.16.1.35 precalc\_powers\_ins\_phase()

```
template<class T >
void IMRPhenomD< T >::precalf_powers_ins_phase (
    T f,
    T M,
    useful_powers< T > * Mf_pows ) [virtual]
```

Pre-calculate powers of *Mf*, to speed up calculations for the inspiral phase.

It seems the `pow()` function is very slow, so to speed things up, powers of *Mf* will be precomputed and passed to the functions within the frequency loops

## 8.16.1.36 precalc\_powers\_PI()

```
template<class T >
void IMRPhenomD< T >::precalf_powers_PI (
    useful_powers< T > * PI_pows ) [virtual]
```

Pre-calculate powers of *pi*, to speed up calculations for the inspiral phase.

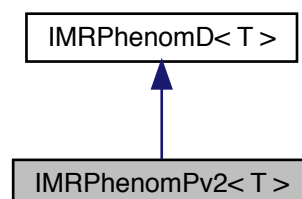
It seems the `pow()` function is very slow, so to speed things up, powers of *PI* will be precomputed and passed to the functions within the frequency loops

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

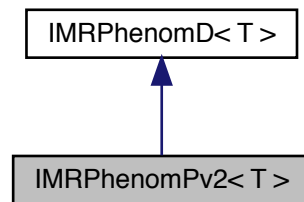
- include/[IMRPhenomD.h](#)
- src/[IMRPhenomD.cpp](#)

## 8.17 IMRPhenomPv2&lt; T &gt; Class Template Reference

Inheritance diagram for IMRPhenomPv2< T >:



Collaboration diagram for IMRPhenomPv2< T >:



## Public Member Functions

- virtual T **alpha** (T omega, T q, T chi2l, T chi2)
- virtual T **epsilon** (T omega, T q, T chi2l, T chi2)
- virtual void **calculate\_euler\_coeffs** (alpha\_coeffs< T > \*acoeffs, epsilon\_coeffs< T > \*ecoeffs, source\_parameters< T > \*params)  
*Pre calculate euler angle coefficients.*
- virtual T **d** (int l, int mp, int m, T s)
- virtual int **construct\_waveform** (T \*frequencies, int length, std::complex< T > \*waveform\_plus, std::complex< T > \*waveform\_cross, source\_parameters< T > \*params)  
*Constructs the waveform for IMRPhenomPv2 - uses IMRPhenomD, then twists up.*
- virtual void **WignerD** (T d2[5], T dm2[5], useful\_powers< T > \*pows, source\_parameters< T > \*params)
- virtual void **calculate\_twistup** (T alpha, std::complex< T > \*hp\_factor, std::complex< T > \*hc\_factor, T d2[5], T dm2[5], sph\_harm< T > \*sph\_harm)
- virtual void **calculate\_euler\_angles** (T \*alpha, T \*epsilon, useful\_powers< T > \*pows, alpha\_coeffs< T > \*acoeffs, epsilon\_coeffs< T > \*ecoeffs)
- virtual void **PhenomPv2\_Param\_Transform** (source\_parameters< T > \*params)
- virtual void **PhenomPv2\_Param\_Transform\_J** (source\_parameters< T > \*params)
- virtual T **L2PN** (T eta, useful\_powers< T > \*pow)

## 8.17.1 Member Function Documentation

### 8.17.1.1 calculate\_euler\_coeffs()

```

template<class T >
void IMRPhenomPv2< T >::calculate_euler_coeffs (
    alpha_coeffs< T > * acoeffs,
    epsilon_coeffs< T > * ecoeffs,
    source_parameters< T > * params ) [virtual]
  
```

Pre calculate euler angle coefficients.

Straight up stolen from LALsuite

## 8.17.1.2 construct\_waveform()

```
template<class T >
int IMRPhenomPv2< T >::construct_waveform (
    T * frequencies,
    int length,
    std::complex< T > * waveform_plus,
    std::complex< T > * waveform_cross,
    source_parameters< T > * params ) [virtual]
```

Constructs the waveform for [IMRPhenomPv2](#) - uses [IMRPhenomD](#), then twists up.

arguments: array of frequencies, length of that array, a complex array for the output waveform, and a [source\\_parameters](#) structure

## Parameters

|                       |  |
|-----------------------|--|
| <i>frequencies</i>    | T array of frequencies the waveform is to be evaluated at        |
| <i>length</i>         | integer length of the array of frequencies and the waveform      |
| <i>waveform_plus</i>  | complex T array for the plus polariaztion waveform to be output  |
| <i>waveform_cross</i> | complex T array for the cross polarization waveform to be output |

## 8.17.1.3 PhenomPv2\_Param\_Transform()

```
template<class T >
void IMRPhenomPv2< T >::PhenomPv2_Param_Transform (
    source_parameters< T > * params ) [virtual]
```

/Brief Parameter transformtion to precalculate needed parameters for PhenomP from source parameters

Pretty much stolen verbatim from lalsuite

## 8.17.1.4 PhenomPv2\_Param\_Transform\_J()

```
template<class T >
void IMRPhenomPv2< T >::PhenomPv2_Param_Transform_J (
    source_parameters< T > * params ) [virtual]
```

/Brief Parameter transformtion to precalculate needed parameters for PhenomP from source parameters – assumed inclination of total angular momentum J is given, not orbital angular momentum (in source frame ( $\hat{L} = \hat{z}$ ))

Pretty much stolen verbatim from lalsuite

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

- [include/IMRPhenomP.h](#)
- [src/IMRPhenomP.cpp](#)

## 8.18 `lambda_parameters< T >` Struct Template Reference

### Public Attributes

- `T rho` [4]
- `T v2`
- `T gamma` [4]
- `T sigma` [5]
- `T beta` [5]
- `T alpha` [7]

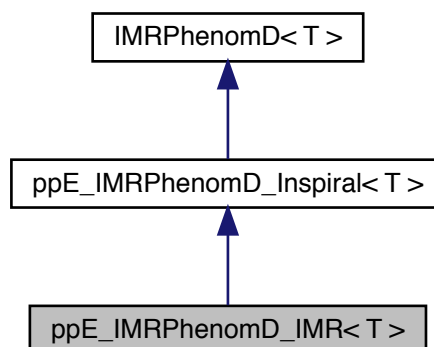
The documentation for this struct was generated from the following file:

- `include/IMRPhenomD.h`

## 8.19 `ppE_IMRPhenomD_IMR< T >` Class Template Reference

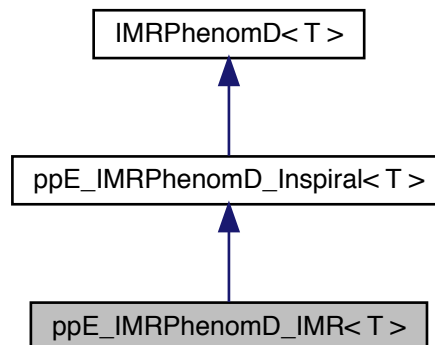
```
#include <ppE_IMRPhenomD.h>
```

Inheritance diagram for `ppE_IMRPhenomD_IMR< T >`:





Collaboration diagram for ppE\_IMRPhenomD\_IMR< T >:



## Public Member Functions

- virtual T `Dphase_mr` (T f, `source_parameters`< T > \*param, `lambda_parameters`< T > \*lambda)  
*Calculates the derivative of the merger-ringdown phase for frequency f.*
- virtual T `phase_mr` (T f, `source_parameters`< T > \*param, `lambda_parameters`< T > \*lambda)  
*Calculates the merger-ringdown phase for frequency f.*
- virtual T `phase_int` (T f, `source_parameters`< T > \*param, `lambda_parameters`< T > \*lambda)  
*Calculates the intermediate phase for frequency f.*
- virtual T `Dphase_int` (T f, `source_parameters`< T > \*param, `lambda_parameters`< T > \*lambda)  
*Calculates the derivative of the intermediate phase for frequency f.*
- virtual void **fisher\_calculation** (double \*frequency, int length, `gen_params` \*parameters, double \*\*amplitude\_deriv, double \*\*phase\_deriv, double \*amplitude, int \*amp\_tapes, int \*phase\_tapes)
- virtual void `amplitude_tape` (`source_parameters`< double > \*input\_params, int \*tape)  
*Creates the tapes for derivatives of the amplitude.*
- virtual void `phase_tape` (`source_parameters`< double > \*input\_params, int \*tape)  
*Creates the tapes for derivatives of phase.*
- virtual void `construct_amplitude_derivative` (double \*frequencies, int length, int dimension, double \*\*amplitude\_derivative, `source_parameters`< double > \*input\_params, int \*tapes=NULL)  
*Construct the derivative of the amplitude for a given source evaluated by the given frequency.*
- virtual void `construct_phase_derivative` (double \*frequencies, int length, int dimension, double \*\*phase\_↔ derivative, `source_parameters`< double > \*input\_params, int \*tapes=NULL)  
*Construct the derivative of the phase for a given source evaluated by the given frequency.*

### 8.19.1 Detailed Description

```
template<class T>
class ppE_IMRPhenomD_IMR< T >
```

Class that extends the `IMRPhenomD` waveform to include non-GR terms in the full phase. This is an appropriate waveform choice for propagation effects

## 8.19.2 Member Function Documentation

### 8.19.2.1 `amplitude_tape()`

```
template<class T >
void ppE_IMRPhenomD_IMR< T >::amplitude_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of the amplitude.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

#### Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented from [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

### 8.19.2.2 `construct_amplitude_derivative()`

```
template<class T >
void ppE_IMRPhenomD_IMR< T >::construct_amplitude_derivative (
    double * frequencies,
    int length,
    int dimension,
    double ** amplitude_derivative,
    source_parameters< double > * input_params,
    int * tapes = NULL ) [virtual]
```

Construct the derivative of the amplitude for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta$  :  $\theta$  {A0,tc, phic, chirp mass, eta, symmetric spin, antisymmetric spin}

#### Parameters

|                             |   |
|-----------------------------|---|
| <i>frequencies</i>          | input array of frequency  |
| <i>length</i>               | length of the frequency array   |
| <i>amplitude_derivative</i> | < dimension of the fisher output array for all the derivatives $\text{double}[\text{dimension}][\text{length}]$ |
| <i>input_params</i>         | Source parameters structure for the source  |
| <i>tapes</i>                | int array of tape ids, if NULL, these will be calculated  |

Reimplemented from [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

## 8.19.2.3 construct\_phase\_derivative()

```
template<class T >
void ppE_IMRPhenomD_IMR< T >::construct_phase_derivative (
    double * frequencies,
    int length,
    int dimension,
    double ** phase_derivative,
    source_parameters< double > * input_params,
    int * tapes = NULL ) [virtual]
```

Construct the derivative of the phase for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta$  :  $\theta$  {A0,tc, phic, chirp mass, eta, symmetric spin, antisymmetric spin}

## Parameters

|                         |  |
|-------------------------|--|
| <i>frequencies</i>      | input array of frequency   |
| <i>length</i>           | length of the frequency array  |
| <i>phase_derivative</i> | < dimension of the fisher output array for all the derivatives double[dimension][length] |
| <i>input_params</i>     | Source parameters structure for the source   |
| <i>tapes</i>            | int array of tape ids, if NULL, these will be calculated                                 |

Reimplemented from [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

## 8.19.2.4 Dphase\_int()

```
template<class T >
T ppE_IMRPhenomD_IMR< T >::Dphase_int (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the derivative of the intermediate phase for frequency f.

For phase continuity and smoothness return a T

Reimplemented from [IMRPhenomD< T >](#).

## 8.19.2.5 Dphase\_mr()

```
template<class T >
T ppE_IMRPhenomD_IMR< T >::Dphase_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the derivative of the merger-ringdown phase for frequency f.

For phase continuity and smoothness return a T

Reimplemented from [IMRPhenomD< T >](#).

### 8.19.2.6 phase\_int()

```
template<class T >
T ppE_IMRPhenomD_IMR< T >::phase_int (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the intermediate phase for frequency f.

return a T

Reimplemented from [IMRPhenomD< T >](#).

### 8.19.2.7 phase\_mr()

```
template<class T >
T ppE_IMRPhenomD_IMR< T >::phase_mr (
    T f,
    source_parameters< T > * param,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the merger-ringdown phase for frequency f.

return a T

Reimplemented from [IMRPhenomD< T >](#).

### 8.19.2.8 phase\_tape()

```
template<class T >
void ppE_IMRPhenomD_IMR< T >::phase_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of phase.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

#### Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented from [ppE\\_IMRPhenomD\\_Inspiral< T >](#).

