Environmental Monitoring: Coupling Function Calculator

Julia Kruk[1] and Robert Schofield[2]

[1] Cornell University, Ithaca, NY 14850
julia.kruk@ligo.org, jk2326@cornell.edu
[2] LIGO Hanford Observatory, Hanford WA 99343
University of Oregon, Eugene OR 97403
rmssrmss@gmail.com

Abstract. With the discoveries of GW150914 and GW151226 last year, it became evident that the LIGO collaboration is likely to make frequent detections sooner than was originally anticipated. This, in turn, increased the need for software that would automate the signal validation procedures conducted by the Environmental Monitoring team at LLO and LHO. To study the effect of ambient environmental noise on the interferometers, coupling functions are calculated to survey the estimated response in the differential arm movement to various environmental noise signals. In preparation for LIGO's second observation run, a program called the Coupling Function Calculator, written in Python, was created to automate the calculation of these functions as well as the calculation of estimated ambients, signal coherence, and amplitude density spectra. The output of this program includes plots of the coupling functions, amplitude density spectra, and coherence graphs, as well as csv files containing all the calculated data for each frequency bin.

1 Introduction

The Environmental Monitoring system is a study of how ambient environmental noise affects the interferometers at Hanford, WA and Livingston, LA. These instruments are capable of measuring relative mirror displacement as small as 10^{-18} meters. At these sensitivities, a broad variety of environmental phenomena could induce magnetic, acoustic or vibrational coupling that would produce noise signals in the DARM (differential arm movement) signal. This can include features of the surrounding environment such as seismic events, strong winds, large magnetic storms, electronic devices left in the LVEA, or even traffic on the highway next to the site. In order to understand what kind of noise signals these environmental phenomena produce, PEM injections are conducted before each observation run. These are injections of magnetic, acoustic and vibrational signals in various regions of in interferometer for the purpose of surveying the response they have in DARM. The signal data is then compared to PEM sensor signal readings and used to calculate coupling factors. Coupling functions created from these factors are much like transfer functions; the only difference being that incoherence between signals is welcomed to an extent. The significance and nature of coupling functions will be discussed later in this paper.

During and before the first observation run (O1), coupling functions were calculated by hand, often only for a specific frequency band of an amplitude density spectrum for a certain channel. They were used to locate areas of the interferometer that may be especially susceptible to certain kinds of ambient noise signals.This procedure that then would allow for mechanical alterations to the instrument that would improve sensitivity. The functions were also used in analyzing gravitational wave triggers to ensure that the signal was not caused by environmental phenomena. Coupling functions were only calculated when necessary, because detections were not expected to happen in high frequency any time soon. However, the discovery of GW150914 and GW151226 created a demand for software that would automate these calculations. A major benefit of having the ability to produce coupling functions for various channels in a specific region of the interferometer very rapidly is that it allows one to verify the validity of the data being collected during the PEM injection process. Depending on the location from which the signal is injected, it can sometimes create very high upper limit coupling functions for a particular sensor channel. This may not necessarily be because there is in fact a lot of coupling occurring in that area. If coupling function plots could be generated in a matter of seconds, then one could look over the data and see whether, and how, the PEM injections need to be redone.

By ensuring that the data collected during the PEM injection period is as accurate as possible, we can effectively decrease the chance of a false dismissal of a gravitational wave due to false classification as environmental noise by factors of ten. The Coupling Function Calculator program was written to do more than just generate large amounts of coupling function plots at a very rapid rate. Over the time of its development the program became a broader data analysis tool that could calculate and plot amplitude density spectra, coherence and the estimated ambient at each frequency bin. It was also made to plot multiple coupling functions from various channels on the same figure when requested, as well as to accept broad-band PEM injection data and plot it in a way that makes up and down conversions easily identifiable. The program runs through many calculations, calibrations and conversions, all of which will be described below.

