A new method to search for long-duration gravitational wave signals

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CONTINUOUS GRAVITATIONAL WAVES

Transient CW-signal in the data

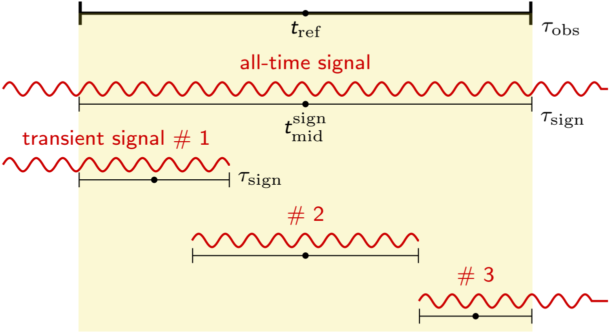


Figure: Scheme of various overlaps of a signal with the observing data.

In the absence of the glitch information, we search for a transient signal with unknown start time and duration in the available data.

Matched-filtering transient search

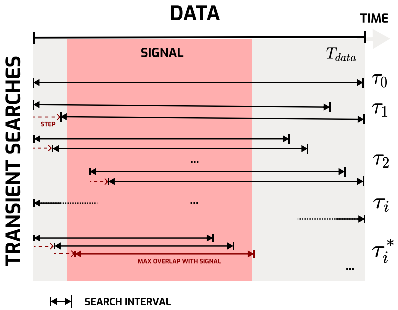


Figure: Scheme of the matched-filtering transient searches.

Matched-filtering method (Prix et al., 2011)

1. Searches over various durations with steps (shifts) in time.
2. At every search duration the templated search in phase parameters is performed.
3. From every search the maximum statistical value ($2\mathcal{F}$) is recorded.
4. Decision about the signal detection is based on the maximum value over all the searches.
5. The corresponding search duration is taken as an estimate of the signal localisation.

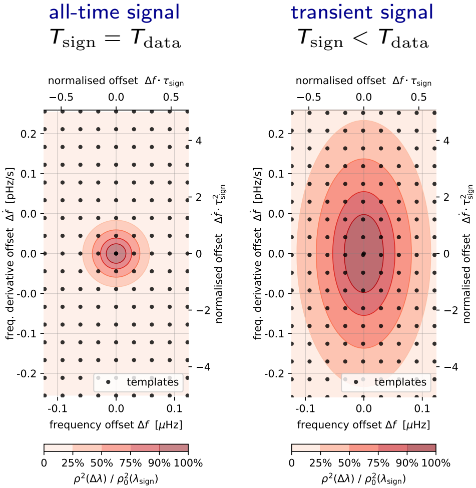
The matched-filtering is the most sensitive method to search for long-duration transients with unknown signal frequency and time parameters

Initial search

Initial search – a search over all the available data is the most computationally expensive search

Can we learn something about a transient signal already from the initial search?

SNR-reduction profile of a transient signal



The SNR-reduction profile of a transient signal does not change, while the template resolution scales with the observation span $\tau_{\rm obs}$.

- The signal parameters are defined at the reference time $t_{\rm ref}$ of a search.
- At different times the values of the frequency and frequency derivatives will in general be different from those at $t_{\rm ref}$.

The orientation of the SNR-reduction ellipse

The iso-overlap surface is an ellipsoid in $f - \dot{f} - \ddot{f}$ space.
Consider slices of this surface at fixed values of $\ddot{f}$.
As the reference time changes these slices also change:

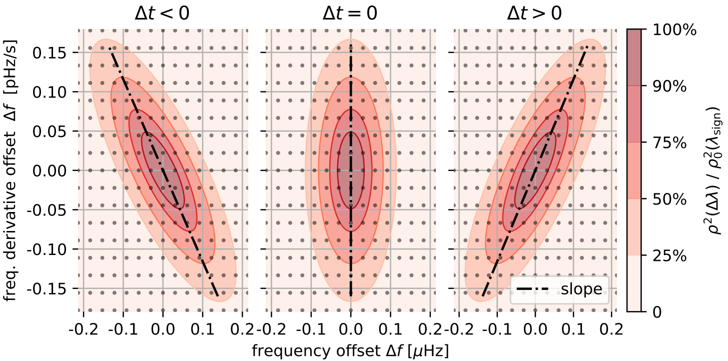


Figure: The SNR-reduction profile for three values of the distance Δt between the reference time of the search and the mid-time of the signal.