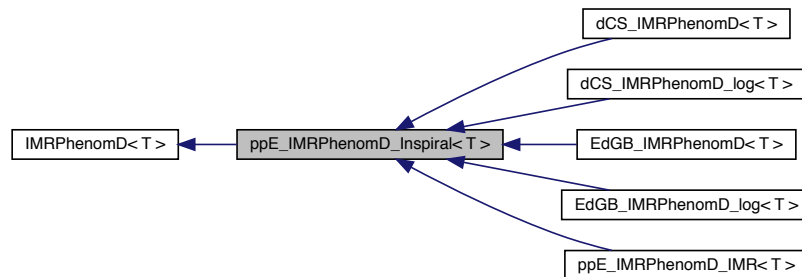
The documentation for this class was generated from the following files:

- [include/ppE\\_IMRPhenomD.h](#)
- [src/ppE\\_IMRPhenomD.cpp](#)

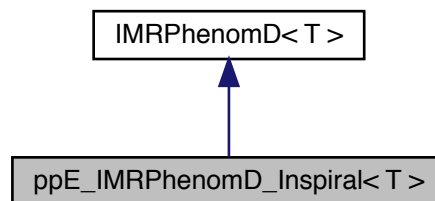
## 8.20 ppE\_IMRPhenomD\_Inspiral< T > Class Template Reference

```
#include <ppE_IMRPhenomD.h>
```

Inheritance diagram for ppE\_IMRPhenomD\_Inspiral< T >:



Collaboration diagram for ppE\_IMRPhenomD\_Inspiral< T >:



### Public Member Functions

- virtual T [phase\\_ins](#) (T f, [source\\_parameters](#)< T > \*param, T \*pn\_coeff, [lambda\\_parameters](#)< T > \*lambda, [useful\\_powers](#)< T > \*pow)  
*Overloaded method for the inspiral portion of the phase.*
- virtual T [Dphase\\_ins](#) (T f, [source\\_parameters](#)< T > \*param, T \*pn\_coeff, [lambda\\_parameters](#)< T > \*lambda)  
*Calculates the derivative of the inspiral phase for frequency f.*
- virtual void **fisher\_calculation** (double \*frequency, int length, [gen\\_params](#) \*parameters, double \*\*amplitude\_deriv, double \*\*phase\_deriv, double \*amplitude, int \*amp\_tapes, int \*phase\_tapes)
- virtual void [amplitude\\_tape](#) ([source\\_parameters](#)< double > \*input\_params, int \*tape)  
*Creates the tapes for derivatives of the amplitude.*
- virtual void [phase\\_tape](#) ([source\\_parameters](#)< double > \*input\_params, int \*tape)  
*Creates the tapes for derivatives of phase.*
- virtual void [construct\\_amplitude\\_derivative](#) (double \*frequencies, int length, int dimension, double \*\*amplitude\_derivative, [source\\_parameters](#)< double > \*input\_params, int \*tapes=NULL)  
*Construct the derivative of the amplitude for a given source evaluated by the given frequency.*
- virtual void [construct\\_phase\\_derivative](#) (double \*frequencies, int length, int dimension, double \*\*phase\_derivative, [source\\_parameters](#)< double > \*input\_params, int \*tapes=NULL)  
*Construct the derivative of the phase for a given source evaluated by the given frequency.*

### 8.20.1 Detailed Description

```
template<class T>
class ppE_IMRPhenomD_Inspiral< T >
```

Class that extends the [IMRPhenomD](#) waveform to include non-GR terms in the inspiral portion of the phase. This is an appropriate waveform choice for generation effects, but not necessarily for propagation effects

### 8.20.2 Member Function Documentation

#### 8.20.2.1 `amplitude_tape()`

```
template<class T >
void ppE_IMRPhenomD_Inspiral< T >::amplitude_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of the amplitude.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

##### Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented from [IMRPhenomD< T >](#).

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

#### 8.20.2.2 `construct_amplitude_derivative()`

```
template<class T >
void ppE_IMRPhenomD_Inspiral< T >::construct_amplitude_derivative (
    double * frequencies,
    int length,
    int dimension,
    double ** amplitude_derivative,
    source_parameters< double > * input_params,
    int * tapes = NULL ) [virtual]
```

Construct the derivative of the amplitude for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta : \theta \in \{A_0, \eta, \chi, \text{chirp mass}, \eta, \text{symmetric spin}, \text{antisymmetric spin}\}$

## Parameters

|                             |  |
|-----------------------------|--|
| <i>frequencies</i>          | input array of frequency   |
| <i>length</i>               | length of the frequency array  |
| <i>amplitude_derivative</i> | < dimension of the fisher output array for all the derivatives double[dimension][length] |
| <i>input_params</i>         | Source parameters structure for the source   |
| <i>tapes</i>                | int array of tape ids, if NULL, these will be calculated                                 |

Reimplemented from [IMRPhenomD< T >](#).

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

## 8.20.2.3 construct\_phase\_derivative()

```
template<class T >
void ppE_IMRPhenomD_Inspiral< T >::construct_phase_derivative (
    double * frequencies,
    int length,
    int dimension,
    double ** phase_derivative,
    source_parameters< double > * input_params,
    int * tapes = NULL ) [virtual]
```

Construct the derivative of the phase for a given source evaluated by the given frequency.

Order of output:  $dh/d\theta$  :  $\theta$  {A0,tc, phic, chirp mass, eta, symmetric spin, antisymmetric spin}

## Parameters

|                         |  |
|-------------------------|--|
| <i>frequencies</i>      | input array of frequency   |
| <i>length</i>           | length of the frequency array  |
| <i>phase_derivative</i> | < dimension of the fisher output array for all the derivatives double[dimension][length] |
| <i>input_params</i>     | Source parameters structure for the source   |
| <i>tapes</i>            | int array of tape ids, if NULL, these will be calculated                                 |

Reimplemented from [IMRPhenomD< T >](#).

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

## 8.20.2.4 Dphase\_ins()

```
template<class T >
T ppE_IMRPhenomD_Inspiral< T >::Dphase_ins (
    T f,
    source_parameters< T > * param,
    T * pn_coeff,
    lambda_parameters< T > * lambda ) [virtual]
```

Calculates the derivative of the inspiral phase for frequency  $f$ .

For phase continuity and smoothness return a  $T$

Reimplemented from [IMRPhenomD< T >](#).

#### 8.20.2.5 phase\_tape()

```
template<class T >
void ppE_IMRPhenomD_Inspiral< T >::phase_tape (
    source_parameters< double > * input_params,
    int * tape ) [virtual]
```

Creates the tapes for derivatives of phase.

For efficiency in long runs of large sets of fishers, the tapes can be precomputed and reused

##### Parameters

|                     |   |
|---------------------|---|
| <i>input_params</i> | source parameters structure of the desired source |
| <i>tape</i>         | tape ids  |

Reimplemented from [IMRPhenomD< T >](#).

Reimplemented in [ppE\\_IMRPhenomD\\_IMR< T >](#).

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

- [include/ppE\\_IMRPhenomD.h](#)
- [src/ppE\\_IMRPhenomD.cpp](#)

## 8.21 sampler Struct Reference

### Public Attributes

- int **types\_of\_steps** = 4
- double \*\* **step\_prob**
- double \*\* **prob\_boundaries**
- double \* **chain\_temps**
- bool \* **waiting**
- int \* **chain\_pos**
- double **swp\_freq**
- int **chain\_N**
- int **numThreads**
- int **N\_steps**
- int **dimension**
- bool **fisher\_exist**
- bool \* **de\_primed**
- int \* **priority**



- double \*\*\* **output**
- bool **pool**
- int **progress** =0
- bool **show\_progress**
- int **num\_threads**
- int **history\_length**
- int **history\_update**
- int \* **current\_hist\_pos**
- double \*\*\* **history**
- double \* **current\_likelihooods**
- int \* **check\_stepsize\_freq**
- double \* **max\_target\_accept\_ratio**
- double \* **min\_target\_accept\_ratio**
- int \* **gauss\_last\_accept\_ct**
- int \* **gauss\_last\_reject\_ct**
- int \* **de\_last\_accept\_ct**
- int \* **de\_last\_reject\_ct**
- int \* **fish\_last\_accept\_ct**
- int \* **fish\_last\_reject\_ct**
- double \*\* **randgauss\_width**
- double \*\*\* **fisher\_vecs**
- double \*\* **fisher\_vals**
- int \* **fisher\_update\_ct**
- int **fisher\_update\_number**
- std::function< double(double \*, int, int)> **lp**
- std::function< double(double \*, int, int)> **ll**
- std::function< void(double \*, int, double \*\*, int)> **fish**
- gsl\_rng \*\* **rvec**
- int \* **nan\_counter**
- int \* **num\_gauss**
- int \* **num\_fish**
- int \* **num\_de**
- int \* **num\_mmala**
- double **time\_elapsed\_cpu**
- double **time\_elapsed\_wall**
- double **time\_elapsed\_cpu\_ac**
- double **time\_elapsed\_wall\_ac**
- int \* **fish\_accept\_ct**
- int \* **fish\_reject\_ct**
- int \* **de\_accept\_ct**
- int \* **de\_reject\_ct**
- int \* **gauss\_accept\_ct**
- int \* **gauss\_reject\_ct**
- int \* **mmala\_accept\_ct**
- int \* **mmala\_reject\_ct**
- int \* **swap\_accept\_ct**
- int \* **swap\_reject\_ct**
- int \* **step\_accept\_ct**
- int \* **step\_reject\_ct**
- double \*\*\* **ll\_lp\_output**

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

- [include/mcmc\\_sampler\\_internals.h](#)

## 8.22 `source_parameters< T >` Struct Template Reference

### Static Public Member Functions

- static `source_parameters< T >` `populate_source_parameters` (`gen_params` \*param\_in)  
*Builds the structure that shuttles source parameters between functions -updated version to incorporate structure argument.*
- static `source_parameters< T >` `populate_source_parameters_old` (`T` mass1, `T` mass2, `T` Luminosity\_↔ Distance, `T` \*spin1, `T` \*spin2, `T` phi\_c, `T` t\_c, `bool` sky\_average)  
*Builds the structure that shuttles source parameters between functions- outdated in favor of structure argument.*

### Public Attributes

- `T` mass1
- `T` mass2
- `T` M
- `T` q
- `T` spin1z
- `T` spin2z
- `T` spin1x
- `T` spin2x
- `T` spin1y
- `T` spin2y
- `T` chirpmass
- `T` eta
- `T` chi\_s
- `T` chi\_a
- `T` chi\_eff
- `T` chi\_pn
- `T` DL
- `T` delta\_mass
- `T` fRD
- `T` fdamp
- `T` f1
- `T` f3
- `T` f1\_phase
- `T` f2\_phase
- `T` phic
- `T` tc
- `T` A0
- `T` s
- `T` chil
- `T` chip
- `T` f\_ref
- `T` phi\_aligned
- `T` incl\_angle
- `T` phiRef
- `T` alpha0
- `T` thetaJN
- `T` zeta\_polariz
- `T` \* betappe
- `int` \* bppe
- `int` Nmod

- T **phi**
- T **theta**
- T **SP**
- T **SL**
- bool **sky\_average**
- gsl\_spline \* **Z\_DL\_spline\_ptr** =NULL
- gsl\_interp\_accel \* **Z\_DL\_accel\_ptr** =NULL
- std::string **cosmology**

## 8.22.1 Member Function Documentation

### 8.22.1.1 populate\_source\_parameters()

```
template<class T >
source_parameters< T > source_parameters< T >::populate_source_parameters (
    gen_params * param_in ) [static]
```

Builds the structure that shuttles source parameters between functions -updated version to incorporate structure argument.

Populates the structure that is passed to all generation methods - contains all relevant source parameters

### 8.22.1.2 populate\_source\_parameters\_old()

```
template<class T >
source_parameters< T > source_parameters< T >::populate_source_parameters_old (
    T mass1,
    T mass2,
    T Luminosity_Distance,
    T * spin1,
    T * spin2,
    T phi_c,
    T t_c,
    bool sky_average ) [static]
```

Builds the structure that shuttles source parameters between functions- outdated in favor of structure argument.

Populates the structure that is passed to all generation methods - contains all relevant source parameters

#### Parameters

|                            |  |
|----------------------------|--|
| <i>mass1</i>               | mass of the larger body - in Solar Masses  |
| <i>mass2</i>               | mass of the smaller body - in Solar Masses |
| <i>Luminosity_Distance</i> | Luminosity Distance in Mpc                 |
| <i>spin2</i>               | spin vector of the larger body {sx,sy,sz}  |
| <i>phi_c</i>               | spin vector of the smaller body {sx,sy,sz} |
| <i>t_c</i>                 | coalescence phase                          |
| <i>sky_average</i>         | coalescence time                           |

## 8.22.2 Member Data Documentation

### 8.22.2.1 chi\_a

```
template<class T>
T source_parameters< T >::chi_a
```

Antisymmetric spin combination

### 8.22.2.2 chi\_eff

```
template<class T>
T source_parameters< T >::chi_eff
```

Effective spin

### 8.22.2.3 chi\_pn

```
template<class T>
T source_parameters< T >::chi_pn
```

PN spin

### 8.22.2.4 chi\_s

```
template<class T>
T source_parameters< T >::chi_s
```

Symmetric spin combination

### 8.22.2.5 chirpmass

```
template<class T>
T source_parameters< T >::chirpmass
```

Chirp mass of the binary

### 8.22.2.6 delta\_mass

```
template<class T>
T source_parameters< T >::delta_mass
```

Delta mass combination

#### 8.22.2.7 DL

```
template<class T>
T source_parameters< T >::DL
```

Luminoisity Distance

#### 8.22.2.8 eta

```
template<class T>
T source_parameters< T >::eta
```

Symmetric mass ratio

#### 8.22.2.9 f1

```
template<class T>
T source_parameters< T >::f1
```

Transition Frequency 1 for the amplitude

#### 8.22.2.10 f1\_phase

