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BACHELOR'S DEGREE IN
SOFTWARE ENGINEERING

GRAVITATIONAL WAVE SIMULATION: PHYSICS, EMISSION, AND PROPAGATION

PETRUS DAVI DE OLIVEIRA SAMPAIO

Brasília - DF, 2025

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Undergraduate thesis presented as a partial requirement for obtaining the Bachelor's degree in Software Engineering from the Instituto Brasileiro de Ensino, Desenvolvimento e Pesquisa (IDP).

Advisor
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DEDICATION

I dedicate this work to the restlessness that never left me in peace, and perhaps for that reason, has taken me so far. To the mind that thinks too much, errs too much, but never settles for the shallow. To those who understand that intelligence is less about knowing everything, and more about doubting everything, including oneself. This effort is not a celebration of talent, but of the silent persistence that kept me going when the light of reason seemed insufficient to justify the burden.

I thank God, whose presence in my soul sustained my spirit during the bad days, and my father, Edgard, whose influence was essential for me to walk this path. It was he who, with words and choices, planted the idea and, more than that, the possibility that I could reach this place. If I am here today, it is also because he believed before there was any evidence. To my mother, Fabiane, the most beautiful soul with whom I have had the grace to walk through this existence. If I allowed myself the possibility of loving this world, it was because she loved me first.

And, ultimately, to myself, not to who I am, but to who I have become despite who I am.

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To the colleagues and friends who shared doubts, reading materials, broken code, and excited discoveries, especially when the journey seemed too lonely. Your companionship brought lightness to the rigor and humanity to the science.

ABSTRACT

This work investigates the physics of gravitational waves regarding their emission, propagation, and intrinsic nature, combining theory and computational simulation. Grounded in General Relativity, the study analyzes the behavior of these spacetime perturbations and establishes a direct comparison with electromagnetic waves using the GW170817 event, which was simultaneously detected by the LIGO interferometers and the Fermi-GBM telescope. The methodology relies on the quantitative analysis of real data from the GWOSC, processed via Python scripts using the GWpy, NumPy, SciPy, Matplotlib, and Astropy libraries. Butterworth digital filters were applied to isolate noise and enable the clear identification of the gravitational chirp peaks and the gamma pulse associated with GRB 170817A. The results demonstrate a strong agreement in arrival times, corroborating the theoretical prediction that both waves travel at the speed of light. Furthermore, the simulations highlight fundamental differences in physical nature: while electromagnetic waves are oscillations of vector fields, gravitational waves manifest as distortions in the geometry of spacetime itself. It is concluded that the adopted computational approach not only validates General Relativity and multi-messenger astronomy but also creates tangible bridges between abstract mathematical formulation and its observable manifestation.

Keywords: Gravitational waves, electromagnetic waves, general relativity, computational simulation, python.

RESUMO

Este trabalho investiga a física das ondas gravitacionais em relação à sua emissão, propagação e natureza intrínseca, combinando teoria e simulação computacional. Com base na Relatividade Geral, o estudo analisa o comportamento dessas perturbações espaço-temporais e estabelece uma comparação direta com as ondas eletromagnéticas a partir do evento GW170817, detectado simultaneamente pelos interferômetros LIGO e pelo telescópio Fermi-GBM. A metodologia fundamenta-se na análise quantitativa de dados reais do GWOSC, processados via scripts em Python com as bibliotecas GWpy, NumPy, SciPy, Matplotlib e Astropy. Foram aplicados filtros digitais de Butterworth para isolar o ruído e permitir a identificação clara dos picos do chirp gravitacional e do pulso gama associado ao GRB 170817A. Os resultados demonstram uma forte concordância nos tempos de chegada, corroborando a previsão teórica de que ambas as ondas viajam à velocidade da luz. Além disso, as simulações evidenciam as diferenças fundamentais de natureza física: enquanto as ondas eletromagnéticas são oscilações de campos vetoriais, as gravitacionais manifestam-se como distorções na geometria do próprio espaço-tempo. Conclui-se que a abordagem computacional adotada não apenas valida a Relatividade Geral e a astronomia multimensageira, mas também cria pontes tangíveis entre a formulação matemática abstrata e sua manifestação observável.

Palavras-chave: Ondas gravitacionais, ondas eletromagnéticas, relatividade geral, simulação computacional, python.

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1 INTRODUCTION

Throughout the history of Physics, humanity has sought to understand the different ways the cosmos manifests its complexities and dynamics. Among these manifestations, two types of waves fundamental to modern Physics and Astrophysics stand out: gravitational and electromagnetic waves.

Both intrinsically convey information and energy through the spacetime continuum. However, their origins, behaviors, and detection mechanisms are distinct. This duality resides in the way each interacts with the universe, exposing complementary layers of the cosmic architecture.

Gravitational waves constitute minute deformations in the geometry of spacetime, initially predicted by Albert Einstein in 1916 as a direct consequence of the Theory of General Relativity. These waves propagate, as theoretically demonstrated and shown here in this work, at the speed of light and originate in astrophysical events of extreme magnitudes, such as collisions between black holes, neutron star mergers, or other supermassive bodies [1].

For their detection, the use of technologies such as highly sensitive laser interferometers becomes inevitable, for example, the *Laser Interferometer Gravitational-Wave Observatory* (LIGO), *Vibrational Observatory for Gravitational Radiation* (VIRGO), and *Kamioka Gravitational Wave Detector* (KAGRA). These devices operate via laser interferometry and are capable of detecting minute perturbations in spacetime geometry. They feature two perpendicular arms, on the order of several kilometers in length, through which laser beams travel opposite paths and are reflected by suspended mirrors isolated with a high degree of precision. Upon returning, these beams are recombined at a beam splitter, and the analysis of the resulting interference pattern allows for inferring relative changes in the arm lengths. Since the laser is a coherent electromagnetic wave, small variations in the distance between the mirrors generate perceptible phase shifts, making the detection of extremely subtle distortions in spacetime possible [1–3].

