

# Description of PowerFlux 2 algorithms and implementation (draft)

LIGO-T1000272-v4

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# 1 Introduction

PowerFlux is a program for estimating the flux of monochromatic gravitational waves from a particular source in the sky. It uses short Fourier transform files (SFTs) of 30 minute duration (also called “coherence time”) as input data. Because of this, PowerFlux is much less sensitive to variations in phase than coherent methods (for example ComputeFStatistic). The result is a trade-off of sensitivity for drastic reduction of search space, allowing for full-sky full-bandwidth searches to be completed in reasonable time.

This algorithm has been previously described in [1, 2, 3].

The original PowerFlux code was designed for efficient computation of power sums in 0.25 Hz bands while iterating over sky templates, spindowns and polarizations. A Feldman-Cousins algorithm [4] was then used to obtain upper limits. A number of auxiliary values were collected as well, in particular signal-to-noise ratios, locations of outliers and values of Kolmogorov-Smirnov tests to verify Gaussianity of underlying data.

The all-sky search of full S5 dataset which spanned 2 years of data presented a number of challenges:

- The spindown step used in the search had to be decreased to  $3 \times 10^{-11}$  Hz/s from  $5 \times 10^{-10}$  Hz/s used in previous searches. This greatly increased the computing time needed to cover the same range of parameters.
- The larger dataset strained memory limits of available computing clusters. At the moment the largest cluster is ATLAS which makes available 2 GB of memory per node - a soft limit as actual quad-core machines have 8 GB of memory which is shared between 4 nodes.
- For a good portion of frequency range full S5 dataset is the most sensitive to date and is expected to be superseded only when advanced LIGO or Virgo detectors come into operation. This presents a problem as we cannot rely on more sensitive data to confirm or reject potential candidates.

These issues were met by rewriting PowerFlux analysis pipeline to accommodate new search methods and increase efficiency. The existing startup code - including sky grid generation, SFT input-output and software injection engine - was reused with only minimal changes to accommodate new pipeline. Thus both original (PowerFlux) and new (PowerFlux2) codes can

be compiled from the same common code base and tested using the same software injection code.

Both executables can run from the same configuration file and the options not applicable to the particular code are ignored.

The following features are new in PowerFlux2:

- Partial power sum cache provides 5-10x speedup when running in single bin mode.
- The ability to produce upper limits for subsets of the entire data broken down by time and interferometers, as well as their combinations. Thus outliers for individual interferometers and using all interferometers together are obtained from the same instance.
- Utilization of vector processing instructions of modern CPUs.
- Extensibility to new methods of computation power sums.
- Higher sensitivity (but slower) *loosely coherent* mode [5] of computing power sums.

## 2 Overview of PowerFlux and loosely coherent methods

PowerFlux estimates power coming from particular direction on the sky by computing the following weighted sum:

$$P[k, f_t, a_t] = \frac{\sum_{t \in SFTs} a_t^2 |z_{t, k+f_t}|^2 / w_t^4}{\sum_{t \in SFTs} a_t^4 / w_t^4}$$

Here we use  $a_t$  for the series of amplitude response coefficients for a particular polarization and direction on the sky,  $f_t$  denotes the series of frequency bin shifts due to Doppler effect and spindown,  $|z_{t, f_t}|^2$  is the power in bin  $f_t$  for SFT acquired at time  $t$  and  $k$  indexes bin number of the resulting power sum. The weights  $w_t$  describe level of noise in individual SFTs and do not depend on sky location or polarization.

This power is computed for 501 contiguous frequency bins at a time for a fixed sky location, spindown and polarization. These 501 numbers are used to compute signal-to-noise ratios, upper limits and other statistics.

The new loosely coherent mode takes a controllable amount of phase information into account trading computational efficiency for higher sensitivity. The particular implementation used in PowerFlux2 uses a double sum with a Lanczos kernel:

$$L[k, f_t, a_t] = \frac{\sum_{t_1, t_2 \in SFT_s} a_{t_1} \bar{a}_{t_2} K_{t_1, t_2}(\delta) \Phi(t_1) \bar{\Phi}(t_2) z_{t_1, k+f_{t_1}} \bar{z}_{t_2, k+f_{t_2}} / (w_{t_1}^2 w_{t_2}^2)}{\sum_{t_1, t_2 \in SFT_s} a_{t_1}^2 \bar{a}_{t_2}^2 K(t_1 - t_2) / (w_{t_1}^2 w_{t_2}^2)}$$

Here  $K_{t_1, t_2}(\delta)$  is the kernel configured at compile time and  $\Phi(t_1)$  is the phase correction obtained by computing emission time in solar system barycenter frame of reference. The parameter  $\delta$  governs the amount of phase drift the search can tolerate in 1800 seconds. The tested values include  $\pi$ ,  $\pi/2$  and  $\pi/5$ . For these values of  $\delta$  most cross terms are zero and a number of approximations (discussed later) can significantly speedup the computation.

By analyzing data with successively smaller values of  $\delta$  the loosely coherent code can confirm or reject outliers from original PowerFlux analysis, while still preserving a large degree of immunity to phase variations that benefit original PowerFlux method. This provides greater feedback on the nature of the signal (instrumental or astrophysical) that caused the outlier as well as confidence that small deviations from accepted astrophysical signal model.

In addition, the method has sufficient speed to analyze large areas of the sky at low frequencies where Doppler shifts are small and original PowerFlux method has difficulty distinguishing between instrumental artifacts and real signal.

### 3 Power sum caching

The most significant change in PowerFlux is the introduction of partial power sum cache. The idea is as follows: suppose we are analyzing a stretch of data several month long. Then the minimal change in spindown value that the search can tolerate is determined by this large timebase.

Consider now a partition of the power sum over the entire dataset into stretches 2 week long. Each stretch can tolerate significantly larger spindown step. If we precompute the partial power sums for each stretch we can quickly conclude the entire computation by picking the appropriate partial power sum altered by some constant frequency shift for each finer spindown value.

This approach can be further elaborated by noting that the other large source of frequency shift is Doppler effect from Earth orbital velocity vector which also stays almost constant on the scale of a few weeks. Thus additional savings can be realized by extending the same principle to groups of nearby sky templates.

The actual implementation groups all of these concepts together.

First, we compute power sums for groups of sky templates for which we can assume constant amplitude response (we will call such a group a “patch”).

Secondly, the only thing that matters for computation of power sums are per-SFT frequency shift and, for the loosely coherent search, the relative phase adjustment.

Then an associative cache that uses sequences of frequency shifts as key will provide a model-independent way to accelerate the code and take advantage of degeneracy between signal parameters on short timescales.

Several nuances result in improved performance:

- In practice the frequency shifts are real numbers. To use them as a key one should round them to the nearest point on a frequency grid. For single bin PowerFlux mode this means rounding to the nearest frequency bin.
- Two sequences of shifts that are different by the same constant in every term can be easily derived from the same power sum if it had enough extra points to accommodate the offset.
- It is best to group SFTs by the magnitude of their frequency shift. This way they are more likely to differ by only a constant shift from previously computed group.

The result of all these improvements is that a single spindown run in single-bin PowerFlux mode usually sees cache efficiency on the order of 90%, while a multiple spindown run can achieve efficiency of 95%. The cached sums still need to be accumulated and analyzed, so the overall gain in speed is between 5x (for single spindown run) to 10x (for multiple spindowns).



## 4 PowerFlux2 architecture

### 4.1 Data flow

The data flow of PowerFlux can be followed on figure 1. We start with 1800-second short Fourier transforms (SFTs), which are first analyzed without demodulation to establish general noise levels and isolation sharp lines which are typically caused by detector artifacts.

A summing engine generates sky and spindown templates and precomputes quantities needed to determine Doppler shift, emission times in solar system barycenter frame and amplitude response. An index of SFTs needed to analyze the particular chunk of data is created and populated with information for each template in turn.

With this summing plan in hand we query the cache engine for computed **partial power sums**. If an existing sum is found in cache it is returned immediately. If not the caching engine calls an appropriate function to compute the partial power sum.

When partial power sums computed for all chunks they are passed on to the statistics code which produces upper limits and signal-to-noise ratios for any combination of consecutive chunks for individual interferometer or all interferometers combined and the results are saved into log files.

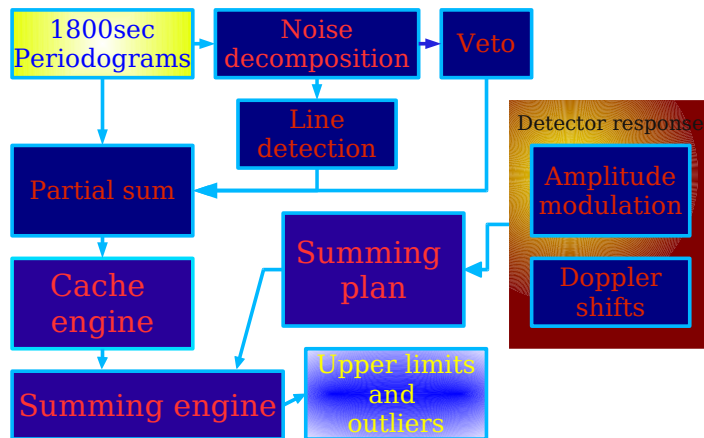


Figure 1: Flowchart of PowerFlux code

## 4.2 Data structures overview

Like its predecessor, PowerFlux2 is structured as a computational engine where a library of functions operates on data structures that carry information throughout the pipeline.