```
template<class T>
T source_parameters< T >::f1_phase
```

Transition frequency 1 for the phase

#### 8.22.2.11 f2\_phase

```
template<class T>
T source_parameters< T >::f2_phase
```

Transition frequency 2 for the phase

#### 8.22.2.12 f3

```
template<class T>
T source_parameters< T >::f3
```

Transition Frequency 2 for the amplitude

#### 8.22.2.13 fdamp

```
template<class T>
T source_parameters< T >::fdamp
```

Dampening frequency after merger

**8.22.2.14 fRD**

```
template<class T>
T source_parameters< T >::fRD
```

Ringdown frequency after merger

**8.22.2.15 M**

```
template<class T>
T source_parameters< T >::M
```

Total mass

**8.22.2.16 mass1**

```
template<class T>
T source_parameters< T >::mass1
```

mass of the larger component

**8.22.2.17 mass2**

```
template<class T>
T source_parameters< T >::mass2
```

mass of the smaller component

**8.22.2.18 Nmod**

```
template<class T>
int source_parameters< T >::Nmod
```

Number of modifications to phase

**8.22.2.19 phic**

```
template<class T>
T source_parameters< T >::phic
```

Coalescence phase

**8.22.2.20 spin1x**

```
template<class T>
T source_parameters< T >::spin1x
```

x-Spin component of the larger body

**8.22.2.21** `spin1y`

```
template<class T>
T source_parameters< T >::spin1y
```

y-Spin component of the larger body

**8.22.2.22** `spin1z`

```
template<class T>
T source_parameters< T >::spin1z
```

z-Spin component of the larger body

**8.22.2.23** `spin2x`

```
template<class T>
T source_parameters< T >::spin2x
```

x-Spin component of the smaller body

**8.22.2.24** `spin2y`

```
template<class T>
T source_parameters< T >::spin2y
```

y-Spin component of the smaller body

**8.22.2.25** `spin2z`

```
template<class T>
T source_parameters< T >::spin2z
```

z-Spin component of the smaller body

**8.22.2.26** `tc`

```
template<class T>
T source_parameters< T >::tc
```

Coalescence time

The documentation for this struct was generated from the following files:

- `include/util.h`
- `src/util.cpp`

## 8.23 sph\_harm< T > Struct Template Reference

### Public Attributes

- `std::complex< T > Y22`
- `std::complex< T > Y21`
- `std::complex< T > Y20`
- `std::complex< T > Y2m1`
- `std::complex< T > Y2m2`

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

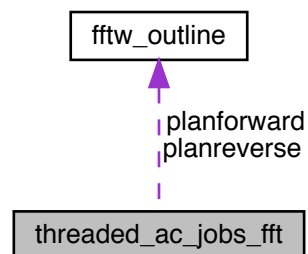
- `include/utl.h`

## 8.24 threaded\_ac\_jobs\_fft Class Reference

Class to contain spectral method jobs.

```
#include <autocorrelation.h>
```

Collaboration diagram for `threaded_ac_jobs_fft`:



### Public Attributes

- `double ** data`
- `int * length`
- `int * start`
- `int * end`
- `int dimension`
- `fftw_outline * planforward`
- `fftw_outline * planreverse`
- `int * lag`
- `double * target`



### 8.24.1 Detailed Description

Class to contain spectral method jobs.

### 8.24.2 Member Data Documentation

#### 8.24.2.1 dimension

```
int threaded_ac_jobs_fft::dimension
```

Read only – end index

#### 8.24.2.2 end

```
int* threaded_ac_jobs_fft::end
```

Read only – start index

#### 8.24.2.3 lag

```
int* threaded_ac_jobs_fft::lag
```

fftw plan to use for spectral method

#### 8.24.2.4 length

```
int* threaded_ac_jobs_fft::length
```

Read only – Data to use – full chain

#### 8.24.2.5 planforward

```
fftw_outline* threaded_ac_jobs_fft::planforward
```

Read only – dimension being analyzed

#### 8.24.2.6 planreverse

```
fftw_outline* threaded_ac_jobs_fft::planreverse
```

fftw plan to use for spectral method

#### 8.24.2.7 start

```
int* threaded_ac_jobs_fft::start
```

Read only – length of total data

#### 8.24.2.8 target

```
double* threaded_ac_jobs_fft::target
```

READ AND WRITE – final lag

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

- include/[autocorrelation.h](#)

## 8.25 threaded\_ac\_jobs\_serial Class Reference

Class to contain serial method jobs.

```
#include <autocorrelation.h>
```

### Public Attributes

- double \*\* **data**
- int \* [length](#)
- int \* [start](#)
- int \* [end](#)
- int [dimension](#)
- int \* [lag](#)
- double \* [target](#)

### 8.25.1 Detailed Description

Class to contain serial method jobs.

### 8.25.2 Member Data Documentation

#### 8.25.2.1 dimension

```
int threaded_ac_jobs_serial::dimension
```

Read only – end index

#### 8.25.2.2 end

```
int* threaded_ac_jobs_serial::end
```

Read only – start index

#### 8.25.2.3 lag

```
int* threaded_ac_jobs_serial::lag
```

Read only – dimension being analyzed

#### 8.25.2.4 length

```
int* threaded_ac_jobs_serial::length
```

Read only – Data to use – full chain

#### 8.25.2.5 start

```
int* threaded_ac_jobs_serial::start
```

Read only – length of total data

#### 8.25.2.6 target

```
double* threaded_ac_jobs_serial::target
```

READ AND WRITE – final lag

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

- include/[autocorrelation.h](#)

## 8.26 threadPool< jobtype, comparator > Class Template Reference

Class for creating a pool of threads to asynchronously distribute work.

```
#include <threadPool.h>
```

## Public Member Functions

- `ThreadPool` (`std::size_t numThreads, std::function< void(int, jobtype)> work_fn`)  
*Constructor – starts thread pool running.*
- `~ThreadPool` ()  
*Destructor – stops threads.*
- `void enqueue` (`jobtype job_id`)  
*Places jobs in queue to wait for scheduling.*
- `int get_num_threads` ()  
*Get the number of threads being used by the thread pool.*
- `int get_queue_length` ()  
*Get the current length of the job queue.*

### 8.26.1 Detailed Description

```
template<class jobtype = int, class comparator = default_comp<jobtype>>
class ThreadPool< jobtype, comparator >
```

Class for creating a pool of threads to asynchronously distribute work.

Template parameters:

`jobtype` defines a structure or class that represents a job or task

`comparator` defines how to compare jobs for sorting the list

Default options correspond to jobs being defined by an integer `job_id`, and no sorting of the list (first in first out)

### 8.26.2 Member Function Documentation

#### 8.26.2.1 enqueue()

```
template<class jobtype = int, class comparator = default_comp<jobtype>>
void ThreadPool< jobtype, comparator >::enqueue (
    jobtype job_id ) [inline]
```

Places jobs in queue to wait for scheduling.

`job_id` is sorted if a comparator is provided

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

- include/`ThreadPool.h`

## 8.27 `threadPool< jobtype, comparator >` Class Template Reference

Class for creating a pool of threads to asynchronously distribute work.

```
#include <threadPool.h>
```

### Public Member Functions

- `threadPool` (`std::size_t numThreads`, `std::function< void(int, jobtype)> work_fn`)  
*Constructor – starts thread pool running.*
- `~threadPool` ()  
*Destructor – stops threads.*
- `void enqueue` (`jobtype job_id`)  
*Places jobs in queue to wait for scheduling.*
- `int get_num_threads` ()  
*Get the number of threads being used by the thread pool.*
- `int get_queue_length` ()  
*Get the current length of the job queue.*

### 8.27.1 Detailed Description

```
template<class jobtype = int, class comparator = default_comp<jobtype>>
class threadPool< jobtype, comparator >
```

Class for creating a pool of threads to asynchronously distribute work.

Template parameters:

`jobtype` defines a structure or class that represents a job or task

`comparator` defines how to compare jobs for sorting the list

Default options correspond to jobs being defined by an integer `job_id`, and no sorting of the list (first in first out)

### 8.27.2 Member Function Documentation

#### 8.27.2.1 `enqueue()`

```
template<class jobtype = int, class comparator = default_comp<jobtype>>
void threadPool< jobtype, comparator >::enqueue (
    jobtype job_id ) [inline]
```

Places jobs in queue to wait for scheduling.

`job_id` is sorted if a comparator is provided

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

- `include/threadPool.h`

## 8.28 `useful_powers< T >` Struct Template Reference

To speed up calculations within the for loops, we pre-calculate reoccurring powers of  $M \cdot F$  and  $\pi$ , since the `pow()` function is prohibitively slow.

```
#include <util.h>
```

### Public Attributes

- `T MFthird`
- `T MFsixth`
- `T MF7sixth`
- `T MF2third`
- `T MF4third`
- `T MF5third`
- `T MFsquare`
- `T MF7third`
- `T MF8third`
- `T MFcube`
- `T MFminus_5third`
- `T MF3fourth`
- `double PIsquare`
- `double Picube`
- `double Pithird`
- `double PI2third`
- `double PI4third`
- `double PI5third`
- `double PI7third`
- `double PIminus_5third`

### 8.28.1 Detailed Description

```
template<class T>
struct useful_powers< T >
```

To speed up calculations within the for loops, we pre-calculate reoccurring powers of  $M \cdot F$  and  $\pi$ , since the `pow()` function is prohibitively slow.

Powers of  $\pi$  are initialized once, and powers of  $MF$  need to be calculated once per for loop (if in the inspiral portion).

use the functions `precalc_powers_ins_amp`, `precalc_powers_ins_phase`, `precalc_powers_pi` to initialize

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

- `include/util.h`

## Chapter 9

# File Documentation

### 9.1 `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):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)

#### 9.1.1 Detailed Description

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

### 9.2 `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**

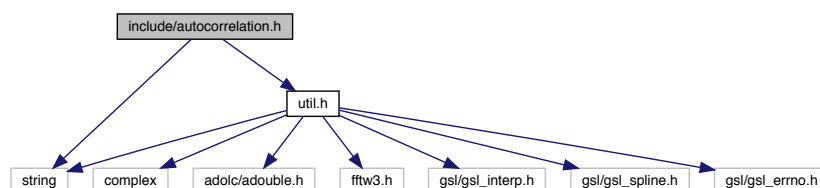
### 9.2.1 Detailed Description

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

## 9.3 include/autocorrelation.h File Reference

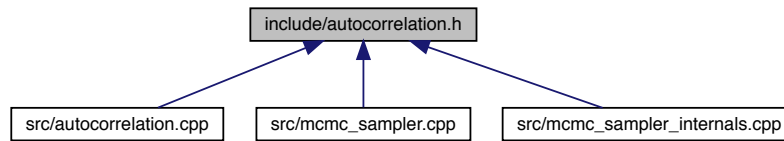
```
#include <string>
#include "util.h"
```

Include dependency graph for autocorrelation.h:





This graph shows which files directly or indirectly include this file:



## Classes

- class [threaded\\_ac\\_jobs\\_fft](#)  
*Class to contain spectral method jobs.*
- class [threaded\\_ac\\_jobs\\_serial](#)  
*Class to contain serial method jobs.*
- class [comparator\\_ac\\_fft](#)  
*comparator to sort ac-jobs*
- class [comparator\\_ac\\_serial](#)  
*comparator to sort ac-jobs*

## 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 convience – 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=10, int final\_length=50, double target\_length=.01)  
*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 autocorr\_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 autocorr\_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.*

### 9.3.1 Detailed Description

Autocorrelation header file

### 9.3.2 Function Documentation

#### 9.3.2.1 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 segements 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   |

## 9.3.2.2 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 |

## 9.3.2.3 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                                    |

#### 9.3.2.4 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.

#### 9.3.2.5 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 |

#### 9.3.2.6 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

## 9.3.2.7 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/>

## 9.3.2.8 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

## 9.3.2.9 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

## 9.3.2.10 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   |

### 9.3.2.11 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 )
```

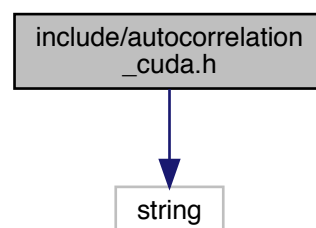
#### Parameters

|                     |  |
|---------------------|--|
| <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   |

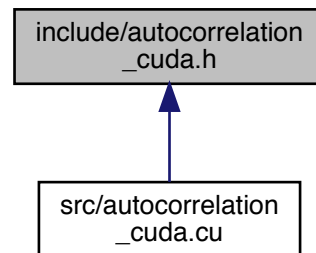
## 9.4 include/autocorrelation\_cuda.h File Reference

```
#include <string>
```

Include dependency graph for autocorrelation\_cuda.h:



This graph shows which files directly or indirectly include this file:



## Macros

- `#define THREADS_PER_BLOCK 512`

## Functions

- 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 \*\*output, 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 [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 [ac\\_gpu\\_wrapper](#) (int thread, int job\_id)  
*Wrapper function for the thread pool.*
- void [auto\\_correlation\\_spectral\\_accel](#) (double \*chains, int length, double \*autocorr)

### 9.4.1 Detailed Description

Header file for CUDA accelerated algorithms

Currently, no algorithms are used in any other parts of the project, so if CUDA or CUDA-enabled devices are not available, this file can be skipped in compilation by commenting out the OBJECTSCUDA line in the makefile

### 9.4.2 Function Documentation

#### 9.4.2.1 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      |

#### 9.4.2.2 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         |

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

```
void write_file_auto_corr_from_data_accel (
    std::string acfile,
    double ** output,
    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>output</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    |

## 9.4.2.4 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 )
```

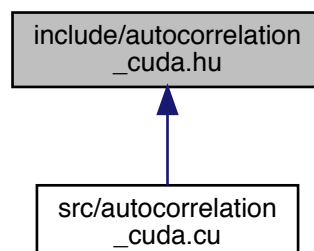
Write data file for autocorrelation lengths of the data given a data file name, as written by the mcmc\_sampler.

