Magnetic Noise and Schumann Resonances in LIGO's Gravitational Wave Detectors

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Abstract

Gravitational wave detectors are extremely sensitive instruments, as gravitational waves provide very subtle effects. Due to this sensitivity, the detectors are very sensitive to environmental noise, including magnetic noise. This thesis investigates the effects of magnetic field noise in the LIGO detectors, as measured by magnetometers located close to the LIGO observatories. In this analysis, we conduct broken power law fits to the coupling (transfer function) of the magnetic field to the LIGO detector's strain channel and track the behavior of the fits over time, during the LIGO third observation run.

1 Introduction

A gravitational wave far from its source can be approximated as a time-dependent perturbation of the space-time metric. These perturbations can be expressed as a pair of dimensionless strain polarization h_+ and $h_\times$. The Advanced LIGO detectors are multi-kilometer Michelson-based interferometers, and act as a transducer to convert the space-time perturbations into measurable signals. The mirrors in the interferometer act as 'freely falling' test masses. The Advanced LIGO detectors measure linear differential displacement along the arms, which is proportional to the gravitational-wave strain amplitude [1]. The differential displacement is defined by

$$\Delta L = \delta L_x - \delta L_y \tag{1}$$

where $L_x = L_y = L$ are the lengths of two orthogonal interferometer arms. The gravitational-wave strain and the displacement in the interferometer arms are related by

$$\Delta L = hL \tag{2}$$

where h is a linear combination of h_+ and $h_\times$ [1].

Figure 1 shows a schematic of the Advanced LIGO interferometers. To measure the distortion of space-time between the interferometer arms, the test masses are used as coordinate reference points. Since gravitational waves produce very small displacements in the interferometer, it is necessary for the mirrors to be free from environmental disturbances [1].Of particular interest to this paper is the magnetic noise, which is the most relevant at frequencies below 100Hz. [1].

2 Schumann Resonances and Magnetic-Field Noise

In order to reject transient environmental disturbances, coincident detection between the LIGO detectors is used. One interesting source of environmental noise is created by magnetic noise transients caused by electromagnetic discharges in the Earth's atmosphere [2] which can induce correlations between geographically displaced locations, such as the LIGO observatories in Hanford, WA and Livingston, LA. These correlated magnetic noises, such as the Schumann resonances, induce forces on the magnetically susceptible materials in the test mass suspension system, and over time, can create systematic errors in the Stochastic Gravitational Wave Background (SGWB) search. [2] [3].

The Schumann resonances are characteristic structures in the Earth's electromagnetic spectrum [2]. These resonances are extremely low frequency (ELF) electromagnetic waves propagating around the Earth and can create globally coherent magnetic fields. This can lead to correlated noise in the LIGO detectors, leading to a systematic error in the SGWB search.

The main source of ELF waves in the Earth-ionsphere waveguide are negative cloud-to-ground lightning discharges. On Earth, about one thousand storm