The following data structures are particularly important:

- `PARTIAL_POWER_SUM` carries the results of accumulating power from a subset of available SFTs. Instead of specializing to particular polarizations (as has been done in earlier version of PowerFlux) we carry the coefficients of the polynomials (quadratic in power and quartic in weight) that depend on polarization coefficients.
- `SEGMENT_INFO` is filled in with information on a single SFT to be included into `PARTIAL_POWER_SUM`
- `SIMPLE_CACHE` keeps the cache of previously computed partial power sums.
- `POWER_SUM` contains information on particular template (sky location, spindown and sub-bin frequency shift) and computed partial power sum.
- `SUMMING_CONTEXT` carries the parameters that define which particular flavour of power sum is being computed as well as information local to a particular computational thread. In the current code there is one such structure for each allocated thread.
- `ALIGNMENT_COEFFS` specifies a particular polarization and contains pre-computed coefficients ready to convert a `PARTIAL_POWER_SUM` into a weighted sum for computation of upper limits.
- `POINT_STATS` is used to store computed upper limit, signal-to-noise ratio and other statistics for a particular polarization, sky location, spindown and sub-bin frequency shift.
- `POWER_SUM_STATS` carries aggregate information for a particular power sum or a set of templates.
- `EXTREME_INFO` carries aggregate information for the entire computation. The skymap members are `NULL` by default which saves memory in batched analysis.

### 4.3 Partial power sum

The figure 2 shows the declaration of the `PARTIAL_POWER_SUM` structure. The weighted power sum depends quadratically on amplitude modulation, while the sum of weights depends on it in the fourth degree. The individual components are labeled `pp`, `pc` and `cc` for the quadratic case and `pppp`, `pppc` and so on for the quartic case.

```
typedef struct {
    int type;
    int nbins;

    REAL c_weight_pppp;
    REAL c_weight_pppc;
    REAL c_weight_ppcc;
    REAL c_weight_pccc;
    REAL c_weight_cccc;

    REAL *weight_pppp;
    REAL *weight_pppc;
    REAL *weight_ppcc;
    REAL *weight_pccc;
    REAL *weight_cccc;

    /* power sums - plus^2, plus*cross and cross^2*/
    REAL *power_pp;
    REAL *power_pc;
    REAL *power_cc;

    int offset; /* this is the index of the bin with index 0 in the output (i.e. first bin) */

    int weight_arrays_non_zero;
    int collapsed_weight_arrays;
} SUFFIX(PARTIAL_POWER_SUM);
```

Figure 2: `PARTIAL_POWER_SUM`

There are two sets of fields accumulating weights - the constant fields hold overall weight, while weight arrays are used only if line avoidance is being performed.

## 4.4 SFT information

The array of structures `SEGMENT_INFO` 3 is used as a summing plan for the un-cached power sum functions. It carries the information on which SFTs with what frequency shifts and amplitude response coefficients will be summed. The actual functions are thus isolated from a specific signal model that is used in the power sum accumulation function.

The code implementing partial power sum cache ignores amplitude response coefficients, so they should be kept fixed between calls to reset the cache.

```
typedef struct {
/* fields below are filled in when computing power */

/* amplitude response factors to use in power sum - note these are kept constant through
float f_plus;
float f_cross;

/* bin shift to apply, this is in units of 1/coherence_time - as opposed to power sums *
double bin_shift;
double diff_bin_shift; /* linear component, drift from one frequency bin to another */

/* fields below are filled in when locating segments */

/* for convenience, same as datasets[dataset].gps[segment] */
double gps;
double detector_velocity[3]; /* also from datasets[dataset] */
double coherence_time;

/* segment coordinates */
int dataset;
int segment;
int index; /* arbitrary index for use by power_sum accumulation code, typically for refer
} SEGMENT_INFO;
```

Figure 3: `SEGMENT_INFO`

## 4.5 Simple cache

To speedup computation PowerFlux keeps an associative cache 4 of computed partial power sums. The `id` member identifies which particular pipeline flavour created it.

During execution the cache collects statistics on its performance. Besides basic `hits` and `misses` counters, a cache fault can be caused by an `overwrite` when key collision occurs or `large_shift` when we are requesting to compute a power sum with a constant frequency offset too large to be accommodated by built-in window.

The cache structure is reset for different sets of templates (“patches”) and different SFT sets. The SFT count it expects is kept in `segment_count` variable. The actual cache keys are the sequences of `SEGMENT_INFO` structures kept in `si` member. Their hashes are stored in the `key` field of the structure.

```
typedef struct {
long id;

/* statistics */
long hits;
long misses;
long overwrites;
long large_shifts;
int max_size;

/* cache contents */
int segment_count;
int size;
int free;
int *key;
SEGMENT_INFO **si;
PARTIAL_POWER_SUM_F **pps;
} SIMPLE_CACHE;
```

Figure 4: SIMPLE\_CACHE

## 4.6 Power sums

The `POWER_SUM` data structure wraps `PARTIAL_POWER_SUM` with information sufficient to calculation frequency shift and amplitude response passed to partial power sum functions. It thus acts as a template. The partial power sum will hold the accumulated data, and `min_gps` and `max_gps` members record the actual sampled timebase.

An array of power sum structures is passed to power sum accumulation function and all the templates specified by the array are computed simultaneously and share the same cache.

```
typedef struct S_POWER_SUM {
float freq_shift; /* additional shift e.g. for half-bin sampling */
float spindown;
float ra;
float dec;
float patch_ra;
float patch_dec;

double min_gps;
double max_gps;

float e[26];
float patch_e[26];

int skyband;

PARTIAL_POWER_SUM_F *pps;
} POWER_SUM;
```

Figure 5: `POWER_SUM`

## 4.7 Summing context

The summing context keeps thread specific information as well as methods defining which particular computation is being done.

The figure 6 shows the declaration of the structure. The method `get_uncached_power_sum` performs the actual computation of partial power sum and defines the search

```

typedef struct S_SUMMING_CONTEXT {
void (*get_uncached_power_sum)(struct S_SUMMING_CONTEXT *ctx, SEGMENT_INFO *si, int count);
void (*accumulate_power_sum_cached)(struct S_SUMMING_CONTEXT *ctx, SEGMENT_INFO *si, int count);
void (*accumulate_power_sums)(struct S_SUMMING_CONTEXT *ctx, struct S_POWER_SUM *ps, int count);

int cache_granularity;
double inv_cache_granularity;
double half_inv_cache_granularity;

int diff_shift_granularity;
double inv_diff_shift_granularity;
double half_inv_diff_shift_granularity;

int sidereal_group_count; /* group sfts falling on similar times of the day in this many groups */
double summing_step; /* process SFTs in blocks of this many seconds each */
int time_group_count; /* group SFTs by their GPS time within a block into this many groups */

void *cache;
void (*free_cache)(struct S_SUMMING_CONTEXT *ctx);
void (*print_cache_stats)(struct S_SUMMING_CONTEXT *ctx);
void (*reset_cache)(struct S_SUMMING_CONTEXT *ctx, int segment_count, int template_count);

void *patch_private_data;

/* dynamic parameters */
int loose_first_half_count;

} SUMMING_CONTEXT;

```

Figure 6: SUMMING\_CONTEXT

being performed. The accumulate methods implement the cache of previously computed power sums as well as calling sequence that makes most use of it. The same method can be shared between different search codes, but usually needs tuning to make the most of the cache while still accurately computing the power sums.

The most important tuning parameter is `cache_granularity` which controls the sub-frequency bin tolerance of the cache for the purpose of computing frequency shifts. The parameter `diff_shift_granularity` performs the same function for frequency-dependent Doppler shift variation that loosely coherent search is sensitive to.

To make the most use of the cache the SFTs are partitioned in blocks of `summing_step` seconds and each block is further partitioned into `sidereal_group_count` groups by the magnitude of the frequency shift - in most cases it mostly depends on the hour of day.

## 4.8 Alignment coefficients

The `ALIGNMENT_COEFFS` 7 structure holds precomputed amplitude response coefficients, which make easy to compute numerator and denominator of weighted power sum by simply taking a dot product of  $(pp, pc, cc)$  and  $(pppp, pppc, ppcc, pccc, cccc)$  members of the alignment structure with accumulated `PARTIAL_POWER_SUM`.

An array of alignment coefficients is allocated - one for each sampled polarization. A circular polarization is always added, so the total number of polarizations sampled is `npsi·niota+1`.

## 4.9 Point statistics

The point statistics structure 8 contains upper limit and signal-to-noise ratio estimates for a particular template and particular polarization, as well as many other statistic parameters of various usefulness. The `iota` and `psi` members specify particular polarization this data was computed for. The four last fields are used to convey complete information on point for which the values were achieved - which is the maximum of upper limit and signal-to-noise ratio (both maximums are achieved for the same frequency bin).