2 Coupling Functions

As it was mentioned before, coupling functions are similar to transfer functions. Coupling functions are ratios assigned to each frequency bin in an amplitude density spectrum, that when multiplied with the amplitude value from a PEM sensor channel at the corresponding frequency, will yield the estimated response in DARM at that bin. They are calculated in the following way:

For frequency bin $\boldsymbol{i}$, injection time $\boldsymbol{j}$, darm_quiet time $\boldsymbol{u}$, and sensor_quiet $\boldsymbol{v}$

$$cFact_i = \sqrt{\frac{darm_{ij}^2 - dram_{iu}^2}{sensor_{ij}^2 - sensor_{iv}^2}} \tag{1}$$

Notice that four data extractions need to be made from the server: two from the PEM sensor channel, from the time of the injection and from a quiet (background) time, and again with the DARM channel. The background amplitude at each frequency bin is subtracted from the injection amplitude before the ratio is computed. The main difference between coupling functions created from these factors and transfer functions is how much coherence matters. Non-coherent data is very important to the Environmental Monitoring system because it can be an indication of up or down conversion occurring in the noise signal. Down conversion is, for example, when an injection at over 1200 Hz produces a noise signal in DARM at around 800 Hz. Up conversion functions the same way; only the response would be at a higher frequency than the injection. In general, up or down conversions occur when the response is found within a different frequency band than the injection that caused it. The image below demonstrates how down conversion can appear in the data. By looking at the superimposed spectra of a broad-band injection, you could see the an injected at 800 1200 Hz produced a response between 100 200 Hz (in red):

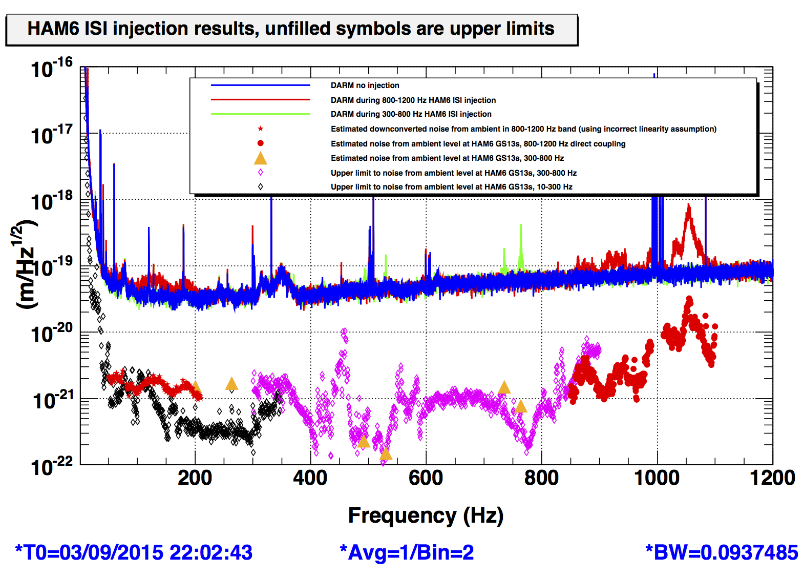

Fig. 1. Created with O1 PEM injection data. [1]

If the program were to disregard data with poor coherence, we would not be able to see these events.

When calculating the coupling factors, a specific threshold is applied to verify that there is a significant noise signal appearing in DARM during the injection. In order for a coupling factor to be "real", the injection amplitude must be X times greater than the background amplitude for DARM and Y times greater for the sensor (X and Y being variables that can be adjusted by the user). If the DARM condition is not met but the sensor condition is, then that coupling factor is considered to be an "upper limit". It is important to keep in mind that coupling functions are already upper-limits. So this kind of factor would be the "upper-limit of the upper-limit", and is plotted with a different marker to be easily identified as less reliable data. It is less reliable than "real" coupling factors because if the leakage into DARM is not great enough, then, if the sensor amplitude values are relatively small, it could make the coupling factor very large even though there is not a significant amount of coupling at that sensor's location. If neither of these conditions are met, then no coupling factor is calculated at that frequency bin.

