Detecting long-duration gravitational wave signals

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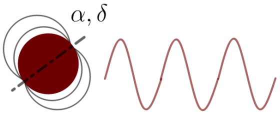
CONTINUOUS
GRAVITATIONAL
WAVES

Continuous gravitational waves (CWs)

- quasi-sinusoidal emission
- sources: isolated spinning neutron stars (pulsars);
- slowly varying frequency
- almost constant amplitude
- emission mechanisms:
  - non-axisymmetric deformations (mass-quadrupole)
  - currents (current-quadrupole)
- CWs are weak but always emitted as long as the neutron star is deformed / the currents exist.
- (almost) infinite duration



$$\lambda^{\mathrm{CW}} = \{\phi, f, \dot{f}, \ddot{f}, ...\}$$

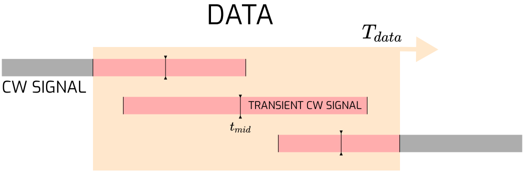
CWs are long-duration (from months to years) gravitational waves from pulsars with almost unchangeable amplitude and slowly varying frequency.

Transient CW-signal: physical sources

- finite duration: from days to months.
- a phase-coherent CW is broken due to a *sudden spin-up* (glitch) in the pulsar's timing.
- glitching sources:
  - observed: Vela, Crab, the fastest young pulsar PSR J0537-6910 (Antonopoulou et al., 2018);
  - expected: the newly born pulsars according to the *r-mode emission* theory (Andersson, 1998)
- actual time parameters of a signal are unknown from electromagnetic observations.
- Example: no glitch information for the regularly glitching pulsar PSR J0537-6910 in O1 and O2 LIGO runs.

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

Transient CW-signal in the data



Transient CW-signal in the data is when the signal overlaps the data from detectors.

Matched-filtering transient search

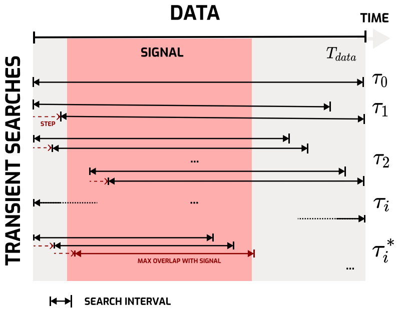


Figure: Scheme of the matched-filtering transient searches. *Figure credit: A. Vishnevskaya*

Method (Prix et al., 2011)

- Searches over various time-intervals with steps (shifts) in time and over the frequency range with an appropriate template grid.
- From every search the maximum statistical value ($2\mathcal{F}$) is recorded.

Detection

- Decision about the signal detection is based on the maximum value over all the searches.
- The corresponding search duration is taken as an estimate of the signal duration.

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

New approach: Estimation of the middle time of a transient signal

Estimation of the middle time of a signal

1. There is a transient signal of unknown time parameters in the data.
2. Perform a template search in frequency over all the available data.
3. The SNR-reduction profile from the search has a slope depending on the distance between the reference time of the search and the mid-time of the signal.

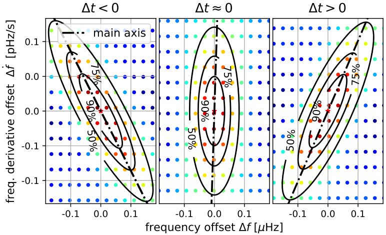


Figure: The SNR-reduction profile for three values of the distance Δt between the reference time of the search and the mid-time of the signal.

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

Post-following transient searches

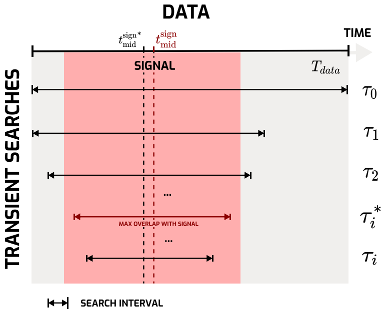


Figure: Scheme of the post-following transient searches around an estimated middle time of a signal *Figure credit: A. Vishnevskaya*

Method (Fesik and Papa, 2022)

- Searches over various time-intervals with the common reference time – the estimated middle time of a signal, and over the frequency range with an appropriate template grid.
- From every search is recorded the maximal statistical value ($2\mathcal{F}$).

Detection

- Decision about the signal detection is based on the maximum value from the searches.
- The corresponding search duration is taken as an estimate of the signal duration.

With the estimated middle time of a signal, we are able to localise the signal in duration and recover its signal-to-noise ratio.

The recovered SNR and signal duration

Estimation of the signal duration

- an error in the estimation of the middle time produces over- or underestimate of the signal duration.
- the larger is an error, the greater is the deviation of the recovered duration.

Recovered transient-signal SNR

- The minimum recovered signal SNR from the transient searches is limited by the value recovered in the initial search.
- The deviation of the recovered signal duration is also limited.

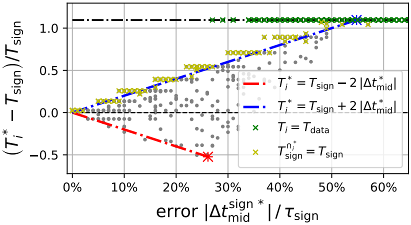


Figure: The recovered signal duration T_i^* as a function of the errors $|\Delta t_{\rm mid}{}^*|$ in the estimate of the mid-time of a transient signal.

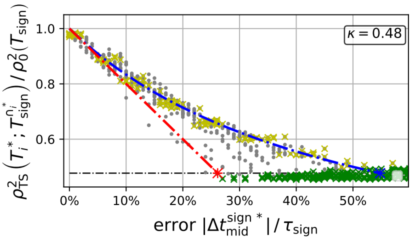


Figure: The value $\rho^2_{\rm TS}\,(T_i^*;\,T^{\cap_i^*}_{\rm sign})/\rho^2_0\,(T_{\rm sign})$ as a function of the errors $|\Delta t_{\rm mid}{}^*|$.

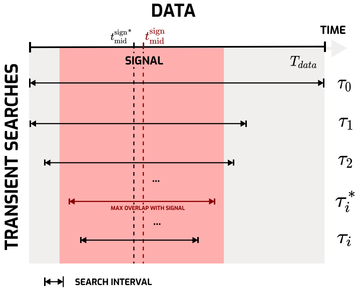
Application of the method

The method can be applied in the absence of the glitch information during the observation period.

Possible objects to search

- Glitching pulsar PSR J0537-6910: there were no timing information about the glitches during the O1 and O2 LIGO observing runs.
- Other objects with accident or periodic glitch activity, which have not been explored yet.

Summary



1. Initial search over all available data in the frequency range.
2. Estimation of the middle time of a signal.
3. Search with various time-intervals around the estimated middle time.
4. The best statistical result is recorded as signal's candidate and the corresponding interval is an estimate of the signal's duration.

We propose the method, which allows to localise a transient CW-signal in time and recover the signal's SNR in the absence of the glitch information.

References

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Thank you for your attention!