Correlated Noise in LIGO Detectors from Schumann Resonance

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Abstract

Schumann resonances are global peaks in the magnetic field of the earth, with a primary peak at 7.8Hz of a few pT and subsequent peaks every 6.5Hz [1]. These resonances are the result of lightning storms that occur all over the world, and as such are coherent on the scales of the distance between LIGO detectors and are time variant. Because of this being able to measure these peaks in real time and remove the parts of the spectrum that are coherent across the detectors is essential to achieving the projected noise floor in aLIGO. Here I discuss the initial the magnetic field measurements made around the LIGO Livingston and Hanford Observatories (LLO and LHO) as well as the techniques used to identify and/or remove local external sources of magnetic noise from the magnetic spectra. In addition I examine the properties of the Schumann resonances near LLO and LHO and compare their strength to the noise floors of current and (potential) future magnetometers. Finally I speculate on the potential effectiveness of using subtraction and/or wiener filtering to clean the on site magnetometer channels at LLO and LHO.

Introduction

It has been demonstrated that Schumann resonances can be seen in on LIGO magnetometers for integration times as short as 100 days [2]. This means noise from Schumann resonances could place a limit on the effectiveness of cohering long streams of data at low frequencies [3], the technique used to analyze the stochastic gravitational wave background. In order to better understand the how the Schumann peaks behave in real time it is necessary to use magnetometers sensitive enough to detect the Schumann peaks directly. These peaks occur have a typical magnetic field strength of a 1-3 $\mathrm{pT/Hz^{1/2}}$. For this paper a magnetometer from the Laboratory for Electromagnetic Innovation, the LEMI-120, was obtained for on site and off site testing at the two observatories. The LEMI was chosen for it's low noise floor in the low frequency regime ($\leq 0.1\ \mathrm{pT/Hz^{1/2}}$ in the 1-100Hz frequency range).

The LEMI was able to show several important features of Schumann resonances. In addition to confirming the presence of Schumann resonances on and off site the LEMI showed that the peaks heights and frequency has small variations in time. This means that in order to remove the correlated signal from Schumann resonances it will be necessary to have multiple magnetometers (at least one at each site) that would be used to clean LIGO's magnetometers channels. The data also shows how sensitive these detectors are to other external noise sources. Electronic noise and signals from local traffic disrupt the signal enough to hide the Schumann peaks in some cases. By testing the LEMI magnetometer at various locations it was determined that the on site detectors can not be located in stations at the end of the arms because local electronic noise is too loud. However there are off site locations that may provide a low enough noise floor to allow the for subtraction.

Theory

For two detectors the coherence is given by (1). Here G_{xy} is the cross-spectral-density of two channels x and y and G_{xx} and G_{yy} auto spectral density of x and y. If two signals are uncorrelated and data is available for a finite amount of time, then the coherence will decrease as the inverse of the time over which the coherence is performed. However if the signals are correlated then the coherence will asymptotically approach a non-zero value. That value indicates how correlated the two signals are. For example if the coherence was found to approach 0.01 then 1% of the signal in the two detectors is coherent (either coming from the same source

