PEM vetting report for Sept. 14 candidate, Nov., 2015

Summary:
PEM spectra from the time of the event were checked by multiple people for anomalies or malfunctioning channels. About 15% of PEM channels had not been installed or were not working at the time of the candidate, but redundant channels provided good coverage. We checked Omega Scan configuration files to make sure the necessary channels and bands were searched. Since Omega Scans are limited to a 4096 sample rate, and vibrations over 2500 Hz have been shown to down-convert into the 200 Hz region of DARM, we checked relevant PEM spectra directly for high frequency events. Coupling estimates from PEM injections were used to calculate the estimated SNR in DARM for every PEM channel that triggered Omega Scan in 30-350 Hz band during the second around the candidate, without regard to the time-frequency path. The loudest PEM event would have had to be at least (upper limit) 17 times louder in order to produce an event in DARM with the same SNR as the candidate. Potential environmental mechanisms for producing the Sept. 14 candidate are discussed and rejected. In summary we have found no reason to doubt that the candidate represents the first direct detection of gravitational waves.

Robert Schofield[1], Vinny Roma[1], Jordan Palamos[1], Terra Hardwick[2], Anamaria Effler[3], Ray Frey[1], Dipongkar Talukder[1]

[1]University of Oregon
[2]Louisiana State University
[3]LIGO Livingston Observatory

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?

We prepared Excel sheets containing all PEM channels (attached below). Linked to each channel entry are spectra for 104s and 1s of data, centered roughly on the event (red spectra) and 200s before the event (blue spectra).

The spectra were examined by three people who had familiarity with the channels, from working on installation and calibration (0 = not working, 0.5 = don’t know, 1 = working, -1 = irrelevant).

At LHO, of 156 channels, 24 (15%) were not working or had not been installed at the time of the event.

At LLO, of 126 channels, 16 (13%) were not working or had not been installed at the time of the event.

b. Are malfunctioning or uninstalled channels a coverage issue?

We do not think that the missing channels seriously compromised PEM coverage. Each of the channels that were not working are tabulated below and the effect on coverage evaluated. The most important missing channels were the entire set of mains voltage monitors at LLO. But voltage glitches also produce magnetic glitches and magnetometers were working.

In addition, some magnetometers at each site were not working, but every building had at least one functioning magnetometer.

Table 1. Channels that were not working at LHO and evaluation of effect on coverage (excluded from this list are temperature channels)

PEM channel	Coverage evaluation
H1:PEM-EX_MAG_EBAY_SUSRACK_X_DQ	other ebay and VEA magnetometers working
H1:PEM-EX_MAG_EBAY_SUSRACK_Y_DQ	other ebay and VEA magnetometers working
H1:PEM-EX_MAG_EBAY_SUSRACK_Z_DQ	other ebay and VEA magnetometers working
H1:PEM-EY_MAG_EBAY_SEIRACK_X_DQ	other ebay and VEA magnetometers working
H1:PEM-EY_MAG_EBAY_SEIRACK_Y_DQ	other ebay and VEA magnetometers working
H1:PEM-EY_MAG_EBAY_SEIRACK_Z_DQ	other ebay and VEA magnetometers working
H1:PEM-VAULT_MAG_1030X195Y_COIL_X_DQ	many building magnetometers working
H1:PEM-VAULT_MAG_1030X195Y_COIL_Y_DQ	many building magnetometers working
H1:PEM-VAULT_MAG_1030X195Y_COIL_Z_DQ	many building magnetometers working
H1:PEM-MY_SEIS_VEA_FLOOR_X_DQ	seismometers in CS, EY, EX working
H1:PEM-MY_SEIS_VEA_FLOOR_Y_DQ	seismometers in CS, EY, EX working
H1:PEM-MY_SEIS_VEA_FLOOR_Z_DQ	seismometers in CS, EY, EX working
H1:PEM-CS_ACC_LVEAFLOOR_BS_Y_DQ	redundant with seismometers and other accelerometers
H1:PEM-CS_ACC_LVEAFLOOR_HAM1_Z_DQ	redundant with seismometers and other accelerometers
H1:PEM-EX_TILT_VEA_FLOOR_X_DQ	redundant with seismometers
H1:PEM-EX_TILT_VEA_FLOOR_Y_DQ	redundant with seismometers
H1:PEM-EY_ACC_BSC10_ETMY_Z_DQ	redundant with other accelereometers
H1:PEM-VAULT_SEIS_1030X195Y_STS2_X_DQ	many building seismometers working
H1:PEM-VAULT_SEIS_1030X195Y_STS2_Y_DQ	many building seismometers working
H1:PEM-VAULT_SEIS_1030X195Y_STS2_Z_DQ	many building seismometers working
H1:PEM-CS_RADIO_ROOF1_BROADBAND_DQ	not installed but channels for in-building antennae were working and these monitor the same frequencies as the roof antennae
H1:PEM-CS_RADIO_ROOF2_BROADBAND_DQ	not installed but channels for in-building antennae were working and these monitor the same frequencies as the roof antennae
H1:PEM-CS_RADIO_ROOF3_BROADBAND_DQ	not installed but channels for in-building antennae were working and these monitor the same frequencies as the roof antennae
H1:PEM-CS_RADIO_ROOF4_BROADBAND_DQ	not installed but channels for in-building antennae were working and these monitor the same frequencies as the roof antennae