Once all of these calculations are complete, the program plots all the factors, producing a coupling function. The image below displays a coupling function generated for a microphone sensor at End Station Y:

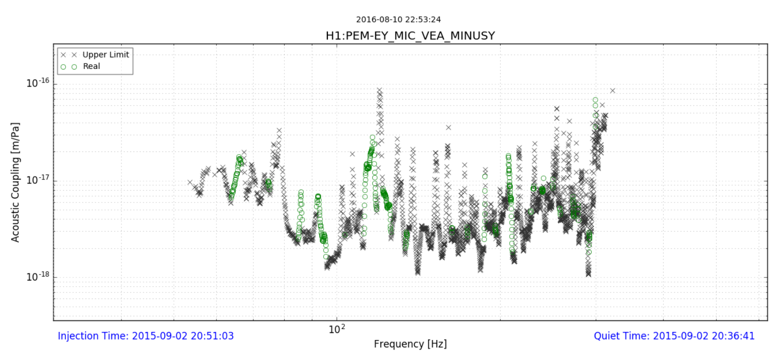

Fig. 2. Coupling Function for PEM microphone at End Y.

By looking at this figure, one could easily distinguish between real coupling factors, and upper limits.

Broad-Band Coupling Functions The environmental monitoring team often does broad-band injections that require a different process of evaluation. These injections are split up by frequency band, and conducted at different times. If the input data is applied correctly, the program will be able to identify that each specified time applies to the same sensor channel. And in turn will plot only real coupling factors in various colors that correspond with the injection that produced them. Broad-band injection plotting is yet another way to identify up/down conversion in coupling:

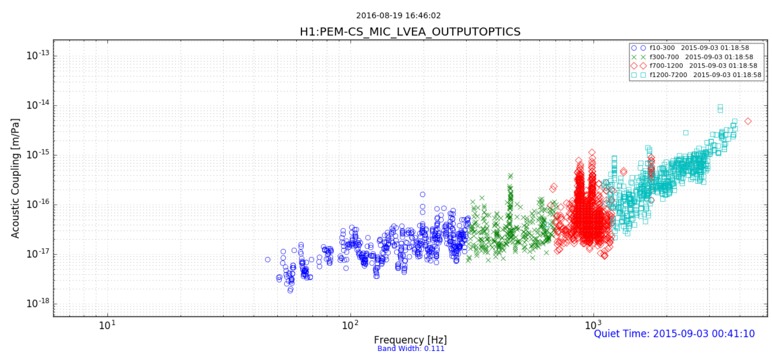

Fig. 3. Broad-band injection coupling Function for PEM microphone in the LVEA.

The spectrum that is created for a broad-band injection is a superposition of DARM spectra at the times of injection and the background. The result is much like Figure.1 which was used to explain down conversion.

3 Program Features

3.1 Spectrum Plotting and Estimated Ambients

Aside from calculating and plotting coupling functions, this program also plots the super-imposed spectra of the DARM background and DARM during injection, along with the estimated ambient at each frequency bin. Generating figures with the super-imposed spectra allows the user to see how much the DARM signal deviates from the background during the PEM injection. On these plots, down conversion can be easily spotted and the magnitude of the noise in DARM can be scaled. If the coupling function appears strange, it is also a good way to investigate why that would be.

An estimated ambient is the DARM background at that bin multiplied with the calculated coupling factor. This yields the expected signal in DARM in the presence of the type of coupling being investigated. In other words, it demonstrates the expected signal in DARM with a particular environmental signal affecting it. Comparing these values with a trigger (a possible gravitational wave candidate) will either help validate the signal or confirm that it is in fact ambient environmental noise. Upon request, the program will generate spectrum plots and estimated ambients for each channel being run. An example of the outputted data is presented below:

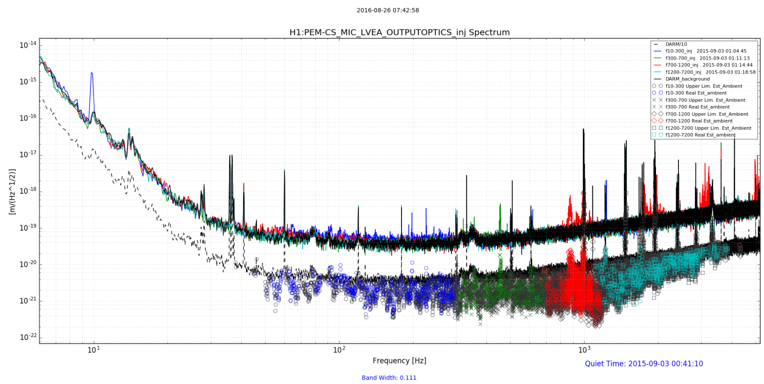

Fig. 4. Broad-band amplitude density spectrum with estimated ambients.