The orientation of the SNR-reduction ellipse

How the iso-overlap ellipse evolves in time

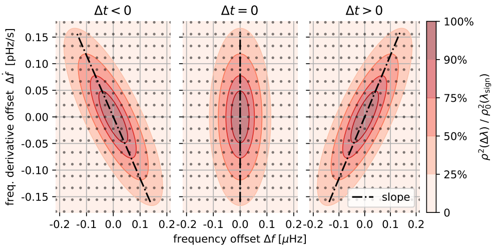


Figure: The SNR-reduction profile for three values of the distance Δt between the reference time of the search and the mid-time of the signal.

$$\Delta t = t_{\mathrm{ref}} - t_{\mathrm{mid}}^{\mathrm{sign}} = \frac{\Delta f(t_{\mathrm{ref}})}{\Delta \dot{f}(t_{\mathrm{ref}})} \qquad (1)$$

- t_{ref} – the reference time of the search;
- $t_{\mathrm{mid}}^{\mathrm{sign}}$ – the mid-time of the signal.

Based on the information recovered in an all data search, one can estimate the mid-time of a transient signal:

$$t_{\mathrm{mid}}^{\mathrm{sign}\,*} = \frac{\Delta f(t_{\mathrm{ref}})}{\Delta \dot{f}(t_{\mathrm{ref}})} - t_{\mathrm{ref}} \qquad (2)$$

Estimation of the middle time of a transient signal

We assume there is a transient signal of unknown time-localisation in the data.

Estimation of the middle time of a signal

1. Perform a template search in frequency over all the available data in a thin phase parameter space around a candidate.
2. Find the main axis of the SNR-reduction profile from the search.
3. Estimate the signal mid-time from its slope:

$$t_{\mathrm{mid}}^{\mathrm{sign}\,*} = \frac{\Delta f(t_{\mathrm{ref}})}{\Delta \dot{f}(t_{\mathrm{ref}})} - t_{\mathrm{ref}} \tag{3}$$

t_{ref} – the reference time of the search.

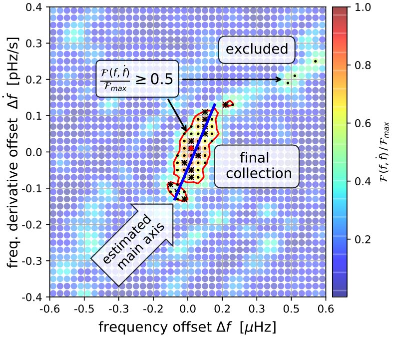


Figure: Illustration of the proposed algorithm to estimate the main axis.

Errors in the determination of the signal mid-time

Relative error in the estimation of the mid-time

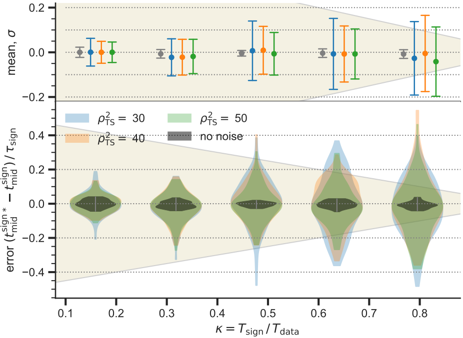


Figure: Violin plots for the distributions of the errors in the determination of the signal mid time. The top plot shows the mean and the standart deviation of every distribution. The domain of the maximum errors for transient searches are represented by yellow

Distance between the estimated middle time and the actual middle time of a signal:

$$\Delta t^{\mathrm{sign}\,*}_{\mathrm{mid}} = t^{\mathrm{sign}\,*}_{\mathrm{mid}} - t^{\mathrm{sign}}_{\mathrm{mid}} \qquad (4)$$

Relative error in the estimation of the mid-time of a signal: $\Delta t^{\mathrm{sign}\,*}_{\mathrm{mid}} / \tau_{\mathrm{sign}}$.

