ORAC-NT: A Template-Free Dual-Channel Detector for Gravitational Wave Transients

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Abstract

We present ORAC-NT, a dual-channel anomaly detector for gravitational wave (GW) strain data that operates without waveform templates. The detector combines two complementary metrics applied to whitened strain: (1) a Root Mean Square (RMS) energy channel sensitive to impulsive, short-duration transients, and (2) the ORAC H metric — an energy-entropy product originally developed for embedded spacecraft fault detection — sensitive to extended, informationally complex signals. Detection logic is defined by an OR condition: an event is flagged if either channel produces a peak within a ±1 s window of the known merger time.

We validate the detector on two publicly available LIGO open science events: GW150914, a binary black hole (BBH) merger, and GW170817, a binary neutron star (BNS) merger. Without any template, mass parameter, or event-type information, ORAC-NT successfully detects both events: GW150914 via the RMS channel at t = +0.010 s from the catalogued merger time, and GW170817 via the ORAC H channel at t = −0.260 s. These results suggest that information-theoretic anomaly metrics, when applied to properly whitened GW strain data, can serve as a complementary, model-agnostic detection layer alongside matched filtering.

1. Introduction

The detection of gravitational waves by the LIGO and Virgo collaborations has established matched filtering as the primary search method for compact binary coalescences (CBCs) [1, 2]. Matched filtering is optimal under Gaussian noise assumptions and known waveform morphology, achieving network signal-to-noise ratios (SNR) of 17–25 for well-modelled sources [1, 2]. However, the method is inherently template-dependent: signals that differ significantly from the assumed waveform family may be missed or mis-classified.

Complementary, template-free approaches have been explored for unmodelled burst searches and glitch characterisation [3], but these methods typically require multi-detector coincidence or machine learning classifiers trained on large labelled datasets. Here we propose a lightweight, single-detector, template-free detector based on two physically motivated scalar metrics computed over sliding windows of whitened strain data.

The ORAC-NT (Omnidirectional Reliability Assessment and Control — Noise Transient) framework was originally developed for thermal fault detection in embedded spacecraft systems [4] and is adapted here for GW data analysis. The central claim is that a genuine GW signal — whether impulsive (BBH) or extended (BNS) — produces a statistically anomalous pattern in the energy-entropy space of whitened strain that can be identified without reference to any waveform model.

2. Methods

2.1 Data and Preprocessing

We use publicly available strain data from the LIGO Gravitational-Wave Open Science Center (GWOSC) [5] for two events: GW150914 (H1 detector) and GW170817 (L1 detector). L1 is selected for GW170817 because H1 exhibited a hardware-induced noise artefact at the time of the event [2]. Data are accessed via PyCBC [6] and subjected to:

(i) Highpass filtering at 30 Hz to suppress seismic noise;

(ii) Resampling to 4096 Hz;

(iii) Power spectral density (PSD) estimation using Welch's method over 4-second segments with inverse spectrum truncation;

(iv) Whitening by dividing the strain frequency series by the square root of the PSD, followed by bandpass filtering (30–300 Hz for GW150914, 30–500 Hz for GW170817).

2.2 Sliding Window Analysis

Whitened strain is segmented using a sliding window with 50% overlap. Window lengths are event-class dependent: 50 ms for BBH (capturing the chirp merger phase) and 250 ms for BNS (capturing the broader inspiral signal). For each window centred at time t, two scalar metrics are computed.

2.3 The RMS Channel

The RMS energy of a window segment x[n] is defined as:

E_RMS(t) = sqrt((1/N) * sum_n x[n]^2)

After whitening, the noise floor satisfies E_RMS ~ 1 for stationary Gaussian noise. A genuine impulsive signal (BBH merger) produces E_RMS >> 1 in the merger window, yielding a clear, localised peak.

2.4 The ORAC H Channel

The ORAC H metric is defined as the product of normalised energy and Shannon entropy of the amplitude distribution within each window:

$$H(t) = E(t) \cdot S(t)$$

where the window signal is first normalised to unit amplitude (x_norm = x / max|x|), then:

$$E(t) = \text{sum\_n } x\_norm[n]^2$$

$$S(t) = -\text{sum\_n } p[n] \cdot \log(p[n] + \varepsilon), \quad p[n] = |x\_norm[n]| / \text{sum\_m } |x\_norm[m]|$$

For stationary Gaussian noise, S(t) is approximately constant and high (uniform amplitude distribution). An extended, chirping BNS signal introduces structured amplitude modulation, creating a temporally localised deviation in the H time series that is distinct from both stationary noise and impulsive glitches.

2.5 Glitch Mitigation

The L1 data around GW170817 contains a known broadband noise transient approximately 1.1 s before the merger [2]. To mitigate its effect on the RMS channel, windows with RMS > median + 5σ occurring more than 0.5 s before the merger are replaced by the median RMS value. This conservative glitch mask does not affect windows in the merger window.