`ks_value` has the value of Kolmogorov-Smirnov statistic when `statistics-function` is set to `sorted`. Otherwise the code fills in `m1_neg`, `m3_neg` and `m4` members which are the negative parts of first and third moments and a fourth moment. These are used to check for Gaussianity of computed power sums.



```

typedef struct {
float iota;
float psi;

float pp;
float pc;
float cc;

float pppp;
float pppc;
float ppcc;
float pccc;
float cccc;
} ALIGNMENT_COEFFS;

```

Figure 7: ALIGNMENT\_COEFFS

`weight_loss_fraction` describes how much underlying data was discarded due to line veto.

## 4.10 Accumulated statistics

`POWER_SUM_STATS` 9 holds the accumulated statistics from `POINT_STATS` structures computed for many polarizations and templates.

The inclusion of complete `POINT_STATS` structures for highest upper limit and signal-to-noise ratio points allows to identify where they were achieved.

## 4.11 Extremal points

The structure `EXTREME_INFO` 10 carries information about points which achieve maxima and minima of various statistics over different sets of templates. The skymap members contain maxima over spindowns, polarizations and frequencies. They can be set to `NULL` to conserve memory. The `band_info` members carry information about extremal points in each sky band.

There is one extreme info structure for each chunk of SFT data under analysis. The member `first_chunk` and `last_chunk` specify the start and end of the contiguous set of SFTs to analyze. `veto_num` indicates whether we are

```

typedef struct {
double iota;
double psi;

double ul;
double ll;
double centroid;
double snr;

double M;
double S;
double ks_value;
double m1_neg;
double m3_neg;
double m4;
double max_weight;
double weight_loss_fraction;

int ks_count;

int bin;

/* the following fields are for convenience and are filled in by outside code based on v
double frequency;
double spindown;
double ra;
double dec;

} POINT_STATS;

```

Figure 8: POINT\_STATS

```
typedef struct {
POINT_STATS highest_ul;
POINT_STATS highest_snr;
POINT_STATS highest_ks;
POINT_STATS highest_M;
POINT_STATS highest_S;
POINT_STATS highest_circ_ul;
double max_weight_loss_fraction;
double max_weight;
double min_weight;
double max_m1_neg;
double min_m1_neg;
double max_m3_neg;
double min_m3_neg;
double max_m4;
double min_m4;
int ntemplates;
} POWER_SUM_STATS;
```

Figure 9: POWER\_SUM\_STATS

using SFTs from a particular detector only, or all detectors simultaneously (-1).

```
typedef struct {
char *name;

float *ul_skymap;
float *circ_ul_skymap;
float *snr_skymap;
float *ul_freq_skymap;
float *circ_ul_freq_skymap;
float *snr_freq_skymap;
float *snr_ul_skymap;
float *max_weight_skymap;
float *min_weight_skymap;
float *weight_loss_fraction_skymap;
float *ks_skymap;

POWER_SUM_STATS *band_info;
int *band_valid_count;
int *band_masked_count;

/* convenience info for keeping track of which ei is which */
int first_chunk;
int last_chunk;
int veto_num;
} EXTREME_INFO;
```

Figure 10: EXTREME\_INFO

## 5 Single bin semi-coherent statistic

The single-bin semi-coherent summing mode is turned on by specifying `averaging-mode=one`. This implements conventional weighted power sum algorithm, with several optimizations that increase speed by up to a factor of 10 when iterating over many small spindown steps. The “single-bin” refers to the use of a single power bin from each Hann windowed SFT. It is possible to create a variation of the same algorithm that uses several SFT bins for more accurate

power estimation (called “matched filter” mode), however the matched filter employed for that purpose is computationally expensive and the results are more sensitive to sub-bin frequency shift.

## 5.1 Computation of partial power sums

The uncached partial power sum function computes the partial power sum taking into account amplitude modulation and SFT noise level. The weight estimation can be performed either by using the `TMedians` as in the first version of `PowerFlux`, or by computing variance of SFT bins actually used. This results in small improvement in sensitivity. The non-robustness of variance is actually useful as it deemphasizes SFTs with large spikes. Which of the two methods is used is determined by `tmedian-noise-level` parameter.

If line veto is on, the algorithm avoids lines by subtracting out the contribution of affected frequency bins.

Two variants of the function has been written - a regular C implementation and an optimized version using explicit calls to functions implementing vector based arithmetic.

## 5.2 Caching of partial power sums

The cached accumulation function implements a hash table that holds previously computed power sums. This assumes that amplitude modulation constants are the same for all templates being processed, therefore, the cache is emptied at the start of each patch with different amplitude modulation constants.

The key is based on the well-known modulo arithmetic algorithm applied to frequency bin shifts. The value of the first bin shift is subtracted out as translation by integer number of frequency bin can be easily accommodated by computing slightly more frequency bins than necessary.

## 5.3 Power sum accumulation

The power sum accumulation function computes the power sums in blocks of `summing_step` seconds (by default 10 days). Each block is partitioned into SFT groups by the magnitude of the frequency shifts. The total number of groups is governed by `sidereal-group-count` parameter. Note that the

groups do not have to be equal in length, in fact computation will be more efficient in the case of one large group.

## 6 Loosely coherent statistic

The loosely coherent method is activated by specifying `averaging-mode=loose_single_bin`. This turns on higher sensitivity, though slower, mode meant for investigation of small portions of the sky.

The code is contained in files `single_bin_loosely_coherent_sum.c` and `single_bin_loosely_coherent_sum.h` which define uncached partial power sum function as well as corresponding accumulation methods.

### 6.1 Computation of partial power sums

The uncached partial power sum function assumes that its input is split into two sets of SFTs (which may coincide). The number of SFTs in the first step is governed by parameter `loose_first_half_count` in the summing context. This function returns the double sum:

$$P_k = \sum_{i,j} b_{kj}^* K_{ji} a_{ki}$$

where  $a_{ki}$  are phase corrected SFT bins from the first set, index  $k$  differentiates different SFT bins, while  $i$  corresponds to time.  $b_{ki}$  denotes the phase corrected SFT bins from the second set. The kernel  $K_{ij}$  is a suitable loosely coherent kernel. In the present implementation we have explored exponential kernel described in [5], the sinc kernel and two variations of the Lanczos kernels. The latter have been chosen for regular use as it provides the best trade-off between flatness for a limited amount phase mismatch and keeping the most coefficients of  $K_{ij}$  zero.

The kernel presently used is based on Lanczos kernel with parameter 3 defined in function `lanczos_kernel3`:

$$\tilde{K}_{ij}(\delta) = \begin{cases} \delta |t_i - t_j| / 1800.0 \text{ sec} > 3.0 & 0.0 \\ \text{else} & \text{sinc}(\delta |t_i - t_j| / 1800.0 \text{ sec}) \text{sinc}(\delta |t_i - t_j| / 5400.0 \text{ sec}) \end{cases}$$

where  $\text{sinc}(x) = \frac{\sin(x)}{x}$  is the well-known *sinc* function.  $t_i$  are the GPS times of the SFTs being summed and  $\delta$  is the parameter describing tolerance to the phase mismatch.

The full kernel takes into account weights and amplitude modulation:

$$K_{ij} = F \sqrt{w_j} \tilde{K}_{ji} \sqrt{w_i}$$

where  $w_i$  are the conventional inverse square PowerFlux weights and  $A$  is one of quadratic amplitude modulation factors  $F_+^2$ ,  $F_\times^2$  or  $F_+F_\times$ . The imaginary component of amplitude modulation is neglected to fit the existing PowerFlux array layout (more details are in section 7).

Neither background subtraction nor line avoidance are implemented.

## 6.2 Caching of partial power sums

The cached accumulation function follows the same algorithm as the one for `single_bin` power sum method, except that key depends on differential shift as well as a regular one - this is to account for phase variance between neighbouring frequency bins.

## 6.3 Power sum accumulation

The power sum accumulation function is different in two respects: first, it is a double sum over SFT sets from each group. Secondly, the block is partitioned into groups both by sidereal time (as in `single_bin` case) and, in addition, by time as well. The latter is done to speed up computation - for large  $\delta$  values there is no reason to compute matrix elements between groups widely spaced SFT sets.

Also, the default value of `summing_step` parameter that describes the length of one block is 3 days, not 10 as for single bin code.

# 7 Processing of amplitude modulation in PowerFlux2

There are two ways to derive the formulas for universal polarization coefficients appropriate for computing bilinear products. One way is to apply mathematical technique of polarization of homogeneous polynomials, while the other is to derive it from the basics.

We will follow the formalism of [1, 6, 7, 8]

Let us consider a single SFT and an elliptically polarized source with major axis tilted at an angle  $\psi$  w.r.t. vertical axis.

We assume that during SFT period (usually 30 minutes or less) the frequency of source can be assumed constant.

$$\begin{aligned} h'_+ &= A_+ \cos(\omega t) \\ h'_\times &= A_\times \sin(\omega t) \end{aligned}$$

A generic pulsar signal can be represented as  $A_+ = h_0 (1 + \cos^2(\iota)) / 2$ ,  $A_\times = h_0 \cos(\iota)$ , with  $h_0 = A_+ + \sqrt{A_+^2 - A_\times^2}$  and  $\cos(\iota) = A_\times / (A_+ + \sqrt{A_+^2 - A_\times^2})$

We will assume that demodulation is performed for a fixed frame of plus and cross polarizations rotated at an angle  $\alpha$ . In this coordinate system we have:

$$\begin{aligned} h_+ &= A_+ \cos(\omega t) \cos(\epsilon) - A_\times \sin(\omega t) \sin(\epsilon) \\ h_\times &= A_+ \cos(\omega t) \sin(\epsilon) + A_\times \sin(\omega t) \cos(\epsilon) \end{aligned}$$

where we introduced  $\epsilon = 2(\psi - \alpha)$ .

