Search for Cosmic Ray Induced Transient Noise at LIGO Hanford

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Abstract

We analyze LIGO data from the O4a observing run to search for excess transient noise in DARM induced by cosmic ray showers. The cosmic ray detector at LIGO Hanford and its characterization with data is described. Several methods are discussed and implemented in attempts to uncover induced noise. We find no evidence for an association of transient noise in DARM with cosmic rays, including dense showers of 1000 cosmic ray muons incident near a suspended test mass.

1 Introduction

Cosmic ray particles, primarily muons, reach the earth's surface at a rate of approximately 60/hr/cm^2 at sea level. Several potential mechanisms have been considered by which cosmic ray particles might produce observable noise transients in detectors such as LIGO. Several potential mechanisms have been proposed for the interaction of cosmic rays with suspended optics, especially the final test masses. Cosmic ray muons pass through an optic, but deposit energy via ionization of the medium in the process. This results in direct transfer of momentum and heating to the optic mass. Also, the addition of charge might create transient disruptions of the test mass with the electrostatic drive. As discussed briefly below and by Braginsky, et al. [1], an isolated cosmic ray muon will not impart an impactful momentum transfer to a test mass. A similar conclusion was reached for transient modes rung up by heating of the optic[2]. On the other hand, a different calculation of transients induced by cosmic ray heating[5] implicated cosmic rays as the source of blip glitches. An analogous, detailed calculation has not been carried out for potential charge-related transients, however the potential for noise due to charge hopping was considered by Weiss[3]. The Weiss model was used to estimate potential charging effects for aLIGO by Harry[4], who found such effects to be negligible.

Even very energetic cosmic ray showers, which originate high in the atmosphere and become diffuse at sea level, would not be considered problematic sources of transient noise. However, a high energy primary cosmic ray particle (typically protons) can with low probability interact near sea level and initiate a large cosmic ray shower which remains relatively collimated as it interacts with the LIGO detectors. Such a possibility was also considered in Ref.[2] and found to be vanishingly unlikely. Nevertheless, as near-detector showers had the greatest potential for being observable in DARM, and given the uncertainties in predicting the effects, especially for charge-related mechanisms, we designed the cosmic ray detector to be tightly proximate to a test mass. For example, taking the hypothesis that blip glitches are due to large cosmic ray showers, it would be expected that approximately 1/4 of the glitches observed at LHO – those affecting ITMX – would have an associated signal in the cosmic ray detector.

As shown in Fig. 1, a cosmic ray detector is installed on the LVEA floor, directly below a test mass at LHO. It was originally installed for iLIGO[6]. For aLIGO, it is located below ITMX at LHO. The iLIGO system employed a readout which produced event records which were independent of LIGO frame data. Nevertheless, the system worked well[7]. No correlation between (large) cosmic ray signals and DARM transients was observed. Had an effect been observed, more detectors would have been built to provide full coverage of test massses at both sites.[1] The same instrumentation, but with different readout electronics, was employed at LHO for aLIGO. This was used successfully for initial GW discoveries to demonstrate that cosmic rays were not responsible for the observed signals. However, as the GW detectors become increasingly sensitive, it is important to continue experimental interrogation, especially since modeling the potential effects have uncertainties.

In this note, we present results from an evaluation of cosmic ray and DARM data during the O4a run. This was aided by an enhancement to the electronic readout during the O4a observing run. The following section describes the cosmic ray instrumentation at LHO. This is followed in Section 3 with results for the response of the detector to cosmic rays. Section 4 provides the main results searching for transient noise in DARM coinciding with cosmic ray showers. Finally, Section 5 provides a summary and perspective.

2 Instrumentation

As shown in Fig. 1, the LHO cosmic ray detector consists of two 1-inch thick, 80 cm by 80 cm plastic scintillator slabs, which were rescued from a particle physics project at the SLAC National Lab, cut and polished and each affixed with two photomultiplier tubes. For each detector, one photomultiplier tube (PMT) is low gain (10 stages) and one high gain (11 stages). This combination provides a very large dynamic range, so that they are sensitive to single cosmic ray muons, but will not saturate for the largest imaginable low-altitude showers, i.e. thousands of muons). Having the PMTs coupled directly to the (cut and polished) scintillator corners without any additional light collection (e.g. a wavelength shifting edge panel) meant that the photon efficiency was sub-optimal and non-uniform over the detector area. It was expected that the overall efficiency for detecting single cosmic ray muons is 10-20%. However, since the focus of the design was for multi-muon showers, this was not considered problematic and was out-weighed by the simple, robust design. Cosmic ray showers are easily distinguished from any noise artifacts by demanding time-coincident signals in the two separate scintillator slabs, and less robustly by time coincidences between the two PMTs of each slab. In fact, coincident signals could be easily seen using an oscilloscope.

