Possible associated signal with GW150914 in the LIGO data

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Abstract. We present a simple method for the identification of weak signals associated with gravitational wave events. Its application reveals a signal with the same time lag as the GW150914 event in the released LIGO strain data with a significance of approximately 3.2\textsigma. This signal starts about 10 minutes before GW150914 and lasts for about 45 minutes. Subsequent tests suggest that this signal is likely to be due to external sources.

Keywords: gravitational wave detectors, gravitational waves / experiments

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1 Introduction

The announcement by LIGO of the first observed gravitational wave (GW) event GW150914 [1] has opened a new era in astrophysics and generated considerable interest in the observation and identification of associated signals. Currently, attention has largely been focussed on electromagnetic signals, especially gamma rays [2–4], that have the potential to confirm both the existence and nature of GW150914. However, there is also work that suggests no electromagnetic radiation can be detected in such mergers [5]. In this work, we consider a rather different approach intended to identify weaker signals in the LIGO strain data that have the same time lag as GW150914 itself. The observation of such associated signals is potentially useful in understanding the nature of the primary GW event.

2 How to search for an associated signal

At the time of the GW150914 event, the LIGO experiment had two running sites: Hanford (H) and Livingston (L). Let the filtered strain data from them be $H(t)$ and $L(t)$, and let the arrival time delay between the two sites be $\tau$ in the allowed range of $-10 \leq \tau \leq 10$ ms. For convenience, we write the H/L strain data in time range $(t_a,t_b)$ as $H_{t_a}^{t_b}$ and $L_{t_a}^{t_b}$, respectively. The correlation coefficient between the H/L strain data at time $t$ with delay $\tau$ and window width $w$ is

$$C(t,\tau,w) = \text{Corr}(H_{t+\tau}^{t+w},L_{t+\tau}^{t+w}).$$

(The GW150914 signal arrived first at the Livingston site and reached the Hanford site approximately 6.9 ms later [1]. Thus, eq. (2.1) has been written so that $\tau$ is positive for GW150914.) Here, Corr($x,y$) is the Pearson cross-correlation coefficient between two records $x$ and $y$ defined as

$$\text{Corr}(x,y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \cdot \sum (y - \bar{y})^2}}.$$
where the sums extend over all entries contained in the time interval considered and where $\bar{x}$ and $\bar{y}$ are the corresponding average values of the entries in $x$ and $y$, respectively. Note that this cross-correlator is independent of the overall scales of $x$ and $y$ and of their average values.

Characterizing the GW150914 by the time of its effective start, $t_{gw}$, and its duration, $w = 0.1$ s, we define

$$C_{gw}(\tau) = \text{Corr}\left(H_{t_{gw}+\tau}^{t_{gw}+0.1s}, L_{t_{gw}}^{t_{gw}+0.1s}\right).$$

(2.3)

Evidently the strongest correlation and the largest magnitude of $C_{gw}(\tau)$ is expected for $\tau = 6.9$ ms. This is confirmed by figure 1.

If there is a secondary signal associated with the GW150914 event in some time interval given by $(t_1, t_2)$, we would expect to find that the corresponding correlator, $C(t, \tau, w)$ is similar to $C_{gw}(\tau)$ in that they will both show a strong anti-correlation for the same value of $\tau = 6.9$ ms. This expectation is independent of both the strength of the associated signal and its shape. If, however, the associated signal is weak, its presence can be obscured by background noise. Since the background noise in the H and L detectors is presumed to be uncorrelated, noise can be suppressed by integrating $C(t, \tau, w)$ over the time stream. Thus, keeping $w = 0.1$ s, we introduce

$$D(\tau) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} C(t, \tau, 0.1s) dt.$$  

(2.4)

The net contribution of noise to $D(\tau)$ should vanish with increasing $(t_1 - t_2)$. If both $(t_2 - t_1)$ and the duration of the associated signal are sufficiently long, we expect that $D(\tau)$ will reveal a significant correlation for $\tau \approx 6.9$ ms even if the associated signal is weak.