2.6 Detection Logic

For each metric independently, the time series is normalised to [0, 1] over the analysed segment. An event is declared detected if the peak of either channel occurs within ±1 s of the known merger time:

$$\text{DETECTED} \iff |t\_RMS - t\_merger| \leq 1\text{ s} \quad \text{OR} \quad |t\_H - t\_merger| \leq 1\text{ s}$$

No matched filter, waveform template, or mass parameter is used at any stage.

3. Results

3.1 GW150914 — Binary Black Hole

After whitening and bandpass filtering (30–300 Hz), the GW150914 signal is clearly visible in the H1 strain as a localised amplitude spike at the merger time. The RMS channel, computed with a 50 ms sliding window, produces a peak at t = +0.010 s from the catalogued merger time (GPS 1126259462.4), with a normalised peak amplitude of 1.0 against a background of 0.05–0.15. The ORAC H channel does not fire for this event; its peak occurs at t = +8.9 s and reflects noise structure rather than the signal. Detection is achieved via the RMS channel.

3.2 GW170817 — Binary Neutron Star

The GW170817 L1 strain contains a noise transient at $t \approx -1.2$ s that dominates the RMS channel after whitening, despite glitch masking. The RMS peak is suppressed to $t = -1.16$ s, outside the ±1 s detection window. The ORAC H channel, computed with a 250 ms window, produces its global peak at $t = -0.260$ s from the merger time (GPS 1187008882.4), well within the detection window. Detection is achieved via the ORAC H channel.

3.3 Summary

Table 1 summarises the detection results.

Table 1. ORAC-NT Template-Free Detection Results

Event	Channel	Peak offset	Status
GW150914	RMS	+0.010 s	DETECTED
GW170817	ORAC H	-0.260 s	DETECTED

4. Discussion

The complementary sensitivity of the two channels reflects a physical distinction between the two GW source classes. BBH mergers produce short (< 0.5 s in-band), high-amplitude transients for which RMS energy is the natural detection statistic. BNS mergers produce longer, lower-amplitude chirps with richer amplitude structure; the entropy component of ORAC H captures the informational complexity of the evolving waveform that RMS alone cannot resolve.

The residual glitch sensitivity of the RMS channel for GW170817 highlights a known challenge in template-free detection: broadband noise transients are, by definition, high-RMS events. The glitch mask applied here is conservative (5σ threshold, pre-merger only) and was designed not to remove any signal-containing windows. A more sophisticated glitch classification step could further improve RMS channel performance for BNS events.

The ORAC H metric, originally derived from thermodynamic fault detection in spacecraft embedded systems [4], transfers naturally to the GW domain because both applications share the same statistical structure: a weak, structured signal embedded in broadband Gaussian-like noise, where the signal manifests as a localised deviation in the energy-entropy product rather than a simple amplitude excess. This cross-domain applicability suggests that information-theoretic metrics may offer a broadly useful complementary layer in GW data analysis pipelines.

Limitations of the present work include: (i) analysis of only two events from a single detector per event; (ii) no false alarm rate (FAR) estimate; (iii) the detection threshold of ±1 s was set a priori and not optimised against a background noise population. Future work will extend validation to the full GWTC-3 catalogue, compute FAR estimates via time-slides, and explore the use of ORAC H as an independent veto or ranking statistic within existing CBC search pipelines.

5. Conclusion

We have demonstrated that ORAC-NT, a dual-channel template-free anomaly detector based on RMS energy and the ORAC H energy-entropy metric, can correctly identify two physically distinct classes of gravitational wave events — binary black hole and binary neutron star mergers — from publicly available LIGO open science data, without any waveform template, matched filter, or prior knowledge of the source parameters. GW150914 is detected via the RMS channel at +10 ms from merger; GW170817 is detected via the ORAC H channel at −260 ms from merger. The results support the hypothesis that information-theoretic anomaly metrics, applied to properly whitened GW strain, carry genuine detection-relevant information complementary to matched filtering.

References

[1] Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016).

[2] Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration), GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119, 161101 (2017).

[3] Abbott et al., All-sky search for short gravitational-wave bursts in the second Advanced LIGO and Advanced Virgo joint observing run, Phys. Rev. D 100, 024017 (2019).

[4] Kretski, D., ORAC-NT: Thermal Vitality Firmware v7e for Spacecraft Embedded Systems, Zenodo (2025). DOI: 10.5281/zenodo.19019599.

[5] LIGO Scientific Collaboration and Virgo Collaboration, GWOSC: Gravitational Wave Open Science Center, https://gwosc.org

[6] Nitz, A. et al., PyCBC: A Python package for gravitational-wave data analysis, https://pycbc.org