The intrinsic timing resolution of the cosmic ray detector (1 ns) far exceeds what is needed for LIGO. However, in the iLIGO readout, the timing resolution was preserved by using a readout path which did not write into frame data. The rising edge of the signals were used for timing, while the amplitude was taken from the integrated signals. For aLIGO, the decision was made that it would be more valuable to include the data in standard frame format, so the slower, integrated signals were to be used. The responsibility for

[1] A cosmic ray detector was also built and sent to LLO, but was never installed.

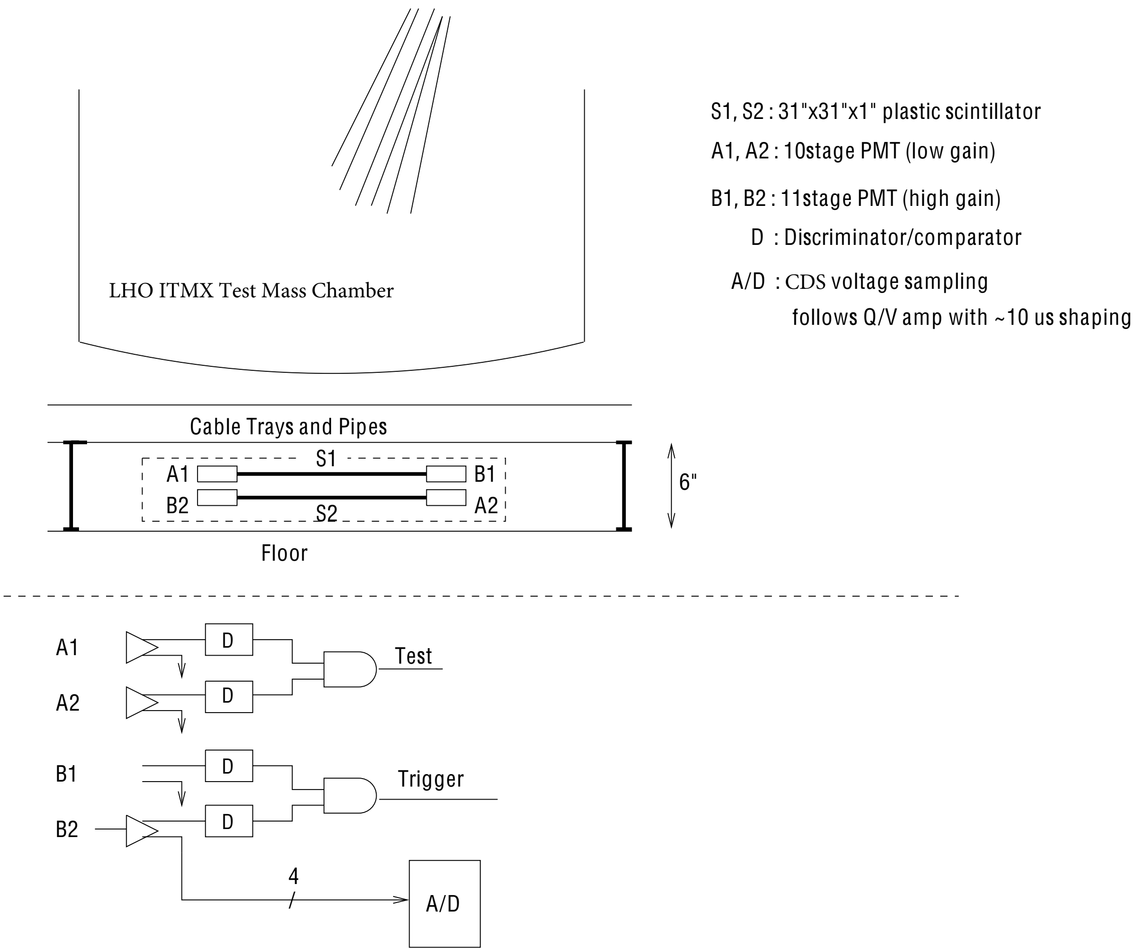


Figure 1: Schematic of cosmic ray detector at LHO. Above the dashed line is a sketch of the physical layout. Below the dashed line is a diagram of the front end electronics.

