H1 L1 PEM vetting report for the Aug. 17, 2017 BNS candidate

Summary:
In summary, we found no reason to veto the candidate. Only one of the core PEM channels was not working at the time of the candidate, and redundant channels provided good coverage. No signals on environmental channels evolved in time and frequency like the candidate. Based on injection and other studies, no signals were present on environmental channels that would produce the candidate through non-linear processes. However, the time-frequency paths of multiple environmental signals crossed the candidate's long-lasting time-frequency path, and several signals were large enough that further investigations would be needed in order to claim that environmental signals made no contribution to DARM along the time-frequency path of the candidate. The estimates of the maximum environmental signal level in DARM, made from PEM injection studies, reached an SNR of 4. Any environmental contributions to DARM were small enough that they were not visible in DARM Omega Scans. The environmental signals were found to be local and non-correlated environmental noise in the two DARMs is accounted for in time-slide background estimates. Special attention was paid to EM data, including data from external EM observatories.

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End time of vetted event:
August 17, 2017, 12:41:04 UTC, 1187008882.4434

I. Primary sensors of environmental coupling

1. Status of sensors: were they working and were they properly monitored by event detectors?

a. Were the channels installed and functioning properly?

There was one malfunctioning core channel, an accelerometer on the LHO PSL table that was not working and there was a non-core low-f microphone that wasn't working at LLO (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11954). In addition, the RF scanner and the LEMI magnetometer at LHO were not working. We are relying more on LigoCAM as vetting becomes more automated, so the core PEM channel spectra were not all examined by hand.

In checks of the standard DetChar configuration files for Omega Scans, we found that some channels were missing and others had the wrong frequency range. This is mainly due to improvements associated with O2, suggesting that the automatically generated DetChar configuration files should be updated.

b. Are malfunctioning or uninstalled channels a coverage issue?

The missing channels were not a coverage issue. There are 5 other accelerometers that monitor PSL table motion. LigoCAM is not as good as expert-examination for identifying marginal channels, but we have redundant coverage and the channel failure rate is low (e.g. only a couple in O2). The RF scanner at

LHO was not working, because of a data storage failure, and the LHO LEMI magnetometer was broken, so we examined data recorded by external observatories.

2. Events in sensors: were any environmental signals loud enough to account for or contribute to the event detected in DARM?

The primary veto scheme is to visually compare the time-frequency paths of the candidate in DARM to coincident events in environmental monitoring channels, detected by the same software (Omega Scans). In addition to looking for TF paths that overlap the candidate, we check for events in other frequency bands that could, according to our understanding of coupling, produce a candidate-like event in DARM. The main characteristic that we look for is that the TF path coincide in time with the candidate in DARM. We assume, based on multiple studies, that the coupling does not change rapidly in time (so, for example, if the PEM event lasts longer than the candidate, without decreasing in SNR, it is dismissed). And we pay special attention to know mechanisms of up or down-conversion. The primary Omega Scans used for TF path vetting were:
https://ldas-jobs.ligo.caltech.edu/~robert.schofield/Omegascans/GW170817/T-LHO2048s-152s-AllOnFullSampleQ75-100/

https://ldas-jobs.ligo.caltech.edu/~robert.schofield/Omegascans/GW170817/U-LLO2048s-152s-AllOnFullSampleQ75-100/

This BNS candidate was more than an order of magnitude longer than previously vetted events (75s pyCBC template), and it required modifications of our previous procedures. First, the event did not trigger Omega Scan for the GW channel with the standard settings, though the inspiral was visible in the scans. For this reason, we examined Omega Scans of all PEM and GS13 channels. The second major modification was made to increase and limit the Q range to 75-100. This was to focus on long narrow-band events like the BNS inspiral, chosen to maximize the visibility of the inspiral in the Omega Scans. In the future, a more distant BNS candidate may not appear in Omega Scans so DetChar may need to develop a template-based search of auxiliary channels.

While we found no PEM events that could account for the candidate, there were events that might have contributed modestly to DARM in small regions along the inspiral TF path. This is based on estimates of the environmental contribution to DARM using coupling functions from PEM injections. Because the TF path lasted so long, there were more than 100 Omega Scan triggers on PEM channels. We estimated contributions to DARM for the highest SNR events and for the events that had long lasting time frequency paths. Several of these events were loud enough that we cannot claim that they could not have contributed to DARM along the path of the inspiral. None were estimated to produce events in DARM with SNRs greater than 4 (from an H1 PSL table accelerometer, Fig. 3), and we observed no correlation in Omega Scans between environmental signals and features in DARM. Several of the loudest environmental events are illustrated below.

3. Focus on important events

The Omega Scan images below are from the run linked above and from:

https://ldas-jobs.ligo.caltech.edu/~robert.schofield/Omegascans/GW170817/X-LLOspecialstudiesfromU/

https://ldas-jobs.ligo.caltech.edu/~robert.schofield/Omegascans/GW170817/Y-LHOSpecialStudiesFromT/

Configuration files are linked from the top of the web pages.

a. Magnetometer events.