Table 2. Channels that were not working at LLO and evaluation of effect on coverage (excluded from this list are temperature channels):

L1:PEM-CS_MAINSMON_EBAY_1_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-CS_MAINSMON_EBAY_2_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-CS_MAINSMON_EBAY_3_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-CS_RADIO_LVEA_IMC_DQ	Test setup
L1:PEM-CS_RADIO_ROOF1_BROADBAND_DQ	These frequencies are also read by the narrow band receivers with their antennae inside the building
L1:PEM-CS_RADIO_ROOF2_BROADBAND_DQ	These frequencies are also read by the narrow band receivers with their antennae inside the building
L1:PEM-EX_MAINSMON_EBAY_1_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches

L1:PEM-EX_MAINSMON_EBAY_2_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-EX_MAINSMON_EBAY_3_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-EY_MAG_VEA_FLOOR_X_DQ	not good but ebay magnetometer was working
L1:PEM-EY_MAG_VEA_FLOOR_Y_DQ	not good but ebay magnetometer was working
L1:PEM-EY_MAG_VEA_FLOOR_Z_DQ	not good but ebay magnetometer was working
L1:PEM-EY_MAINSMON_EBAY_1_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-EY_MAINSMON_EBAY_2_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-EY_MAINSMON_EBAY_3_DQ	Had not been hooked up. But magnetometers should cover 60 Hz glitches
L1:PEM-EX_TILT_VEA_FLOOR_X_DQ	Redundant with seismometers
L1:PEM-EX_TILT_VEA_FLOOR_Y_DQ	Redundant with seismometers
L1:PEM-EY_LOWFMIC_VEA_FLOOR_DQ	Redundant with seismometers

c. Cosmic ray detector check

After the event, we checked that the cosmic ray detector was functioning properly by observing events from the PMTs using a scope and checking that coincident events produced triggers that were recorded in the cosmic ray channel.

d. Radio double check

At LHO we checked that the functioning radio channels were working by injecting from the "station" near the water tank after the event.

e. Are all coverage-related channels being properly checked by glitch detectors and are the configuration files OK?

We examined Omega Scan configuration files used to vet the event and found that certain channels were missing and some of the frequency ranges were incorrect. We informed DetChar and re-ran Omega Scan with the correct configurations. As with the original Omega Scans, nothing was found that could produce the candiate. However, Omega Scans are limited to a sample rate of 4096 Hz. We have found that the non-linear coupling at HAM6 (both sites), produced by intermodulation of the vibration frequency and the OMC length dither (4100 Hz at LHO), can down-convert vibration above 2500 Hz into the 30-350 Hz event band (see video of this happening here: https://www.youtube.com/watch?v=PQ0qv5yFdC4). For this reason we checked certain microphone and accelerometer spectra directly for high-f events during the candidate. No signal was visible over background. For similar reasons, we recommend that the sample rate of the HAM6 geophones be increased to 8 kHz.