3.2 Multi-Plotting

Another major function of this program is that, when specified by the user, it accepts a number of channel names and plots their calculated coupling functions all on the same figure. This makes comparing the functions easy, and will be very useful when the user needs to generate data figures for documentations and presentations. When the Multi-Plotting function is requested, spectra are generated individually for each channel run in the process. For example, this is a spectrum for a magnetometer in the LVEA:

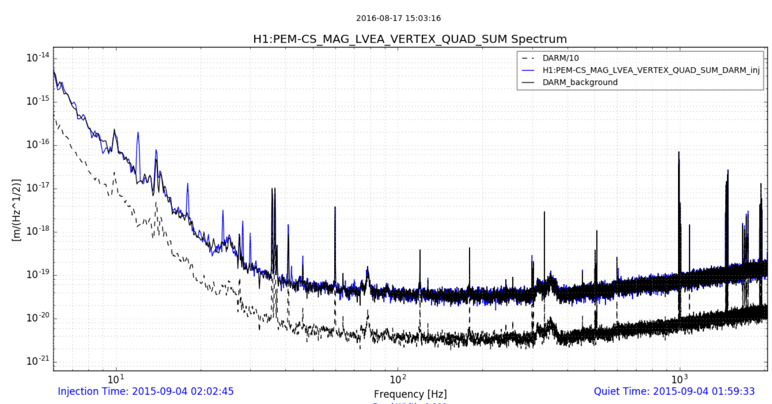

Fig. 5. Amplitude density spectrum for PEM magnetometer in the LVEA.

3.3 Coherence

Although the environmental monitoring team is interested in non-coherent data, it is still beneficial to investigate the coherence between two signals in case a check is need to be done regarding the accuracy of the data. With the proper specification, the program will produce a coherence plot for every channel:

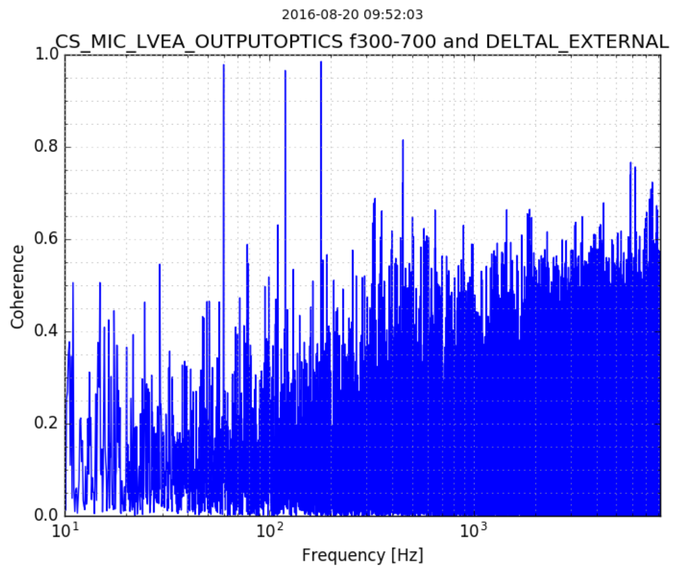

Fig. 6. Coherence plot for a PEM microphone in the LVEA.

3.4 CSV Output File

With every run the program executes, all the calculated data is recorded in a CSV file that specifies the value and flag of the coupling factor at every frequency bin. The user would be unable to retrieve specific enough coupling factors from the plots alone, and therefore if need be, could refer to the outputted CSV file for the precise value. Whenever a coherence plot is requested, the coherence values at each frequency are also reported in the CSV ouput file. This was also created in case the data needed to be used in other data figures and evaluations.

3.5 User Friendliness

User friendliness was one of the pillars of this project. People working on the Environmental Monitoring Team at LLO and LHO, as well as graduate students and future SURF students, may not have much coding experience in Python. Each script consists of over 2000 lines of code. Navigating through a program that large would be incredibly difficult for anyone who did not participate in its creation. Therefore, it was designed to remain a black box for as long as possible. It is equipped with an options parser, two configuration files (one default, one custom) and an interactive system to make running this code easier on new users. There also exists an easy-to-read instructions manual that is kept as a text file in the same directory as all other components of the code. The interactive system can be called upon from the options parser with a simple -i command. This will prompt the code to explicitly ask for raw inputs after instructing the user about the proper format of the input they need to provide.