$$C_{xy} = \frac{|G_{xy}|^2}{G_{xx}G_{yy}} \tag{1}$$

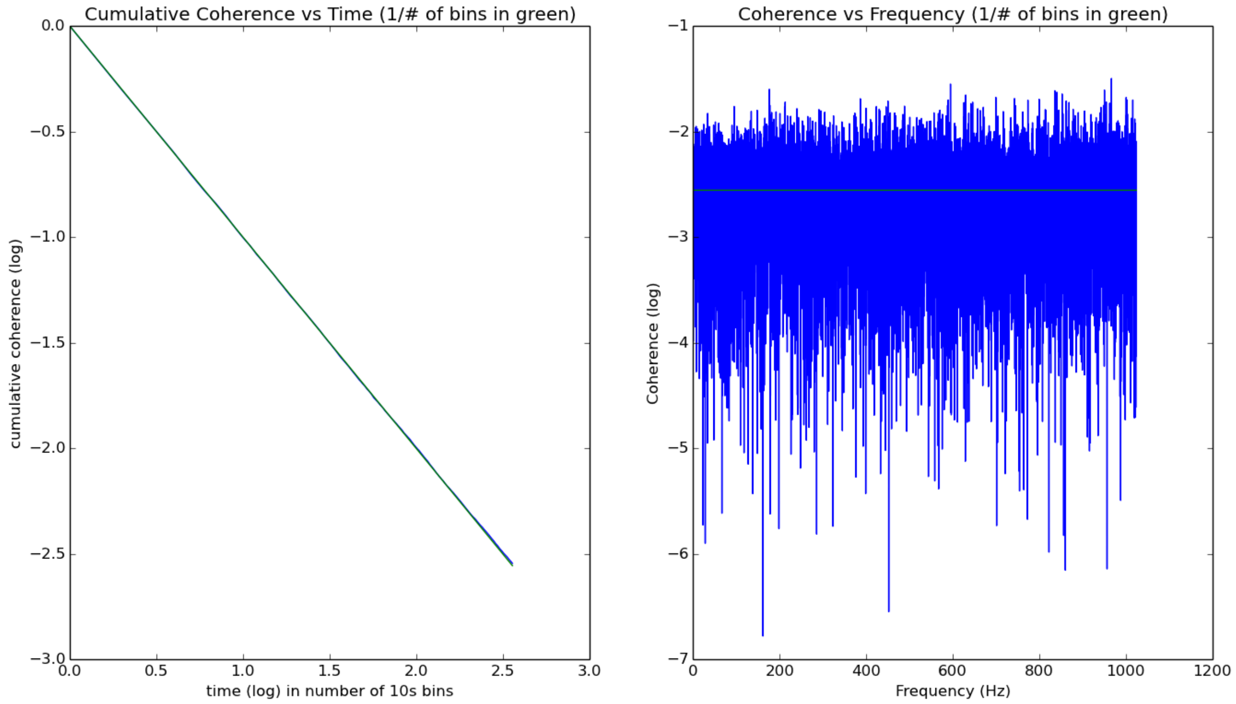

Figure 1: The graph on the left shows the cumulative coherence as a function of time (log-log). The plot agrees exactly with the inverse of the number of time bins used. The graph on the right shows the coherence as a function of frequency. Increasing the run time will lower the average coherence in uncorrelated data and averaging multiple runs together will reduce the noise in the coherence. Both graphs are for 1 hour of random data generated at a frequency of 2048 Hz.