## 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    |

## 9.5 include/autocorrelation\_cuda.hu File Reference

This graph shows which files directly or indirectly include this file:



## Classes

- struct [GPUplan](#)

## 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\_kernal (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 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.*

### 9.5.1 Function Documentation

#### 9.5.1.1 `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 |

#### 9.5.1.2 `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 |

#### 9.5.1.3 auto\_corr\_internal\_kernal()

```

__global__ void auto_corr_internal_kernal (
    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                                |

#### 9.5.1.4 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 |

#### 9.5.1.5 deallocate\_gpu\_plan()

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

Deallocates memory for the autocorrelation–GPU structure.

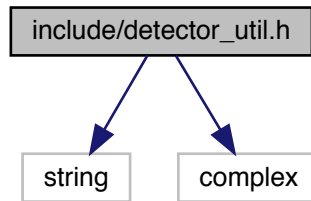
##### Parameters

|                     |  |
|---------------------|--|
| <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 |

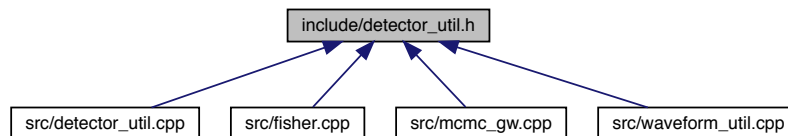
## 9.6 include/detector\_util.h File Reference

```
#include <string>
#include <complex>
```

Include dependency graph for detector\_util.h:



This graph shows which files directly or indirectly include this file:



## Functions

- void [populate\\_noise](#) (double \*frequencies, std::string detector, double \*noise\_root, int length=0)  
*Function to populate the squareroot of the noise curve for various detectors.*
- double [aLIGO\\_analytic](#) (double f)  
*Analytic function approximating the PSD for aLIGO.*
- std::complex< double > [Q](#) (double theta, double phi, double iota)  
*Utility for the overall amplitude and phase shift for spin-aligned systems.*
- double [right\\_interferometer\\_cross](#) (double theta, double phi)  
*Response function of a 90 deg interferometer for cross polarization.*
- double [right\\_interferometer\\_plus](#) (double theta, double phi)  
*Response function of a 90 deg interferometer for plus polarization.*
- double [Hanford\\_O1\\_fitted](#) (double f)  
*Numerically fit PSD to the Hanford Detector's O1.*
- void [celestial\\_horizon\\_transform](#) (double RA, double DEC, double gps\_time, std::string detector, double \*phi, double \*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)

## Variables

- const double **H\_LAT** = 0.81079526383
- const double **H\_LONG** = -2.08405676917
- const double **H\_azimuth\_offset** = 2.199
- const double **H\_radius** = 6367299.93401105
- const double **H\_elevation** = 142.554
- const double **L\_LAT** = 0.53342313506
- const double **L\_LONG** = -1.58430937078
- const double **L\_azimuth\_offset** = 3.4557
- const double **L\_radius** = 6372795.50144497
- const double **L\_elevation** = -6.574
- const double **V\_LAT** = 0.76151183984
- const double **V\_LONG** = 0.18333805213
- const double **V\_azimuth\_offset** = 1.239
- const double **V\_radius** = 6374824.24470673
- const double **V\_elevation** = 51.884
- const double **RE\_polar** = 6357e3
- const double **RE\_equatorial** = 6378e3

### 9.6.1 Detailed Description

Header file for all detector-specific utilities

### 9.6.2 Function Documentation

#### 9.6.2.1 aLIGO\_analytic()

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

Analytic function approximating the PSD for aLIGO.

CITE (Will?)

#### 9.6.2.2 celestial\_horizon\_transform()

```
void celestial_horizon_transform (
    double RA,
    double DEC,
    double gps_time,
    std::string detector,
    double * phi,
    double * 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 |

## 9.6.2.3 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 |

## 9.6.2.4 DTOA()

```
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

## 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                        |

### 9.6.2.5 Hanford\_O1\_fitted()

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

Numerically fit PSD to the Hanford Detector's O1.

CITE (Yunes?)

### 9.6.2.6 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  |

### 9.6.2.7 Q()

```
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

### 9.6.2.8 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 |

## 9.6.2.9 right\_interferometer\_cross()

```
double right_interferometer_cross (  
    double theta,  
    double phi )
```

Response function of a 90 deg interferometer for cross polarization.

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

## 9.6.2.10 right\_interferometer\_plus()

```
double right_interferometer_plus (  
    double theta,  
    double phi )
```

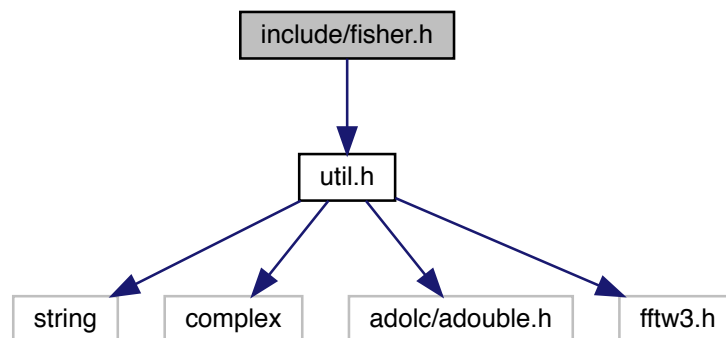
Response function of a 90 deg interferometer for plus polarization.

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

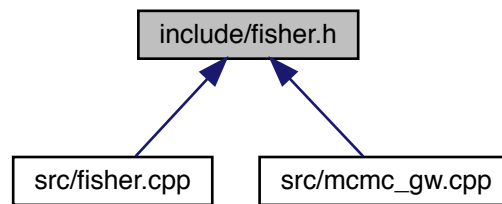
## 9.7 include/fisher.h File Reference

```
#include "util.h"
```

Include dependency graph for fisher.h:



This graph shows which files directly or indirectly include this file:



## Functions

- void [fisher](#) (double \*frequency, int length, string generation\_method, string detector, double \*\*output, int dimension, [gen\\_params](#) \*parameters, int \*amp\_tapes=NULL, int \*phase\_tapes=NULL, double \*noise=NULL)  
*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, string generation\_method, string detector, double \*\*output, int dimension, [gen\\_params](#) \*parameters, int \*amp\_tapes=NULL, int \*phase\_tapes=NULL, double \*noise=NULL)  
*Calculates the fisher matrix for the given arguments to within numerical error using automatic differentiation - slower than the numerical version.*

### 9.7.1 Function Documentation

#### 9.7.1.1 [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.

## 9.7.1.2 fisher()

```

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

```

Calculates the fisher matrix for the given arguments.

## 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 |

## 9.7.1.3 fisher\_autodiff()

```

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

```

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

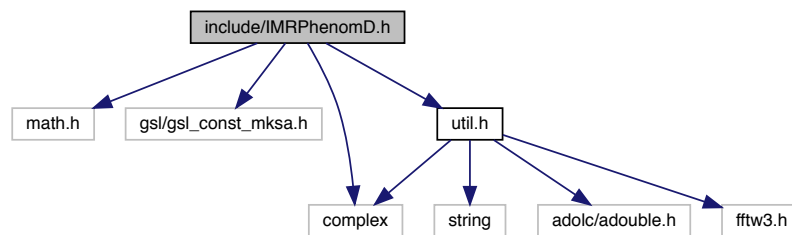
## Parameters

|                    |   |
|--------------------|---|
| <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 |

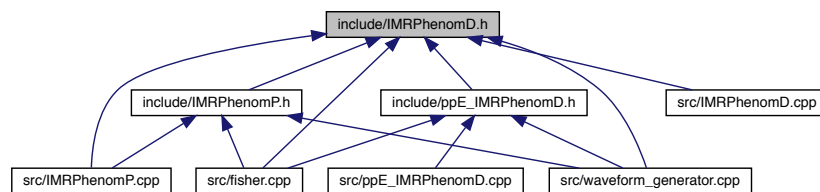
## 9.8 include/IMRPhenomD.h File Reference

```
#include <math.h>
#include <gsl/gsl_const_mksa.h>
#include <complex>
#include "util.h"
```

Include dependency graph for IMRPhenomD.h:



This graph shows which files directly or indirectly include this file:



### Classes

- struct [lambda\\_parameters< T >](#)
- class [IMRPhenomD< T >](#)

### Variables

- const double [lambda\\_num\\_params](#) [19][11]

#### 9.8.1 Detailed Description

Header file for utilities

#### 9.8.2 Variable Documentation

### 9.8.2.1 lambda\_num\_params

```
const double lambda_num_params[19][11]
```

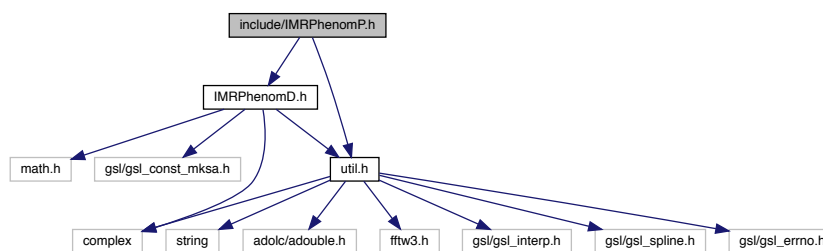
Numerically calibrated parameters from arXiv:1508.07253 see the table in the data directory for labeled version

## 9.9 include/IMRPhenomP.h File Reference

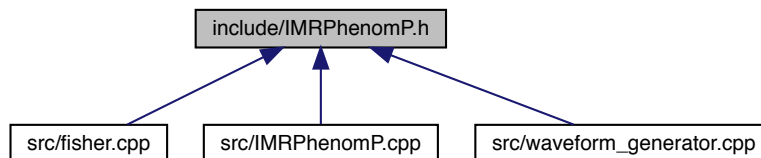
```
#include "IMRPhenomD.h"
```

```
#include "util.h"
```

Include dependency graph for IMRPhenomP.h:



This graph shows which files directly or indirectly include this file:



## Classes

- struct [alpha\\_coeffs< T >](#)
- struct [epsilon\\_coeffs< T >](#)
- class [IMRPhenomPv2< T >](#)

### 9.9.1 Detailed Description

Header file for IMRPhenomP functions

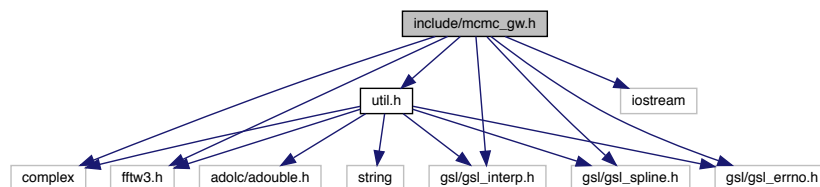
Currently, only Pv2 is supported.