carrying out the new readout was taken by LIGO Lab. But unfortunately, this was not carried out. The only signal which appeared in the frames for runs O1-O3 was a discriminator output (labeled 'Test' in the figure). This was good enough to make checks for GW candidate events. For example, for GW150914, the distribution of these signals in time around the GW signal was found to be consistent with the Poissonian expectation for the nearby off-source data. However, lacking an amplitude channel(s), this readout was not sufficient to look for subtle transients, since such effects would be expected to be correlated with larger cosmic ray showers.

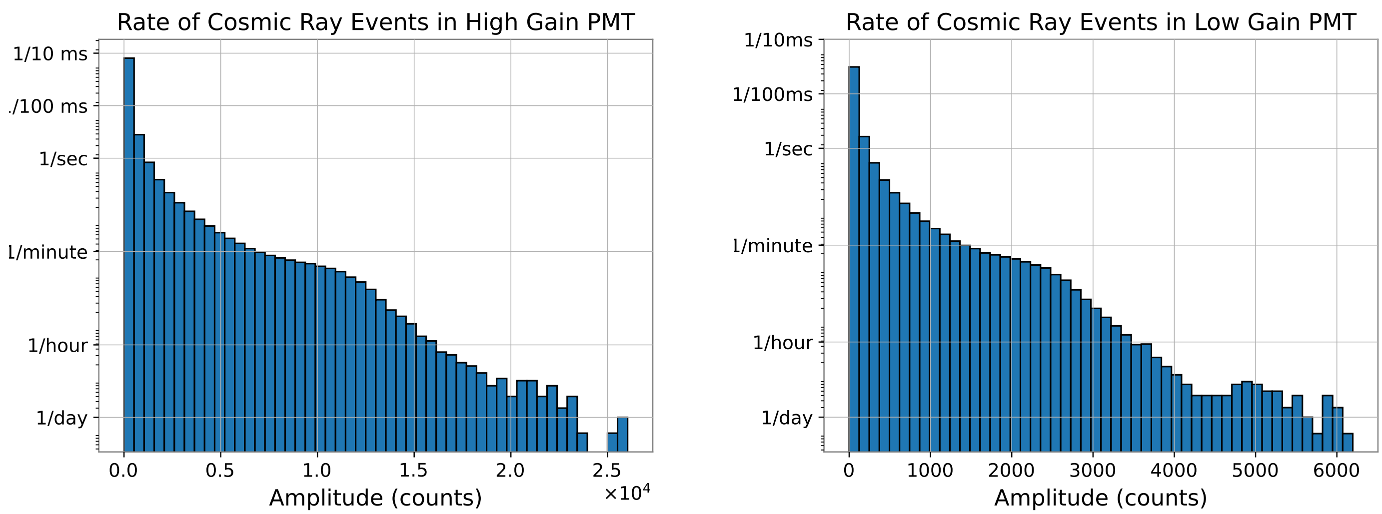
In Summer 2023, the analog signals from the old electronics, which included a front-end enalog integrator with $\sim 10\ \mu$s time constant, were connected directly to standard CDS A/D converters (labeled 'A/D' in the figure). There are two issues with the configuration as implemented. First, the A/D digitization rate of 16 kHz is a bit too slow compared to the 10 μs shaping time of the analog front end integrator. And because there is no peak sensing, this means that on average we miss about 20% of the peak amplitude, with an estimated RMS error of $\sim$ 10%. (**To be checked!**) Second, the analog electronics output appears as a differential pair, to be consumed as such by the A/D converter. However, as seem in Fig. 3 both polarities of the analog output are digitized, resulting in bi-polar signals. We did check that the negative and positive peak amplitudes are tightly correlated. In the analyses below, we use only the positive polarity [**check**] signals. Nevertheless, these limitations were found to not limit the analyses presented here in any significant manner.

