

Followup procedure in time-domain \mathcal{F} -statistic searches for continuous gravitational waves

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Potentially interesting gravitational-wave candidates (outliers) from the blind all-sky searches have to be confirmed or rejected by studying their origin and precisely estimating their parameters. We present the design and first results for the followup procedure of the **Polgraw** all-sky search pipeline: a coherent search for almost-monochromatic gravitational-wave signals in several-day long time segments using the \mathcal{F} -statistic method followed by the coincidences between the candidate signals. Approximate parameters resulting in these two initial steps are improved in the final followup step, in which the signals from detectors are studied separately, together with the network combination of them, and the true parameters and signal-to-noise values are established.

1 Introduction

The all-sky time-domain \mathcal{F} -statistic pipeline¹ (Jaranowski et al., 1998) aims at detecting almost monochromatic continuous gravitational-wave (GW) signals of a frequency f and its time derivative \dot{f} .

An astrophysical source providing a periodically time-varying mass or current quadrupole is e.g. a non-axisymmetric rotating, spinning-down neutron star. The deviation from axisymmetry may be caused by elastic or magnetic stresses, instabilities, accretion or non-equilibrium heating (see e.g. Lasky, 2015, for a review).

The **Polgraw** all-sky search pipeline is composed of the following components: (I) preparation of the initial narrow-band time-domain series (typically 1 Hz width and a few days long, with the sampling rate of the order of 1 s) and ephemerides needed for the position of the detectors with respect to the source, and the optimal grid of templates (Pisarski & Jaranowski, 2015) in the parameter space of frequency f , frequency derivative (spindown) \dot{f} , right ascension α and declination δ , (II) the **search** code i.e.: a coherent search for candidate signals in narrow-band time-domain segments of length $T \simeq$ few days (definition of the \mathcal{F} -statistic is given in Jaranowski et al. 1998).

The pipeline has been used in the all-sky search for periodic GWs in the Virgo VSR1 data (Aasi et al., 2014), LIGO O1 data (Abbott et al., 2017) and in the LIGO S6 Mock Data Challenge (Walsh et al., 2016). For a recent summary of search methods used by the LIGO/Virgo collaboration see e.g.: Bejger (2017).

¹Project repository and documentation: <https://github.com/mbejger/polgraw-allsky>

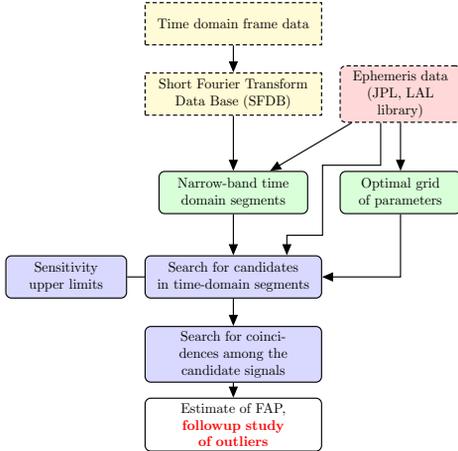


Fig. 1: Block diagram of the time-domain \mathcal{F} -statistic pipeline.

First implementation of the all-sky algorithm was presented in Astone et al. (2010). Currently the data from a network of N detectors may be combined coherently, resulting in the sensitivity improvement proportional to \sqrt{N} (see Abbott et al., 2017), (III) coincidences code i.e.: incoherent search for coincidental candidate signal between the time-domain segments (see Aasi et al., 2014, and the code documentation for detailed description), (IV) calculation of the sensitivity upper limits by software injections (`sensitivity-scripts`), (V) estimation of the False Alarm Probability of coincidences (FAP) and the followup of promising coincidences. Block diagram of the pipeline is presented in Fig. 1.

2 The followup procedure

The `followup` code implements the last stage of the time-domain \mathcal{F} -statistic pipeline: final validation to confirm the astrophysical origin of the promising candidates, establish their signal-to-noise ratio (SNR) and estimate their parameters (f , \dot{f} , δ , α). Input data consists of time series (divided into 6-days segments), detector ephemeris and optimal grid (much denser than in the `search` code). Main goal of the code is to find maximum of \mathcal{F} -statistic in the optimal and fastest way. Here is the description of the `followup` procedure. In stage 1a a promising (low FAP) candidate from `coincidences` results is selected, and the closest point on a dense optimal grid is found. Then at some nearby grid points (e.g., ± 2 points in all directions \rightarrow 625 points) the \mathcal{F} -statistic is evaluated (employing OpenMP parallelization). Point with the highest \mathcal{F} -statistic (highest SNR) is the initial point for stage 1b that consists of direct maximum search by either Simplex Nelder–Mead method (Nelder & Mead, 1965) or MADS (Mesh Adaptive Direct Search; Audet & Dennis Jr, 2006) algorithm. Stage 1 is repeated for next data segment. Stage 2 consists of concatenating adjacent data segments and their ephemerides, calculating weighted (by the SNR) mean of results and taking it as an initial point; finally, running `followup` for the concatenated data (directly with Simplex or MADS). Fig. 2 left panel contains an example of the non-trivial structure of the \mathcal{F} -statistic shape.