Wrapped around [IMRPhenomD](#)

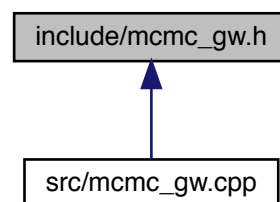
## 9.10 include/mcmc\_gw.h File Reference

```
#include <complex>
#include <fftw3.h>
#include "util.h"
#include <iostream>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
#include <gsl/gsl_errno.h>
```

Include dependency graph for mcmc\_gw.h:



This graph shows which files directly or indirectly include this file:



## 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\\_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 [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\\_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 [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\\_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 [MCMC\\_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 \*detector, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string checkpoint\_filename)  
*Wrapper for the MCMC\_MH function, specifically for GW analysis.*
- void [continue\\_MCMC\\_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 \*detector, int Nmod, int \*bppe, std::string generation\_method, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string final\_checkpoint\_filename)  
*Takes in an MCMC checkpoint file and continues the chain.*
- void [MCMC\\_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\\_wrapper](#) (double \*param, int dimension, int chain\_id)  
*log likelihood function for MCMC for GW*

### 9.10.1 Detailed Description

Header file for the Graviational Wave specific MCMC routines

### 9.10.2 Function Documentation

#### 9.10.2.1 `continue_MCMC_MH_GW()`

```
void continue_MCMC_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 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

#### 9.10.2.2 `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.



## 9.10.2.3 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.

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

## 9.10.2.4 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.

## 9.10.2.5 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 phic and tc.

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 |
|------------------|-----------------|

9.10.2.6 `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 |
|------------------|-----------------|

9.10.2.7 `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 |
|------------------|-----------------|

9.10.2.8 `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 |
|------------------|-----------------|

## 9.10.2.9 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 |
|------------------|-----------------|

## 9.10.2.10 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 |
|------------------|-----------------|

#### 9.10.2.11 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

#### 9.10.2.12 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

**9.10.2.13 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  $t_c$ ,  $\phi_{ic}$ ,  $D$ , and  $\phi_{iRef}$ , the reference frequency - for unaligned spins

Ref: arXiv 1603.02444v2

**9.10.2.14 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

**9.10.2.15 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

**9.10.2.16 MCMC\_method\_specific\_prep()**

```
void MCMC_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

### 9.10.2.17 MCMC\_MH\_GW()

```
void MCMC_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 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](#) - 8 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2

[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)

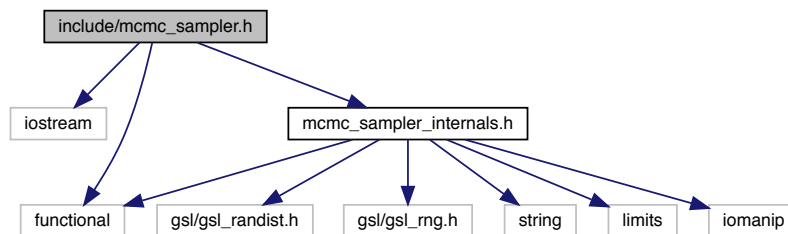
[IMRPhenomPv2](#) - 9 dimensions – cos J\_N, ln chirpmass, eta,  $|\chi_1|$ ,  $|\chi_1|$ , theta\_1, theta\_2, phi\_1, phi\_2

## Parameters

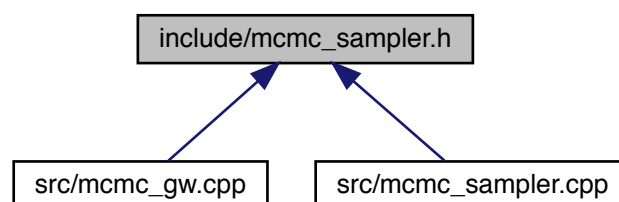
|                            |   |
|----------------------------|---|
| <i>statistics_filename</i> | Filename to output sampling statistics, if empty string, not output               |
| <i>chain_filename</i>      | Filename to output data (chain 0 only), if empty string, not output               |
| <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                |

## 9.11 include/mcmc\_sampler.h File Reference

```
#include <iostream>
#include <functional>
#include "mcmc_sampler_internals.h"
Include dependency graph for mcmc_sampler.h:
```



This graph shows which files directly or indirectly include this file:



## Functions

- void **mcmc\_step\_threaded** (int j)
- void **mcmc\_swap\_threaded** (int i, int j)
- void **continue\_MCMC\_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 end\_checkpoint\_file)

- void `continue_MCMC_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 end\_checkpoint\_file)
- void `MCMC_MH_loop` (sampler \*sampler)

*Internal function that runs the actual loop for the sampler.*

- void `MCMC_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 checkpoint\_filename)
- void `MCMC_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 checkpoint\_filename)
- void `MCMC_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)> log\_prior, std::function< double(double \*, int, int)> log\_likelihood, std::function< void(double \*, 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 checkpoint\_filename)

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

- void `continue_MCMC_MH_internal` (std::string start\_checkpoint\_file, double \*\*\*output, int N\_steps, int swp\_freq, std::function< double(double \*, int, int)> log\_prior, std::function< double(double \*, int, int)> log\_likelihood, std::function< void(double \*, 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 end\_checkpoint\_file)

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

### 9.11.1 Detailed Description

Header file for mcmc\_sampler

### 9.11.2 Function Documentation

#### 9.11.2.1 `continue_MCMC_MH()` [1/2]

```
void continue_MCMC_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 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>end_checkpoint_file</i>   | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

9.11.2.2 `continue_MCMC_MH()` [2/2]

```

void continue_MCMC_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 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                       |

## Parameters

|  |                            |  |
|--|----------------------------|--|
|  | <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>end_checkpoint_file</i> | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

## 9.11.2.3 continue\_MCMC\_MH\_internal()

```
void continue_MCMC_MH_internal (
    std::string start_checkpoint_file,
    double *** output,
    int N_steps,
    int swp_freq,
    std::function< double(double *, int, int)> log_prior,
    std::function< double(double *, int, int)> log_likelihood,
    std::function< void(double *, 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 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]   |
|     | <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 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  |
|     | <i>pool</i>                  | Boolean for whether to use <code>deterministic</code> or <code>vsstochastic</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>end_checkpoint_file</i>   | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved                  |

#### 9.11.2.4 MCMC\_MH() [1/2]

```
void MCMC_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 checkpoint_filename )
```

##### 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>checkpoint_filename</i> | Filename to output data for checkpoint, if empty string, not saved                                       |

#### 9.11.2.5 MCMC\_MH() [2/2]

```
void MCMC_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 checkpoint_filename )

```

#### 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>checkpoint_filename</i> | Filename to output data for checkpoint, if empty string, not saved                                       |

#### 9.11.2.6 MCMC\_MH\_internal()

```

void MCMC_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)> log_prior,
std::function< double(double *, int, int)> log_likelihood,
std::function< void(double *, 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 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>checkpoint_file</i>     | Filename to output data for checkpoint, if empty string, not saved  |

## 9.11.2.7 MCMC\_MH\_loop()

```
void MCMC_MH_loop (
    sampler * sampler )
```

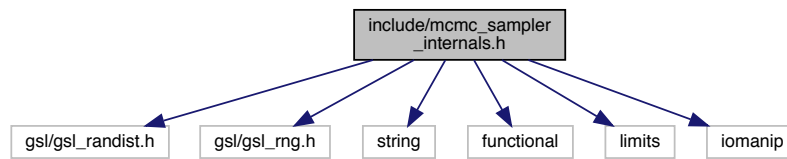
Internal function that runs the actual loop for the sampler.

## 9.12 include/mcmc\_sampler\_internals.h File Reference

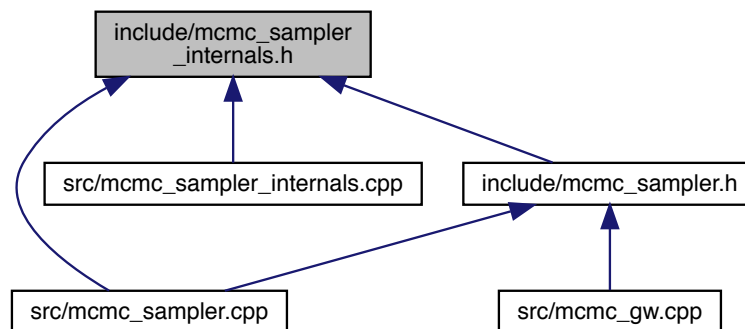
```
#include <gsl/gsl_randist.h>
#include <gsl/gsl_rng.h>
#include <string>
#include <functional>
#include <limits>
```

```
#include <iomanip>
```

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



This graph shows which files directly or indirectly include this file:



## Classes

- struct [sampler](#)

## Functions

- int [mcmc\\_step](#) ([sampler](#) \*[sampler](#), double \*current\_param, double \*next\_param, 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 chain\_id)  
*Straight gaussian step.*
- void [fisher\\_step](#) ([sampler](#) \*[sampler](#), double \*current\_param, double \*proposed\_param, int chain\_index)  
*Fisher informed gaussian step.*
- void [update\\_fisher](#) ([sampler](#) \*[sampler](#), double \*current\_param, int chain\_index)
- void [mmala\\_step](#) ([sampler](#) \*[sampler](#), double \*current\_param, double \*proposed\_param)  
*MMALA informed step – Currently not supported.*
- void [diff\\_ev\\_step](#) ([sampler](#) \*[sampler](#), double \*current\_param, double \*proposed\_param, int chain\_id)  
*differential evolution informed step*
- void [chain\\_swap](#) ([sampler](#) \*[sampler](#), double \*\*\*output, 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 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 `allocate_sampler_mem` (`sampler *sampler`)
- void `deallocate_sampler_mem` (`sampler *sampler`)
- void `update_history` (`sampler *sampler`, double \*new\_params, 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_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)

## Variables

- const double `limit_inf` = -std::numeric\_limits<double>::infinity()

### 9.12.1 Detailed Description

Internal functions of the generic MCMC sampler (nothing specific to GW)

### 9.12.2 Function Documentation

#### 9.12.2.1 `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

#### 9.12.2.2 `chain_swap()`

```
void chain_swap (
    sampler * sampler,
    double *** output,
    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>step_num</i> | current step number             |

**9.12.2.3 diff\_ev\_step()**

```
void diff_ev_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    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 |

**9.12.2.4 fisher\_step()**

```
void fisher_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    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 |

## 9.12.2.5 gaussian\_step()

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

## 9.12.2.6 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

## 9.12.2.7 mmala\_step()

```
void mmala_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param )
```

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 |

## 9.12.2.8 single\_chain\_swap()

```
int single_chain_swap (
    sampler * sampler,
```

```
double * chain1,
double * chain2,
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>T1_index</i> | number of chain swappe in chain_temps   |
| <i>T2_index</i> | number of chain swapper in chain_temps  |

#### 9.12.2.9 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.

### 9.12.3 Variable Documentation

#### 9.12.3.1 limit\_inf

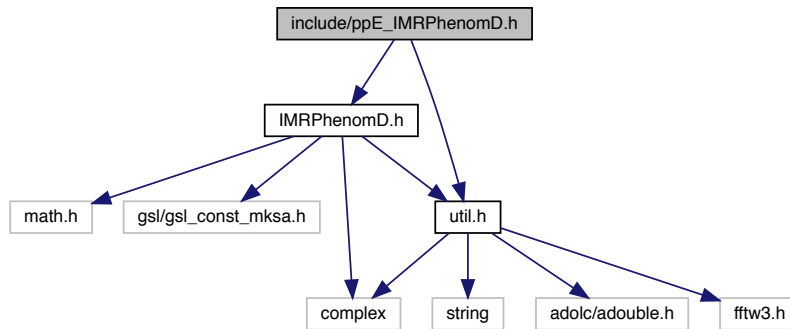
```
const double limit_inf = -std::numeric_limits<double>::infinity()
```

Structure storing everything that defines an instance of the sampler

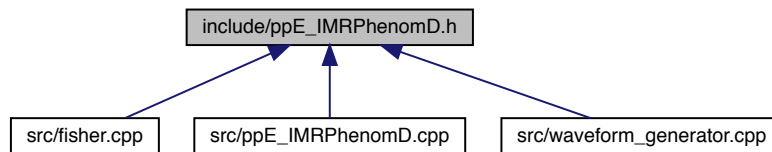
## 9.13 include/ppE\_IMRPhenomD.h File Reference

```
#include "IMRPhenomD.h"
#include "util.h"
```

Include dependency graph for ppE\_IMRPhenomD.h:



This graph shows which files directly or indirectly include this file:



## Classes

- class [ppE\\_IMRPhenomD\\_Inspiral< T >](#)
- class [ppE\\_IMRPhenomD\\_IMR< T >](#)
- class [dCS\\_IMRPhenomD\\_log< T >](#)
- class [dCS\\_IMRPhenomD< T >](#)
- class [EdGB\\_IMRPhenomD\\_log< T >](#)
- class [EdGB\\_IMRPhenomD< T >](#)

## 9.14 include/threadPool.h File Reference

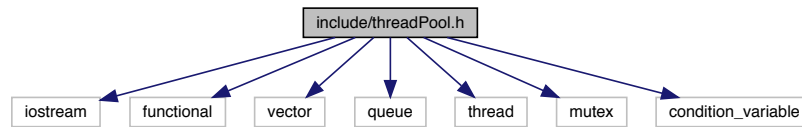
```

#include <iostream>
#include <functional>
#include <vector>
#include <queue>
#include <thread>
#include <mutex>

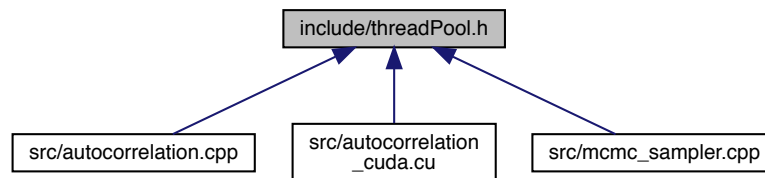
```

```
#include <condition_variable>
```

Include dependency graph for `threadPool.h`:



This graph shows which files directly or indirectly include this file:



## Classes

- class `default_comp< jobtype >`  
*Default comparator for priority\_queue in `threadPool` – no comparison.*
- class `threadPool< jobtype, comparator >`  
*Class for creating a pool of threads to asynchronously distribute work.*

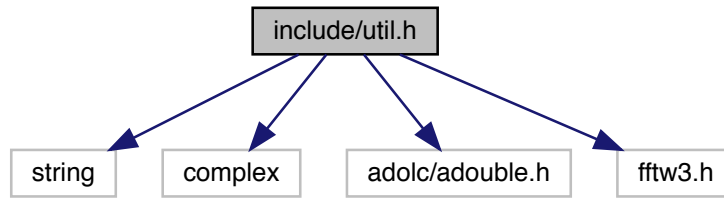
### 9.14.1 Detailed Description

Header file (declarations and definitions because of template functions) for the implementation of a generic thread pool

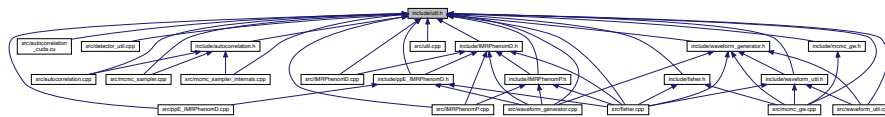
## 9.15 include/util.h File Reference