Upon passing through the Earth, a gravitational wave induces a minuscule distortion in spacetime, altering the distances between the mirrors on scales of the order of 10^{-19} m, a distance smaller than the diameter of a proton. This modification is detected as a variation in the laser interference pattern, which is converted into digital data.

However, given the high level of intrinsic noise in the captured signals, the application of sophisticated computational techniques for filtering, analysis, and comparison with theoretical models becomes imperative, with the aim of discerning the real phenomenon from environmental and instrumental interferences [4, 5].

In contrast to gravitational waves, electromagnetic waves constitute perturbations that propagate in space, transporting energy through the coupled oscillation of electric and magnetic fields, which are mutually perpendicular and perpendicular to the direction of propagation. Unlike mechanical waves, electromagnetic waves do not depend on a material medium for their propagation, traveling in a vacuum at the speed of light (c = 299,792,458 m/s).

Within the scope of this work, a comparison is made between the speed of an electromagnetic wave, recorded by the Fermi telescope operating in Earth orbit, and the speed of gravitational waves detected by the LIGO interferometers, installed respectively in Hanford (Washington state) and Livingston (Louisiana state), both in the USA, originating from the same astrophysical event resulting from the neutron star merger detected in 2017. Through the analysis of processed data and the identification of peak times in the different detectors, the intention is to estimate the time delay between the two types of signals.

Both raw and processed data are available to the public through the Gravitational Wave Open Science Center (GWOSC) repository, maintained by the responsible scientific collaborations, granting direct access to the collected signals for researchers, students, and enthusiasts [3].

The present work proposes a comparative and exploratory analysis of the physical and behavioral aspects of gravitational waves, through the development of computational simulations implemented in the Python language, utilizing the scientific libraries NumPy, Matplotlib, SciPy, GWpy, and Astropy. The choice of Python is grounded, on one hand, in the clarity and accessibility of its syntax, and on the other, in the robustness and diversity of its ecosystem, which encompasses specific tools for mathematical modeling, numerical analysis, and graphical data visualization—attributes that make it particularly effective in the scientific realm [6–10].

Although compiled languages, such as C or C++, offer superior computational performance in raw terms, Python enables rapid prototyping and a less steep learning curve, a characteristic of paramount importance in exploratory and iterative investigations. Furthermore, its widespread adoption by the scientific community and compatibility with high-performance hybrid environments consolidate it as a strategic language for computational investigations of complex physical phenomena [11].

It is in this scenario that the question becomes pertinent: given the inherent complexity of phenomena in non-linear gravitation regimes and the limitations of direct observation, how have computational simulations redefined research paradigms, and what is their essential contribution to the validation of theoretical models and the extraction of astrophysical parameters from extreme cosmological events?

The answer to this question is clear: computational simulations redefine research paradigms in Astrophysics by allowing the investigation of extreme gravity phenomena and extreme cosmological events, inaccessible to direct observation. Their essential contribution lies in the validation of theoretical models and the precise extraction of astrophysical parameters, driving the advancement of knowledge.

By combining theoretical foundations with modern computational tools, this research goes beyond simple quantitative analysis. It seeks to reveal profound connections between the phenomena governing the universe. Through the use of advanced computational methods, it becomes possible to validate physical hypotheses and expand our understanding of the limits and possibilities of observing the cosmos. Thus, computing establishes itself as a fundamental pillar for contemporary scientific investigation. Substantiating this perspective, the present work outlines its specific objectives by employing computational simulations for the numerical analysis of the speed and propagation behavior of gravitational and electromagnetic waves, as well as establishing a computational comparison between the intrinsic characteristics of these phenomena, verifying the consistency of the simulated results with fundamental theoretical principles.

2

2 LITERATURE REVIEW

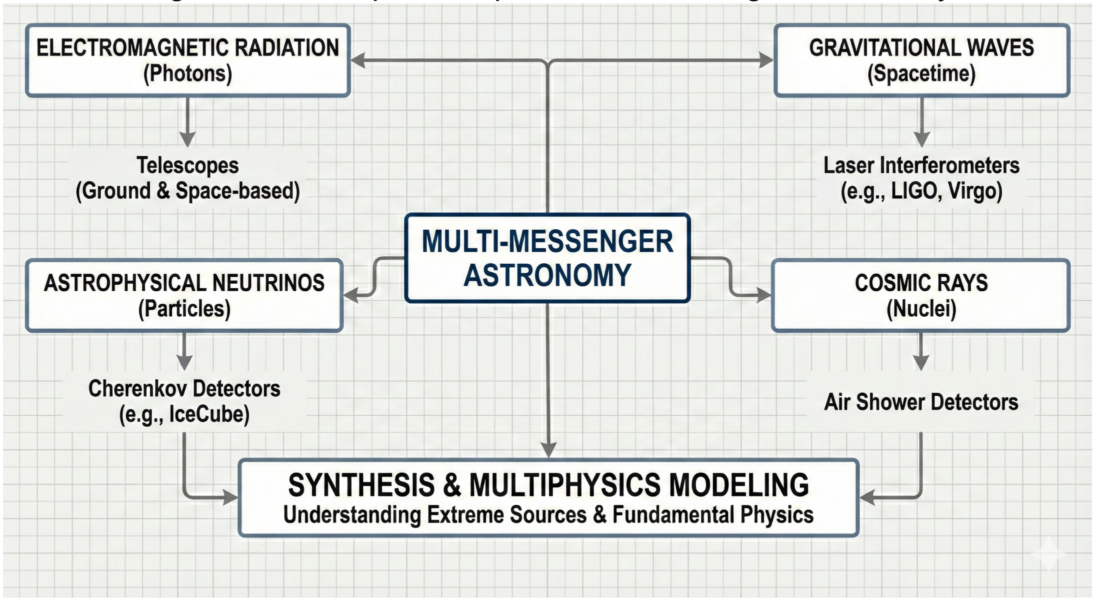
The understanding of gravitation has undergone a profound transformation from Newtonian physics to the theories developed by Einstein. In the 19th century, the Michelson-Morley experiment sought to detect the aether, the hypothetical medium in which light was thought to propagate. However, the negative result of this experiment indicated limitations in classical physics regarding the description of light propagation, contributing to a scenario of questioning that preceded the formulation of Special Relativity [1, 4].