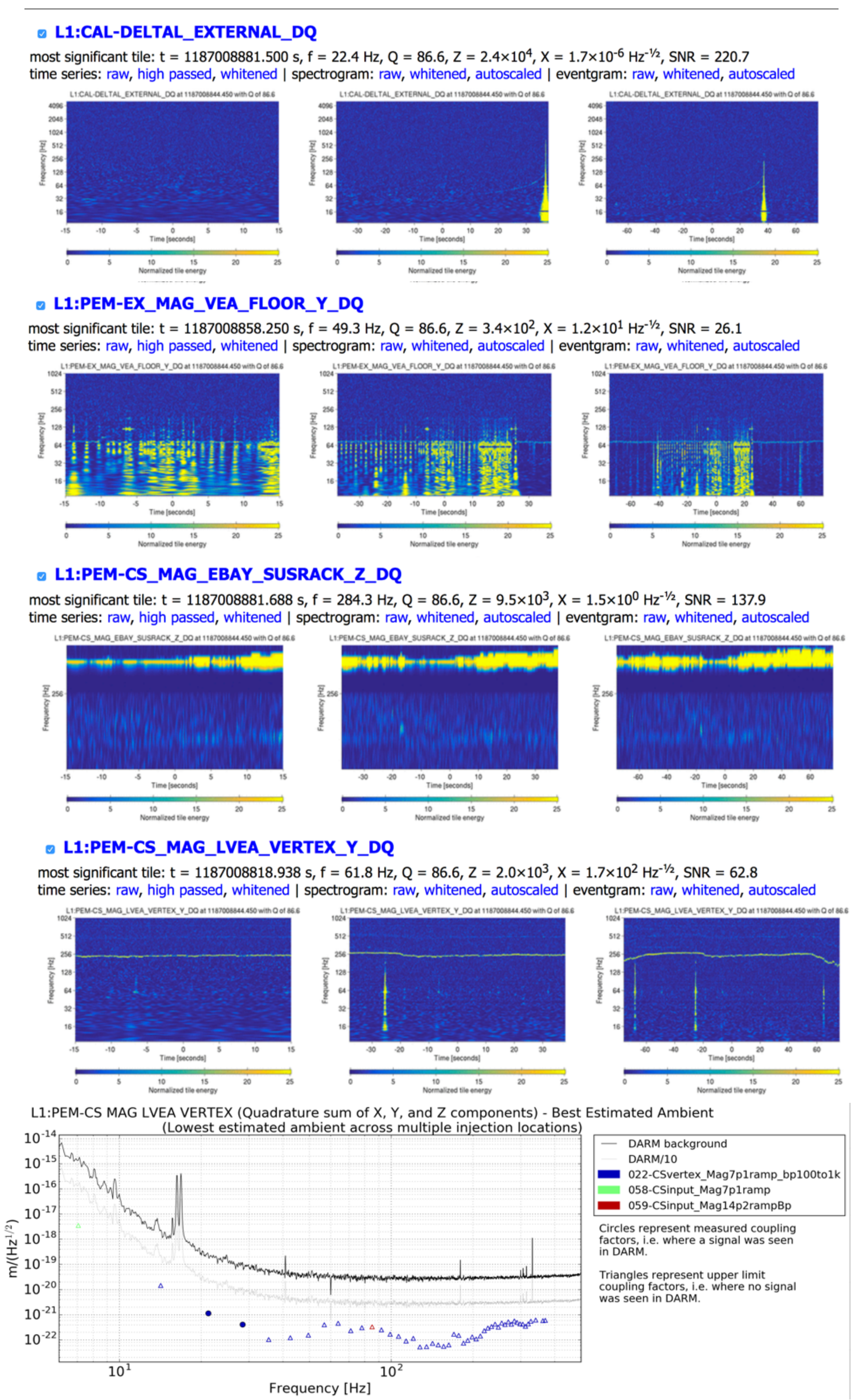

Figure 1. A sample of the loudest magnetometer events at LLO during the candidate. The Omega Scan search region (and the reported SNRs) are for the period of time in the second column, encompassing 76s before the coalescence. All except the EX VEA magnetometer exceed the threshold for claiming that DARM is not affected. The plot at the bottom is the plot from PEM injections used for estimating the contribution of the magnetic event in the row above it: the dots are estimated contributions from the

background and are multiplied by the SNR of 62.8 at 62 Hz to produce an estimate that is close to the level of DARM.