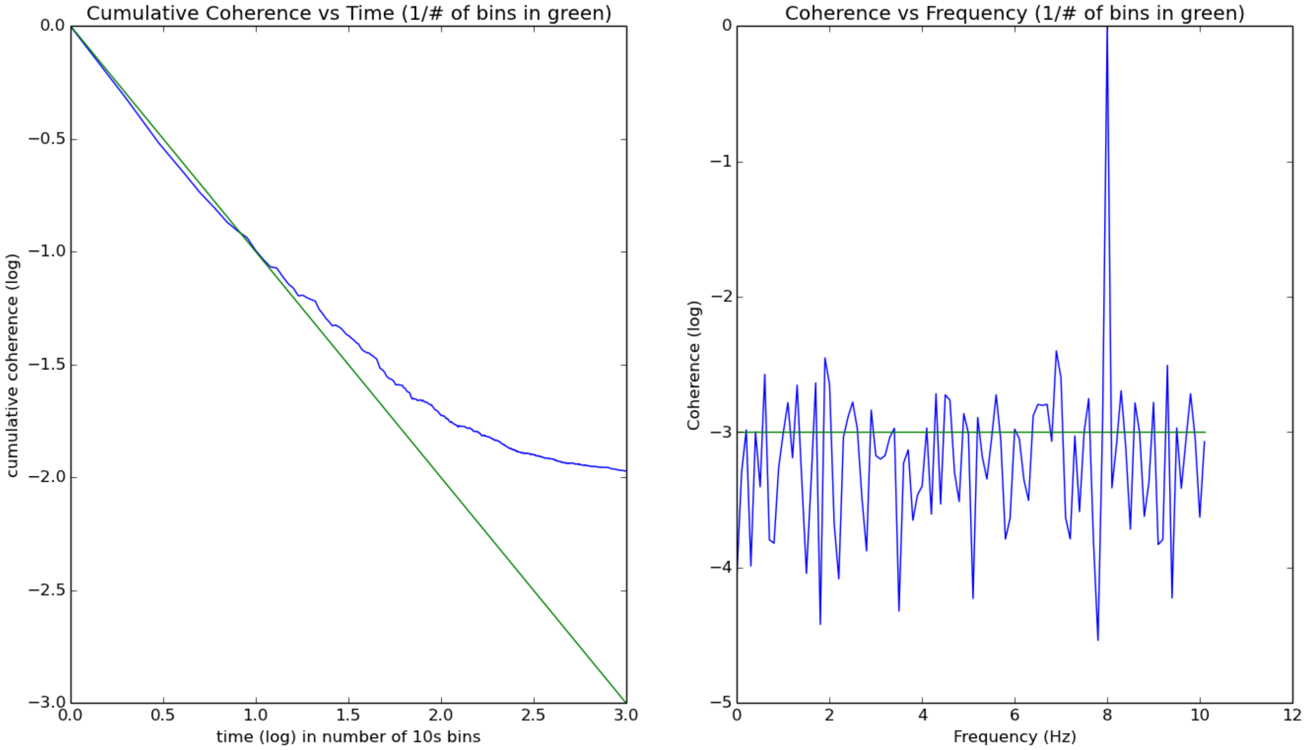

Figure 2: The graph on the left shows the cumulative coherence as a function of time. After around 100 time bins (1,000 seconds of data) the coherence from the 8Hz bin begins to dominate the average coherence across all frequency bins. Continuing to to use more integration time will be less and less effective as the cumulative coherence approaches the limit where all the coherence comes from just the 8 Hz bin. The graph on the right shows the coherence as a function of frequency. For most frequencies the coherence agrees with the inverse of the integration time (shown in green). However at 8 Hz the coherence is one and will remain one regardless of the integration time.

affecting both detectors or two local sources that create the same signal). Figures 1 and 2 show the coherence as a function of time and frequency for randomly generated data as well as for randomly generated data with a small sinusoidal added to the random noise.

Methods

The data used in this paper was gathered by Robert Schofield and Anamaria Effler. Robert recorded data at LHO itself as well as various off site locations including Table Mountain and Drumheller. Anamaria recorded data at LLO and Tickfaw State park in Louisiana. In order to see the Schumann peaks the raw data was broken into ten second bins in order to give 0.1 Hz frequency resolution. The power spectral density was computed for each 10 second bin. In order to remove excess noise from local spikes in magnetic activity (such as electronic equipment turning on/off and traffic) the power in each 10 second bin was compared with its neighbors. If a bin showed a significantly stronger magnetic field than it’s neighbors (typically 2-10 times stronger, but tolerance was different for different runs) then the bin was removed. The affect of such cleaning was a lower noise floor and clearer Schumann peaks. Figure 3 shows the results of this cleaning technique on LEMI data taken in the woods near LLO in Tickfaw State Park. Once