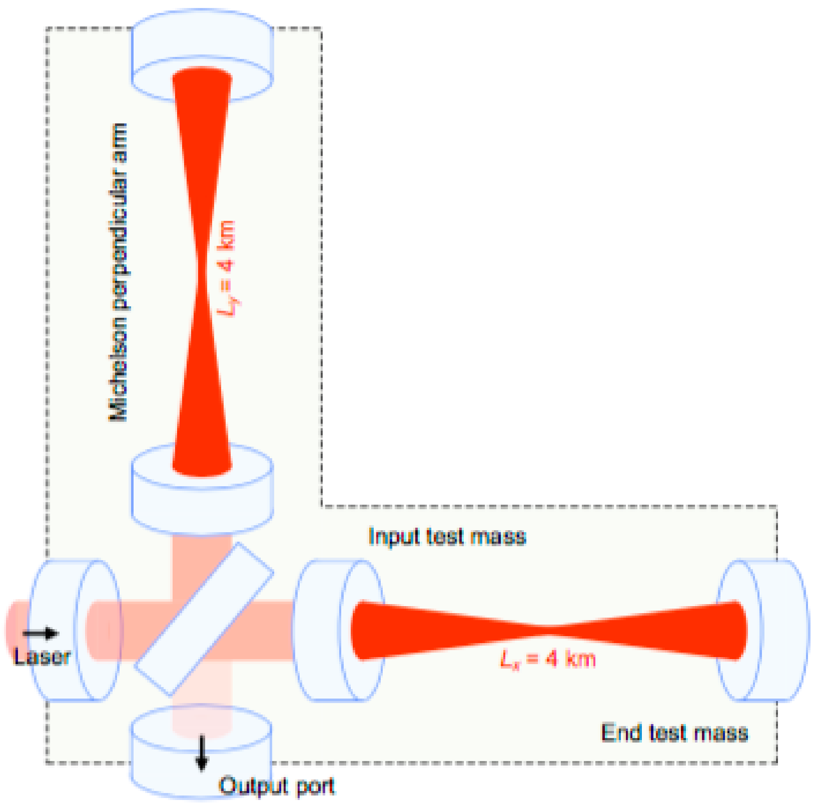

Figure 1: Schematic of the Advanced LIGO detector's interferometer.[1]

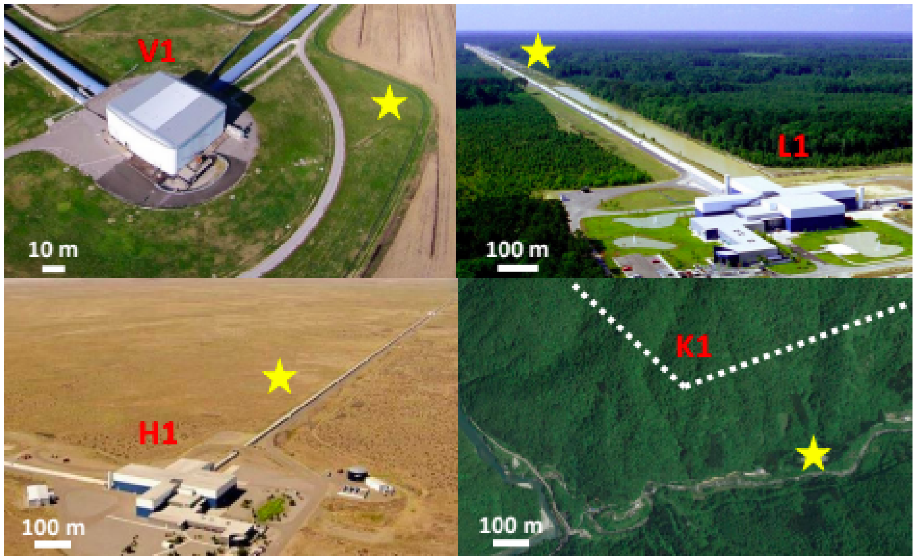

Figure 2: Locations of the magnetometers across the detectors. V1 is the Virgo detector, and its coordinates in the (x,y) interferometer system are (80,-72)m. L1 and H1 are the Livingston and the Hanford detectors, respectively at (120,3000)m and (1030,195)m. Lastly, K1 is the KAGRA detector, located at (400,-600)m[3].

cells are constantly active, and generate around 50 negative cloud-to-ground discharges per second. The lightning discharge radiates electromagnetic waves which propagate around the world and interfere with each other. This results in the atmospheric noise spectrum having a resonant character. This was first predicted by W. O. Schumann in 1952. He solved the field equations in the spherical Earth-ionsphere cavity built of the perfectly conducting ground and the ionsphere. He obtained certain eigenfrequencies, which were later measured for the first time in 1960 [2]. The Schumann resonance peaks are relatively wide, and occur at at 8, 14, 21, 27 and 32 Hz [3], frequencies in (or near) the most sensitive band of LIGO detectors. We must then study the effect of the Schumann resonances in gravitational wave detectors.

With that in mind, LIGO, VIRGO and KAGRA scientists placed magnetometers at strategic locations around their observatory sites. Figure 2 shows the locations of the magnetometers with respect to their observatories [3]. The magnetometers are located in strategic places around the observatory sites, and are close to the test-masses. The magnetic-field measurements are made in the three Cartesian directions, with x and y being defined by the interferometer arms, and the z-direction is normal to the Earth's surface. The presence of metal in the buildings that house the detectors distorts the field direction and allows for observation of the Schumann magnetic field in the z directed magnetometers as well [2].

Both the LIGO and Virgo magnetometers are broadband induction coil magnetometers, and are designed to measure the variations of the Earth's magnetic field. They are placed close enough to measure the same Schumann resonances the detectors do, but are far enough that they are not sensitive to local magnetic noise. With that said, it is easy to see the importance of computing magnetometer correlations with gravitational-wave detector data to measure the effect from Schumann resonances [3].