The analysis software can easily take the place of any coincidence logic indicated in the figure. Happily, the analog signals were still healthy, although one (of the four) PMT channels showed indications of a degradation, most likely in the front end analog electronics. However, we found this to not be crucial to our analysis. The subsequently recorded data from the O4a run from Fall 2023 is used for the analyses reported in this note.

3 Observing Cosmic Rays

We tested the cosmic ray detector using the predicted rate of 60 muons/hr/cm^2 and the area of the scintillator plates (6,400 cm^2). Thus, we would expect to see roughly 384,000 muons/hr or 1 muon/ms. We can compare that to the rate of events seen in our detector in Figure 2. The lowest amplitude events will be individual low-energy muons, so looking at the first bin we can compare the measured rate to the predicted rate. The high gain PMTs detect a rate of about 1 muon/10 ms, which is a detector efficiency of $\sim$10%, and the low gain PMTs detect 1 muons/50 ms, giving a detector efficiency of $\sim$2%.

We now want to consider the effect a passing muon has on our mirrors. Our mirrors are made of fused silica which has a density of $\rho = 2.2$ g/cm^3. An average muon reaches the surface with an energy of 4 GeV and deposits energy into fused silica through inionization at a rate of I = 2.049 MeV$\cdot$cm^2/g. We consider the scenario where the muon travels along the beam-axis and through the d = 20 cm width of the mirror. Thus, the amount of energy the passing muon would deposit into the mirror is:



(a)

(b)

Figure 2: The detection rate of various amplitudes of cosmic ray events in the high-gain PMTs (left) and the low-gain PMTs (right) using 3 days of data. The lowest amplitude bin aligns with what we expect from individual muons. The highest amplitude events includes large cosmic ray showers that are seen by multiple PMTs like in Figure 3.

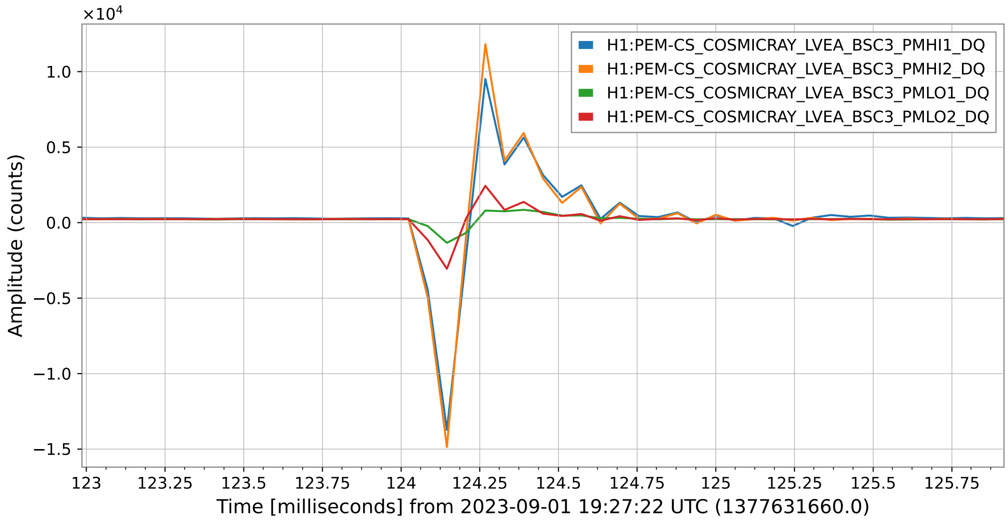


Figure 3: A typical cosmic ray shower recorded by the cosmic ray detector. The two channels connected to high-gain PMTs are labelled 'PMHI' and the low-gain PMTs are labelled 'PMLO'.

$$\Delta E = I\rho d = 90 \text{ MeV} \tag{1}$$

Following the same approach as [1], we consider the the movement of the mirror on timescale of $\tau = 0.01$ s. Given that our mirrors have a mass of M = 40 kg, we would expect:

$$\Delta x = \frac{\Delta E \tau}{Mc} = 1.2 \times 10^{-23} \text{ m} \tag{2}$$

Finally, with the length of the laser arms $x_0 = 4$ km, the expected strain would be about $\Delta x / x_0 = 3{\times}10^{-27}$. Therefore, we expect the effect of individual cosmic rays to be far below what LIGO is capable of detecting. However, in the scenario where $\sim$ 1000's of cosmic rays are passing through the mirror in a large cosmic ray shower, there could potentially be an effect.