Special Relativity, formulated by Einstein in the early 20th century, states that the laws of physics are invariant in inertial reference frames and that light in a vacuum has a constant speed for any observer independently. This theory broke with the notion of absolute space and time, translating effects such as time dilation and spatial contraction, consolidated in the geometry of spacetime. However, by not addressing gravitation, it served as the basis for a broader formulation: General Relativity(GR) [4, 12].

Published in 1915, GR describes gravity as the curvature of spacetime, caused by energy. Bodies in free fall do not experience traditional forces but follow geodesics, trajectories defined by the metric of the space-time continuum. The theory was confirmed by observations such as the precession of Mercury's perihelion and, in weak fields, recovers the results of Newtonian physics. Its mathematical formulation employs tensors and the language of differential geometry [1, 4, 12].

GR predicted the existence of gravitational waves, whose direct detection occurred in 2015 with the event GW150914, resulting from the merger of two black holes. In 2017, the event GW170817, originating from the collision of neutron stars, was observed in both gravitational waves and electromagnetic emission, marking the beginning of multi-messenger astronomy.

Figure 1: Conceptual Map of Multi-messenger Astronomy



Source: Elaborated by the author.

Note: The diagram illustrates the convergence of distinct signals: gravitational waves (detected by interferometers like LIGO) and electromagnetic radiation (detected by telescopes like Fermi-GBM), originating from a single astrophysical event (Binary Neutron Star Merger).

Such observations depend on advanced detectors like LIGO, VIRGO, and KAGRA, with future perspectives expanded by projects such as the *Laser Interferometer Space Antenna* (LISA).

In the field of computational simulation, numerical relativity is essential for modeling events such as black hole and neutron star mergers, generating waveforms that are compared with detector data. The Python language is frequently used in these simulations, with libraries such as NumPy and SciPy for numerical and statistical calculations, Matplotlib for data visualization in graphs, Astropy for astronomical data manipulation in celestial coordinates, and GWpy, developed by the LIGO community, for gravitational wave data analysis [1, 6, 8–10].

To overcome certain limitations of GR, alternative theories have been proposed that modify spacetime geometry, including the possibility of additional properties beyond simple curvature, such as torsion. These approaches seek to broaden the description of gravity in contexts where classical theory presents difficulties. To validate these hypotheses, complex computational simulations are performed to test the predictions of these new geometric structures [13].

In summary, the reviewed literature describes the evolution of gravity, from Newton to GR, highlights the importance of gravitational waves and multi-messenger astronomy, and emphasizes the role of computational tools, such as Python, in the simulation of gravitational phenomena.

2.1 THEORETICAL FRAMEWORK

Regarding the propagation of electromagnetic waves, it is necessary to delve into the fundamental laws that govern it. In classical electromagnetism, it is possible to find a cohesive set of structures and equations that unify electric and magnetic phenomena respectively, completely transforming the perception held of light and all forms of electromagnetic radiation. This theoretical framework, masterfully consolidated by Maxwell's equations, represents one of the most elegant syntheses of modern physics, unifying, under the same formalism, electric and magnetic phenomena, until then treated as separate entities.

2.1.1 Classical Electrodynamics

The four Maxwell's equations detailed below describe with exactitude the local behavior of electric (**E**) and magnetic (**B**) fields, relating their space-time variations to the physical sources that generate them, namely, charge and current densities. The power of these equations lies not only in their ability to predict phenomena with rigor but in the way they reveal the underlying symmetry between the fields [14].

- **Gauss's Law for the Electric Field**
  The divergence of the electric field is proportional to the volumetric electric charge density (ρ), as defined by Eq. (1):

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \tag{1}$$

  Here, ε_0 represents the vacuum permittivity, whose value is $\varepsilon_0 = 8{,}854\,187\,817 \times 10^{-12}$ F/m.

- **Gauss's Law for Magnetism**
  The divergence of the magnetic field is always zero, Eq. (2):

$$\nabla \cdot \mathbf{B} = 0 \tag{2}$$

- **Faraday's Law of Induction**
  A time-varying magnetic field induces a rotational electric field, as per Eq. (3):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3}$$

- **Ampère–Maxwell Law**
  A varying electric field can generate a magnetic field even in a vacuum, Eq. (4):

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{4}$$

where μ_0 is the vacuum permeability, **J** is the conduction current density, and the displacement term $\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ ensures current continuity [14].

Despite the elegance and completeness with which Maxwell's equations describe electromagnetic phenomena in inertial frames, their validity is limited to flat spacetime. When we seek to understand phenomena on cosmic scales, such as wave propagation in strongly gravitational environments, it becomes necessary to resort to a more general framework, where the geometry of spacetime itself participates in the physical dynamics: it is in this context that GR emerges.

2.1.2 General Relativity

When seeking to understand the deep structure of the universe, the confrontation with the nature of gravitation becomes inevitable, an interaction that, unlike other fundamental forces, does not reveal itself through localized classical fields, but rather through the geometry of spacetime itself. The theory of GR, proposed by Albert Einstein in 1915, emerges from this context as a radical reformulation of gravitational physics. Instead of interpreting gravity as a conventional force, Einstein conceived it as a manifestation of the curvature of the space-time continuum induced by the presence of matter and energy [15].

Such construction rests on a central principle: the *equivalence principle*, which establishes the complete indistinguishability, at a local level, between an accelerated reference frame and the action of a gravitational field. This idea, both conceptual and experimental in character, paves the way for a new description of motion no longer governed by external forces, but by the geodesics of a curved geometry [15].

Unlike classical electrodynamics, which operates on Minkowski's flat spacetime, GR demands a mathematical language capable of dealing with the variability of the substrate itself where phenomena occur. This language is provided by Riemannian geometry, in which spacetime is treated as a manifold endowed with a dynamic metric, sensitive to the distribution of energy and momentum.