2. 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 varying static electric fields will be accompanied by current-generated magnetic fields. Mains electric currents are monitored by magnetometers and by voltage sensors (although there were no voltage sensors at LLO during the event). Injections show that RF fields above 10 kHz have no influence on the interferometer at RF amplitudes that are orders of magnitude above 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) 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.

3. Events in sensors: any environmental signals loud enough to conceivably produce an event 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). No similar paths were found. As a redundant check, we compared the SNR of environmental events within half a second of the event, to the SNR needed in the environmental channel to produce a signal in the DARM channel with the SNR of our candidate. The required SNRs can be obtained from the PEM injections of environmental signals (https://alog.ligo-wa.caltech.edu/aLOG/uploads/23305_20151111082650_SummaryWithPlots.pdf).
We ran Omega Scan on PEM and ISI signals with the frequency band limited to 30-350 Hz. Those channels with events during the candidate second are tabulated below, along with the ratio of the PEM SNR to the PEM SNR required to produce an event in DARM with the SNR of the candidate.

The loudest PEM or ISI signal at LHO would have had to be more than 31 times louder to appear in DARM at the SNR of the candidate. At LLO, the loudest signal would have to have been about 23 times louder.

Table 3. LHO PEM events during the candidate second and how much louder they would have to be to reach the same SNR in DARM as the candidate. Omega Scan: https://ldas-jobs.ligo.caltech.edu/~vincent.roma/wdq/LHO_30_350/

Channel	SNR of PEM Chan event	Lowest SNR to show in DARM	SNR required to reach DARM	How much bigger the PEM channel event would

	within 0.5 s of central time of candidate	between 40 and 350 Hz (ratio of DARM floor to Estimated Ambient level)	SNR of event in DARM Omega Scan (SNR = 12.0)	have to be to account for the SNR of candidate: (SNR required/SNR)
H1:PEM-EY_ACC_BSC10_ETMY_Z_DQ	16.4	NOT WORKING		
H1:PEM-CS_MAG_EBAY_LSCRACK_X_DQ	6.5	600 actual, 42 Hz 100 upper limit	>1200	>185
H1:PEM-CS_MAG_EBAY_LSCRACK_Y_DQ	9.3	600 actual, 42 Hz 100 upper limit	>1200	>129
H1:PEM-CS_MAG_EBAY_LSCRACK_Z_DQ	6.8	600 actual, 42 Hz 100 upper limit	>1200	>176
H1:PEM-CS_MAG_EBAY_SUSRACK_Z_DQ	6.2	600 actual, 42 Hz 100 upper limit	>1200	>194
H1:PEM-EX_MAG_EBAY_SEIRACK_QUAD_SUM_DQ	5.9	700 actual limit 350 Hz	>8400	>1423
H1:PEM-EY_SEIS_VEA_FLOOR_QUAD_SUM_DQ	6.4	UL 40, 44 Hz	>480	>75
H1:PEM-EY_SEIS_VEA_FLOOR_X_DQ	15.5	UL 40, 44 Hz	>480	>31
H1:PEM-EY_SEIS_VEA_FLOOR_Y_DQ	6	UL 40, 44 Hz	>480	>80
H1:PEM-EX_TILT_VEA_FLOOR_T_DQ	6.5	Temperature signal, probably seeing some kind of pickup		
H1:PEM-EY_TILT_VEA_FLOOR_T_DQ	5.5	Temperature signal, probably seeing some kind of pickup		

Table 4. LLO PEM events during the candidate second and how much louder they would have to be to reach the same SNR in DARM as the candidate. Omega Scan: https://ldas-jobs.ligo.caltech.edu/~vincent.roma/wdq/LLO_30_350/

Channel	SNR of PEM Chan event within 0.5 s of central time of candidate	Lowest SNR to show in DARM between 40 and 350 Hz (ratio of DARM floor to Estimated Ambient level, either at the closest point in 40-	SNR required to reach DARM SNR of event in DARM Omega Scan (9.6)	How much bigger the PEM channel event would have to be to account for the candidate SNR