3 Measuring the Historical Values of the Magnetic Coupling Functions

To estimate how magnetic fields couple into the interferometers, we can perform "physical environmental monitoring injections" (PEM injections). Such coupling estimates can be combined with measurements of the correlation of the magnetic fields on long distance scales to give an idea of the correlated strain noise level expected between widely separated interferometers [4].

The magnetic coupling measurements are made by LIGO commissioners on site by generating large magnetic fields in various locations around the interferometers. These fields can couple into the strain channel. According to Meyers [4], there are two coupling mechanisms that are likely to happen:

1. Coupling to the magnets on the second-to-last stage of the quadrupole pendulum suspensions for the test masses.

2. Coupling through electronics.

The large magnetic fields are generated at a specific set of frequencies, which allow us to measure the coupling. The fields then couple into the strain channel and can be seen as lines in the strain spectrum. The magnetic coupling can then be calculated by taking the ratio of the peak seen in the strain channel with the peak seen in a magnetometer inside the building where the injection was made. Several magnetometers will observe the peak, and the magnetometer which sees the largest peak is the one used for the coupling measurements of the injection [4].

This gives a coupling ratio between the the magnetic field and the detector, which is the coupling/transfer function. In this thesis, we aimed to measure the power-law index of the magnetic coupling functions. Since we only had data from the Hanford observatory (LHO), we set to determine the broken power-law indexes α_1 and α_2 from the following model:

$$T(f) = a\Big(\frac{f}{f_1}\Big)^{\alpha_1} \quad \text{for} \quad f < f_{knee} \tag{3}$$

$$T(f) = b\Big(\frac{f}{f_{knee}}\Big)^{\alpha_2} \quad \text{for} \quad f > f_{knee} \tag{4}$$

where α_1 is the power-law index of the first slope, α_2 is the power-law index of the second slope, f is the frequency, f_1 is an arbitrary frequency, f_{knee} is the frequency in which the power-law breaks and both a and b are normalization factors. We then set out to create a python code which would estimate three different parameters α_1, α_2 and f_{knee}. The parameters will be described below in more detail, as well the process of conducting the broken power-law fit. Additionally, it is important to point out that the broken power-law is a continuous function, and both fits must agree at f_{knee}.

The first step in the analysis is to remove the large spectral features of the magnetic spectrum. Once the large spectral features are removed, we check if there were any glitches in the data. To do that, background data is taken before and after the PEM injections. Since the injection in the gravitational wave channel is visible only below 100Hz, there should not be large changes at frequencies above 100 Hz. Therefore, in the bands above 100Hz, we check if the added noise is above the statistical fluctuations of the detector noise. If there is no elevated noise at frequencies above 100Hz, then this indicates there is no glitch in the data.

Once those two steps are done, we conduct two least-squares fits to obtain the transfer function. The first fit finds parameters for the normalization factor a, the power-law index α_1 and the breaking frequency f_{knee}. The normalization factor a is defined as the value of the transfer function at f_1. The transfer function itself is independent of the frequency we choose for f_1, so we can pick any arbitrary frequency. In this analysis, we chose f_1 to be 20Hz. Once that is done, we write the normalization factor b as a function of the other variables. By doing this, we ensure that the transfer function is continuous and that both fits agree at the f_{knee} value. The second fitting finds the values of α_2 and f_{knee}. Essentially, f_{knee} is found by the joint fit of both equations. The residuals are then calculated, allowing us to find which parameter value produces the smallest residual between the fit and the data. We end up minimizing the residuals given by

$$R = \sum_i \left(\frac{T_{fit}(f_i) - T_{data}(f_i)}{T_{data}(f_i)} \right)^2 \tag{5}$$

where R is the residual value, T_{fit} the transfer function values obtained using Eqs. 3 and 4, T_{data} is the measured transfer function during a PEM injection, and f_i is is the frequency. We used scipy's function least_squares() which chi-squared minimization routine that allow us to find the parameter combination that minimizes R. Once such parameters are found, we produce a plot of the all data from previous injections, up to the date being analyzed. This allows us to check if the fitting is also a good estimate for other PEM injections. Figure 3 shows the least squares fit done on the transfer function of the injection done on 03/09/2019. On top of showing the fit, Figure 3 also shows the data collected from all other injections done up until 03/09/2019. The first slope is α_1, and the second slope is α_2. The frequency in which the slope changes its value is what we call f_{knee}. The large spectral peaks seen under 100Hz, are the peaks we remove before fitting the data. It is important to note that the fit is done only