It is within this structure that Einstein's field equations arise, originally introduced in 1916 [15], whose role is to establish the relationship between spacetime curvature and the physical sources that determine it. In their general formulation, with the cosmological constant, these equations are expressed by:

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R + \Lambda g^{\mu\nu} = kT^{\mu\nu} \tag{5}$$

They synthesize, remarkably, the dynamics of the cosmos: matter and energy shape spacetime, and this, in turn, dictates the motion of matter. Thus, gravitation ceases to be an external agent acting upon the scenario, and becomes the modulation of the stage itself where physical events unfold [15].

This conception of gravitation as geometry establishes the foundations for the study of the propagation of metric perturbations, gravitational waves, and their relationship with other wave phenomena, such as electromagnetic ones, in the cosmological scenario.

2.2 RELATED WORKS

This section is dedicated to the critical analysis of previous studies that, due to their methodological nature or investigative scope, articulate directly or tangentially with the purpose of this monograph. Such a survey is not reduced to a descriptive compendium but seeks to understand how certain authors faced analogous problems, which computational and physical approaches were mobilized, the limits they encountered, and, above all, the epistemic gaps that still subsist and to which this work, to some extent, intends to address a response.

2.2.1 Parallelized inference for gravitational-wave astronomy

Talbot's article deals with the optimization of Bayesian inference applied to gravitational-wave astronomy, especially given the computational bottlenecks imposed by analyses requiring considerable processing power. The authors focus on the parallelization of computationally expensive operations, notably waveform generation and likelihood function evaluation, utilizing Graphics Processing Units (GPUs) architecture for this purpose [16].

The implementation was performed in Python, making extensive use of the `CuPy` library (interface for CUDA). Parallelizable versions of waveforms such as `TAYLORF2` (in Python with `CuPy`) and `IMRPHENOMPV2` (in CUDA, derived from C code) were developed. Performance tests were conducted on NVIDIA P100 GPUs, in contrast to Intel Gold 6140 CPUs [16].

The results demonstrate expressive speedups: approximately 50 times in the generation of compact binary waveforms, and from 10x to 80x in longer signals, such as those originating from neutron star mergers (~ 100 seconds). For population inference, gains exceeding 100x were recorded, with execution time reduced from one week to less than 24 hours, using 2×10^5 samples. Additionally, prior memory allocation on GPU (buffer) proved advantageous in contexts with low frequency density [16].

However, the authors acknowledge structural limitations: in waveforms with fewer than 10^5 *bins*, GPU performance decays, primarily due to the overhead associated with memory allocation. Added to this is the absence of Earth's rotation as a dynamic factor in long-duration models, besides the frequently idealized assumption that experimental noise is Gaussian and stationary [16].

The relevance of the study to this monograph is unequivocal. The use of Python, here adopted not as a language of convenience, but as a tool capable of integrating performance and scientific abstraction through specialized libraries, methodologically supports the approach proposed herein. It is thus demonstrated that the use of interpreted languages can be effective, provided it is associated with contemporary computational strategies, such as GPU parallelization, a resource that, although not directly explored in this work, legitimizes the choice of an analogous computational ecosystem.

2.2.2 The future of gravitational wave science – unlocking ligo's potential: Ai-driven data analysis and exploration

In this article, the authors conduct an exhaustive review of the application of Artificial Intelligence (AI) techniques in the analysis of data from gravitational wave detectors, notably LIGO, between the years 2021 and 2024. The objective lies in investigating how learning algorithms can mitigate noise, detect signals in real-time, and refine the interpretation of astrophysical data [17].

Four approaches were examined: Supervised Learning, Unsupervised Learning, Deep Learning, and Reinforcement Learning. Evaluation metrics included accuracy, precision, True Positive Rate (TPR), False Positive Rate (FPR), and computational performance [17].

Deep Learning and Supervised Learning techniques stood out as the most effective, with accuracy rising from 0.94 to 0.97 in the analyzed period, and precision from 0.93 to 0.96. Computational efficiency, initially limited, became moderate starting in 2023. Unsupervised and reinforcement approaches, although less precise, revealed themselves to be highly efficient, with potential for real-time detection applications.

Despite the advances, the study makes significant barriers explicit: AI models prove sensitive to data quality, the nature of which is frequently affected by non-stationary and non-Gaussian noise. Furthermore, the difficulty in model generalization regarding the morphological variety of astrophysical sources is highlighted.

This article explicitly reaffirms that contemporary gravitational wave science is inextricably linked to computational sophistication. Although the present monograph does not directly implement AI techniques, the use of modern scientific tools, such as `NumPy`, `SciPy`, `Matplotlib`, and `GWpy`, aligns with the trend of integration between data science and theoretical physics, pointed out by the study as a vector of progress in the area [17].

2.2.3 From binary black hole simulation to triple black hole simulation

In this work, the authors investigate the gravitational dynamics of binary and triple black hole systems, especially those in which a third massive body (for example, a supermassive black hole in a globular galaxy) exerts perturbative influence on a binary system. The methodology is based on numerical relativity (NR), without simplifying assumptions, through the BSSN formalism, with adaptive mesh refinement ("moving box"), executed on supercomputers [18].

To circumvent exacerbated computational costs, a perturbational method is proposed, treating the gravitational field of the third body as a weak perturbation. Code parallelization was implemented via MPI (between computational nodes) and OpenMP (within nodes) [18].

The results indicate substantial effects on the emitted waveforms: delays or advances in the merger; amplitude reduction by the action of gravitational redshift; wavelength elongation; increased orbital eccentricity; and excitation of higher modes (such as $l = 3$, $m = 1$), whose amplitude grows non-linearly with the gravitational potential of the third black hole, a phenomenon that may serve as a distinctive signature for triple systems [18].

Acknowledged limitations include the neglect of the binary system's backreaction on the third body, as well as the high computational cost, intensified by the disparity of spatial scales between the black holes.