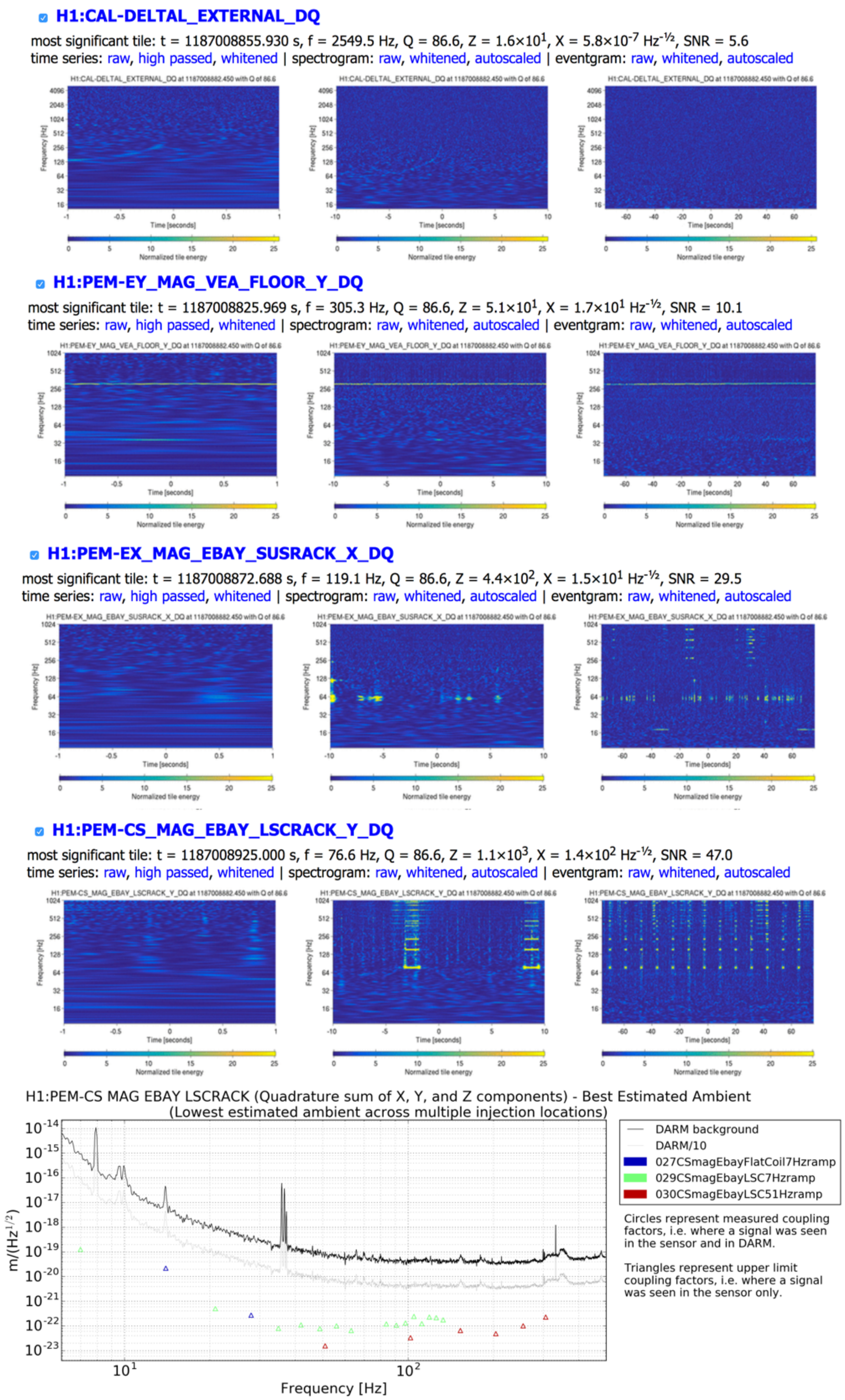

Figure 2. A sample of the loudest magnetometer events at LHO during the candidate. The Omega Scan search region (and the reported SNRs) are for the period of time in the second column, encompassing the candidate. All plotted events exceeded the threshold for claiming that DARM is not affected. The

plot at the bottom is the plot from PEM injections used for estimating the contribution of the magnetic event in the row above it: the dots are estimated contributions from the background and are multiplied by the SNR of 47.8 to produce an estimate that is right at the level of our 1/10th DARM threshold