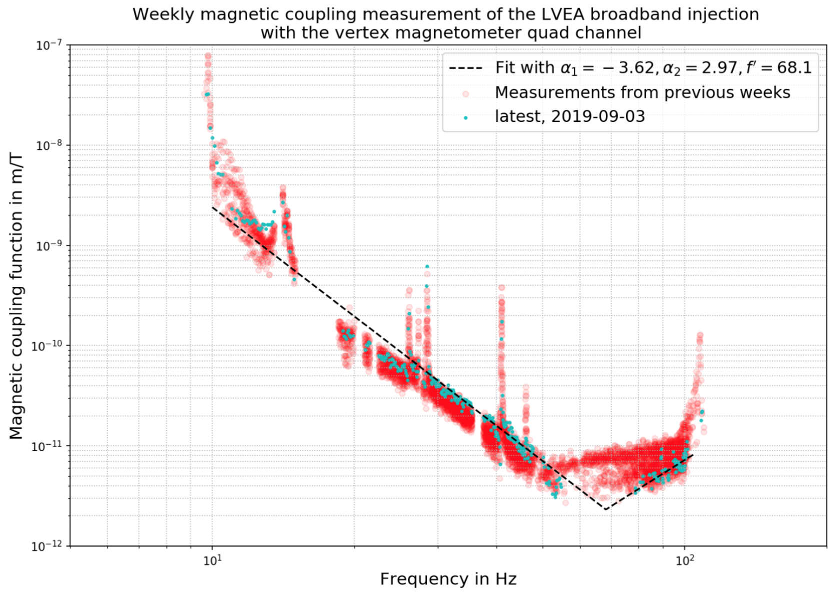

Figure 3: Plot of the weekly magnetic coupling measurement of the LVEA broad injection on 09/03/19. The plot shows the least squares fit as well the measurements from previous weeks.

on the data of the injection being analyzed (in this case, this was the injection done on 03/09/2019).

4 Results and Conclusion

After analyzing over 25 dates, we obtained that the mean value for α_1 was of -3.4 $\pm$ 0.2. Meyers [4] estimated that the power-law index value α_1 would be -3.55, which is within 0.74σ of the value we obtained. The mean value for α_2 obtained was of 2.5 $\pm$ 2.2, and the mean value of f_{knee} was (62.5 $\pm$ 8.63) Hz. Figures 4, 5 and 7 show the historical values of α_1, α_2 and f_{knee} respectively. By looking at Figure 4 we can see that the α_1 values increased over time, but stayed in a range between -3.77 and -3.14. In Figure 5, we see that the values for α_2 had a slight increase and its values were between -0.14 and 8.62. Additionally, by looking at Figure 5 we can see that only a few of the injections had an α_2 value above 4. Figure 6 is a plot of the magnetic coupling vs. frequencies for a date in which α_2 was 8.62. It appears that the fit at high frequencies was not very good. Therefore large values of α_2 should be used with caution. Lastly, as shown in Figure 7, the f_{knee} values also increased over time, and stayed in the range between 46.7 Hz and 77.6 Hz.