This article has direct pertinence to the scope of this monograph. Although the focus here falls on neutron star mergers, the emphasis on high-complexity computational simulations, as well as on the geometric influence of spacetime on waveforms, resonates with the objectives of this work. The discussion on higher modes, signal deformations, and robust computational requirements reinforces the importance of allying the GR theoretical framework with effective computational instruments, a dimension equally present in this study.

2.2.4 Critical Synthesis and Insertion of the Work in the State of the Art

The three aforementioned researches, although distinct in approach and chronology, converge on a fundamental point: the modeling, detection, and analysis of gravitational waves cannot dispense with modern computational apparatus.

The work of Bai establishes the foundations of simulations in relativistic geometry for multi-body systems, exposing not only the dynamic complexity of these systems but also the limits imposed by computation. Talbot, in turn, demonstrates the concrete possibility of mitigating such restrictions through the use of GPU parallelism, even within the Python environment. Meanwhile, Yong Xiao's study projects Artificial Intelligence as a vector of excellence in the analysis of large volumes of noisy data, a scenario increasingly common to contemporary astrophysics [16–18].

The present work inserts itself into this context as an effort of applied synthesis. It is proposed here to use modern computational tools, more specifically, the Python language and its set of scientific libraries, in the construction of simulations that allow for a comparative analysis between gravitational and electromagnetic waves. It is an investigation that unites, in the same scope, physical, mathematical, and computational aspects, offering a specific, yet necessary, contribution to the consolidation of multi-messenger astrophysics. The proposal is not, therefore, merely to reproduce techniques, but to situate them critically in the resolution of a concrete problem, evidencing how the intersection between theory and computation can, in fact, broaden the intelligibility of the cosmos.

2.3 WORK PLAN

Table 1: Planning of the Final Stages of the TCC (June–November 2025)

Month	Planned Activities
June	• Consolidate theoretical foundation on gravitational and electromagnetic waves. • Review literature related to the GW170817 event. • Organize code structure for data analysis.
July	• Import and process real data from the GW170817 event using libraries such as `GWpy`, `Astropy`, and `NumPy`. • Generate preliminary graphs of gravitational waves with `Matplotlib`. • Apply filters and identify the wave peak.
August	• Identify and analyze electromagnetic signals recorded by the Fermi telescope. • Estimate the arrival time of the electromagnetic wave. • Initiate comparison between the arrival times of both wave types.
September	• Calculate the time difference between signals and estimate the speed difference. • Verify uncertainties and possible sources of error in the analysis. • Document all results obtained so far.
October	• Elaborate final sections of the work: discussion of results and conclusion. • Generate definitive graphs and assemble figures for the TCC. • Begin textual revision and formatting.
November	• Final text revision and technical adjustments. • Insertion of cross-references and citation verification. • Final submission and preparation for presentation/defense.

3

3 METHODOLOGY

The methodology adopted in this study is grounded in a quantitative, experimental, and analytical approach, built directly from the public data of the GW170817 event made available by the *GWOSC*. This approach focuses on the gravitational signal recorded by the LIGO H1 and L1 interferometers, which serve as the primary detectors of the Laser Interferometer Gravitational-Wave Observatory located in Hanford, Washington, and Livingston, Louisiana. The analysis seeks, above all, to understand the internal structure of the *chirp*, identify the instant of maximum observational amplitude in each detector, and, based on the difference between these instants, estimate the time delay between the stations [3].

This delay constitutes one of the most direct indicators of the agreement between the propagation speed of the gravitational wave and the speed of light in a vacuum, as predicted by GR, consolidating a bridge between the geometric theory of spacetime and the empirical behavior of waves recorded by interferometric instrumentation.

The entire analysis was performed in a Python environment, utilizing a consolidated ecosystem of scientific libraries: `GWpy`, `NumPy`, `SciPy`, `Matplotlib`, `Seaborn`, `Astropy`, and `Seaborn`. The combination of these tools establishes a robust computational architecture capable of manipulating high-resolution time series, applying efficient digital filters, extracting relevant observational features, and producing interpretative graphical representations [6–10, 19].

This methodology is widely reproducible, transparent, and compatible with the procedures routinely employed in initial data inspections by members of the LIGO/Virgo/KAGRA collaborations themselves, thus ensuring technical rigor and fidelity to contemporary practices in gravitational wave astrophysics.

3.1 GENERAL STRUCTURE OF THE PYTHON SCRIPT

The code was structured in a modular and sequential manner, evidencing a clear and rational methodological flow. The internal organization follows this logic:

1. Import of fundamental libraries;

2. Definition of global parameters (detectors, coalescence time, time window, cutoff frequency, etc.);

3. Acquisition of raw data directly from the GWOSC repository;
4. Application of the Butterworth digital filter;
5. Identification of the *chirp* peak instants;
6. Generation of graphical representations.

The initial block of imports is presented below:

```
import numpy as np
import matplotlib.pyplot as plt
from gwpy.timeseries import TimeSeries
from scipy.signal import butter, filtfilt
import seaborn as sns
import logging
```

Each library fulfills specific and complementary functions:

- **GWpy**: high-level abstractions for acquisition, reading, manipulation, and visualization of calibrated LIGO/Virgo data;
- **NumPy**: mathematical base for vectorized operations and high-precision numerical manipulation;
- **SciPy.signal**: core of the digital filtering methods used in processing;
- **Matplotlib** and **Seaborn**: visualization libraries destined for the construction of scientific figures;
- **Logging**: informative logging and exception handling during the execution flow.

3.1.1 Initial Analysis Parameters

```
MERGER_TIME = 1187008882.43   # GPS time of the GW170817 coalescence
ANALYSIS_WINDOW = (-4, 4)     # Analysis time window around the event
CUTOFF_FREQ = 300             # Cutoff frequency for the Butterworth filter
```

These parameters are fundamental. The constant `MERGER_TIME` defines the absolute instant of coalescence in GPS time. The analysis window, with a total amplitude of 8 seconds, ensures the integral capture of the *chirp*'s ascent, from its first detectable oscillations to its apex immediately preceding the merger of the compact bodies. The cutoff frequency of 300 Hz is physically and instrumentally justified: below this value, the GW170817 signal presents the highest signal-to-noise ratio, while above it, the regime dominated by instrumental noise, mechanical vibrations, and limitations of the interferometer itself begins to predominate.