```
#include <string>
#include <complex>
#include "adolc/adouble.h"
#include <fftw3.h>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
```

```
#include <gsl/gsl_errno.h>
```



This graph shows which files directly or indirectly include this file:



## Classes

- struct `fftw_outline`
- struct `sph_harm< T >`
- struct `gen_params`
- struct `useful_powers< T >`

*To speed up calculations within the for loops, we pre-calculate reoccurring powers of  $M \cdot F$  and  $P_i$ , since the `pow()` function is prohibitively slow.*

- struct **source\_parameters**< T >

## Macros

- `#define PBSTR "|||||`
- `#define PBWIDTH 60`

## 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.*

- double [DL\\_from\\_Z](#) (double Z, std::string cosmology)  
*Calculates the luminosity distance given the redshift.*
- double [cosmology\\_interpolation\\_function](#) (double x, double \*coeffs, int interp\_degree)  
*Custom interpolation function used in the cosmology calculations.*
- double [cosmology\\_lookup](#) (std::string cosmology)  
*Helper function for mapping cosmology name to an internal index.*
- adouble [Z\\_from\\_DL](#) (adouble DL, std::string cosmology)  
*Calculates the redshift given the luminosity distance adouble version for ADOL-C implementation.*
- adouble [DL\\_from\\_Z](#) (adouble Z, std::string cosmology)  
*Calculates the luminosity distance given the redshift adouble version for ADOL-C implementation.*
- adouble [cosmology\\_interpolation\\_function](#) (adouble x, double \*coeffs, int interp\_degree)  
*Custom interpolation function used in the cosmology calculations adouble version for ADOL-C.*
- 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 \*\* [allocate\\_2D\\_array](#) (int dim1, int dim2)  
*Utility to malloc 2D array.*
- void [deallocate\\_2D\\_array](#) (double \*\*array, int dim1, int dim2)  
*Utility to free malloc'd 2D array.*
- double \*\*\* [allocate\\_3D\\_array](#) (int dim1, int dim2, int dim3)  
*Utility to malloc 3D array.*
- void [deallocate\\_3D\\_array](#) (double \*\*\*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.*
- 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\_chirpmass** (double mass1, double mass2)
- Calculates the chirp mass from the two component masses.*
- adouble **calculate\_chirpmass** (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)
- void **celestial\_horizon\_transform** (double RA, double DEC, double gps\_time, double LONG, double LAT, double \*phi, double \*theta)
- Utility to transform from celestial coord RA and DEC to local horizon coord for detector response functions.*
- double **gps\_to\_GMST** (double gps\_time)
- Utility to transform from gps time to GMST <https://aa.usno.navy.mil/faq/docs/GAST.php>.*
- double **gps\_to\_JD** (double gps\_time)
- Utility to transform from gps to JD.*
- 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 >  
T **trapezoidal\_sum\_uniform** (double delta\_x, int length, T \*integrand)  
*Trapezoidal sum rule to approximate discrete integral - Uniform spacing.*
- template<class T >  
T **trapezoidal\_sum** (double \*delta\_x, int length, T \*integrand)  
*Trapezoidal sum rule to approximate discrete integral - Non-Uniform spacing.*
- template<class T >  
T **simpsons\_sum** (double delta\_x, int length, T \*integrand)  
*Simpsons sum rule to approximate discrete integral - Uniform spacing.*
- 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)
- 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)
- double **cbirt\_internal** (double base)  
*Fucntion that just returns the cuberoot.*
- adouble **cbirt\_internal** (adouble base)  
*Fucntion that just returns the cuberoot ADOL-C doesn't have the cbirt function (which is faster), so have to use the power function.*

## Variables

- const double **gamma\_E** = 0.5772156649015328606065120900824024310421
- const double **c** = 299792458.
- const double **G** = 6.674e-11\*(1.98855e30)
- const double **MSOL\_SEC** = 4.925491025543575903411922162094833998e-6
- const double **MPC\_SEC** = 3.085677581491367278913937957796471611e22/c

### 9.15.1 Detailed Description

General utilities (functions and structures) independent of modelling method

### 9.15.2 Function Documentation

#### 9.15.2.1 `allocate_2D_array()`

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

Utility to malloc 2D array.

#### 9.15.2.2 `allocate_3D_array()`

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

Utility to malloc 3D array.

#### 9.15.2.3 `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)  $3/4 \cdot T_{\text{obs}}$  in front of trigger, and  $1/4 \cdot T_{\text{obs}}$  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            |

## 9.15.2.4 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

## 9.15.2.5 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

## 9.15.2.6 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

## 9.15.2.7 celestial\_horizon\_transform()

```
void celestial_horizon_transform (
    double RA,
    double DEC,
    double gps_time,
    double LONG,
    double LAT,
    double * phi,
    double * 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)     |

9.15.2.8 `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

9.15.2.9 `deallocate_2D_array()`

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

Utility to free malloc'd 2D array.

9.15.2.10 `deallocate_3D_array()`

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

Utility to free malloc'd 2D array.

**9.15.2.11 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

**9.15.2.12 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

**9.15.2.13 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

**9.15.2.14 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

### 9.15.2.15 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

### 9.15.2.16 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                                |

### 9.15.2.17 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 |

**9.15.2.18 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     |

**9.15.2.19 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

**9.15.2.20 simpsons\_sum()**

```
template<class T >
T simpsons_sum (
    double delta_x,
    int length,
    T * integrand )
```

Simpsons sum rule to approximate discrete integral - Uniform spacing.

More accurate than the trapezoidal rule, but must be uniform

#### 9.15.2.21 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

#### 9.15.2.22 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

#### 9.15.2.23 trapezoidal\_sum()

```
template<class T >
T trapezoidal_sum (
    double * delta_x,
    int length,
    T * integrand )
```

Trapezoidal sum rule to approximate discrete integral - Non-Uniform spacing.

This version is slower than the uniform version, but will handle non-uniform spacing

#### 9.15.2.24 trapezoidal\_sum\_uniform()

```
template<class T >
T trapezoidal_sum_uniform (
    double delta_x,
    int length,
    T * integrand )
```

Trapezoidal sum rule to approximate discrete integral - Uniform spacing.

This version is faster than the general version, as it has half the function calls

Something may be wrong with this function - had an overall offset for real data that was fixed by using the simpsons rule - not sure if this was because of a boost in accuracy or because something is off with the trapezoidal sum



#### 9.15.2.25 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)

#### 9.15.2.26 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                                |

#### 9.15.2.27 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  |

### 9.15.2.28 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         |

### 9.15.2.29 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

### 9.15.2.30 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

**9.15.2.31 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

**9.15.3 Variable Documentation****9.15.3.1 c**

```
const double c = 299792458.
```

Speed of light m/s

**9.15.3.2 G**

```
const double G =6.674e-11*(1.98855e30)
```

Gravitational constant in  $m^3/(s^2 \text{ SolMass})$

**9.15.3.3 gamma\_E**

```
const double gamma_E = 0.5772156649015328606065120900824024310421
```

Euler number

**9.15.3.4 MPC\_SEC**

```
const double MPC_SEC = 3.085677581491367278913937957796471611e22/c
```

consts.kpc.to('m')\*1000/c Mpc in sec

**9.15.3.5 MSOL\_SEC**

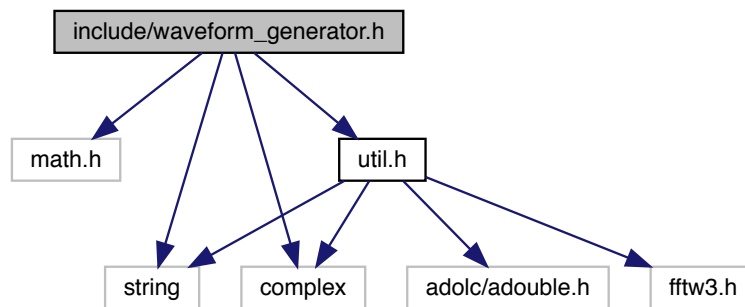
```
const double MSOL_SEC =4.925491025543575903411922162094833998e-6
```

G/c<sup>3</sup> seconds per solar mass

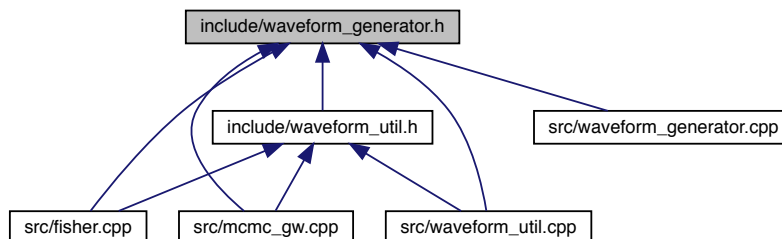
## 9.16 include/waveform\_generator.h File Reference

```
#include <math.h>
#include "util.h"
#include <complex>
#include <string>
```

Include dependency graph for waveform\_generator.h:



This graph shows which files directly or indirectly include this file:



## Functions

- `int fourier_waveform (double *frequencies, int length, std::complex< double > *waveform_plus, std::complex< double > *waveform_cross, std::string generation_method, gen\_params *parameters)`
- `int fourier_waveform (double *frequencies, int length, double *waveform_plus_real, double *waveform_plus_imag, double *waveform_cross_real, double *waveform_cross_imag, std::string generation_method, gen\_params *parameters)`
- `int fourier_waveform (double *frequencies, int length, std::complex< double > *waveform, std::string generation_method, gen\_params *parameters)`
- `int fourier_waveform (double *frequencies, int length, double *waveform_real, double *waveform_imag, std::string generation_method, gen\_params *parameters)`
- `int fourier_amplitude (double *frequencies, int length, double *amplitude, std::string generation_method, gen\_params *parameters)`
- `int fourier_phase (double *frequencies, int length, double *phase, std::string generation_method, gen\_params *parameters)`

## 9.17 include/waveform\_generator\_C.h File Reference

### Functions

- int **fourier\_waveformC** (double \*frequencies, int length, double \*waveform\_plus\_real, double \*waveform\_plus\_imag, double \*waveform\_cross\_real, double \*waveform\_cross\_imag, char \*generation\_method, double mass1, double mass2, double DL, double spin1x, double spin1y, double spin1z, double spin2x, double spin2y, double spin2z, double phic, double tc, double f\_ref, double phiRef, double \*ppE\_beta, int \*ppE\_b, int Nmod, double incl\_angle, double theta, double phi)
- int **fourier\_amplitudeC** (double \*frequencies, int length, double \*amplitude, char \*generation\_method, double mass1, double mass2, double DL, double spin1x, double spin1y, double spin1z, double spin2x, double spin2y, double spin2z, double incl\_angle, double theta, double phi)
- int **fourier\_phaseC** (double \*frequencies, int length, double \*phase, char \*generation\_method, double mass1, double mass2, double DL, double spin1x, double spin1y, double spin1z, double spin2x, double spin2y, double spin2z, double phic, double tc, double f\_ref, double phiRef, double \*ppE\_beta, int \*ppE\_b, int Nmod, double incl\_angle, double theta, double phi)
- void **initiate\_LumD\_Z\_interp\_C** ()
- void **free\_LumD\_Z\_interp\_C** ()

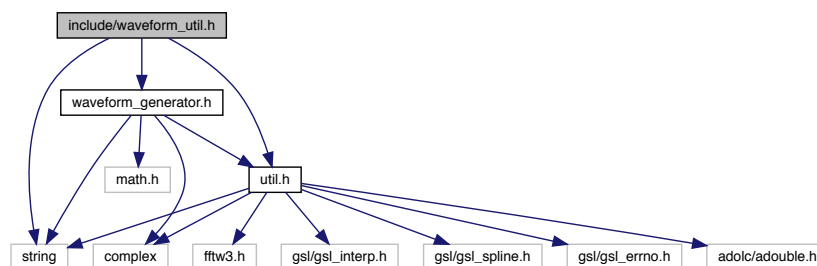
### 9.17.1 Detailed Description

Header file for the C wrapping of the waveform\_generation.cpp

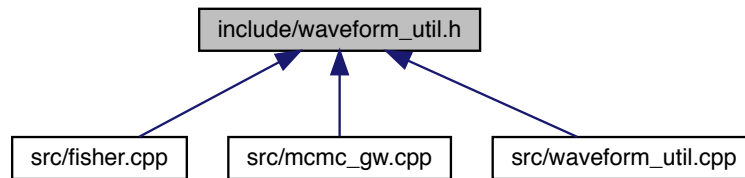
## 9.18 include/waveform\_util.h File Reference

```
#include "waveform_generator.h"
#include "util.h"
#include <string>
```

Include dependency graph for waveform\_util.h:



This graph shows which files directly or indirectly include this file:



## 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  $\phi_{\text{HC}}$  and  $t_c$ .*
- 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)  
*Calculates the snr given a detector and waveform (complex) and frequencies.*
- int [fourier\\_detector\\_response](#) (double \*frequencies, int length, std::complex< double > \*hplus, std::complex< double > \*hcross, std::complex< double > \*detector\_response, double theta, double phi, std::string detector)
- int [fourier\\_detector\\_response](#) (double \*frequencies, int length, std::complex< double > \*response, std::string detector, std::string generation\_method, [gen\\_params](#) \*parameters)  
*Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary.*
- 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.*

### 9.18.1 Detailed Description

Header file for waveform specific utilites

### 9.18.2 Function Documentation

#### 9.18.2.1 `calculate_snr()`

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

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

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

## 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                                    |

## 9.18.2.2 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   |
| <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>             | <a href="#">gen_params</a> structure for the template                        |

## 9.18.2.3 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>             | <a href="#">gen_params</a> structure for the template                        |

9.18.2.4 `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

9.18.2.5 `fourier_detector_response()` [1/2]

```
int fourier_detector_response (
    double * frequencies,
    int length,
    std::complex< double > * hplus,
    std::complex< double > * hcross,
    std::complex< double > * detector_response,
    double theta,
    double 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 |



9.18.2.6 `fourier_detector_response()` [2/2]

```
int fourier_detector_response (
    double * frequencies,
    int length,
    std::complex< double > * response,
    std::string detector,
    std::string generation_method,
    gen_params * 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

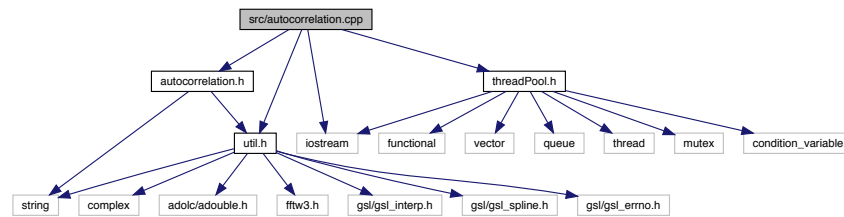
|     |                          |  |
|-----|--------------------------|--|
|     | <i>frequencies</i>       | double array of frequencies for the waveform to be evaluated at            |
|     | <i>length</i>            | integer length of all the arrays   |
| out | <i>response</i>          | complex 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                             |

## 9.19 README.dox File Reference

9.20 `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.*

### 9.20.1 Detailed Description

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

### 9.20.2 Macro Definition Documentation

#### 9.20.2.1 MAX\_SERIAL

```
#define MAX_SERIAL 200000
```

Max length of array to use serial calculation

### 9.20.3 Function Documentation

#### 9.20.3.1 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   |

## 9.20.3.2 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 |

## 9.20.3.3 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                                    |

## 9.20.3.4 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.

## 9.20.3.5 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 |

## 9.20.3.6 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

#### 9.20.3.7 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/>

#### 9.20.3.8 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

#### 9.20.3.9 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

#### 9.20.3.10 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   |

## 9.20.3.11 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 )
```

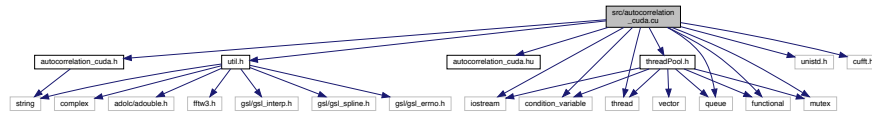
## Parameters

|                     |  |
|---------------------|--|
| <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   |

## 9.21 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`

### 9.21.1 Function Documentation

#### 9.21.1.1 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↔<br/>_id</i> | Job ID      |

## 9.21.1.2 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 |

## 9.21.1.3 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         |

#### 9.21.1.4 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 |

#### 9.21.1.5 auto\_corr\_internal\_kernal()

```
__global__ void auto_corr_internal_kernal (
    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                                |

## 9.21.1.6 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 |

## 9.21.1.7 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 |

## 9.21.1.8 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 <code>MCMC_sampler</code>                                 |
| <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    |

#### 9.21.1.9 `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`.

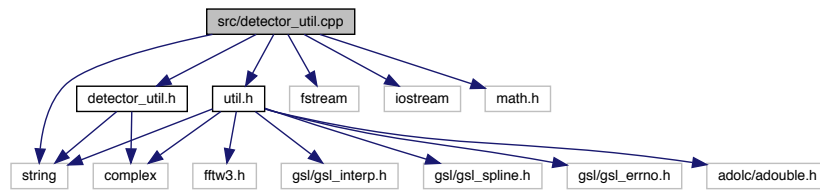
#### Parameters

|                     |   |
|---------------------|---|
| <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    |

## 9.22 `src/detector_util.cpp` File Reference

```
#include "detector_util.h"
#include "util.h"
#include <fstream>
#include <iostream>
#include <string>
#include <math.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)  
*Utility for the overall amplitude and phase shift for spin-aligned systems.*
- double [right\\_interferometer\\_plus](#) (double theta, double phi)  
*Response function of a 90 deg interferometer for plus polarization.*
- double [right\\_interferometer\\_cross](#) (double theta, double phi)  
*Response function of a 90 deg interferometer for cross polarization.*
- void [celestial\\_horizon\\_transform](#) (double RA, double DEC, double gps\_time, std::string detector, double \*phi, double \*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)

### 9.22.1 Detailed Description

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

### 9.22.2 Function Documentation

### 9.22.2.1 aLIGO\_analytic()

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

Analytic function approximating the PSD for aLIGO.

CITE (Will?)

### 9.22.2.2 celestial\_horizon\_transform()

```
void celestial_horizon_transform (
    double RA,
    double DEC,
    double gps_time,
    std::string detector,
    double * phi,
    double * 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 |

### 9.22.2.3 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 |

## 9.22.2.4 DTOA()

```
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

## 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                        |

## 9.22.2.5 Hanford\_O1\_fitted()

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

Numerically fit PSD to the Hanford Detector's O1.

CITE (Yunes?)

## 9.22.2.6 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  |

**9.22.2.7 Q()**

```
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

**9.22.2.8 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 |

**9.22.2.9 right\_interferometer\_cross()**

```
double right_interferometer_cross (
    double theta,
    double phi )
```

Response function of a 90 deg interferometer for cross polarization.

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



## 9.22.2.10 right\_interferometer\_plus()

```
double right_interferometer_plus (
    double theta,
    double phi )
```

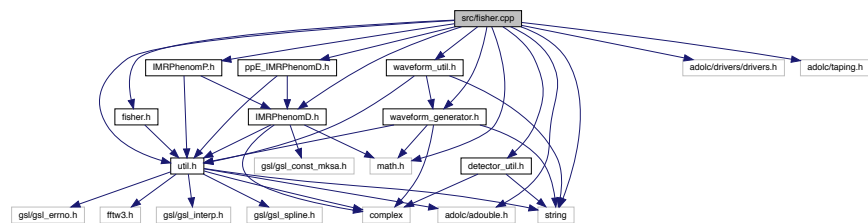
Response function of a 90 deg interferometer for plus polarization.

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

## 9.23 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, 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 to within numerical error using automatic differentiation - slower than the numerical version.*

### 9.23.1 Detailed Description

All subroutines associated with waveform differentiation and Fisher analysis

### 9.23.2 Function Documentation

#### 9.23.2.1 `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.

#### 9.23.2.2 `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.

#### 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 <i>generation_method</i> |
| <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 <i>generation_method</i> |

## 9.23.2.3 fisher\_autodiff()

```

void fisher_autodiff (
    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 to within numerical error using automatic differentiation - slower than the numerical version.

## 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 |

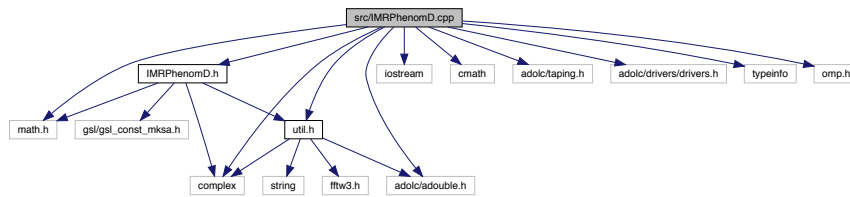
## 9.24 src/IMRPhenomD.cpp File Reference

```

#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`

### 9.24.1 Detailed Description

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

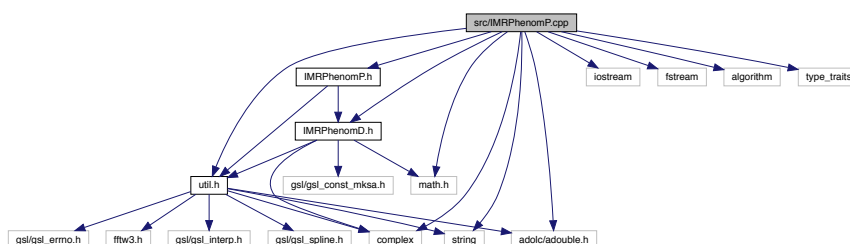
## 9.25 src/IMRPhenomP.cpp File Reference

```

#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 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`

### 9.25.1 Detailed Description

Source code for IMRPhenomP

### 9.25.2 Macro Definition Documentation

#### 9.25.2.1 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
```

#### 9.25.2.2 ROTATEZ

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

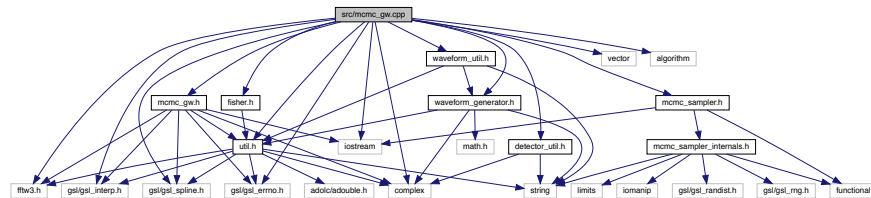
**Value:**

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

## 9.26 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 <vector>
#include <complex>
#include <fftw3.h>
#include <algorithm>
#include <gsl/gsl_interp.h>
#include <gsl/gsl_spline.h>
#include <gsl/gsl_errno.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  $\phi_{hc}$  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 **MCMC\_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 checkpoint\_file)

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

- void **continue\_MCMC\_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 final\_checkpoint\_filename)

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

- void **MCMC\_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\_wrapper** (double \*param, int dimension, int chain\_id)

*log likelihood function for MCMC for GW*

## 9.26.1 Detailed Description

Routines for implementation in MCMC algorithms specific to GW CBC analysis

## 9.26.2 Function Documentation

### 9.26.2.1 `continue_MCMC_MH_GW()`

```
void continue_MCMC_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 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

### 9.26.2.2 `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.



## 9.26.2.3 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.

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

## 9.26.2.4 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.

## 9.26.2.5 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 phic and tc.

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 |
|------------------|-----------------|

9.26.2.6 `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 |
|------------------|-----------------|

9.26.2.7 `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 |
|------------------|-----------------|

9.26.2.8 `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 |
|------------------|-----------------|

## 9.26.2.9 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 |
|------------------|-----------------|

## 9.26.2.10 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 |
|------------------|-----------------|

#### 9.26.2.11 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

#### 9.26.2.12 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

## 9.26.2.13 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  $t_c$ ,  $\phi_{ic}$ ,  $D$ , and  $\phi_{iRef}$ , the reference frequency - for unaligned spins

Ref: arXiv 1603.02444v2

## 9.26.2.14 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

## 9.26.2.15 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

## 9.26.2.16 MCMC\_method\_specific\_prep()

```
void MCMC_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

### 9.26.2.17 MCMC\_MH\_GW()

```
void MCMC_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 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](#) - 8 dimensions – cos inclination, RA, DEC, ln D\_L, ln chirpmass, eta, chi1, chi2

[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                |

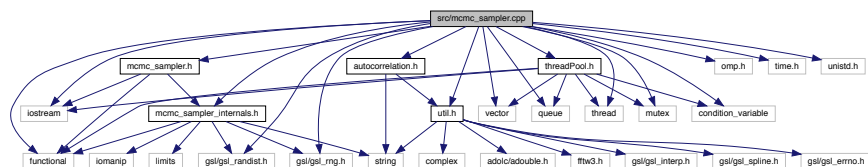
## 9.27 src/mcmc\_sampler.cpp File Reference

```

#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 <omp.h>
#include <time.h>
#include <condition_variable>
#include <mutex>
#include <thread>
#include <vector>
#include <queue>
#include <functional>
#include <unistd.h>

```

Include dependency graph for mcmc\_sampler.cpp:



## Classes

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

## Macros

- `#define omp ignore`

## Functions

- void [MCMC\\_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)> log\_↵prior, std::function< double(double \*, int, int)> log\_likelihood, std::function< void(double \*, 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 checkpoint\_file)

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

- void [continue\\_MCMC\\_MH\\_internal](#) (std::string start\_checkpoint\_file, double \*\*\*output, int N\_steps, int swp\_↵freq, std::function< double(double \*, int, int)> log\_prior, std::function< double(double \*, int, int)> log\_↵likelihood, std::function< void(double \*, 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 end\_checkpoint\_file)

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

- void [MCMC\\_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 [MCMC\\_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 checkpoint\_file)
- void [MCMC\\_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 checkpoint\_file)
- void [continue\\_MCMC\\_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 num\_↵Threads, bool pool, bool show\_prog, std::string statistics\_filename, std::string chain\_filename, std::string auto\_corr\_filename, std::string end\_checkpoint\_file)
- void [continue\\_MCMC\\_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 end\_↵checkpoint\_file)

## Variables

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

### 9.27.1 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](#)



## 9.27.2 Function Documentation

### 9.27.2.1 continue\_MCMC\_MH() [1/2]