Going forward, it will be important to conduct Lorentzian fits of the large

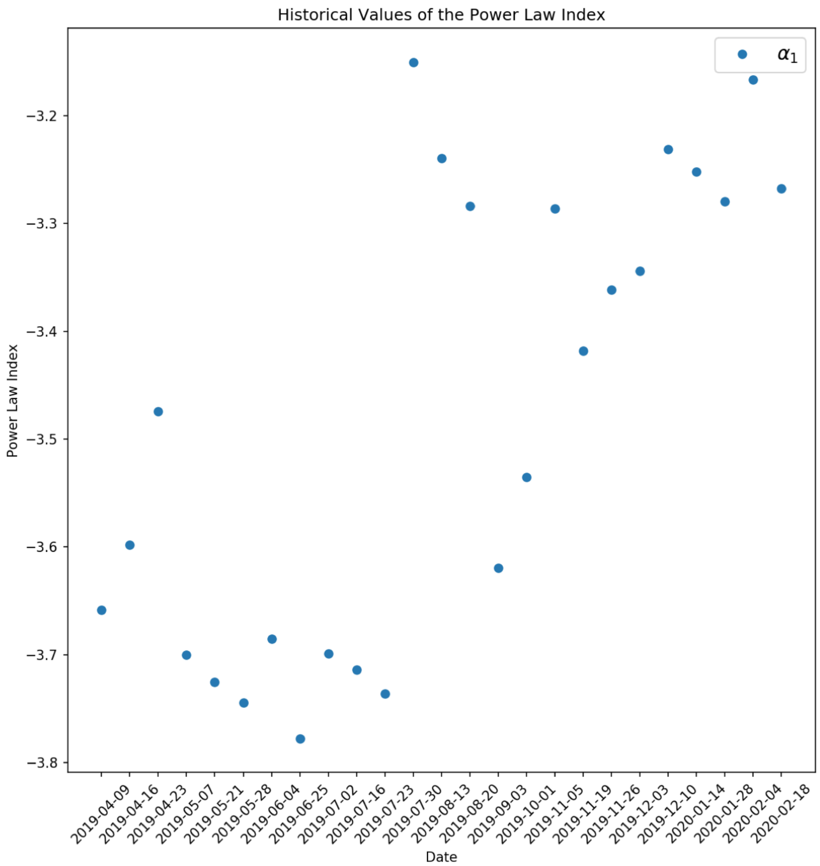

Figure 4: Historical values of α_1.

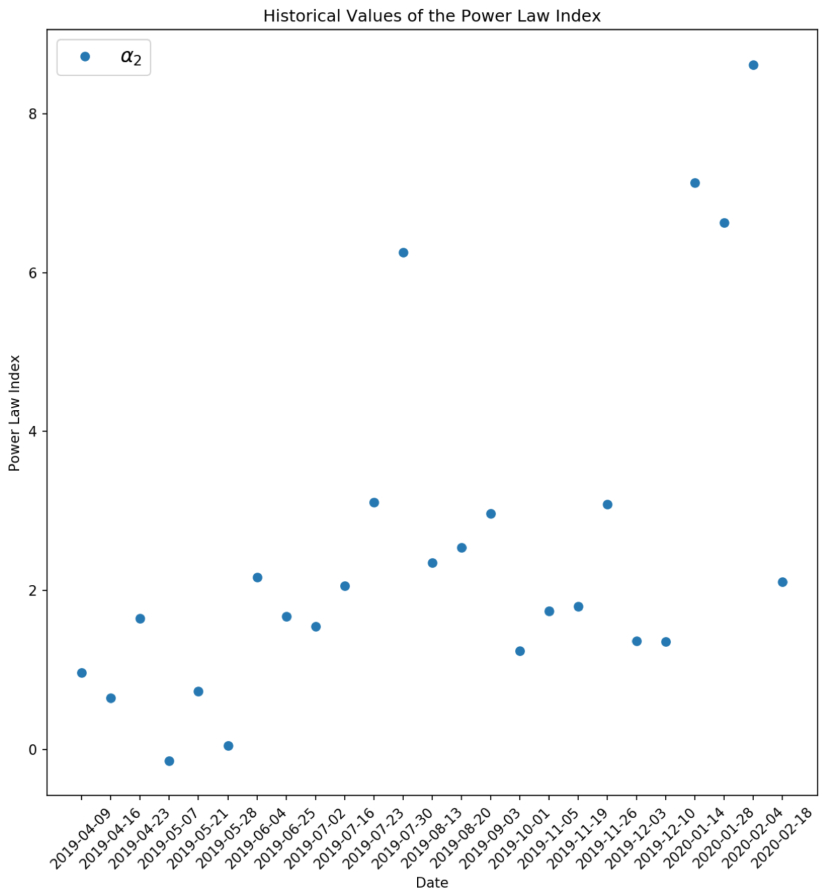

Figure 5: Historical values of α_2.