The signal amplitude in SFT bin corresponding to frequency  $\omega$  is then

$$\begin{aligned} z &= \int (F_+ h_+ + F_\times h_\times) e^{-i\omega t} dt = \\ &= \frac{1}{2} (F_+ (A_+ \cos(\epsilon) + iA_\times \sin(\epsilon)) + F_\times (A_+ \sin(\epsilon) - iA_\times \cos(\epsilon))) \\ &= \frac{1}{2} (A_+ (F_+ \cos(\epsilon) + F_\times \sin(\epsilon)) + iA_\times (F_+ \sin(\epsilon) - F_\times \cos(\epsilon))) \end{aligned}$$

For the computation of loosely coherent statistic we are concerned with the product  $z^1 \bar{z}^2$  of signal amplitudes from two SFTs.

$$\begin{aligned} \text{Re} z^1 \bar{z}^2 &= \frac{1}{4} \text{Re} (A_+ (F_+^1 \cos(\epsilon) + F_\times^1 \sin(\epsilon)) + iA_\times (F_+^1 \sin(\epsilon) - F_\times^1 \cos(\epsilon))) \cdot \\ &\quad \cdot (A_+ (F_+^2 \cos(\epsilon) + F_\times^2 \sin(\epsilon)) - iA_\times (F_+^2 \sin(\epsilon) - F_\times^2 \cos(\epsilon))) = \\ &= \frac{1}{4} (A_+^2 (F_+^1 \cos(\epsilon) + F_\times^1 \sin(\epsilon))(F_+^2 \cos(\epsilon) + F_\times^2 \sin(\epsilon)) + \\ &\quad + A_\times^2 (F_+^1 \sin(\epsilon) - F_\times^1 \cos(\epsilon))(F_+^2 \sin(\epsilon) - F_\times^2 \cos(\epsilon))) \end{aligned}$$



Grouping terms with products of  $F_+$  and  $F_\times$  we obtain:

$$\begin{aligned}
\text{Re}z^1\bar{z}^2 &= \frac{1}{4} (A_+^2(F_+^1 \cos(\epsilon) + F_\times^1 \sin(\epsilon))(F_+^2 \cos(\epsilon) + F_\times^2 \sin(\epsilon)) + \\
&\quad + A_\times^2(F_+^1 \sin(\epsilon) - F_\times^1 \cos(\epsilon))(F_+^2 \sin(\epsilon) - F_\times^2 \cos(\epsilon))) = \\
&= \frac{1}{4} (F_+^1 F_+^2 (A_+^2 \cos^2(\epsilon) + A_\times^2 \sin^2(\epsilon)) + F_+^1 F_\times^2 (A_+^2 - A_\times^2) \cos(\epsilon) \sin(\epsilon) + \\
&\quad + F_\times^1 F_+^2 (A_+^2 - A_\times^2) \cos(\epsilon) \sin(\epsilon) + F_\times^2 F_\times^2 (A_+^2 \sin^2(\epsilon) + A_\times^2 \cos^2(\epsilon))) = \\
&= \frac{1}{4} (F_+^1 F_+^2 (A_+^2 \cos^2(\epsilon) + A_\times^2 \sin^2(\epsilon)) + \\
&\quad + (F_+^1 F_\times^2 + F_\times^1 F_+^2) (A_+^2 - A_\times^2) \sin(2\epsilon) + \\
&\quad + F_\times^1 F_\times^2 (A_+^2 \sin^2(\epsilon) + A_\times^2 \cos^2(\epsilon))) = \\
&= \frac{1}{4} ((F_+^1 F_+^2 + F_\times^1 F_\times^2) (A_+^2 + A_\times^2) + \\
&\quad + (F_+^1 F_+^2 - F_\times^1 F_\times^2) (A_+^2 - A_\times^2) \cos(2\epsilon) + \\
&\quad + (F_+^1 F_\times^2 + F_\times^1 F_+^2) (A_+^2 - A_\times^2) \sin(2\epsilon)) \\
&= \frac{1}{4} (F_+^1 F_+^2 ((A_+^2 + A_\times^2) + (A_+^2 - A_\times^2) \cos(2\epsilon)) + \\
&\quad + F_\times^1 F_\times^2 ((A_+^2 + A_\times^2) - (A_+^2 - A_\times^2) \cos(2\epsilon)) + \\
&\quad + (F_+^1 F_\times^2 + F_\times^1 F_+^2) (A_+^2 - A_\times^2) \sin(2\epsilon))
\end{aligned}$$

Similarly

$$\begin{aligned}
\text{Im}z^1\bar{z}^2 &= \frac{1}{4} \text{Im} (A_+ (F_+^1 \cos(\epsilon) + F_\times^1 \sin(\epsilon)) + iA_\times (F_+^1 \sin(\epsilon) - F_\times^1 \cos(\epsilon))) \cdot \\
&\quad \cdot (A_+ (F_+^2 \cos(\epsilon) + F_\times^2 \sin(\epsilon)) - iA_\times (F_+^2 \sin(\epsilon) - F_\times^2 \cos(\epsilon))) = \\
&= \frac{1}{4} (F_+^1 F_\times^2 A_+ A_\times - F_\times^1 F_+^2 A_+ A_\times) = \\
&= \frac{1}{4} (F_+^1 F_\times^2 - F_\times^1 F_+^2) A_+ A_\times
\end{aligned}$$

Thus the response of a single SFT bin can be decomposed into detector response terms  $F_+^1 F_+^2$ ,  $F_\times^1 F_\times^2$ ,  $F_+^1 F_\times^2 + F_\times^1 F_+^2$  and  $F_+^1 F_\times^2 - F_\times^1 F_+^2$  and corresponding polarization dependent coefficients that are universal for all SFTs. If one computes partial power sums for detector response terms alone - an effort equivalent to sampling 3-5 individual polarizations - then it is possible to reconstruct power sums for any polarization without summing over the entire SFT set.

The single bin code is only concerned with the case  $z_1 = z_2$  in which case the imaginary component is identically zero.

The imaginary component is neglected in loosely coherent search code as original partial power sum structures were constructed for single bin case alone. This does not result in a large impact for two reasons:

- The antenna pattern factors evolve slowly in time making it small for closely spaced SFTs. For  $\pi/2$  search the kernel coefficients is less than 5% of maximum value for SFTs 2 hours apart. For  $\pi/5$  search the distance is 5 hours.

- The product  $A_+A_\times$  is small for linear polarizations which make up the overall upper limit. Thus the losses from not taking  $\text{Im}z^1\bar{z}^2$  into account for elliptically polarized signals are made up by overestimate when demodulating them as linearly polarized signals.

The overall correction is a combination of these two factors. For example, when considering  $\pi/2$  search we can bound the effect of evolution of amplitude modulation factors as 2 hours/24 hours = 8.3%. As the power injected by the signal varies by a factor of 8 between linearly polarized signals and circularly polarized signals the overall upper limit will not be affected.

## 8 Example output

The figures 12 and 14 contain example output produced using configuration files shown on figures 15, 16 and 17.

These configuration files can be obtained from `lsc-docs` CVS or copy-and-pasted from this document. To reproduce the output put all configuration files in a suitable directory along with ephemeris files `earth05-09.dat` and `sun05-09.dat` which can be found in `lalapps` repository. Then, using either multithreaded version of PowerFlux 2 `powerflux-mt2` or condorized single-threaded executable `powerflux-condor2` run the following commands:

```
powerflux-mt2 --config=config.single_bin
powerflux-mt2 --config=config.single_bin_zoomed
powerflux-mt2 --config=config.loose_pi_2
```

This will create directories `single_bin`, `single_bin_zoomed` and `loose_pi_2` with the images and log files.

In all cases we have made a linearly polarized injection into Gaussian noise that spanned several months. The injection strength was chosen to produce a signal-to-noise ratio of 8.29 - a typical value for an outlier to be followed up. Figure 12 shows the entire sky as would be explored in typical PowerFlux run. Figure 14 shows a skymap produced using regular single-bin code (left) and a skymap made with loosely coherent search with  $\delta = \pi/2$  and 10x magnification.

Figure 13 shows corresponding skymap of upper limits. The injection is barely visible in the top right corner due to less sensitive region at the equator.

