Quantifying the effect of lightning-induced magnetic fields on gravitational wave detectors

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Introduction

I am a graduate student at the University of Oregon and have been a member of the LIGO Detector Characterization group since 2019. I have spent time at the LIGO Hanford (LHO) observatory with Robert Schofield during the third observing run. In my final days on site, I showed that our sensitive magnetometers could measure the magnetic field of lightning strikes in the Caribbean Sea. From there, I was able to show that individual lightning strikes from across the western hemisphere could be coherently measured at both LIGO sites. I demonstrated that the magnetic background created by these strikes could explain a new, elevated, high-frequency magnetic coherence discovered by the Stochastic working group. I also used these strikes to estimate how the field from an individual lightning strike could couple into DARM. This culminated in showing that lightning events coherent between multiple interferometers could couple into DARM in both future observing runs and future detectors at an alarming rate if the magnetic coupling is not reduced. Along with measurements from Anamaria Effler at LIGO Livingston (LLO) [1], I showed that one potential mechanism for this coupling is currents on the metallic beam tubes, and future work is planned to reduce this. Ultimately, I co-led a paper [2] detailing these findings along with calculations of how Stochastic, Burst, and CBC searches would be affected by this coherence that is currently in review.

Correlated Lightning

Correlated environmental noise is one of the biggest concerns for the increasingly sensitive gravitational wave detectors that make up our network. Until this point, environmental noise was generally considered to primarily affect a single detector at a time, allowing the possibility of an astrophysical source to be ruled out. The magnetic field generated by a lightning strike spreads out at near-light speed, reflecting off the ionosphere to travel hundreds of kilometers, with the sub-kHz components capable of remaining coherent at even greater distances [3]. This means that the magnetic fields from a lightning strike could be coherent even at distances of several thousand kilometers, like the distance between gravitational wave observatories.

I collected magnetic transients at both LHO and LLO using Omicron [4]. These transients were then compared to an external lightning detection database called GLD360 from Vaisala [5]. By requiring detected lightnings to be consistent with the time of arrival of transients at each detector, I could generate a list of individual lightnings likely responsible for specific coincident magnetic transients. The sources of these lightnings spanned much of North and Central America and the Caribbean. By removing the data around these individual lightning strikes, I was able to show that this large-scale background was responsible for elevated magnetic coherence above a few hundred Hz. This is of concern to stochastic searches which have to consider this coherent background when performing their analyses.

Impact on Gravitational Wave Detectors

I used individual lightning strikes to make estimates of the outside-to-inside magnetic transfer function. This allowed me to properly estimate the coupling of individual lightning strikes to DARM. While no evidence of coherent, magnetic coupling was found in O3, the prospects for correlated individual lightning events to couple in A+ or third generation detectors was highlighted. I found that A+ could see nearly one coincident, coupled magnetic transient per minute, and a third generation detector could see 10 times that rate if the magnetic coupling effects are the same as now. While these events could be vetted with PEM sensors, the rate of occurrence makes it difficult to filter them out automatically. Long-duration signals like binary neutron star mergers could have several of these coincident transients obstruct the signal track, impacting analyses.

With the help of Anamaria Effler at LLO, we believe we have identified one of the primary mechanisms for magnetic coupling is induced currents on the beam tubes. Ferromagnetic materials in the walls of the facility may also amplify some of these fields. If these coupling mechanisms are confirmed, future observing runs will need additional techniques to mitigate their effects such as active cancellation of the currents or the movement of critical cables and magnetic actuators where these fields enter DARM. Future detectors may need additional infrastructure or different construction materials to eliminate this magnetic contamination channels.

Conclusion

These findings highlight the need to further investigate and carefully measure magnetic coupling. My investigation has highlighted a potentially overlooked source of coherent environmental noise that could affect nearly any ground-based gravitational wave detector network and has demonstrated how close our current detectors are to being susceptible to this correlated noise.

Citations

[1] A Effler et al. aLIGO LHO Logbook. Available at https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=57580, 2021. aLog nr 57580.

[2] K Janssens, M Ball, et al. Correlated 1-1000 Hz magnetic field fluctuations from lightning over earth-scale distances and their impact on gravitational wave searches (in review). 2022.

[3] Fernando Simões, Robert Pfaff, Jean-Jacques Berthelier, and Jeffrey Klenzing. A Review of Low Frequency Electromagnetic Wave Phenomena Related to Tropospheric-Ionospheric Coupling Mechanisms. Space Science Reviews, 168(1):551–593, Jun 2012.

[4] Florent Robinet, Nicolas Arnaud, Nicolas Leroy, Andrew Lundgren, Duncan Macleod, and Jessica McIver. Omicron: A tool to characterize transient noise in gravitational-wave detectors. SoftwareX, 12:100620, 2020.

[5] R. K. Said, M. B. Cohen, and U. S. Inan. Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations. Journal of Geophysical Research: Atmospheres, 118(13):6905–6915, 2013.