The plot of $C_{gw}(\tau)$ in the upper left panel of figure 1 clearly shows the strong anti-correlation at $\tau = 6.9$ ms as expected. It would be natural to think that this local property of the cross-correlator is its only interesting feature. This is not the case. In the absence of noise, any true GW signal would render the records H and L identically except for a time shift. The cross-correlator thus has a form that is similar to that of a convolution of this signal with itself. Using the fact that these records are real functions of time, it is elementary to show that the Fourier transform of the cross-correlator is simply the absolute square of the Fourier transform of the record signal itself. This quantity is immediately recognized as the power spectrum of the signal. This has important consequences. To the extent that two distinct events in the same record thus have the same cross-correlator (as a function of $\tau$), we know that they necessarily have a common power spectrum. Since the power spectrum contains no phase information, it is not the case that the identity of two power spectra implies identical signals in the time domain. Nevertheless, the observation of similarities between $C_{gw}(\tau)$ and $D(\tau)$ might suggest useful constraints on the physical mechanisms that produce them. It is useful to employ the cross-correlator once more to quantify this comparison. Thus, we define

$$E(\tau_1, \tau_2) = \text{Corr}(C_{gw}(\tau), D(\tau)) \text{ with } \tau \in (\tau_1, \tau_2).$$

(2.5)

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1In the LIGO work, GW150914 is assumed to have a duration of 0.2 s, but the strongest part of the signals is found in the later 0.1 s.
Figure 1. The H/L correlation vs. time lag for: GW150914 (upper-left), 30 minutes data before it, 30 minutes data after it (lower-left, see also section 3.1), and both (60 minutes, lower-right). The vertical lines indicate the $6.9 \pm 0.5$ ms range (official value of $\tau$ and its error for GW150914). Data has been rescaled as described in the text.

3 Search for the associated signal and results

Our search for associated signals is based on the publicly available 4096 second H/L strain data taken with a sampling rate of 16384 Hz rate [1, 6, 7]. Data filtering was performed following our previous work [9]. This data set starts at the GPS time 1126257414. Here it is more convenient to use seconds from the beginning of this data set to mark the time. We always exclude 30 seconds at both ends of the data set to avoid the edge problem, and we always exclude the region $\pm 60$ seconds around the GW150914 event (located at $\sim 2048$ seconds) in order to avoid possible contamination of associated signals. Since results were found to be insensitive to the window width, we used the fixed value $w = 0.1$ s for convenience.

3.1 Qualitative test with a simple initial guess

We begin by looking for a signal associated with GW150914 in an arbitrarily chosen region of $\pm 30$ minutes around the primary event. The resulting $D(\tau)$, defined in eq. (2.4), is shown in figure 1. The upper right, lower left and lower right panels show data for 30 minutes before, 30 minutes after and 60 minutes surrounding GW150914. In these three panels we have

\footnote{The LIGO data are publicly available at https://losc.ligo.org/events/GW150914/. In this work, we use the strain time series centered at GPS 1126259462 with a 16384 Hz sampling rate and 32 and 4096 second length. An official tutorial about how to use the data is available at https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html.}

\footnote{In fact, exclusion of $\pm 60$ seconds around the GW150914 event does not significant affect the results.}
shifted and rescaled both $D(\tau)$ and $C_{\text{gw}}(\tau)$ in such a way that they each have an average value of zero and an rms value of 1. This has been done to make the structure in $D(\tau)$ more visible. As might be expected, $D(\tau)$ is quite small. Consider, for example, the right panel of figure 2, the average value of $D(\tau)$ before shifting is $-0.0002$, and the rms deviation from this average value is 0.0010. Although the resulting amplification of the cross-correlator is large, we shall demonstrate below that the structure shown in the figures is significant. From this figure, we see that $D(\tau)$ shows its strongest correlation (marked with a blue circle) for a value of $\tau$ consistent with the accepted value of $6.9 \pm 0.5$ ms for GW150914. Agreement is strongest for the data taken for 30 minutes after GW150914 (for which $E(5\text{ ms},9\text{ ms})=0.82$). These results and the rough similarity of $D(\tau)$ and $C_{\text{gw}}(\tau)$ over the entire physical range of $-10\text{ ms} \leq \tau \leq +10\text{ ms}$ encourage us to seek a more precise estimation of the time and duration of a possible associated signal.