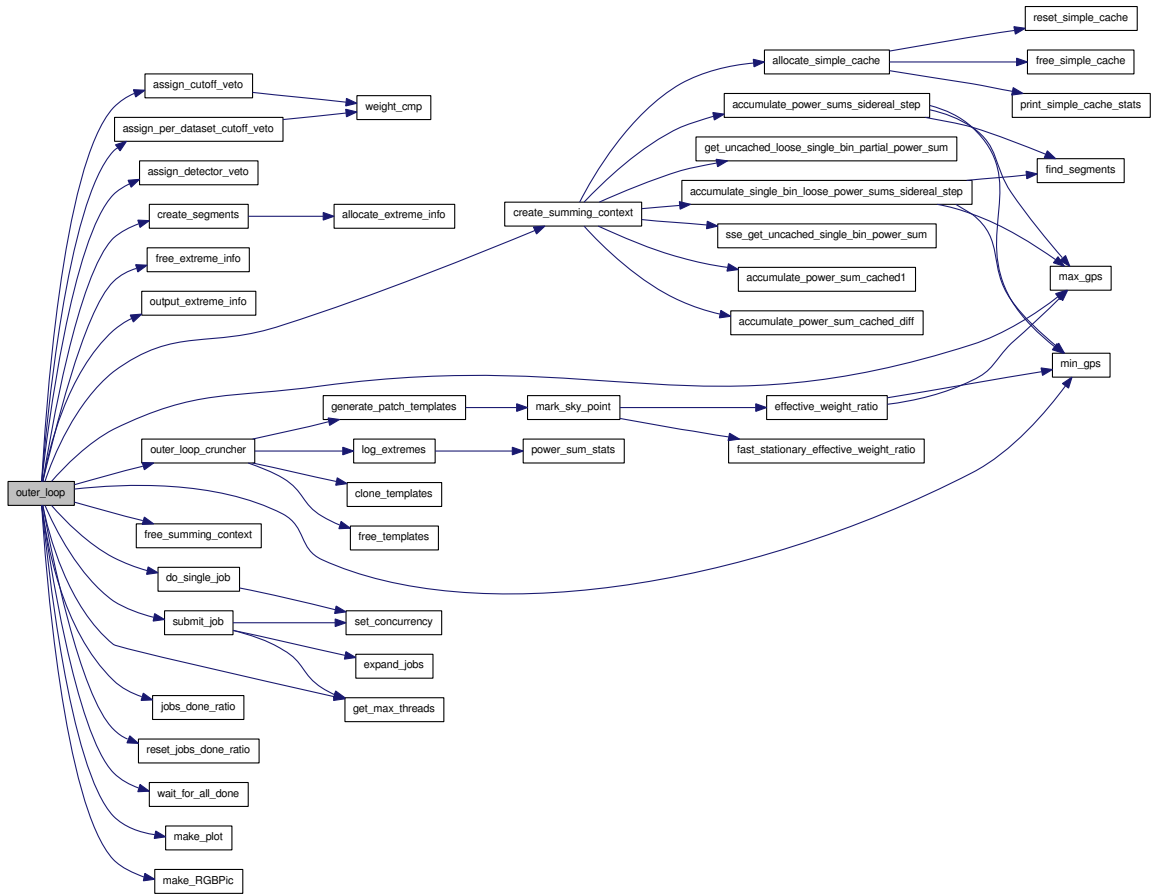


Figure 11: Call graph of PowerFlux2 outer loop function. This does not include calls to methods of summing context.

On all skymaps the square pixels describe patches - multiple templates were sampled for each patch.

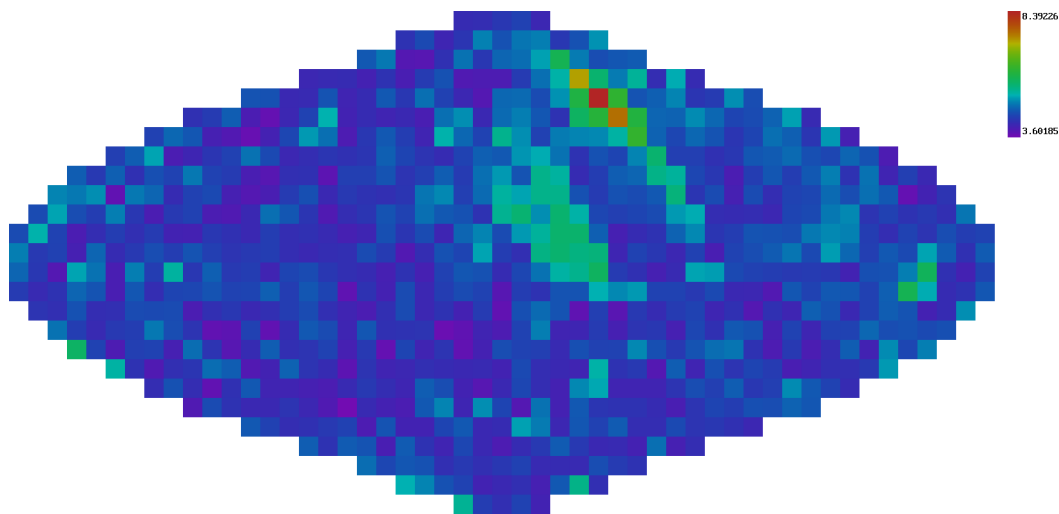


Figure 12: Example skymap of signal-to-noise ratios using single-bin Power-Flux2 mode. The injection was performed at RA=2.0 and DEC=1.0. Each square corresponds to a sky patch - a set of templates that used the same amplitude response coefficients.

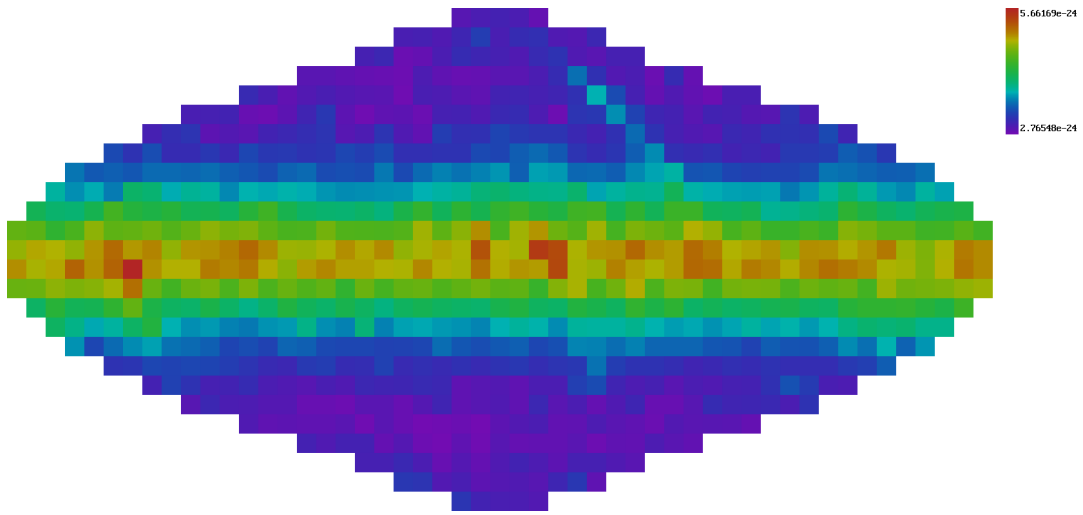


Figure 13: Example skymap of upper limits using single-bin PowerFlux2 mode. The injection was performed at RA=2.0 and DEC=1.0 and is barely visible, compared to equatorial points where we are less sensitive.

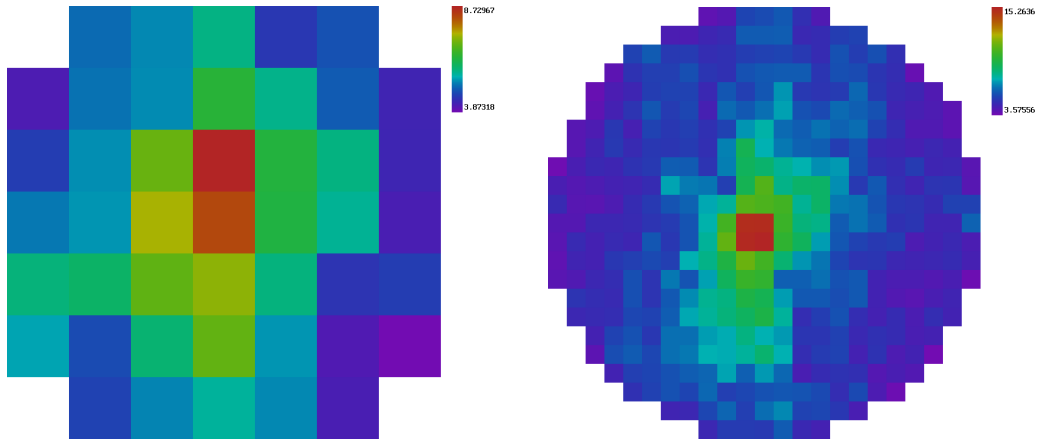


Figure 14: Zoomed view of the injection. The area displayed in both pictures is a disk with 0.3 radians radius centered at the location of the outlier of figure 12. The left image has been made with single-bin code. The right image was produced by loosely coherent code using  $\delta = \pi/2$  and `sky-resolution-ratio=0.25`.

## 9 Running PowerFlux on the cluster

The monolithic PowerFlux binary adapts readily to running on multiple CPUs. The simplest way to use more computing power is to start a multi-threaded version on machine with many cores. It will automatically utilize as many cores as are available, while sharing input and output arrays between different threads.