b. Vibration events

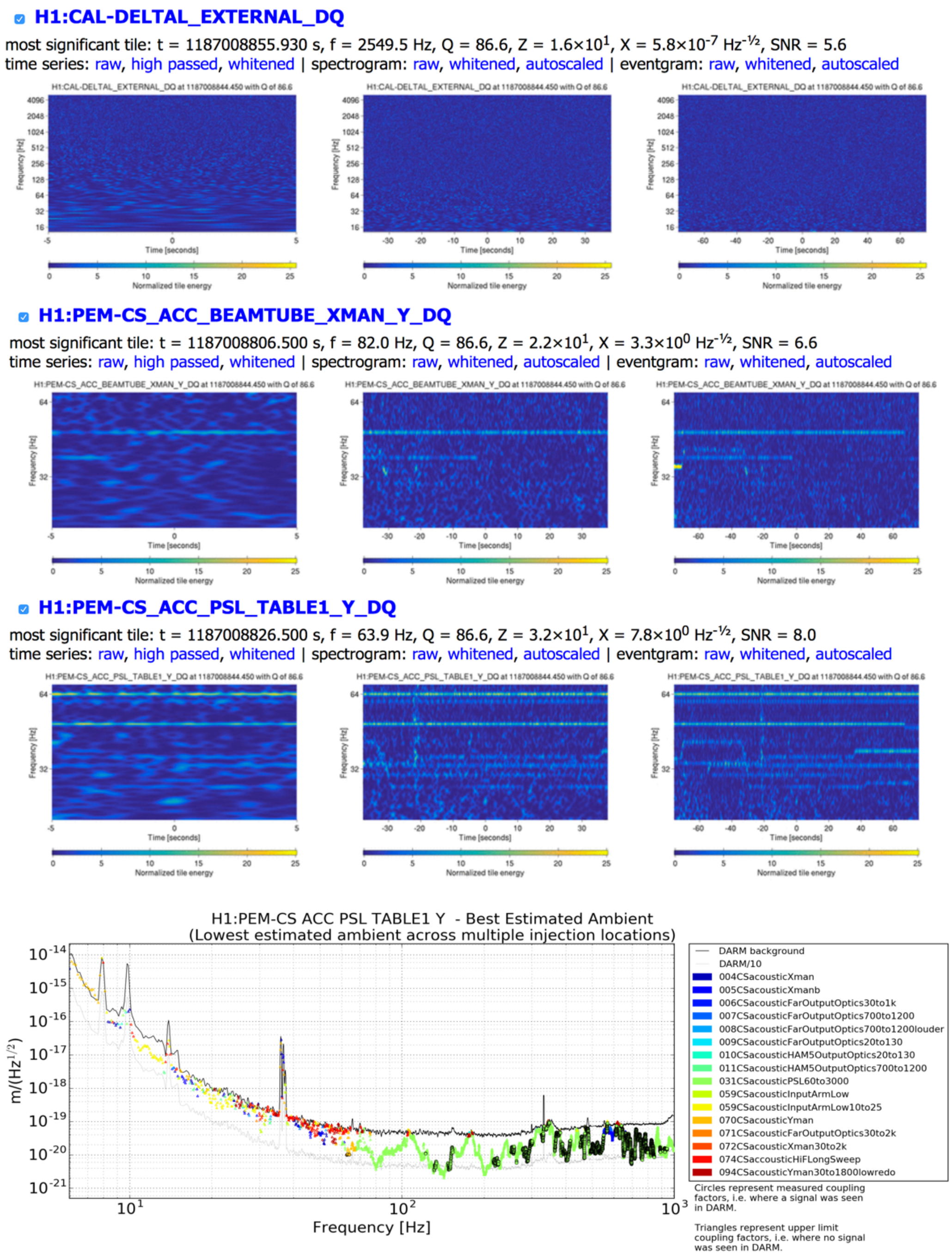

Figure 3. A sample of the loudest vibration events at LHO during the candidate. The Omega Scan search region (and the reported SNRs) are for the period of time in the second column, encompassing the candidate. Both events exceed the threshold for claiming that DARM is not affected. The plot at the bottom is the plot from PEM injections used for estimating the contribution of the vibration event in the

row above it: an SNR of only about 4 in the PSL table accelerometer, at 64 Hz, is needed to reach the level of DARM so the SNR of 8 in the table accelerometer gives an estimate of an SNR of 4 in DARM.

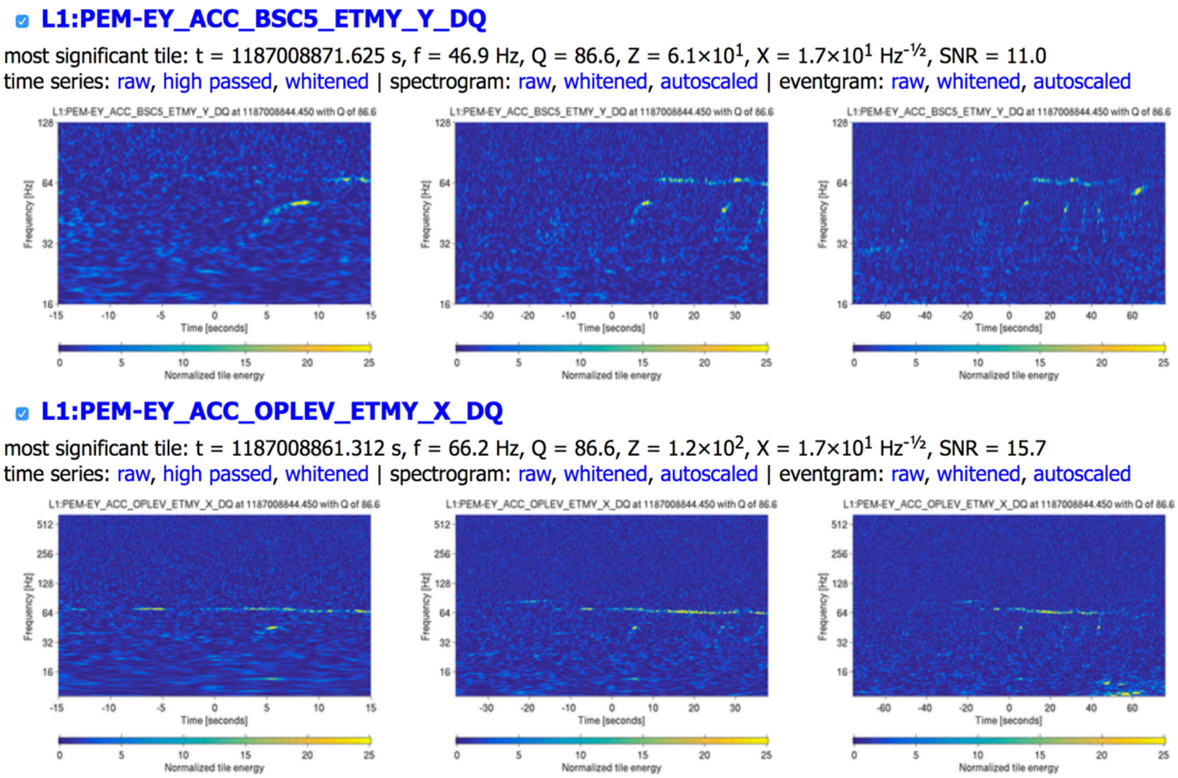

Figure 4. Some of the vibration events at LLO during the candidate. The Omega Scan search region (and the reported SNRs) are for the period of the second column, encompassing the candidate.

c. Mainsmon events

There was a site-wide mains event at LHO during the candidate with an SNR of 38 in H1 EX_MAINSMON_EBAY_2. This SNR multiplied by the SNR upper limit coupling factor (0.033) obtained from PEM injections made to vet a similar (but smaller) event during GW170104, gives an estimated SNR in DARM of 1.3. This exceeds the threshold for claiming that environmental events could not have contributed to DARM during the inspiral, without further studies. An estimate from correlation study of glitches on EY_MAINSMON_EBAY_1 gave a similar estimate of the SNR in DARM (SNR coupling factor: 0.03071).