### 3.2 The duration of the associated signal

In section 3.1, the time range was set arbitrarily at $\pm 30$ minutes around GW150914. One possible way of making an improved estimate of the actual duration of an associated signal is to turn to eq. (2.4)–(2.5) and adjust the interval $(t_1, t_2)$ in order to maximize $E(-10\text{ ms},10\text{ ms})$. Doing this we find $t_1 \approx 1280\text{ s}$ and $t_2 \approx 4050\text{ s}$, which means that the associated signal starts $\approx 10$ minutes before GW150914 and lasts for approximately 45 minutes. The results obtained for $D(\tau)$ in this best-fit time range are shown in figure 2. The value $E(-10\text{ ms},10\text{ ms})$ in this time range is 0.84. More details regarding $E(\tau_1, \tau_2)$ are given in table 1.

We note that the strongest correlation is again found close to $\tau = 6.9$ ms as indicated by the blue circle in figure 2. The value $E(5\text{ ms},9\text{ ms})$ in the blue circle increases from 0.82 (figure 1) to 0.96 (figure 2). Since the optimization was performed for $\tau_2 - \tau_1 = 20\text{ ms}$, this improvement provides some support for the validity of the estimation of $(t_1, t_2) \approx (1280\text{ s}, 4050\text{ s})$.
Figure 3. The H/L cross-correlator as a function of time lag for \((t_1, t_2) = (1280\, \text{s}, 4050\, \text{s})\) with a 50–150 Hz bandpass. The correlation between the black and red lines is \(E(-10\, \text{ms}, 10\, \text{ms}) = 0.953\).

3.3 The frequency range of the associated signal

There is no a priori reason for the GW150914 event and its associated signal to have the same frequency range. In particular, one might expect that higher frequencies might be less important in the far longer weak associated signal. Thus, we have considered changing the bandpass range from 50–350 Hz to 50–150 Hz. The result of this change is that \(E(-10\, \text{ms}, 10\, \text{ms})\) increases from 0.84 to 0.95 as shown in figure 3. This remarkable strong similarity between \(C_{gw}(\tau)\) and \(D(\tau)\) (and hence their power spectra) would appear to provide considerable support for the existence of an additional signal at lower frequencies associated with GW150914.

4 Tests and and the estimation of significance

4.1 Possible systematic errors

Given the small amplitude of the associated signal, it is natural to consider the possibility that the similarity between \(C_{gw}(\tau)\) and \(D(\tau)\) is due to unidentified systematic errors. Here we partly reject this hypothesis by application of increasingly narrow bandpass filters. More components of systematic error should be removed as we go through this sequence of increasingly narrow bandpass filters. The fact that this results in monotonically increasing values of \(E(-10\, \text{ms}, 10\, \text{ms})\) (table 2) suggests that the correlation found in section 3 is not due to systematic errors.

Another test is also informative. We split the frequency bands from 30 to 150 Hz into six sub-bands, each of width 20 Hz. In each sub-band we determine the value \(E(-10\, \text{ms}, 10\, \text{ms})\). The results are listed in table 3. Here, we can see all six values of \(E(-10\, \text{ms}, 10\, \text{ms})\) are positive. Moreover, the correlations found in the 50–70 Hz and 90–110 Hz sub-bands are almost perfect. The associated signal appears to be broadly spread in frequency space. Since LIGO systematic errors sources are normally of a well-defined frequency, the results of table 3 suggest that the associated signal is more likely due to external sources than to systematic effects.