When many cosmic rays are passing through our detector, this will likely trigger multiple PMTs at the same time. By looking for times when all of our PMTs are detecting high amplitude events, we can find the cosmic ray showers that are most likely to create an effect in LIGO. Figure 3 shows a typical cosmic ray shower recorded by the cosmic ray detector during Fall 2023. This is a large shower, corresponding to $\sim$ 100 muons passing through the detector, and hence all four PMTs have significant signals.

4 Cosmic Rays and DARM

We now discuss our investigations of excess noise in DARM associated with cosmic rays. We first investigated if cosmic rays could be a source of glitches that have no known sources. Then, we analyzed time series data of DARM near large cosmic rays showers to search for evidence of noise in our gravitational wave channel.

4.1 Correlations with Glitches

Given that cosmic rays can be considered to pass through the test mass instantaneously relative to LIGO's sampling rate, we consider glitches are that are short in duration, broadband in frequency, and with no known source. This includes blips, low-frequency blips, repeating blips, and tomtes.

In our first test, we consider the amplitude of PMT signals near glitches in time. Here we are using a list of glitches reported by GravitySpy from September through December of 2023. We take cosmic ray data within ± 1 second of a glitch, which we call our on-source data, and compare it to 20 seconds of background time far away from each glitch. We then use the Kolmogorov–Smirnov (KS) test to compare the two distributions. P-values close to 1 represent the null hypothesis, meaning the two samples are drawn from the same distribution. If we expect large cosmic ray showers to be the source of these glitches, then we could also expect to see an overabundance of high amplitude cosmic ray events in the on-source population.

Figure 4 shows an example for cosmic ray amplitude around Blips in one high-gain PMT. The following table lists the resulting KS test p-value for each glitch class:

Glitch Class	KS test p-value
Blips	0.281
Low-frequency blips	0.551
Repeating blips	0.534
Tomtes	0.211

No significant difference was found in these two distributions for any glitch type. Cosmic ray activity is measured to be the same around glitches as it is during times there are no gltiches in the data.

Next, we test if large cosmic ray showers are correlated in time with glitches. We take a month of cosmic ray minute-trend data, and consider the top 10% of cosmic ray events. We limit our dataset to cosmic rays that are measured in multiple PMTs to study the largest showers (about 2000 in total). We then take the time difference between cosmic ray showers and the next nearest glitch in time to see if there is any temporal correlation. Figure 5 shows an example with blips. For comparison we did the same with random times throughout the month and found no significant difference from the random distribution.