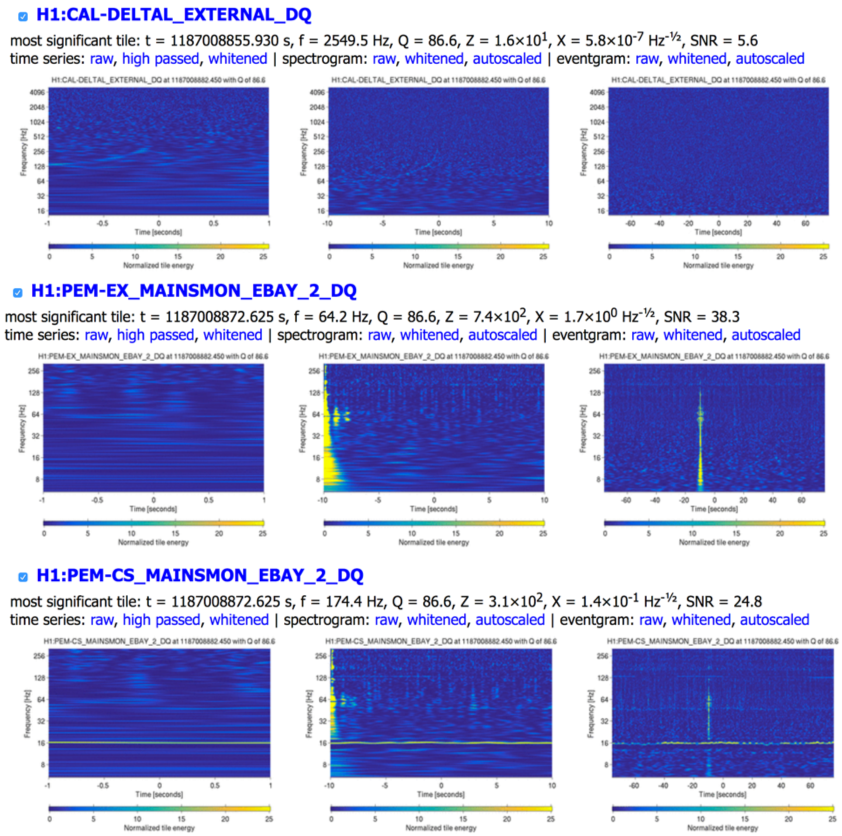

Figure 5. Mainsmons events during the candidate. The Mainsmons feed the mains voltage into the DAQ system via voltage dividers. The two bottom rows show two examples of a glitch that appeared at all stations. As described in the text, the broad band transient was estimated to produce an event in DARM with an SNR of 1.3 (upper limit).

d. Radio events

There were events recorded on the radio channels at both sites (Figure 6). However, these events were short, broad band events and did not appear to be correlated between sites. For the most part, there does not even seem to be a correlation between the LVEA and the ebay, highlighting how local the signals are (probably self-inflicted) and not a concern for correlated RF coupling between the sites.