4.2 Illustration using the LIGO S6 data

In order to estimate the significance of the signal associated with GW150914, it would be useful to have a large data set that does not contain any candidates for a strong GW event.
Unfortunately, no suitable data set is currently publicly available. Thus, although it is far from ideal, we have considered the LIGO S6 data set [8]. This data, which predates the LIGO upgrade that resulted in GW150914, was obtained under different physical conditions and may not be quantitatively useful in understanding data associated with GW150914. Therefore, for the purpose of illustration we downloaded S6 data consisting of 300 records of 4096 duration each. Each record was filtered with a 50–350 Hz band-pass filter and proceed precisely as above. It is clear that there can be remaining systematic effects or even artificial GW signals introduced by the LIGO team for test purposes. Ignoring all such concerns, we find that the value of $E(-10 \text{ ms}, 10 \text{ ms}) = 0.84$ for $(t_1, t_2) = (1280 \text{ s}, 4050 \text{ s})$ described above is larger than that the ones obtained from the S6 data set. Thus the similarity between $C_{gw}(\tau)$ and $D(\tau)$ are likely not a consequence of noise or systematic effects.

### 4.3 Significance estimation

Since the LIGO noise attribute is non-stationary and non-Gaussian, it is difficult to perform a reliable noise simulation. In such cases, it is normal to use real data with an unphysical time lag (i.e., much larger than 10 ms) in order to estimate the significance of detection. We employ a similar approach here. Specifically, we take pairs of Hanford and Livingston data segments from the filtered data that are 10–600 seconds away from each other in the time stream. For each pair, we then shift them again by $-10 \sim 10 \text{ ms}$ in order to produce a realization of $D(\tau)$ for noise. We then calculate $E(-10 \text{ ms}, 10 \text{ ms})$ between each realization of $D(\tau)$ and the original $C_{gw}(\tau)$. This process was repeated 20,000 times. The resulting distribution of cross-correlators is shown in the histogram of figure 4. For these 20,000 realization of the cross-correlator between $C_{gw}(\tau)$ and noise, we find only 15 for which $E(-10 \text{ ms}, 10 \text{ ms}) > 0.84$. This suggests that the probability of obtaining the observed cross-correlation between $C_{gw}(\tau)$ and $D(\tau)$ accidentally and without a physical source is $7.5 \times 10^{-4}$, which corresponds to a significance of 3.2σ.
5 Conclusion

We have presented a method for identifying weak signals associated with gravitational wave events that is based on time integrals of the Pearson cross-correlation coefficient. Applying this method to the LIGO GW150914 event, we have found indications of an associated signal. This signal has same time delay between Hanford and Livingston detectors as the GW150914 event and has a duration of approximately 45 minutes (from approximately 12 minutes before to 33 minutes after GW150914). Due to the weakness of this associated signal and its duration (which appears to be 4 orders of magnitude greater than that of GW150914 itself), it is not possible to determine its shape in the time domain. In spite of its weakness, however, we have argued that it is unlikely that this signal is of systematic origin. Numerical simulations show that this associated signal has a statistical significance of $3.2\sigma$. While it is suggestive (but not conclusive) that this signal is real, it is not possible to offer a convincing suggestion regarding its origin — astrophysical or otherwise. More generally, however, we have shown the value of studying the cross-correlation between two identical signals as a function of the time shift, $\tau$, between them. In such cases the Pearson cross-correlation coefficient (as a function of $\tau$) is independent of the amplitude of the signals and directly related to the power spectrum of the common signal. Thus, the remarkable similarity of the cross-correlators found here for the associated signal before GW150914, the GW150914 event itself, and the associated signal after GW150914 suggests that their power spectra (but not their time domain shapes) are also similar. Given the dramatic physical differences that are to be expected in a system before, during and after a strong GW event, such a constraint on the associated power spectra could provide a valuable diagnostic tool.

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