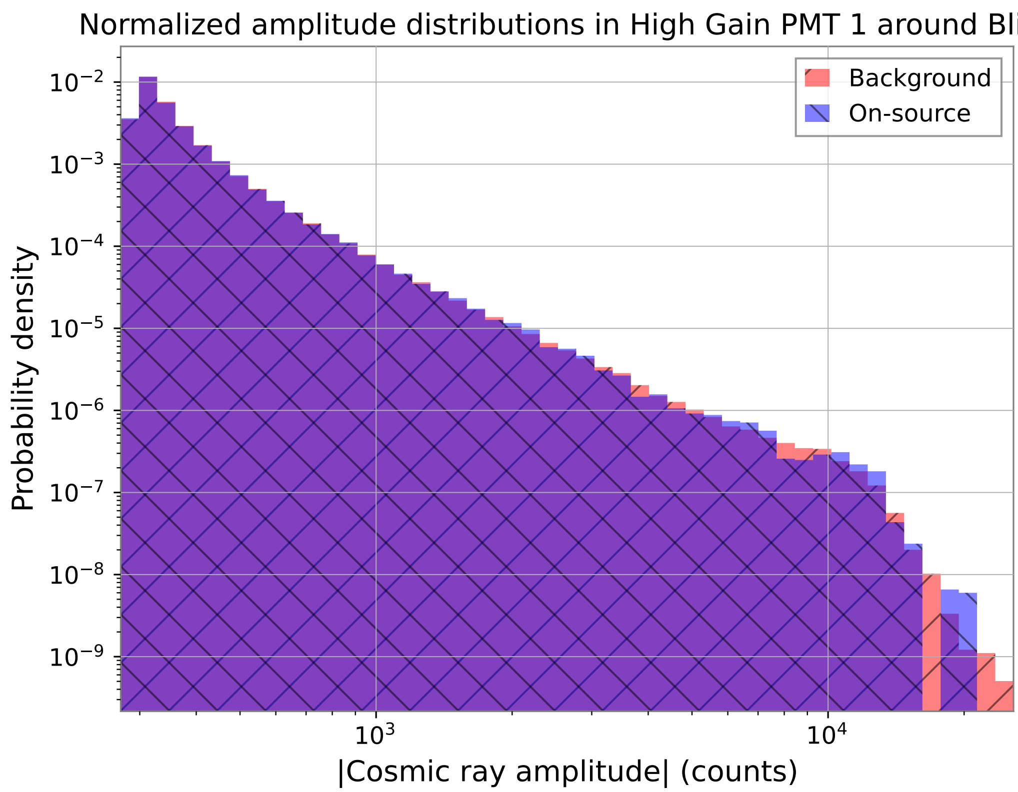


Figure 4: Histogram of cosmic ray amplitudes within 1 second of blip glitches (On-source) compared to times with no glitches (background).

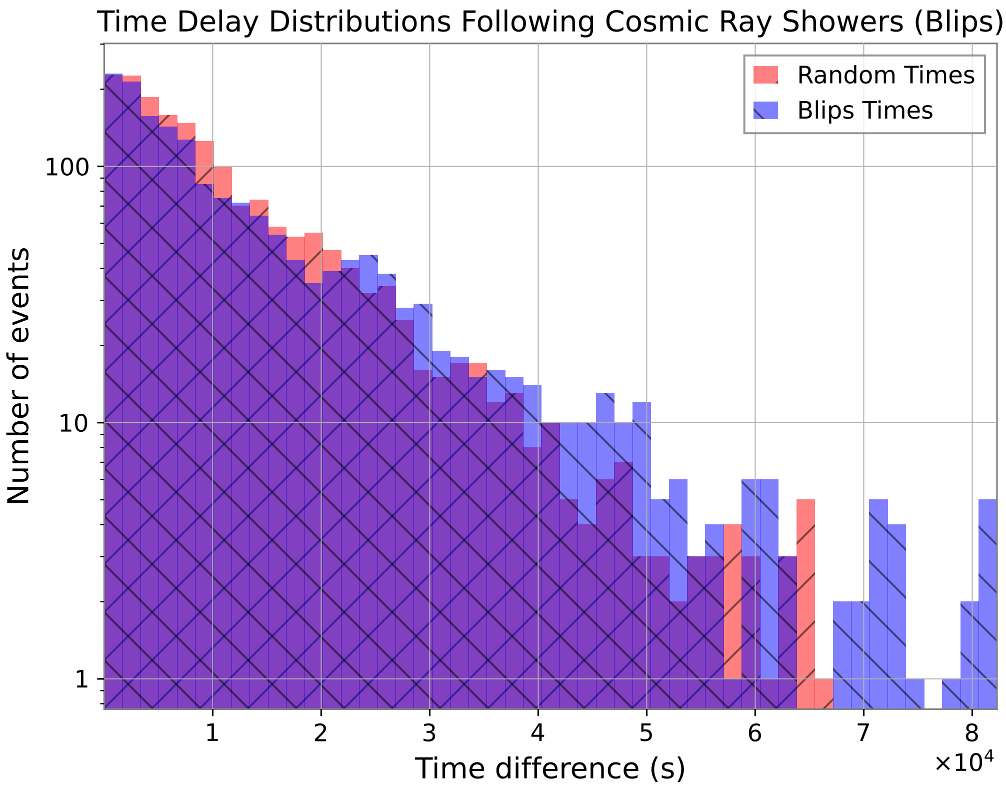


Figure 5: For every large cosmic ray shower, the time difference between the shower and the nearest glitch following the shower was calculated, and the distribution of these values is shown. The same test was done comparing the time difference between cosmic ray showers and random times throughout the month. Both of these follow the expected shape of a Poissonian process, indicating there's no correlation in time.