3 Numerical challenges

Because the computational cost of the `search` code scales with the segment length as $\propto T^5 \log T$ (Astone et al., 2010), one needs to divide data into shorter chunks, like 6-days segments. At the `followup` stage, when one can study the focus only on very narrow part of the parameter space, longer data series are possible. The SNR value increases with the segment length as $\propto \sqrt{T}$, so in principle it is easier

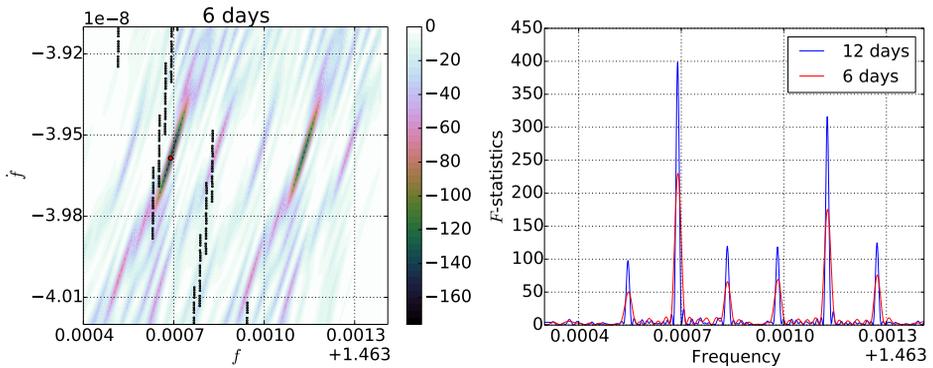


Fig. 2: Left: Shape of the \mathcal{F} -statistic in frequency-spindown plane, with an injected maximum (red point) and points of optimal grid (gray points). Right: Shape of the \mathcal{F} -statistic as a function of the frequency of the 6- and 12-days data segments.

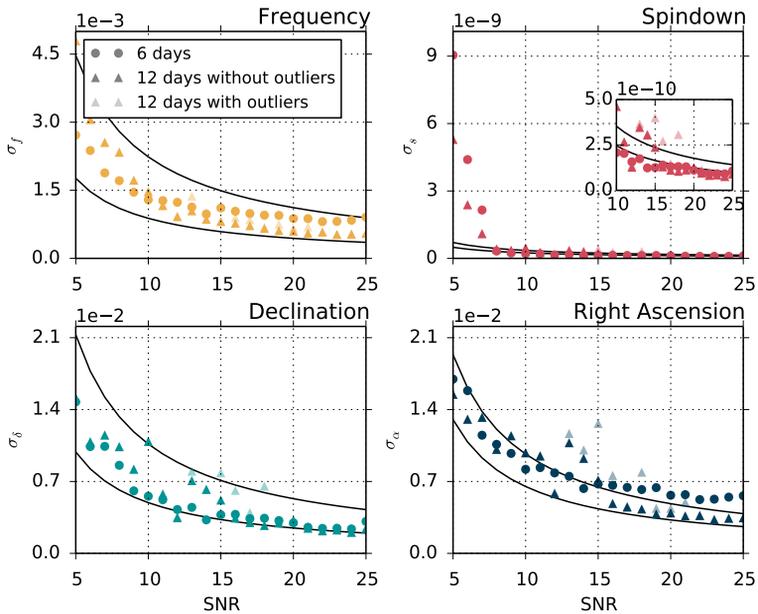


Fig. 3: Standard deviations for 6- and 12-days segments and corresponding theoretical predictions (Cramér-Rao bounds) as black lines: upper for 6 days, lower for 12 days. In a few cases local maxima instead of global ones were found by the `followup` (they were identified and removed not to spoil the comparison).

to find the maximum of the \mathcal{F} -statistic. Alas, with the increasing SNR, some of numerical problems become more vivid: not only the global maximum, but also the local maxima increase. Moreover, all maxima become narrower, therefore when a maximum is found, it is not straightforward to establish whether it is a global or local one. In fact, for concatenated frames, it's easier to find any maximum, but it is more difficult to find a global one (example for concatenated data is presented in Fig. 2 right panel). Results presented in Fig. 3 were obtained by adding a software injection (an artificially generated signal of a given SNR) to a sample of 250 realizations of the Gaussian noise, detecting it with the `followup` procedure and comparing the recovered parameters to the injected signal parameters.

4 Conclusions

We conclude that the `followup` procedure is able to estimate the parameters of injected signals with a satisfactory accuracy, as demonstrated by the comparison with the theoretical predictions. There is still some room for improvement (e.g., with the MADS method). The final goal is to effectively deploy the `followup` procedure on hierarchically-concatenated data consisting of the whole observational run ($\simeq 1$ year of data).

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