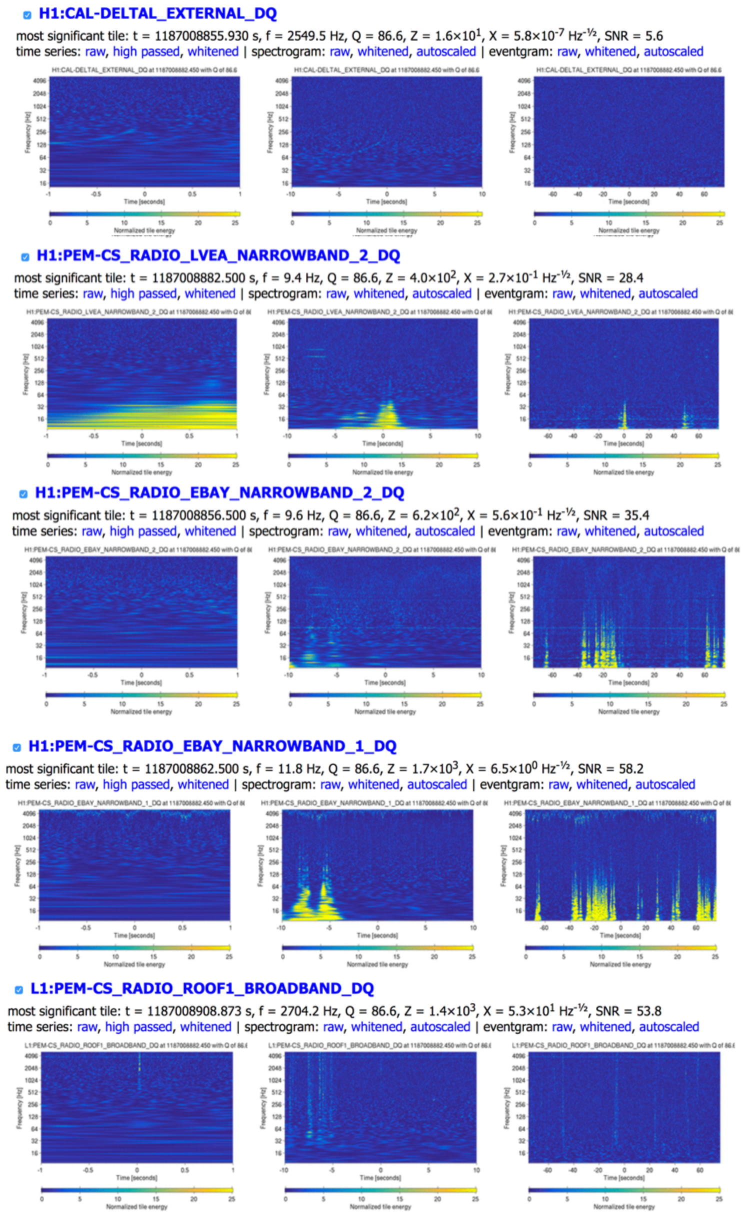

Figure 6. Radio events coinciding with the inspiral. Top row: LHO DARM, coalescence at the center of each plot. Second and bottom rows: RF signals – the frequency on the Y-axis gives the offset from the ~9 MHz (1) or ~45 MHz (2) modulation frequency (which serves as the local oscillator for the receiver). Note the substantial difference between the signals in the LVEA (second row) and the electronics bay a short distance away (third row). This is consistent with locally generated signals. The bottom two rows show what appeared to be the most similar LHO and LLO signals

e. Cosmic rays

Cosmic rays are extremely unlikely to produce non-random coincidences between sites: the high energy particle flux is expected to be nearly 0 only 2-3 km from the axis (Pierre Auger Collaboration, Astroparticle Physics 35 (2011) 266–276). Nevertheless, we monitor them at LHO. The trigger rate was normal (Figures 3 & 4).

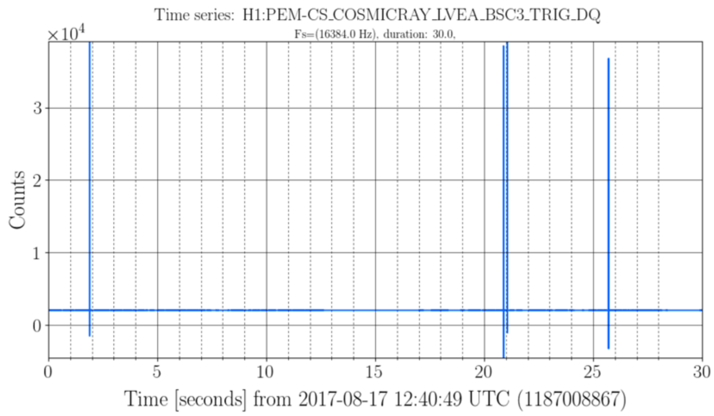

Figure 7. Cosmic ray PMT triggers in the 30s around the coalescence (at 15.45 s).

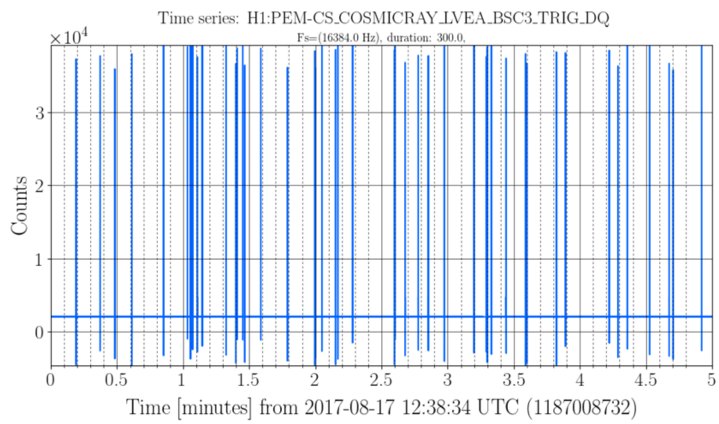

Figure 8. PMT triggers in the 5 minutes surrounding the coalescence, showing no anomalies (Coalescence at about 2.5 minutes).

II. Secondary channels and checks of global environment

1. Our high-sensitivity LEMI magnetometer system

The LEMI magnetometer system, located near the mid-station at LLO (the LHO instrument was not working), show glitches that might overlap with portions of the candidate time frequency path, but these magnetometers are very sensitive and register many glitches in the electromagnetically noisy environment around LLO (see Figure 5). There are no glitches that match the time-frequency path of the candidate. According to PEM injections, the primary magnetometers in the buildings are orders of magnitude more sensitive than needed to detect any inter-site signals that could affect the gravitational wave channel.