3.1.2 Detector Data Acquisition

Data acquisition is performed via the `TimeSeries.fetch_open_data()` function, which directly accesses the public GWOSC repository. The function below encapsulates this operation, including exception handling:

```python
def fetch_detector_data(detector: str, start: float, end: float) -> TimeSeries:
    try:
        logging.info(f"Fetching data for {detector} between {start} and {end}")
        return TimeSeries.fetch_open_data(detector, start, end,
         ↪  sample_rate=4096)
    except Exception as e:
        logging.error(f"Error fetching data for {detector}: {e}")
        raise
```

The acquired data are calibrated time series of the *strain*, that is, the relative deformation of spacetime measured by the interferometers. The sampling rate of $4096\,$Hz provides adequate temporal resolution to identify the gravitational wave arrival delay between H1 and L1 with sub-millisecond precision.

3.1.3 Digital Filtering with Butterworth Filter

Filtering plays an essential role, as the raw signal is submerged in a regime of instrumental and environmental noise that obscures its morphology. To mitigate such undesirable contributions, a fourth-order Butterworth low-pass filter was applied:

```python
def butter_lowpass_filter(data: TimeSeries, cutoff_freq: float, order: int = 4)
↪  -> TimeSeries:
    nyquist = 0.5 * data.sample_rate.value
    normal_cutoff = cutoff_freq / nyquist
    b, a = butter(order, normal_cutoff, btype='low')
    filtered = filtfilt(b, a, data.value)
    return TimeSeries(filtered, t0=data.t0, sample_rate=data.sample_rate)
```

From a mathematical point of view, the Butterworth filter is characterized by having a *maximally flat* response in the passband, i.e., an absence of ripples in both magnitude and phase within the transmission region [20,21]. Its analog transfer function for a filter of order n is given by:

$$|H(\omega)|^2 = \frac{1}{1+(\omega/\omega_c)^{2n}},$$

where ω_c is the cutoff frequency. In the digital context, the coefficients (b, a) are calculated via the bilinear transformation, which maps the analog left half-plane to the interior of the unit circle [20]. Frequency normalization is performed by:

$$\omega_n = \frac{f_c}{f_{\text{Nyquist}}}, \qquad f_{\text{Nyquist}} = \frac{1}{2} f_s,$$

where f_s is the sampling rate. The use of the `filtfilt()` algorithm applies the filter in both forward and reverse directions, eliminating any phase shift and preserving, with integrity, the temporal position of relevant physical structures, which is indispensable when comparing peak instants between distinct detectors [20, 22].

3.1.4 Chirp Peak Identification

The identification of the instant of greatest amplitude is performed computationally by:

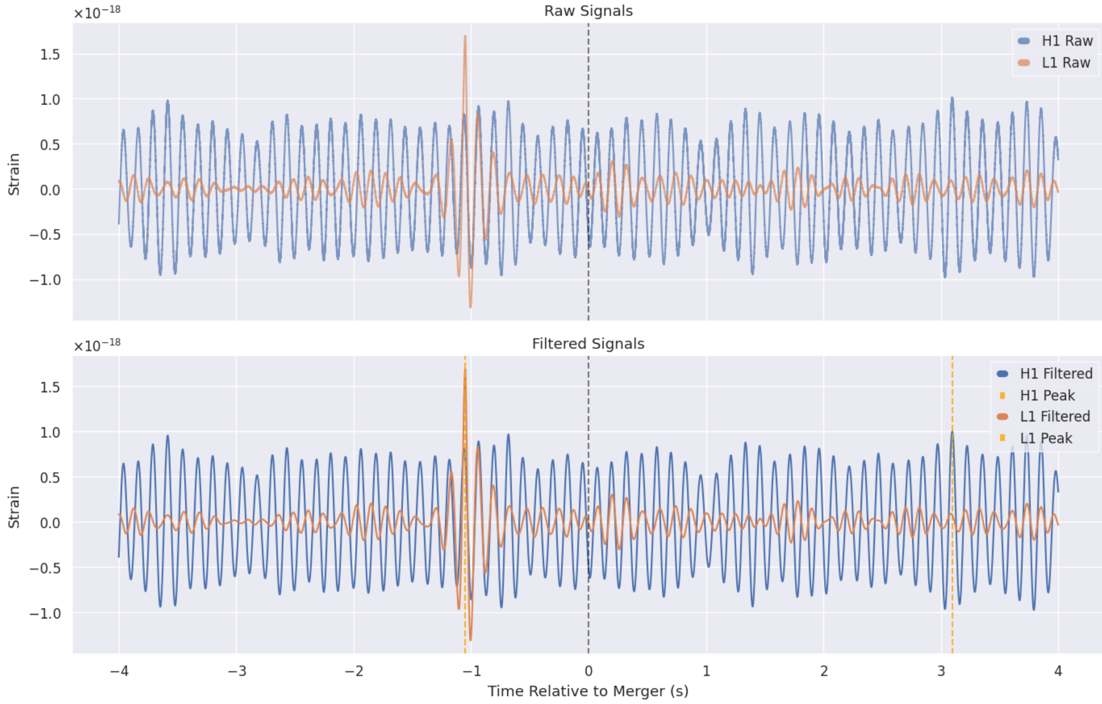
```
peak_index = np.argmax(np.abs(filtered.value))
peak_time  = filtered.times.value[peak_index]
relative_peak = peak_time - MERGER_TIME
```

This instant, although not necessarily coinciding with the exact physical moment of the merger, constitutes a robust observational marker of the final phase of the binary's orbital evolution. The difference between the peaks of H1 and L1 directly provides the time delay between the detectors, reflecting the direction of incidence of the gravitational wave and the geometry of the Earth at the instant the wavefront passes.