```
void continue_MCMC_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 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 "deterministic" vs "stochastic" 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>end_checkpoint_file</i>   | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

### 9.27.2.2 continue\_MCMC\_MH() [2/2]

```
void continue_MCMC_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 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>end_checkpoint_file</i>   | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved |

#### 9.27.2.3 continue\_MCMC\_MH\_internal()

```

void continue_MCMC_MH_internal (
    std::string start_checkpoint_file,
    double *** output,
    int N_steps,
    int swp_freq,
    std::function< double(double *, int, int)> log_prior,
    std::function< double(double *, int, int)> log_likelihood,
    std::function< void(double *, 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 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]   |
|     | <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 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  |
|     | <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>end_checkpoint_file</i>   | Filename to output data for checkpoint at the end of the continued run, if empty string, not saved                  |

## 9.27.2.4 MCMC\_MH() [1/2]

```

void MCMC_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 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] |

## Parameters

|  |                            |  |
|--|----------------------------|--|
|  | <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>checkpoint_file</i>     | Filename to output data for checkpoint, if empty string, not saved                                       |

## 9.27.2.5 MCMC\_MH() [2/2]

```

void MCMC_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 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   |

## Parameters

|                            |  |
|----------------------------|--|
| <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>checkpoint_file</i>     | Filename to output data for checkpoint, if empty string, not saved                                       |

## 9.27.2.6 MCMC\_MH\_internal()

```

void MCMC_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)> log_prior,
    std::function< double(double *, int, int)> log_likelihood,
    std::function< void(double *, 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 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 <code>double[chain_N, N_steps,dimension]</code>  |
|     | <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 <code>double[dimension]</code>   |
|     | <i>seeding_var</i>         | Variance of the normal distribution used to seed each chain higher than 0 - shape <code>double[dimension]</code>   |
|     | <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>           | <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 (=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>checkpoint_file</i>     | Filename to output data for checkpoint, if empty string, not saved   |

## 9.27.2.7 MCMC\_MH\_loop()

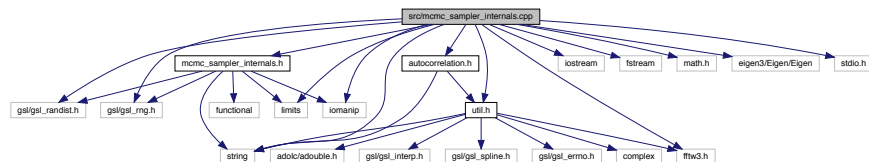
```
void MCMC_MH_loop (
    sampler * sampler )
```

Internal function that runs the actual loop for the sampler.

## 9.28 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 chain\_number)  
*interface function between the sampler and the internal step functions*
- void **gaussian\_step** (sampler \*sampler, double \*current\_param, double \*proposed\_param, int chain\_id)  
*Straight gaussian step.*
- void **fisher\_step** (sampler \*sampler, double \*current\_param, double \*proposed\_param, int chain\_index)  
*Fisher informed gaussian step.*
- void **update\_fisher** (sampler \*sampler, double \*current\_param, int chain\_index)
- void **mmala\_step** (sampler \*sampler, double \*current\_param, double \*proposed\_param)  
*MMALA informed step – Currently not supported.*
- void **diff\_ev\_step** (sampler \*sampler, double \*current\_param, double \*proposed\_param, int chain\_id)  
*differential evolution informed step*
- void **chain\_swap** (sampler \*sampler, double \*\*\*output, 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 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 `allocate_sampler_mem` (`sampler *sampler`)
- void `deallocate_sampler_mem` (`sampler *sampler`)
- void `update_history` (`sampler *sampler`, double \*new\_params, 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_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)

### 9.28.1 Detailed Description

File containing definitions for all the internal, generic mcmc subroutines

### 9.28.2 Function Documentation

#### 9.28.2.1 `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

#### 9.28.2.2 `chain_swap()`

```
void chain_swap (
    sampler * sampler,
    double *** output,
    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>step_num</i> | current step number             |

## 9.28.2.3 diff\_ev\_step()

```
void diff_ev_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    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 |

## 9.28.2.4 fisher\_step()

```
void fisher_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param,
    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 |

### 9.28.2.5 gaussian\_step()

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

### 9.28.2.6 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

### 9.28.2.7 mmala\_step()

```
void mmala_step (
    sampler * sampler,
    double * current_param,
    double * proposed_param )
```

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 |

### 9.28.2.8 single\_chain\_swap()

```
int single_chain_swap (
    sampler * sampler,
```

```
double * chain1,
double * chain2,
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>T1_index</i> | number of chain swappe in chain_temps   |
| <i>T2_index</i> | number of chain swapper in chain_temps  |

#### 9.28.2.9 write\_checkpoint\_file()

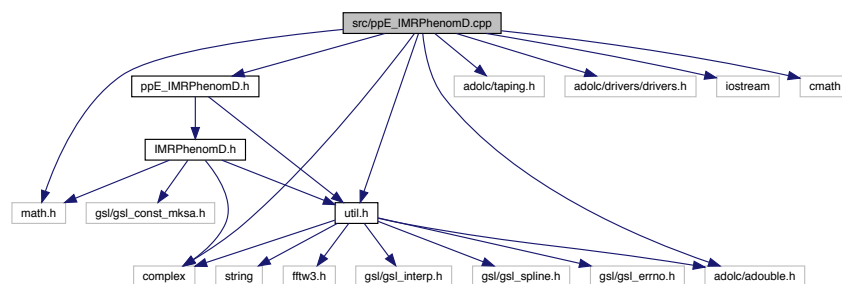
```
void write_checkpoint_file (
    sampler * sampler,
    std::string filename )
```

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

## 9.29 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:



### 9.29.1 Detailed Description

File for the implementation of the ppE formalism for testing GR

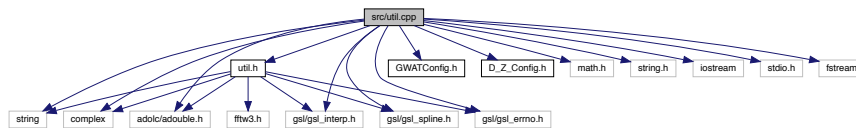
Extends the [IMRPhenomD](#) template to include non-GR phase terms

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

## 9.30 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.*

  - void [deallocate\\_2D\\_array](#) (double \*\*array, int dim1, int dim2)
- Utility to free malloc'd 2D array.*

  - double \*\*\* [allocate\\_3D\\_array](#) (int dim1, int dim2, int dim3)
- Utility to malloc 3D array.*

  - void [deallocate\\_3D\\_array](#) (double \*\*\*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.*
- void `celestial_horizon_transform` (double RA, double DEC, double gps\_time, double LONG, double LAT, double \*phi, double \*theta)  
*Utility to transform from celestial coord RA and DEC to local horizon coord for detector response functions.*
- double `gps_to_GMST` (double gps\_time)  
*Utility to transform from gps time to GMST <https://aa.usno.navy.mil/faq/docs/GAST.php>.*
- double `gps_to_JD` (double gps\_time)  
*Utility to transform from gps to JD.*
- 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)

### 9.30.1 Detailed Description

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

### 9.30.2 Function Documentation

#### 9.30.2.1 `allocate_2D_array()`

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

Utility to malloc 2D array.

9.30.2.2 `allocate_3D_array()`

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

Utility to malloc 3D array.

9.30.2.3 `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 =  $1/(freq[i] - freq[i-1])$  (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            |

#### 9.30.2.4 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

#### 9.30.2.5 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

#### 9.30.2.6 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

#### 9.30.2.7 celestial\_horizon\_transform()

```
void celestial_horizon_transform (
    double RA,
    double DEC,
    double gps_time,
    double LONG,
    double LAT,
    double * phi,
    double * 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) |



#### 9.30.2.8 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

#### 9.30.2.9 deallocate\_2D\_array()

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

Utility to free malloc'd 2D array.

#### 9.30.2.10 deallocate\_3D\_array()

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

Utility to free malloc'd 2D array.

#### 9.30.2.11 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

**9.30.2.12 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

**9.30.2.13 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

**9.30.2.14 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

**9.30.2.15 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

**9.30.2.16 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                                |

## 9.30.2.17 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 |

## 9.30.2.18 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     |

#### 9.30.2.19 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

#### 9.30.2.20 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

#### 9.30.2.21 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

#### 9.30.2.22 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)

**9.30.2.23 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                                |

**9.30.2.24 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  |

**9.30.2.25 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         |

## 9.30.2.26 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

## 9.30.2.27 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

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

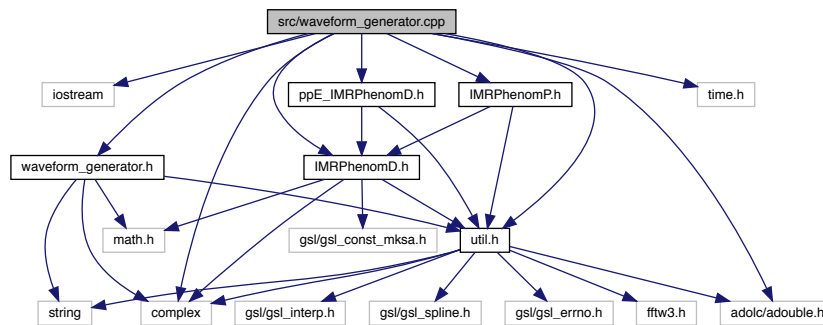
```
double Z_from_DL_interp (
    double DL,
    gsl_interp_accel * Z_DL_accel_ptr,
    gsl_spline * Z_DL_spline_ptr )
```

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

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

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

Include dependency graph for waveform\_generator.cpp:



### Functions

- int [fourier\\_waveform](#) (double \*frequencies, int length, std::complex< double > \*waveform\_plus, std::complex< double > \*waveform\_cross, string generation\_method, [gen\\_params](#) \*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](#) \*parameters)
- 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.*
- 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.*

### 9.31.1 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



## 9.31.2 Function Documentation

### 9.31.2.1 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 |

### 9.31.2.2 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 |

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

```
int fourier_waveform (
    double * frequencies,
    int length,
    std::complex< double > * waveform_plus,
    std::complex< double > * waveform_cross,
    string generation_method,
    gen_params * 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                             |

### 9.31.2.4 `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                             |

**9.31.2.5 `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                             |

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

```

int fourier_waveform (
    double * frequencies,
    int length,

```

```
double * waveform_real,
double * waveform_imag,
string generation_method,
gen_params * parameters )
```

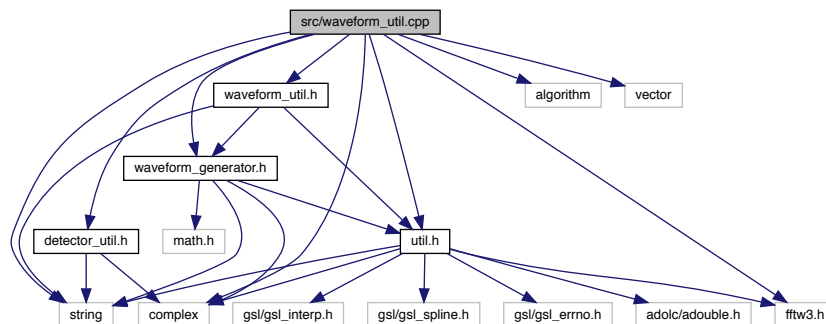
#### Parameters

|                          |  |
|--------------------------|--|
| <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                             |

## 9.32 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  $\phi_{ic}$  and  $t_c$ .
- 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.*
- int `fourier_detector_response` (double \*frequencies, int length, std::complex< double > \*hplus, std::complex< double > \*hcross, std::complex< double > \*detector\_response, double theta, double phi, std::string detector)
- int `fourier_detector_response` (double \*frequencies, int length, std::complex< double > \*response, std::string detector, std::string generation\_method, `gen_params` \*parameters)  
*Function to produce the detector response caused by impinging gravitational waves from a quasi-circular binary.*
- 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.*

### 9.32.1 Detailed Description

Utilities for waveforms - SNR calculation and detector response

includes snr and detector response

### 9.32.2 Function Documentation

#### 9.32.2.1 `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                                    |

#### 9.32.2.2 `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   |
| <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>             | <a href="#">gen_params</a> structure for the template                        |

#### 9.32.2.3 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>             | <a href="#">gen_params</a> structure for the template                        |

9.32.2.4 `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

9.32.2.5 `fourier_detector_response()` [1/2]

```
int fourier_detector_response (
    double * frequencies,
    int length,
    std::complex< double > * hplus,
    std::complex< double > * hcross,
    std::complex< double > * detector_response,
    double theta,
    double 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 |

9.32.2.6 `fourier_detector_response()` [2/2]

```
int fourier_detector_response (
    double * frequencies,
    int length,
    std::complex< double > * response,
    std::string detector,
    std::string generation_method,
    gen_params * 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                             |



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