- Our estimates improve for shorter signals: the SNR-reduction profile is more elongated in $\dot{f}$, which allows to find a slope more precisely.

For signals with duration $\kappa \leqslant 0.6$, we expect to make a relative error in the estimation of the mid-time of a signal smaller than 20%.

Post-following transient searches

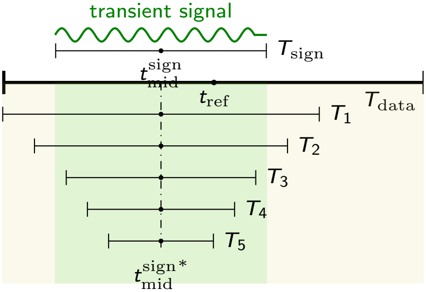


Figure: Scheme of the post-following transient searches around an estimated middle time of a signal

The new method process (Fesik and Papa, 2023)

1. we estimate the middle time $t_{\rm mid}^{\rm sign*}$ of a signal associated with a candidate;
2. we perform searches over different spans τ_i, centered around $t_{\rm mid}^{\rm sign*}$.
3. from each τ_i search we keep the top results $(2\mathcal{F}_{\rm loud})$ in phase parameters for further analysis.
4. T_i^* that yields the maximum detection statistic value is an estimate of the signal duration:

$$T_i^* = \max_{\{T_i\}}[2\mathcal{F}_{\rm loud}\,(\mathcal{T}_i; \mathcal{T}_{\rm sign})], \qquad (5)$$

Recovered signal duration from transient searches

Recovered signal duration with realistic errors

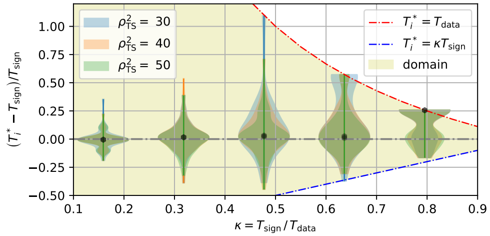


Figure: Violin plots for the distributions of the recovered signal durations for simulated signals of different durations κ. Yellow area – the boundaries.

Relative error in the estimation of the signal duration: $(T_i^* - T_{\rm sign})/T_{\rm sign}$

For signals with duration $\kappa \leqslant 0.6$ we expect to make a relative error in the estimation of the signal duration smaller than 34%.

Computed maximum SNR from transient searches

Computed maximum SNR with realistic errors

SNR computed over a template bank of various signal durations:

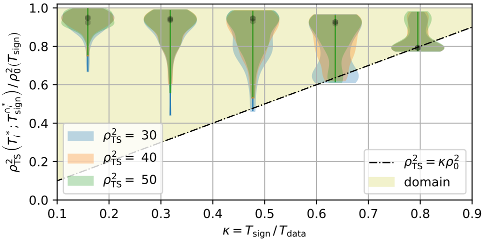


Figure: Violin plots for the distributions of the fraction of the recovered SNR to the perfectly-matched SNR for simulated signals of different durations κ.

The expected SNR loss is never greater than 50%

Summary

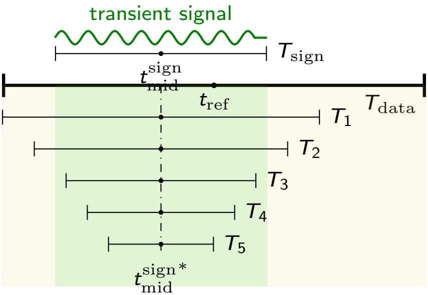


Figure: Scheme of the post-following transient searches around an estimated middle time of a signal

- We propose a method to estimate the middle time of a transient signal, based on the slope of the iso-SNR-reduction profile ellipse of the all-time search.
- We propose a search scheme useful when there are no EM observations to inform on the time of occurrence of the signal.
- We start the transient search based on the results of a search for "always ON" signals.

References

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Thank you for your attention!

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