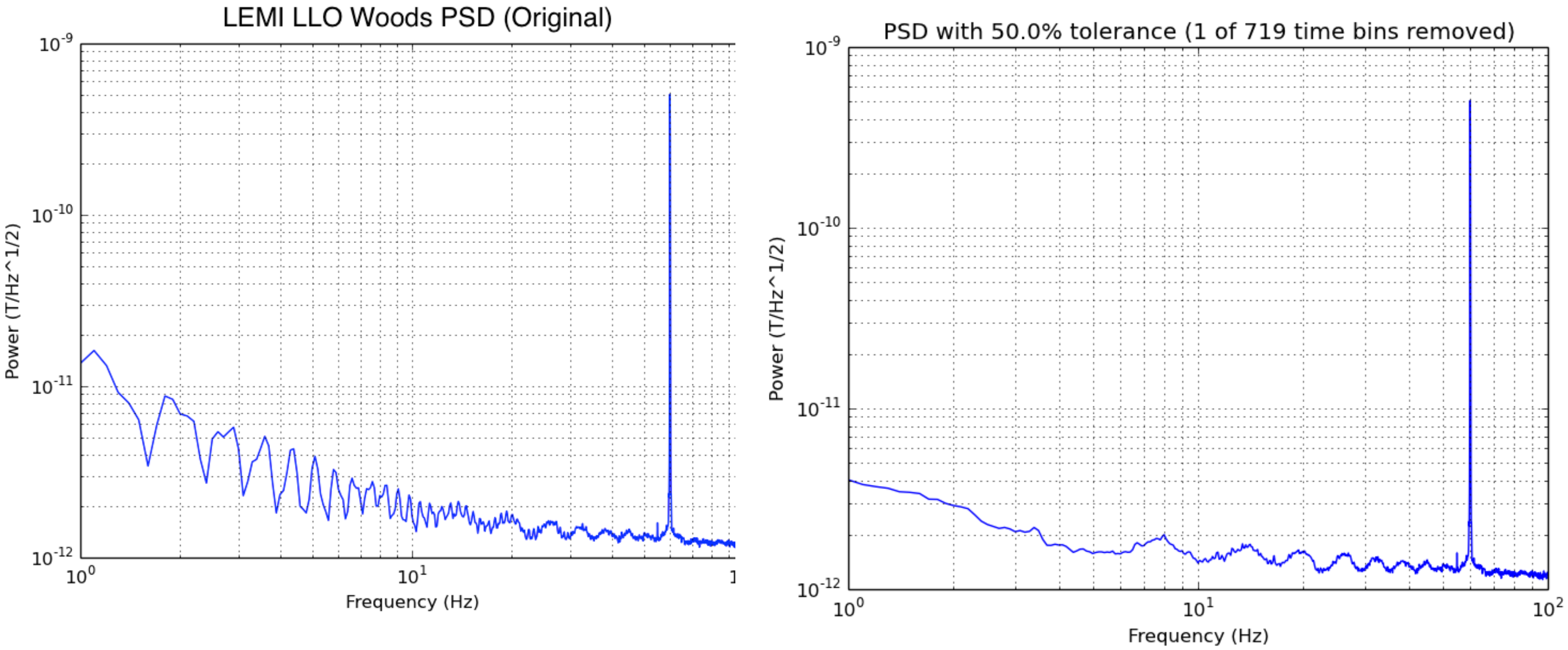

Figure 3: The graph on the left is the original data. A short term burst in magnetic noise cause all of the Schumann peaks to be below the noise level. After removing only one of the 719 time bins the peaks were successfully recovered.

the data was cleaned the primary and secondary Schumann peaks were fitted with gaussians in order to determine the frequencies of the resonances and the amplitude of the peaks.

Results

By comparing the data from all the sites at which the LEMI magnetometer was tested it is clear that all of the off site testing sites are adequate for real time detection of Schumann resonances. On site runs were not as successful and the noise floor was typically the same as the peaks in the resonances. In order to see if on site LEMI's would work for subtraction it would be necessary to try different on site locations. Figure 4 shows all the off site LEMI runs on the same graph for comparison.

Fitting the Schumann peaks showed that the primary resonance had a frequency of 7.82 ± 0.18 Hz and the peak had an amplitude of 1.88 ± 0.56 pT/Hz$^{1/2}$ on average. The secondary resonance had a frequency of 13.96 ± 0.15 Hz and an amplitude of 1.5 ± 0.57 pT/Hz$^{1/2}$. In addition by looking first at the data that was taken when the detector was oriented in the North-South direction and then at the data from when the detector was oriented in the East-West direction it was determined the the frequency and amplitude of the peaks was the same regardless of the orientation of the detector as long as it was parallel to the ground (as expected).