3.1.5 Visualization and Graphical Analysis

Graph construction is performed via the function `plot_signals`, which generates the comparative visualization between raw and processed data. Figure 2 presents the resulting time series. In the upper panel, the original signal is dominated by noise, making the evolutionary structure of the gravitational wave practically invisible. After applying the Butterworth filter, the lower panel clearly shows the emergence of the characteristic *chirp* form: a simultaneous increase in amplitude and frequency as the compact bodies orbit spirally toward the merger.

Figure 2: Raw and filtered time series for LIGO detectors H1 and L1 surrounding the GW170817 coalescence



Source: Elaborated by the author using GWOSC data.

Note: The dashed lines indicate the instants of maximum amplitude identified after the application of the Butterworth filter. The horizontal separation between these lines expresses the time difference between detections.

3.2 ANALYSIS OF THE ELECTROMAGNETIC COUNTERPART

The GW170817 event definitively inaugurated the multi-messenger era of astrophysics. Minutes after the coalescence of two neutron stars, the emergence of a short Gamma-Ray Burst (GRB 170817A) was observed, recorded independently by the *Fermi-GBM* and *INTEGRAL* instruments. The temporal proximity between the gravitational emission and the gamma pulse establishes, unequivocally, the causal link between neutron star mergers and the generation of short GRBs, consolidating a scenario that, until then, remained only within the theoretical realm.

This coincidence between distinct messengers provides one of the most refined empirical confirmations of GR, by allowing direct comparison between the behavior of gravitational waves and electromagnetic waves propagating along the same cosmological trajectory. The observed agreement between both reinforces the solidity of relativistic predictions and evidences the deep link between spacetime geometry and high-energy astrophysical phenomena. In this context, the temporal analysis of gamma emission becomes an essential component for the complete characterization of the multi-messenger event, justifying the technical treatment presented below.

3.2.1 Methodology

The independent reconstruction of the light curve of GRB 170817A was developed from public data from the *Fermi-GBM*, in *Time-Tagged Events* (TTE) mode, using NaI detectors n0 and n1 associated with trigger `bn170817529`. The objective of this stage is to extract, with adequate temporal resolution, the fine structure of the gamma pulse and identify its characteristic markers, elements that will be subsequently compared to the signatures of the gravitational signal within the scope of multi-messenger analysis.

The methodological flow follows:

1. Binning of photon events into intervals of 0.1 s;
2. Application of a fourth-order Butterworth low-pass filter (2 Hz);
3. Automatic determination of the peak count instant in each detector;
4. Comparative visualization of raw and filtered light curves.

3.2.2 Data Source and Fermi-GBM Detectors

The *Fermi Gamma-Ray Burst Monitor* possesses twelve sodium iodide (NaI) detectors, sensitive to the range of ~ 8 keV to 1 MeV, distributed angularly to maximize celestial coverage. Detectors n0 and n1 captured the largest fraction of photons from GRB 170817A, offering the best signal-to-noise ratio.

The TTE mode records each individual photon with high temporal resolution, allowing for precise light curve reconstructions. The files used are:

- `glg_tte_n0_bn170817529_v00.fit`
- `glg_tte_n1_bn170817529_v00.fit`

They can be publicly accessed at HEASARC, under the following hierarchy:

```
fermi/
    data/
        gbm/
            triggers/
                2017/
                    bn170817529/
```

3.2.3 Analysis Parameter Configuration

The analysis parameters are defined in Python as follows:

```python
CONFIG = {
    'time_window': (-10.0, 10.0),     # Time window in seconds
    'time_bin': 0.1,                  # Time bin size
    'cutoff_freq': 2.0,               # Filter cutoff frequency (Hz)
    'detectors': {
        'n0': 'glg_tte_n0_bn170817529_v00.fit',
        'n1': 'glg_tte_n1_bn170817529_v00.fit'
    }
}
```

This configuration fully captures the main pulse, preserves the structure of the short GRB, and removes statistical fluctuations without degrading the signal [23].

3.2.4 Acquisition and Binning of TTE Data

```python
def load_gbm_data(filename: str, time_window: tuple) -> tuple:
    with fits.open(filename) as hdul:
        times = hdul[2].data['TIME']
        trigger_time = hdul[0].header['TRIGTIME']
        bzero = hdul[2].header.get('BZERO', 0.0)

        rel_times = times - (trigger_time - bzero)

        mask = (rel_times >= time_window[0]) & (rel_times <= time_window[1])
        rel_times = rel_times[mask]

        bins = np.arange(
            time_window[0],
            time_window[1] + CONFIG['time_bin'],
            CONFIG['time_bin']
        )
```

This function reads the FITS files, calculates the time relative to the trigger, and constructs the photon arrival histogram.

3.2.5 Filtering and Peak Determination

The Butterworth low-pass filter is applied as follows:

```python
def butter_lowpass_filter(data: np.ndarray, cutoff_freq: float, sample_rate:
↪ float, order: int = 4) -> np.ndarray:
    nyquist = 0.5 * sample_rate
    normal_cutoff = cutoff_freq / nyquist
    b, a = butter(order, normal_cutoff, btype='low')
    return filtfilt(b, a, data)
```

The peak instant of the filtered signal is automatically identified:

```
peak_idx = np.argmax(filtered)
peak_time = time_centroids[peak_idx]
```

3.2.6 Light Curve Visualization

Figure 3 displays the results of the electromagnetic analysis, confirming the temporal morphology of the gamma burst and the relative delay to the gravitational signal, reaffirming the internal consistency of the multi-messenger scenario.

Figure 3: Light curves of GRB 170817A recorded by Fermi-GBM detectors NaI n0 and n1

Source: Elaborated by the author using Fermi-GBM data.
Note: Upper panel: raw counts in 0.1 s bins. Lower panel: filtered signal (2 Hz low-pass) marking the instants of maximum emission in each detector.

3.3 INTEGRATED PROCESSING OF GRAVITATIONAL AND ELECTROMAGNETIC SIGNALS

The final stage of this methodology consists of integrating the gravitational and electromagnetic signals into a single computational pipeline, allowing for the joint visualization of their temporal signatures and the investigation of the relative delay between the observed peak of the gravitational *chirp* and the gamma pulse of GRB 170817A. This integration is essentially illustrative and analytical in nature: it does not seek to estimate the physical delay between the messengers, which is already established by literature, but rather to examine the internal coherence between filtering, peak detection, and temporal alignment within the developed computational environment.