If condor controlled cluster is available it is best to run condor-enabled version of PowerFlux under “standard” universe which enables checkpointing. In this configuration it is feasible to have individual instances run complete over a few days with the entire analysis taking weeks or months. One drawback of this approach is that since we are running single-threaded each instance needs its own input and output arrays which can take 2 GB or more of memory. If memory consumption is a problem the sky can be partitioned into slices to reduce the size of internal skymaps - but there is no workaround if you are dominated by the size of the input data.

Once the analysis is complete the log files `powerflux.log` and `data.log`

should be used to extract upper limits, signal-to-noise ratios, outliers and other statistics.

A number of scripts make setting up dags and collecting data easy. They are stored in the `scripts` subdirectory in PowerFlux tree and should be used as a guide for setting up new analysis.

In particular, the following scripts can be of use:

- `make_run.tcl` - generate dag and other supporting files for PowerFlux analysis run.
- `make_1800_sfts.tcl` - generate dag for producing PowerFlux-style Hann windowed SFTs.
- `normalize_sft_name.tcl` - rename SFTs in accordance with common LDR usage.
- `make_native_sft_injection_run.tcl` - generate dag and supporting files for software injection run.
- `archive.tcl` - compress one or more directories in tarball for archiving. This is done in background. The original directory can be removed on successful completion.
- `find_outlier_matches.tcl` - compile the initial list of coincident outliers from PowerFlux `data.log` file. This is done with very loose constraints to reduce the amount of data to more manageable (several GB) size.
- `make_outlier_histogram.tcl` - compute outlier histogram data from `powerflux.log` file.

The collected data can easily exceed 10 GB for a large run. At these size loading into analysis program such as R is awkward (though possible) and it is best to first upload the data to a database (such as MySQL) and then analyze one frequency band at a time.

## 10 PowerFlux configuration options

When started with `--help` option PowerFlux prints out a summary of available command line switches:

powerflux 1.4.41-64

Powerflux analysis program

Usage: powerflux [OPTIONS]...

-h, --help	Print help and exit
-V, --version	Print version and exit
-c, --config=STRING	configuration file (in gengetopt format) to pass parameters
--label=STRING	arbitrary string to be printed in the beginning of PowerFlux log file (default='')
--sky-grid=STRING	sky grid type (arcsin, plain_rectangular, sin_theta) (default='sin_theta')
--skymap-orientation=STRING	orientation of produced skymaps: equatorial, ecliptic, band_axis (default='equatorial')
--skyband-method=STRING	method of assigning band numbers: angle, S (default='S')
--nskybands=INT	split sky in this many bands for logging maximum upper limits (default='11')
--large-S=DOUBLE	value of S to consider good enough
--band-axis=STRING	which band axis to use for splitting sky into bands (perpendicular to band axis) (possible values: equatorial, auto, explicit(float,float,float) (default='auto'))
--band-axis-norm=DOUBLE	norm of band axis vector to use in S value calculation
--sky-marks-file=STRING	file describing how to mark up a sky
--fine-factor=INT	make fine grid this times finer (default='5')
--skymap-resolution=DOUBLE	specify skymap resolution explicitly
--skymap-resolution-ratio=DOUBLE	adjust default coarseness of the grid by this factor (default='1.0')
--small-weight-ratio=DOUBLE	ratio that determines which weight is too small to include in max statistics (default='0.2')
--strain-norm-factor=DOUBLE	strain normalization factor to prevent



overflowing of the exponent  
 (default='1e-20')

--lock-file=STRING file to lock when reading SFTs in order to  
 globally serialize disk access

--enable-dataset-locking=INT  
 set to 1 to enable dataset level locking  
 (default='1')

--retry-delay=INT number of seconds to wait before retrying I/O  
 (default='2')

--lock-retry-delay=INT number of seconds to wait before trying to  
 acquire lock again (default='10')

-s, --dataset=STRING dataset file

-i, --initial-dataset-seed=INT  
 initial seed to use for generating gaussian  
 data (default='12345')

--input-format=STRING format of input files (GEO, SFT, Power)  
 (default='GEO')

--dump-data=STRING file to output loaded SFT data into, for  
 testing

--dump-sftv2=STRING directory to output loaded data, together with  
 dataset description

-o, --output=STRING output directory

--flat-output=STRING output directory to contain all files, with no  
 subdirectories (for globus condor)

--ephemeris-path=STRING path to detresponse program from lalapps

--earth-ephemeris=STRING Earth ephemeris file, overrides ephemeris-path  
 argument

--sun-ephemeris=STRING Sun ephemeris file, overrides ephemeris-path  
 argument

-f, --first-bin=INT first frequency bin in the band to be analyzed

-n, --nbins=INT number of frequency bins to analyze  
 (default='501')

--side-cut=INT number of bins to cut from each side due to  
 corruption from doppler shifts

--expected-timebase=DOUBLE  
 expected timebase in months (default='6')

--hist-bins=INT number of bins to use when producing histograms  
 (default='200')

-d, --detector=STRING detector location (i.e. LHO or LLO), passed to  
 detresponse

```

--doppler-multiplier=DOUBLE
                                a constant to multiply Doppler shifts by (1.0
                                corresponds to standard physics)
                                (default='1.0')
--dInv=DOUBLE                    inverse distance to expected source in seconds
                                (default='0.0')
--spindown-start-time=DOUBLE
                                specify spindown start time in GPS sec. Assumed
                                to be the first SFT segment by default
--frequency-offset=DOUBLE (small) frequency offset - used to achieve
                                fractional bin shifts (default='0.0')
--spindown-start=DOUBLE          first spindown value to process
                                (default='0.0')
--spindown-step=DOUBLE          step for processing multiple spindown values
                                (default='5e-10')
--spindown-count=INT            how many separate spindown values to process
                                (default='1')
--fdotdot=DOUBLE               second frequency derivative (default='0.0')
--orientation=DOUBLE           additional orientation phase, specifying 0.7853
                                will turn plus into cross (default='0')
--nlinear-polarizations=INT     even number of linear polarizations to profile,
                                distributed uniformly between 0 and PI/2
                                (default='4')
--no-demodulation=INT          do not perform demodulation stage, analyze
                                background only (default='0')
--no-decomposition=INT        do not perform noise decomposition stage,
                                output simple statistics only (default='0')
--no-candidates=INT           do not perform analysis to identify candidates
                                (default='0')
--no-am-response=INT          force AM_response() function to return 1.0
                                irrespective of the arguments (default='0')
--no-secondary-skymaps=INT    do not store values not essential for upper
                                limits and followup (default='0')
--averaging-mode=STRING       1 - use one bin, 3 - average 3, matched - use 7
                                bin matched filter (default='1')
--subtract-background=INT     subtract rank 1 matrix in order to flatten
                                noise spectrum (default='0')
--do-cutoff=INT               neglect contribution from SFT with high

```

effective noise level (default='1')  
 --filter-lines=INT perform detection of lines in background noise  
 and veto corresponding frequency bins  
 (default='1')  
 --ks-test=INT perform Kolmogorov-Smirnov test for normality  
 of averaged powers (default='1')  
 --compute-betas=INT compute beta coefficients as described in  
 PowerFlux polarizations document  
 (default='0')  
 --upper-limit-comp=STRING upper limit compensation factor - used to  
 account for windowing in SFTs (possible  
 values: Hann, flat, arbitrary number)  
 (default='Hann')  
 --lower-limit-comp=STRING lower limit compensation factor - used to  
 account for windowing in SFTs (possible  
 values: Hann, flat, arbitrary number)  
 (default='Hann')  
 --write-dat=STRING regular expression describing which \*.dat files  
 to write (default='.\*')  
 --write-png=STRING regular expression describing which \*.png files  
 to write (default='.\*')  
 --dump-points=INT output averaged power bins for each point in  
 the sky (default='0')  
 --dump-candidates=INT output SFT data for first N candidates  
 (default='0')  
 --focus-ra=DOUBLE focus computation on a circular area with  
 center at this RA  
 --focus-dec=DOUBLE focus computation on a circular area with  
 center at this DEC  
 --focus-radius=DOUBLE focus computation on a circular area with this  
 radius  
 --only-large-cos=DOUBLE restrict computation to points on the sky with  
 cos of angle to band axis larger than a given  
 number