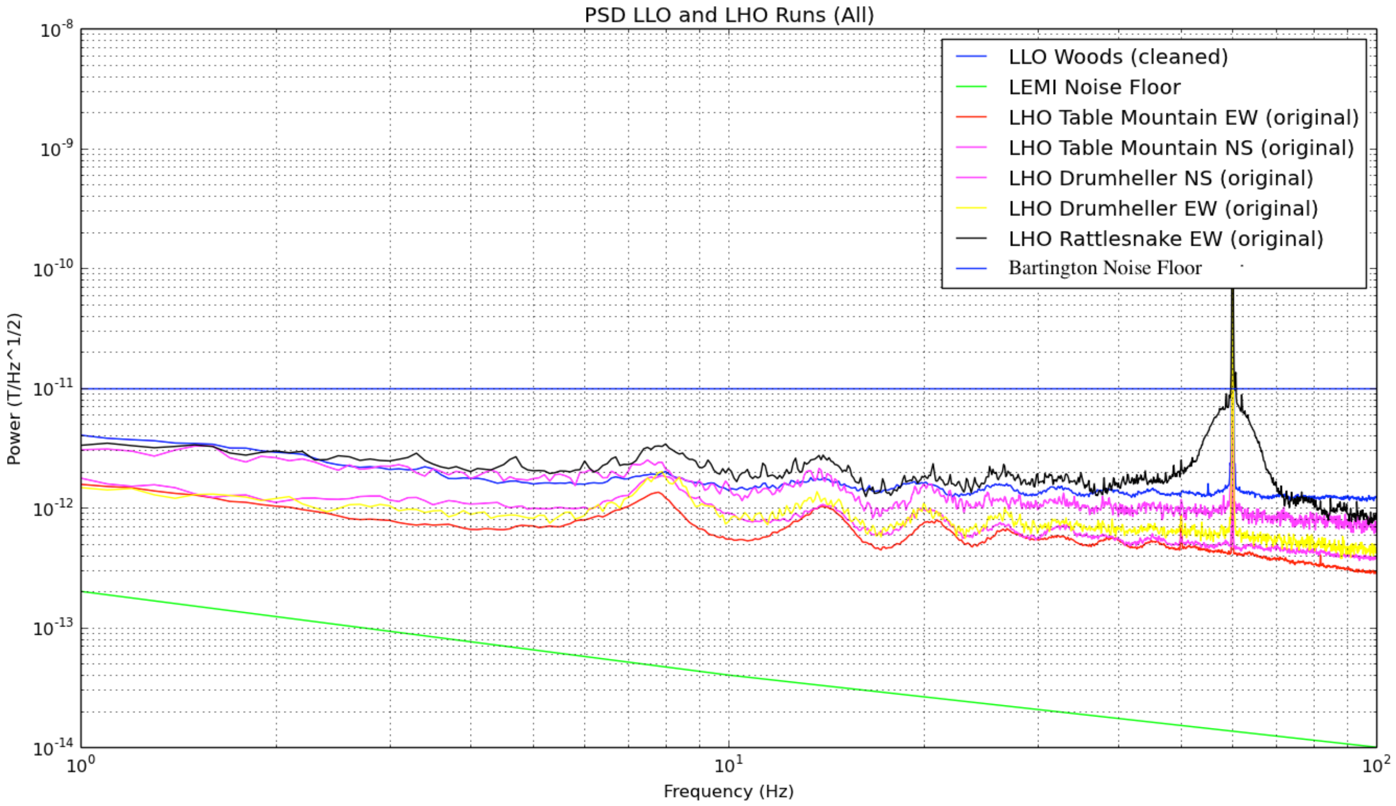

Figure 4: The PSD's for all off site LEMI runs. At least the first 3 peaks can be seen in all runs and the frequencies of the peaks appear consistent throughout all runs. The variations in amplitude are small (factor of ~2-3). At this point it is not possible to determine if these variations are site based or time based because data has not been gathered at each site during the same time period.

Conclusions

The LEMI data confirms that subtraction of the magnetic noise from Schumann resonances will be critical in deterring the shape of the SGWB for low frequencies (10-30 Hz). In order to effectively perform subtraction it may be necessary to have the LEMI's off site, but it would still be useful to check more on site locations to see if a there is a possibility for having the LEMI's on site. Currently only the end stations have been tested. The small variations in the peaks in time mean that the most effective subtraction has to be done in real time, meaning detectors of around the same sensitivity as the LEMI's will be necessary in order to allow for cleaner coherence spectra.

The future of this work should involve placing at least one LEMI at each site in order to begin looking at cleaning techniques. First subtracting the the signals at each detector in order to see what part of the Schumann resonances is actually correlated on short time scales (local lightning storms would cause local changes in the peaks that would not necessarily be seen by both detectors). The the coherent spectrum could then be subtracted from the data from the current on site magnetometers in order to eliminate as much of the coherent noise as possible.

References

[1] Bliokh, P., A. Nicholaenko, and F. Fillipov. "Schumann Resonances in the Earth-ionosphere Cavity." *NASA Astrophysics Data System* (1980): n. pag. *NASA Astrophysics Data System*. Web. 18 June 2014.

[2]Thrane, Eric N., N. Christensen, R. Schofield, and A. Effler. "Correlated Noise in Networks of Gravitational-wave Detectors: Subtraction and Mitigation." Physical Review D 90.2 (2014): 13-30. Web.

[3]Thrane, E. "Correlated Magnetic Noise in Global Networks of Gravitational-wave Detectors: Observations and Implications." Physical Review D 87.12 (2013): 3-9. Web.