		350 or average ratio indicated by "ave")		(required SNR/SNR)
L1:PEM-CS_ACC_IOT1_IMC_X_DQ	15	>46 ave	>441	>29
L1:PEM-CS_ACC_LVEAFLOOR_XCRYO_Z_DQ	5.7	>10	>96	>17
L1:PEM-EY_LOWFMIC_VEA_FLOOR_DQ	10.9	not used		
L1:PEM-EX_MAG_EBAY_SUSRACK_QUAD_SUM_DQ	21.1	50 at 56 Hz UL at 350: 100	480	23
L1:PEM-EX_MAG_EBAY_SUSRACK_X_DQ	10.7	50 at 55 Hz UL at 350: 100	480	45
L1:PEM-EX_MAG_EBAY_SUSRACK_Y_DQ	13.4	50 at 55 Hz UL at 350: 100	480	36
L1:PEM-EX_MAG_EBAY_SUSRACK_Z_DQ	9.7	50 at 55 Hz UL at 350: 100	480	49
L1:PEM-EY_MAG_VEA_FLOOR_QUAD_SUM_DQ	8.9	200 at 42 Hz UL at 350: 50	>480	>53
L1:PEM-CS_RADIO_LVEA_IMC_DQ	18.5	Test setup		
L1:PEM-EX_TILT_VEA_FLOOR_T_DQ	11.2	Temperature signal		
L1:PEM-EY_TILT_VEA_FLOOR_T_DQ	14.1	Temperature signal		

II. Redundant checks of global environment

1. Global electromagnetic environment

The global electromagnetic environment was quiet (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380).

2. Cosmic ray environment

While cosmic rays are unlikely to be able to produce non-random coincidences between sites, the cosmic ray environment was quiet (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11465).

III. Intersite correlation issues

1. 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.

We use external electromagnetic observatories (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380), and cosmic ray observatories (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11465), 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.

2. 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 in order to be seen at both sites, the strikes would have to carry ten times more current then the largest strikes during the investigated period (https://dcc.ligo.org/DocDB/0026/T010108/000/T010108-00.pdf). And to produce a signal in DARM with the candidate SNR, the fields would need to be 1000 times larger then that (https://alog.ligo-wa.caltech.edu/aLOG/uploads/23305_20151111082650_SummaryWithPlots.pdf).

2) Lightning on a global scale, Schumann resonances, 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 our chirp, 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. At their low frequency end, they might couple via mangetic fields but such a signal would have an SNR in our magnetometers of at least 1000 to produce our event (https://alog.ligo-wa.caltech.edu/aLOG/uploads/23305_20151111082650_SummaryWithPlots.pdf). We also check external low-f RF observatories to make sure such events were not happening at the time of the event (they weren't: https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380).

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 30-350 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 (ref to Schuman paper). The highest measured magnetic coupling factor in the 30-350 Hz event band is 7e-10 m/T (https://alog.ligo-wa.caltech.edu/aLOG/uploads/23305_20151111082650_SummaryWithPlots.pdf). Multiplying this by a magnetic signal level of 1e-12 T/sqrt(Hz) gives a DARM value of 7e-22 m/sqrt(Hz).

3) Risers and choruses. If loud enough to affect DARM, would be detected by magnetometers. 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. External observatories did not detect such events at the time of our candidate (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380).

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. We have checked with external RF observatories for redundancy, and found no such signals at the time of our event (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380).

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. Nevertheless, there were no flares at the time of our event. Also, there were no CME-related geomagnetic storms (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11380). The level of geomagnetic influence on the interferometer was estimated to be 5e-28 m/sqrt(Hz) at 100 Hz, using PEM injections and extrapolating from previous solar storms.

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). Nevertheless, we detected no cosmic ray detector triggers coincident with the event with our cosmic ray detector under LHO ITMX, and levels at external detectors were normal during the event (https://alog.ligo-la.caltech.edu/EVNT/index.php?callRep=11465).

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. In addition, only infrasound would be expected to propagate inter-site distances.