Group: injection

--fake-linear Inject linearly polarized fake signal  
 --fake-circular Inject circularly polarized fake signal  
 --fake-ref-time=DOUBLE time of signal start (default='0')  
 --fake-ra=DOUBLE RA of fake signal to inject (default='3.14')

```

--fake-dec=DOUBLE      DEC of fake signal to inject (default='0.0')
--fake-iota=DOUBLE     iota of fake signal to inject (default='0.0')
--fake-psi=DOUBLE      orientation of fake signal to inject
                        (default='0.0')
--fake-phi=DOUBLE      phase of fake signal to inject (default='0.0')
--fake-spindown=DOUBLE spindown of fake signal to inject
                        (default='0.0')
--fake-strain=DOUBLE   amplitude of fake signal to inject
                        (default='1e-23')
--fake-freq=DOUBLE     frequency of fake signal to inject
--fake-dInv=DOUBLE     inverse distance to source of fake signal in
                        seconds (default='0.0')
--fake-modulation-depth=DOUBLE
                        depth of sinusoidal phase modulation in radians
                        (default='0.0')
--fake-modulation-freq=DOUBLE
                        frequency of sinusoidal phase modulation
                        (default='0.0')
--fake-modulation-phase=DOUBLE
                        phase of sinusoidal phase modulation
                        (default='0.0')
--snr-precision=DOUBLE Assumed level of error in detection strength -
                        used for listing candidates (default='0.2')
--max-candidates=INT   Do not optimize more than this number of
                        candidates (default='-1')
--min-candidate-snr=DOUBLE
                        Do not optimize candidates with SNR below this
                        level (default='5.0')
--output-initial=INT   write initial candidates into log file
                        (default='0')
--output-optimized=INT
                        write optimized (second pass) candidates into
                        log file (default='0')
--output-cache=INT     write out all candidates in cache to log file
                        (default='0')
--extended-test=INT    Perform extended self test (default='0')
--max-sft-report=INT   Maximum count of SFTs to report with veto
                        information (default='100')
--num-threads=INT      Use that many threads for computation
                        (default='-1')
--niota=INT            Number of iota values to use in alignment grid

```

```

                                (default='3')
--npsi=INT                       Number of psi values to use in alignment grid
                                (default='6')
--nfshift=INT                    Number of sub-bin frequency shifts to sample
                                (default='2')
--nchunks=INT                   Partition the timebase into this many chunks
                                for sub period analysis (default='5')
--split-ifos=INT               Split interferometers in separate chunks
                                (default='1')
--weight-cutoff-fraction=DOUBLE Discard sfts with small weights that contribute
                                this fraction of total weight
                                (default='0.04')
--per-dataset-weight-cutoff-fraction=DOUBLE Discard sfts with small weights that contribute
                                this fraction of total weight in each dataset
                                (default='0.04')
--power-max-median-factor=DOUBLE This determines scaling factor between median
                                and maximum of exponentially distributed
                                variable. Used for computing power sum
                                weights (default='0.1')
--tmedian-noise-level=INT       Use TMedians to estimate noise level (as
                                opposed to in-place standard deviation)
                                (default='1')
--summing-step=DOUBLE          integration step size, in seconds
--max-first-shift=INT          larger values accomodate bigger spindown ranges
                                but require more bins to be computed in
                                uncached function (default='10')
--statistics-function=STRING   specify statistics postprocessing to apply.
                                Possible values: linear, sorted
                                (default='linear')
--dump-power-sums=INT          Write out all power sum data into data.log
                                file. It is recommend to restrict the sky to
                                very few pixels (default='0')
--compute-skymaps=INT          allocate memory and compute skymaps with final
                                results (default='0')
--fine-grid-skymarks=INT       use sky marks from the fine grid, this uses
                                constant spindown (default='0')

```

```

--half-window=INT      number of bins to exclude to the left and to
                        the right of highest point when computing
                        linear statistics (default='20')
--tail-veto=INT        do not report outlier if its frequency is
                        within that many bins from the tail - happens
                        with steep spectrum (default='10')
--cache-granularity=INT granularity of power cache frequency shift
                        resolution, in fractions of a frequency bin
                        (default='-1')
--sidereal-group-count=INT separate SFTs in that many groups by frequency
                        shift
--time-group-count=INT  separate SFTs in that many groups by gps time
--phase-mismatch=DOUBLE maximal phase mismatch over coherence length to
                        assume when using loosely coherent mode
                        (default='1.570796')
--bypass-powersum-cache=INT bypass partial power sum cache (default='0')

```

## 10.1 config

Specify the first part of SFT file name. The complete name is formed by appending an SFT number to the end.

Instead of specifying arguments on the command line it is possible to create a file with each line containing option value pair. The "--" prefix in front of the option name must to be omitted.

In the following PowerFlux options would be referred by their name as used in the configuration file, for command line use prepend "--".

## 10.2 Input/Output options

### 10.2.1 config

Configuration file with more options. This can be supplied more than once.

### 10.2.2 dataset

Specify file containing description of the data to load.

### 10.2.3 `input-format`

Specify the format of input SFT files.

- `Power` refers to ASCII header binary body power-only files produced by `make_sft_op`
- `SFT` refers to ASCII header binary body SFT files produced by `make_sft_op`
- `GEO` refers to binary header binary body GEO-style SFT files in common use in LSC.

### 10.2.4 `segments-file`

Allows to restrict processing to only SFT files that are inside a list of segments described in the ASCII file specified with this option.

Each line specifies a single segment described the starting GPS time followed by ending GPS time. The rest of line is discarded (this makes possible to use standard segment list files).

### 10.2.5 `veto-segments-file`

Same as `segments-file` except this option specifies the list of times **not** to process. Useful for vetoing parts of data.

### 10.2.6 `ephemeris-path`

Path to files with ephemeris data (they can be found, for example, in `lalapps/src/detresponse/` directory).

### 10.2.7 `earth-ephemeris`

Specify Earth ephemeris file explicitly. This overrides `ephemeris-path` option.

### 10.2.8 `sun-ephemeris`

Specify Sun ephemeris file explicitly. This overrides `ephemeris-path` option.

### 10.2.9 `skymarks`

Specify file describing sky partitioning into areas for data collection.

### 10.2.10 output

Specify directory to put output of PowerFlux into. Everything that PowerFlux writes will be located in this directory.

## 10.3 Analysis parameters

### 10.3.1 first-bin

Specify first bin of 501 bin stretch to analyze. This is an integer in units of 1/1800 Hz. It specifies the *source* (i.e. decoded) frequency, not frequency as received by the detector.

### 10.3.2 nbins

Number of frequency bins to analyze. The default is 501. At the moment this value should not be changed - there are some hard-coded constants that rely on this number. In particular, the Feldman-Cousins method relies on constants produced by Monte-Carlo simulation on the assumption that `nbins= 501`.

### 10.3.3 side-cut

Due to the need to apply Doppler shift the actual number of bins read from SFT file is larger than `nbins` and varies with frequency and spindown. Normally PowerFlux will compute the number of extra bins to read automatically. This option allows an explicit override. Specifying `--side-cut=100` will cause PowerFlux to read all bins from `first-bin-100` to `first-bin+nbins+100`.

### 10.3.4 spindown-start

Specify initial spindown value to process. It is a floating-point value in units of Hz/sec. Negative values correspond to frequency decreasing with time.

### 10.3.5 spindown-count

Specify the number of spindown values to process starting with value specified by `spindown-start` option.



### **10.3.6 spindown-step**

Specify the increment between spindown values to process. Can be positive or negative.

### **10.3.7 nfshift**

Number of sub-bin steps to sample. The frequency resolution will in units of  $1/\text{nfshift}$  of frequency bin.

### **10.3.8 nchunks**

Break up the loaded dataset into **nchunks** equally spaced segments and report results for any contiguous combination.

### **10.3.9 niota**

Sample  $\text{niota} + 1$  values, including 0 (for circular polarization) and  $\pi/2$  (for linear polarization).

### **10.3.10 npsi**

Sample **npsi** orientation values. The total number of polarizations sampled is  $\text{npsi} \cdot \text{niota} + 1$ , as circular polarization does not depend on  $\psi$ .

### **10.3.11 phase-mismatch**

Maximum allowable phase mismatch for loosely coherent searches.

### **10.3.12 doppler-multiplier**

An additional multiplier to apply to Doppler shifts. This is equivalent to adjusting the speed of gravitational waves. This should be set to the default value of 1.0 for loosely coherent modes.

### **10.3.13 dInv**

Inverse distance to expected source in seconds. This is only used by loosely coherent modes which are phase sensitive.

## 10.4 Analysis options

### 10.4.1 no-demodulation

Do not perform demodulation, stop after analyzing background. Since Feldman-Cousins is not performed `nbins` can be specified to an arbitrary number, although values exceeding 25 Hz require lots of computer memory (in excess of 2 Gb).

It is convenient to specify `--side-cut=0` to provide greater control over starting frequency.

### 10.4.2 no-decomposition

Only read in SFT files and output simple statistics. This is even faster than `no-demodulation` option. Same suggestions apply.

### 10.4.3 no-am-response

Assume that amplitude response is always 1.0 irrespective of time or sky position.

### 10.4.4 skymap-resolution

PowerFlux computes optimal resolution of skymaps automatically (It depends mostly on magnitude of Doppler shifts). This options allows to specify resolution explicitly skymaps. This option is very handy for comparing PowerFlux skymap output for different frequency bands.

### 10.4.5 skymap-resolution-ratio

PowerFlux computes optimal resolution of skymaps automatically (It depends mostly on magnitude of Doppler shifts). This options allows to force skymaps to have a finer or coarser resolution by a given factor.

### 10.4.6 small-weight-ratio

PowerFlux discards data in weighted sum that is assigned too small a weight. This option allows to specify it.

For a perfect instrument setting this ratio to 0 will produce the best result as the weighting scheme used will make good use even of data with very small weights.

In practice, discarding SFTs saves CPU cycles so it makes sense to skip those which provide marginal improvement.

Furthermore, the SFTs with small weight can often have radically different noise spectrum. The default value is prudent 0.2.