4 Program Structure

The Coupling Function Calculator is composed of two large scripts, two configuration files, a CSV channel list, a DARM calibration file, and a sensor calibration CSV file that is extracted from the PEM.ligo.org database. The first script, called "PEMcoupling_calculator.py', contains the primary body of the code. It is responsible for all the channel sorting that is necessary for the calibrations and calculations, as well as the interactive system and other directive procedures that identify what calculations are needed depending on sensor type. The second script, titled "PEMcoupling_subroutines.py", contains all the functions, classes and methods called upon in the primary script. Dividing the program into two scripts made it more organized, less repetitive and makes navigating it much easier.

There is a default configuration file titled "default_config.txt" that specifies all the default settings for variables that are used throughout the code. The only alterations the user is expected to make in that file is the input of injection and quiet times. The custom configuration file, "custom_config.txt" is intended to be modified in anyway desirable to the user. Things such as plot axes, marker colors, coherence plotting, frequency band naming, etc. can all be controlled through the configuration files. The DARM calibration file is not meant to be accessed by the user. The name of this calibration file should be specified in the configuration file, and should only be changed if the calibration methods have been updated and a new calibration file has been created. If the user plans to run the program with old data, they would need to be careful with which DARM calibration file they use! For example, a different DARM calibration file was used during O1 than the one being used now.

The sensor calibration CSV file, called "channels_cal.csv" is downloaded from the PEM.ligo.org database and contains the calibration procedures for every channel listed. The program extracts the appropriate calibration coefficient from the csv file and applies it in the coupling factor calculations. Another small script is currently being written that will automatically update this file every time the PEM.ligo.org database is updated. The channel list file, titled O2_channels.txt contains all the PEM channels in use for O2 (observation run 2). The program has a search mechanism that, when provided with search keys, will run through this list and pick out channels that match the desired criteria. The user can also instruct the program to run all of the PEM channels in that list at one time.

All of these scripts and files must exist in the same directory. In addition, the two greatest dependencies of the program are NUMpy [3] and GWpy [2]. These must be accessible from whatever directory the program is running in. If ever an individual would need to enter the script and make necessary edits, having access to documentation on these packages would be essential.

This program is designed to be very fast and highly flexible to various kinds of input. Currently, the program can calculate coupling functions, coherences, estimated ambients and output all the plots for ten channels in about a minute. If the program were asked to just calculate and plot coupling functions, ten channels would take less than 30 seconds. All the exported data is packaged in either a new directory, or a directory specified in the options parser. By producing this data much faster and being able to run calculations on all the channels around a particular chamber, an entire region of the interferometer, or a building, we could improve the PEM injections and generate lower upper limits. This will make the environmental monitoring aspect of the gravitational wave vetting process faster and more accurate.

5 Current and Future Initiatives

In the next few months, this program is likely to see a lot of additions and adjustments as I work with graduate students working on getting the data this code produces onto the PEM.ligo.org page under Robert Schofield. There are two more scripts that will be added to the overall PEMcoupling package, which includes a query code that will automatically update the sensor calibration CSV file every time the PEM.ligo.org database is edited. This also includes a program that will take CSV output files from the Coupling Function Calculator created over a number of injections, and from that information generate the lowest coupling functions for a channel. These two scripts should be on the LIGO Hanford CDS system soon. I will also continue my involvement in the Environmental Monitoring System during the preparation period for O2 and the O2 PEM injections. This is so I could maintain the code in case any errors occur, and make necessary additions and modifications to this code that Robert Schofield would deem necessary.

5.1 Further Documentation

All other documentation and reports that were written on this program can be found on the LIGO DCC Portal, under document number LIGO-T1600387-v1 [4]. There, one can find more comprehensive documentation on this code, geared toward users who may want to understand the structure of the scripts and those who may intend to modify them. The code itself will be published there as well, so that it can be made easily accessible to the LIGO community.

References

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