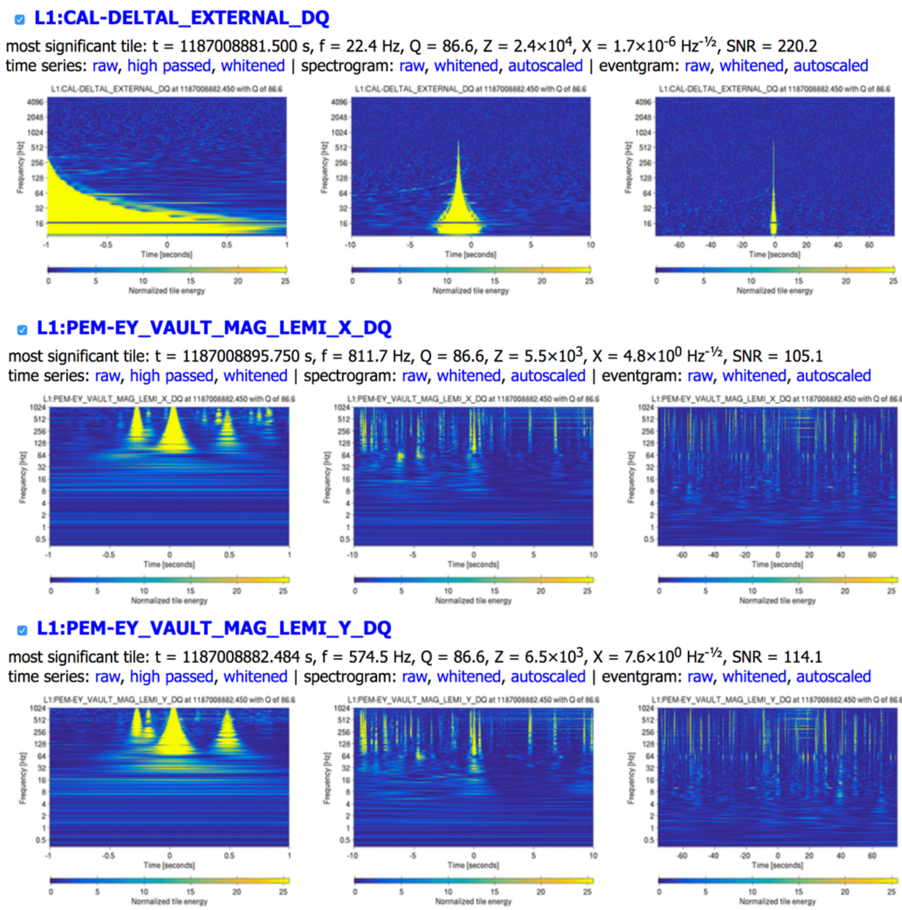

Figure 9. LEMI magnetometer signals at LLO. Any signals loud enough to affect DARM would be registered by the building fluxgates, the primary sensors. No time-frequency path that coincides with the candidate is evident.

2. Global electromagnetic environment from other observatories

The global electromagnetic environment was quiet (see attached report).

III. Coverage and inter-site correlation discussion (not unique to this vetting)

1. Coverage: would primary sensors detect every environmental signal that can influence the IFO?

We attempt to monitor every type of environmental signal that could influence the interferometer, using PEM sensors that are much more sensitive to these signals than the interferometer is. We attempt to distribute sensors so that, for a signal originating further than ten or twenty meters away from the interferometer, there is no coupling location that receives a substantially stronger environmental signal than the nearest PEM sensors.

The environment can influence the interferometer by physical contact, by electromagnetic waves, by static electric and magnetic fields, and possibly by high-energy radiation. Physical contact is made by supporting and other structure, as well as by the air. Physical contact influences the interferometer through vibrations and temperature fluctuations.

We monitor static magnetic and electromagnetic fields up to 2kHz with fluxgate magnetometers. We do not monitor static electric fields, but audio-band fields are highly attenuated by our buildings and chambers and so magnetometers are more sensitive to EM fields (see extensive discussion here: https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11720). Mains electric currents are monitored by magnetometers and by voltage sensors. Injections show that RF fields above 10 kHz have no influence on the interferometer at RF amplitudes that are orders of magnitude above most of the background (https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=23252, https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=22968). The strongest coupling was found to be at the 9 and 45 MHz modulation frequencies. These frequencies were being monitored at both sites with radio receivers. We also monitor 10 kHz to 100 MHz with a scanner at LHO. We monitor vibrations from the contacting media using accelerometers, geophones, seismometers, microphones, temperature and pressure sensors. We monitor for high energy particles with a cosmic ray detector under one of the LHO test masses.

We monitor these signals in the detection band of the interferometer and somewhat below. We monitor higher frequencies when there is a mechanism (e.g. demodulation with known or rouge oscillators) to convert the frequency into the detection band.

By monitoring the immediate environment for signals that can be transmitted through it to the interferometer, we cover the large variety of environmental events that can influence the interferometer. For example, wind can couple through vibrations in the ground and air, and so is covered by seismometers, accelerometers, and microphones. Lighting could couple by magnetic fields, and EM waves at frequencies that we demodulate into the detection band, and so is covered by magnetometers and RF receivers.

2. RF, Cosmic ray, Grid

To the degree that we monitor all environmental influences with sensors that are more sensitive than the interferometers, inter-site coincidences produced by the environment will be vetoed by the PEM channels. Nevertheless, it is especially important to monitor environmental influences that propagate near the velocity of gravitational waves and could influence both sites. We consider global-scale EM events, potentially including power grid events, and global scale high-energy radiation events. We attempt to redundantly monitor these global speed-of-light signals by using sensors at outside observatories. With continued detection of inspirals, our use of external observatories will decline.