#### **10.4.7 three-bins**

Specifying `three-bins=1` causes PowerFlux to average every neighbouring three bins in its analysis. Because of this Doppler tracks are widened and a coarser skymaps may be used while still retaining full sky coverage.

The drawback is a factor of  $\sqrt{2}$  loss in sensitivity.

#### **10.4.8 do-cutoff**

Enabled by default. Setting it to 0 will turn off Cutoff computation. This is similar to specifying `--small-weight-ratio=0.0`

#### **10.4.9 filter-lines**

Perform automatic detection of lines in background noise and veto corresponding frequency bins. Up to 5 frequency bins can be vetoed.

#### **10.4.10 subtract-background**

Subtract rank 1 matrix formed from `TMedians` and `FMedians` in order to improve noise performance for sky positions with large variation in Doppler shifts. Turning this option on will clobber signals from sky positions with small variation in Doppler shifts, therefore one should combine it with `only-large-cos=0.3`.

## **10.5 Data reporting options**

### **10.5.1 skymap-orientation**

The skymaps produced by PowerFlux can have different orientations to please the user. Possible choices are equatorial, ecliptic or "band-axis" - with band axis vector pointing to the North pole.

### 10.5.2 nskybands

Split sky in a given number of bands and report analysis results for each band individually.

### 10.5.3 skyband-method

Specify method used to partition sky into regions.

Possible values are `angle` and `S`. The latter method is useful on short timebases, while the former can be used to partition the sky into bands along declination.

### 10.5.4 band-axis

By default PowerFlux computes optimal band axis automatically (this has to do with average detector acceleration during analyzed data set). However, it may be useful to specify it explicitly - for example for comparison of results between different interferometers.

Possible values are `equatorial`, `auto` and `explicit(%f,%f,%f)`.

### 10.5.5 band-axis-norm

Specify the norm of band axis vector explicitly. This is useful for comparison of results between different IFOs.

### 10.5.6 large-S

Specify values of S function considered to be good enough. All sky points with S value larger or equal to this value will be assigned to band 0.

### 10.5.7 only-large-cos

Restrict computation to only those areas of sky which projection to band axis has absolute value larger than a value specified to this option. If you want to do this (due to presence of line artifacts, for example) the recommended value is 0.3.

This cleans up the results reported for entire skymap and can significantly reduce computation time requirements.

### **10.5.8 ks-test**

Perform and output results of Kolmogorov-Smirnov test for compliance of averaged weighted power with gaussian distribution with parameters employed later to establish Feldman-Cousins limits. This increases the computation time, but is a highly recommended cross check for analysis. High values of KS statistic indicate bands with pathological noise floor behaviour.

### **10.5.9 upper-limit-comp**

A factor to multiply upper limits reported in strain units. One can specify a floating-point number or "Hann" for Hann windowed SFTs. This factor is used to account for the fact that non bin-centered (in frequency) signals would have smaller amplitude than bin-centered ones. For Hann windowed SFTs, using 1-bin mode the factor is 1/0.85.

### **10.5.10 lower-limit-comp**

A factor to multiply lower limits reported in strain units. One can specify a floating-point number or "Hann" for Hann windowed SFTs. This factor is used to account for the fact that non bin-centered (in frequency) signals would have smaller amplitude than bin-centered ones. For Hann windowed SFTs, using 1-bin mode the factor is 1.

### **10.5.11 write-dat**

By default PowerFlux writes a binary file with data for each plot it makes. You can use this option to specify a regular expression to filter what will actually be written.

This can significantly reduce storage requirements for PowerFlux output, as well as speed up computation.

### **10.5.12 write-png**

By default PowerFlux creates a number of plots. You can use this option to specify a regular expression to filter what will actually be written.

This can significantly reduce storage requirements for PowerFlux output, as well as speed up computation.

## 10.6 Software injections

The following options provide interface to software injections done by PowerFlux itself (as opposed to using external programs). The injections are power-only, modeled with assumption of random phase of incoming signal to a particular frequency bin.

### 10.6.1 fake-linear

Perform injection of linearly polarized signal.

### 10.6.2 fake-circular

Perform injection of circularly polarized signal.

### 10.6.3 fake-ra

Specify right ascension of injected signal source in radians (values from 0 to  $2\pi$  are acceptable).

### 10.6.4 fake-dec

Specify declination of injected signal source in radians (values from  $-\pi/2$  to  $\pi/2$  are acceptable).

### 10.6.5 fake-orientation

Specify polarization of injected signal (assumed to be linearly polarized). Valid values are between 0 and  $\pi/4$ .

### 10.6.6 fake-spindown

Specify spindown of injected signal in units of Hz/sec.

### 10.6.7 fake-strain

Specify strain of injected signal.

### 10.6.8 fake-freq

Specify frequency of injected signal.

**10.6.9 fake-dInv**

Specify inverse distance to source of injected signal.

**10.6.10 fake-modulation-depth**

Specify modulation depth  $A$  of injected signal according to the formula  $A \sin(2\pi f_m t + \phi)$ .

**10.6.11 fake-modulation-freq**

Specify modulation frequency  $f_m$  of injected signal according to the formula  $A \sin(2\pi f_m t + \phi)$ .

**10.6.12 fake-modulation-phase**

Specify modulation phase  $\phi$  of injected signal according to the formula  $A \sin(2\pi f_m t + \phi)$ .

## 11 Appendix A: example configuration files

```
dataset random.dst
input-format GEO
earth-ephemeris earth05-09.dat
sun-ephemeris sun05-09.dat
sky-marks all_sky_marks.txt
first-bin 180000
nbins 501
do-cutoff 1
filter-lines 1
averaging-mode one
spindown-start-time 793154935
spindown-start -1e-8
expected-timebase 7

write-dat NONE
#write-png NONE
subtract-background 1
ks-test 1
compute-betas 0
output-initial 1
max-candidates 0

fake-ref-time 793154935
fake-ra 2.0
fake-dec 1.0
fake-iota 1.570796
fake-psi 0.392699
fake-phi 0.0
fake-spindown -1e-8
fake-strain 3e-24
fake-freq 100.1389

skymap-resolution-ratio 1

compute-skymaps 1

initial-dataset-seed 0

nchunks 1
fine-factor 5

output single_bin
```

Figure 15: config.single\_bin



```
dataset random.dst
input-format GEO
earth-ephemeris earth05-09.dat
sun-ephemeris sun05-09.dat
sky-marks all_sky_marks.txt
sky-grid targeted_rectangular
first-bin 180000
nbins 501
do-cutoff 1
filter-lines 1
averaging-mode one
spindown-start-time 793154935
spindown-start -1e-8
expected-timebase 7

write-dat NONE
#write-png NONE
subtract-background 1
ks-test 1
compute-betas 0
output-initial 1
max-candidates 0

fake-ref-time 793154935
fake-ra 2.0
fake-dec 1.0
fake-iota 1.570796
fake-psi 0.392699
fake-phi 0.0
fake-spindown -1e-8
fake-strain 3e-24
fake-freq 100.1389

focus-ra 1.978040
focus-dec 1.009798
focus-radius 0.3

skymap-resolution-ratio 1

compute-skymaps 1

initial-dataset-seed 0

nchunks 1
fine-factor 5

output single_bin_zoomed
```

Figure 16: config.single\_bin\_zoomed

```
dataset random.dst
input-format GEO
earth-ephemeris earth05-09.dat
sun-ephemeris sun05-09.dat
sky-marks all_sky_marks.txt
sky-grid targeted_rectangular
first-bin 180000
nbins 501
do-cutoff 1
filter-lines 0
averaging-mode single_bin_loose
spindown-start-time 793154935
spindown-start -1e-8

expected-timebase 7
write-dat NONE
#write-png NONE
subtract-background 1
ks-test 1
compute-betas 0
output-initial 1
max-candidates 0

fake-ref-time 793154935
fake-ra 2.0
fake-dec 1.0
fake-iota 1.570796
fake-psi 0.392699
fake-phi 0.0
fake-spindown -1e-8
fake-strain 3e-24
fake-freq 100.1389

focus-ra 1.978040
focus-dec 1.009798
focus-radius 0.3
skymap-resolution-ratio 0.25

compute-skymaps 1

initial-dataset-seed 0

nchunks 1
fine-factor 5

output loose_pi_2
```

Figure 17: config.loose\_pi\_2

```

#
# Mark general sky areas
#
band "south" "" 0.0 1.570796 -2.0 -0.65
band "midsouth" "" 0.0 1.570796 -0.65 -0.3
band "equator" "" 0.0 1.570796 -0.3 0.3
band "midnorth" "" 0.0 1.570796 0.3 0.65
band "north" "" 0.0 1.570796 0.65 2.0

#
# Using J2000, equatorial coordinates
# All numbers in radians
#
#disk "North_pole" "" 4.712389 1.16 0.05
#disk "South_pole" "" 1.570796 -1.16 0.05
line_response "Lines" "" 0.05 3

# Mask
#band "" "" 1.570796 0.0 -2 0
#band "" "" 2.199115 0.0 0 2

```

Figure 18: all\_sky\_marks.txt

```

new_dataset "H1_test1"
detector "LHO"
gaussian_fill 793154935 900 20001 1e-24
apply_hanning_filter

```

Figure 19: random.dst

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