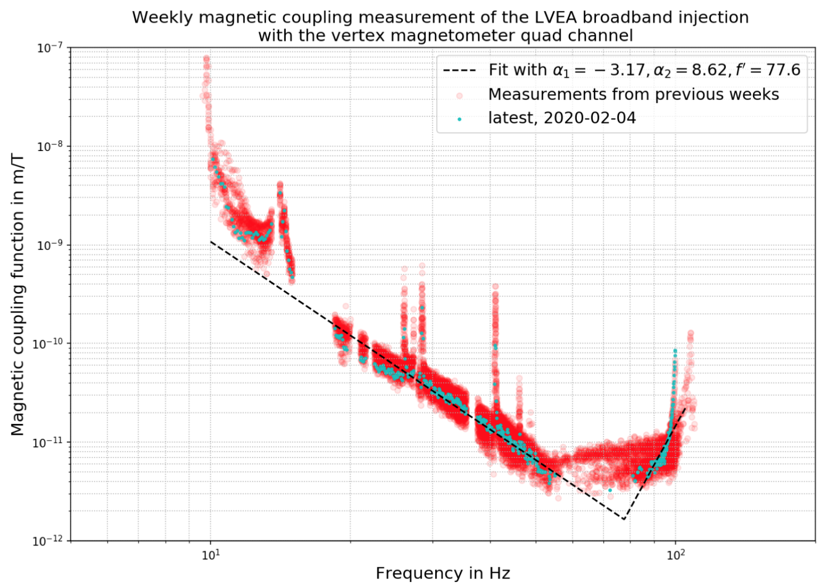

Figure 6: Plot of the weekly magnetic coupling measurement of the LVEA broad injection on 02/04/20. The plot shows the least squares fit as well the measurements from previous weeks.

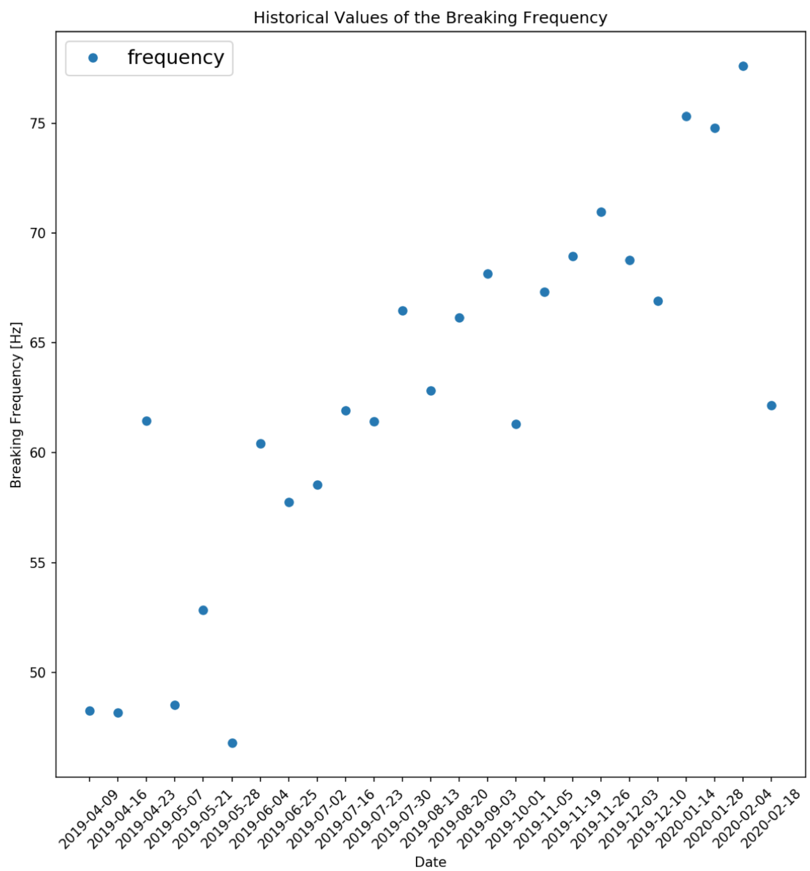

Figure 7: Historical values of the frequencies in which the power-law broke.

spectral features of the magnetic spectrum, so that we can obtain their amplitude, quality factor, and central frequency. Once this is obtained, we can include narrow band features of the transfer function in the fit in addition to the broken power-law. Moreover, it will be extremely important to conduct PEM injections in the other gravitational-wave observatories, so we can obtain more accurate results of the power-law indices of the coupling functions. This will be crucial to determine the influence of the Schumann resonances in the LIGO, VIRGO and KAGRA detectors.

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