In addition to external electromagnetic observatories, we also use cosmic ray observatories, even though the high energy particle flux is expected to be nearly 0 only 2-3 km from the axis (Pierre Auger Collaboration, Astroparticle Physics 35 (2011) 266–276). Since the power grids at Livingston and at Hanford are connected only by AC-DC-AC interconnects, we consider the mains monitors and the magnetometers sufficient and do not check glitch records from the power companies.

3. Synchronized electronics

The hardware and software operating the two LIGO interferometers are similar at each site and their operation is synchronized to GPS time. This precise timing has resulted in low-amplitude combs of spectral lines (e.g. 1 and 16 Hz) that are coherent between sites, produced by slight cyclical corruption of the data. However, we have not seen and do not expect to see transient data corruption events that are synchronized between sites because we do not synchronize transient processes such as hardware reboots. Furthermore, if operation were synchronized, one would expect the events to be simultaneous and not with a reasonable light speed delay, like the candidate has.

IV. Arguments against specific sources for this specific event (not exhaustive)

1) Lightning on a local scale. If loud enough to affect DARM, would be detected by our magnetometers and RF receivers. Lightning produces broad-band EM bursts, not chirps (for global scale see tweaks, whistlers and Schuman resonances below). In an area with a radius comparable to the distance between LHO and LLO, lightning often occurs at a rate of more than 1 per second. We see lightning on our magnetometers out to roughly 100 km, so only rare large events would be seen at both sites (https://dcc.ligo.org/DocDB/0026/T010108/000/T010108-00.pdf). We have detected such events as noted below in the global lightning section.

2) Lightning on a global scale, Schumann resonances, bursts, tweaks and whistlers. If loud enough to affect DARM, would be detected by our magnetometers and RF receivers. Global scale lightning produces audio frequency RF tweaks and whistlers and lower frequency magnetic Schuman resonances and bursts. Tweaks and whistlers descend in frequency, the opposite of inspirals, because of the wave guide and magnetic plasma dispersion relation. They differ in their time-frequency path in other ways as well, including the frequency range and the length of the event.

Schuman resonances are a lightning driven comb of peaks with the fundamental at about 8 Hz (given by light travel time around the earth). They do not dominate the background EM field above 70 Hz, making it highly unlikely that they could produce a 30-300 Hz chirp. The signals are much smaller than the local magnetic noise, but we do detect these in coherence between magnetometers at the two sites (https://dcc.ligo.org/LIGO-P1200167).

There are occasional single lightning-associated events (e.g. gigantic jets) that are observed globally. We detected one of these events in 2009 with high SNR on our magnetometers. No evidence was seen in DARM, as expected for that level of magnetic field, even with the higher magnetic coupling of iLIGO.

For a more detailed report on the effect of lightning, see the report prompted by the p~1e-4 coincidence of a high-current lightning strike over Burkina Faso with GW150914: https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11564.

3) Risers and choruses. If loud enough to affect DARM, would be detected by magnetometers (see extensive discussion here: https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11720). Risers and choruses are audio band RF from nonlinear electron cyclotron resonances beyond the plasmasphere, can rise in frequency like our chirp, but they come in clusters or choruses, not in isolated events like our chirp, and have different time-frequency signatures than our signal. For examples, see spectrograms in: http://www.ann-geophys.net/27/2341/2009/angeo-27-2341-2009.pdf.

4) Global anthropogenic RF traffic. Would be detected by our radio receivers if loud enough to affect DARM. Human-generated RF can occasionally be strong enough to be evident at both sites. In the bands that affect us, the signal would be detected by our magnetometers or radio receivers.

5) Solar events. Would be detected by our RF receivers and our magnetometers if loud enough to affect DARM. Solar radio flares would have been blocked as we were on the night side of the earth. Also, there were no CME-related geomagnetic storms (see attached report).

6) Synchronized DAQ or other electronics or software produced events. We don't synchronize our software or hardware. The precise timing from GPS has lead to combs of lines at certain frequencies at both sites that are coherent, but these don't require that the corruption events producing these combs be synched, only that the frequencies be the same. Events might possibly happen at specific times, like on the hour, but these would be repeated hourly and are not single events like the candidate. Furthermore, if

the candidate were produced by synchronized hardware or software, it would occur at the same time at both sites, not offset by a reasonable light speed delay, as it is.

7) Huge cosmic ray showers. This may not be possible, or may be very unlikely for multiple reasons. For example, the thickness of the atmosphere limits the range of showers to much smaller distances than the distance between our sites. Even for the most energetic showers, the flux is near 0 only 2-3 km from the axis (Pierre Auger Collaboration, Astroparticle Physics 35 (2011) 266–276).

8) Seismic, acoustic or other sub-light speed signals that coincide by chance. These would be detected by our highly redundant vibration monitoring sensors. One would expect a high single-interferometer rate for any such event that produced our candidate since only a tiny fraction would arrive at each site in coincidence (propagation rates are so low that the source would have to be perfectly situated). We do not see high singles rates of our candidate. Also, only at frequencies around 0.03 Hz do seismic signals propagate distances comparable to the distance between sites, because higher frequencies are more attenuated.