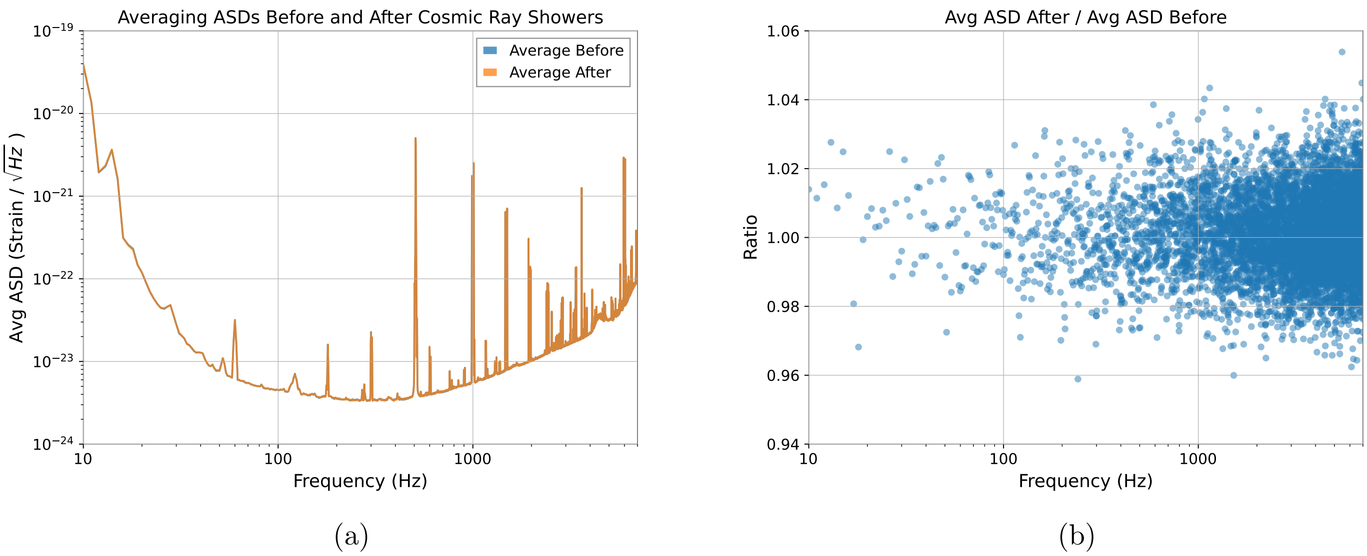


Figure 6: For every large cosmic ray shower in the month, two ASDs were created using 10 seconds of DARM before and after the shower. Note that there are two lines present that are almost entirely overlapping. The average for for all cosmic ray showers is shown on the left, and the ratio of the ASD average after cosmic ratio showers compared to before for each frequency bin is shown on the right.

4.2 Analyzing DARM

Here, we use our set of cosmic ray showers to look at DARM. We perform a search for any low level noise that may be present in the data by combining DARM information around all of the times of cosmic ray showers.

We started by looking at ASDs, both 10 seconds before cosmic ray showers and 10 seconds after. We then average these ASDs over all cosmic ray showers, the results of which are shown in Figure 6a. Figure 6b shows the ratio of these ASDs in each frequency bin. Examining these two plots, we see no evidence of excess noise at any frequency. The averaged ASDs both before and after cosmic ray showers are consistent with the sensitivity curve we expect.

5 Discussion and Conclusions

In this search, we characterized the signals we observe from Hanford's cosmic ray detector and looked for any corrleation with noise in DARM. By comparing distributions of cosmic ray amplitude around blips and tomtes to times away from these glitches, we conclude there is no difference in cosmic ray activity around these classes of glitches. Similarly, we combined cosmic ray information from multiple PMTs to study the largest cosmic ray showers our detector observes. These have no temporal connection with the glitches study.

We also studied DARM following large cosmic ray showers. By averaging our ASD both before and after the largest cosmic ray showers, we saw no difference stand out at any frequency. The ASDs are nearly identical. At our current sensitivity, cosmic rays don't appear to be creating any noise in LIGO.

References

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