The complete script was implemented in Python, utilizing `GWpy`, `NumPy`, `SciPy`, `Astropy`, `Matplotlib`, and `Seaborn`. The code structure is presented below in logical blocks, accompanied by a detailed discussion on the functions, mathematical foundations, adopted parameters, and physical implications of each operation [6–10, 19].

3.3.1 Import of Libraries and General Configurations

```python
import numpy as np
import matplotlib.pyplot as plt
from gwpy.timeseries import TimeSeries
from scipy.signal import butter, filtfilt
from astropy.io import fits
import seaborn as sns
import logging
import os
```

This initial section gathers all essential dependencies. The `GWpy` library provides high-level tools for acquiring and manipulating calibrated LIGO/Virgo data; `Astropy` enables reading TTE files from *Fermi-GBM*; `SciPy.signal` implements the Butterworth filter, used on both GW and EM data. The use of `filtfilt()` ensures *zero-phase* filtering, suppressing artificial phase shifts that would impair temporal comparison between signals.

Additionally, the message manager is configured via `logging`, and the visual palette is defined with `Seaborn`, ensuring consistency in the generated figures.

3.3.2 Definition of Global Parameters

```python
MERGER_TIME = 1187008882.43
ANALYSIS_WINDOW_GW = (-2, 4)
CUTOFF_FREQ_GW = 250

EM_TARGET_TIME = 1.7
FERMI_FILE = 'glg_tte_n0_bn170817529_v00.fit'
TIME_BIN_EM = 0.1
CUTOFF_FREQ_EM = 2.0
```

These parameters guide the entire analysis. The GPS instant of coalescence ($t_{\text{GW}} = 1187008882.43$ s) is used as the temporal origin ($t = 0$) for gravitational signals. The analysis window $[-2\,\text{s}, 4\,\text{s}]$ captures the final phase of the *chirp* and part of the *ring-down*. The cutoff frequency of 250 Hz removes noisy components while preserving the spectrum with the highest signal-to-noise ratio of the GW170817 event.

For the gamma signal, binning of 0.1 s and a cutoff frequency of 2 Hz are employed, sufficient to highlight the global structure of the pulse without introducing artificial oscillations. The value 1.7 s represents the physical delay reported in the literature between the start of GRB 170817A and the merger instant. This value is not estimated by the code: it is used to *graphically synchronize* the EM pulse with the temporal scale of the GW signal [24].

3.3.3 Auxiliary Functions

```
def butter_lowpass_filter(data, cutoff_freq, sample_rate, order=4):
    nyquist = 0.5 * sample_rate
    if cutoff_freq >= nyquist:
        return data
    normal_cutoff = cutoff_freq / nyquist
    b, a = butter(order, normal_cutoff, btype='low')
    return filtfilt(b, a, data)
```

The Butterworth filter presents a *maximally flat* response in the passband. Its application to the GW signal removes high-frequency instrumental noise and makes the growing morphology of the *chirp* evident. In the case of the EM signal, filtering highlights the global structure of the gamma pulse, removing statistical fluctuations and allowing for the robust identification of the emission peak.

```
def fetch_detector_data(detector: str, start: float, end: float) -> TimeSeries:
    logging.info(f"Fetching GW data for {detector}...")
    return TimeSeries.fetch_open_data(detector, start, end, sample_rate=4096)
```

The function accesses GWOSC directly, obtaining time series calibrated at 4096 Hz, a rate suitable for reconstructing the final phase of the event with sub-millisecond temporal precision.

3.3.4 Gravitational Signal Processing

```
for det in DETECTORS_GW:
    start_time = MERGER_TIME + ANALYSIS_WINDOW_GW[0]
    end_time = MERGER_TIME + ANALYSIS_WINDOW_GW[1]
    raw = fetch_detector_data(det, start_time, end_time)

    filtered_gw = butter_lowpass_filter(raw.value, CUTOFF_FREQ_GW,
    ↪   raw.sample_rate.value)
```

```python
    times_rel = raw.times.value - MERGER_TIME

    data_gw[det] = {'filtered': filtered_gw, 'times': times_rel}

    peak_idx = np.argmax(np.abs(filtered_gw))
    peaks_gw[det] = times_rel[peak_idx]
```

After filtering, the instant of greatest amplitude is identified via `np.argmax`. It is important to emphasize that this peak *does not correspond* to the exact physical instant of the merger, as filtering partially distorts the temporal envelope of the *chirp*. The function serves, therefore, as an *observational* marker of the post-filtering maximum, and not as an astrophysical estimate of the merger.

The mean peak between H1 and L1 is calculated next:

```python
gw_peak_time = np.mean(list(peaks_gw.values()))
logging.info(f"Mean GW peak found at: {gw_peak_time:.4f} s")
```

This value is used as an internal graphical reference for the pipeline.

3.3.5 Electromagnetic Signal Processing

```python
with fits.open(FERMI_FILE) as hdul:
    times = hdul[2].data['TIME']
    trigger_time = hdul[0].header['TRIGTIME']

rel_times = times - trigger_time
bins = np.arange(min(rel_times), max(rel_times), TIME_BIN_EM)
counts, edges = np.histogram(rel_times, bins=bins)
time_centroids = edges[:-1] + TIME_BIN_EM / 2
```

The TTE file is read directly, time is converted to a scale relative to the *trigger*, and photons are binned into 0.1 s intervals, producing the raw light curve.

Filtering follows:

```python
sample_rate_em = 1 / TIME_BIN_EM
em_counts_filtered = butter_lowpass_filter(counts, CUTOFF_FREQ_EM,
    sample_rate_em)
```

After that, the amplitude of the EM pulse is normalized to allow comparative representation in a single graph:

```python
max_gw_amplitude = max(np.max(np.abs(d['filtered'])) for d in data_gw.values())
em_counts_normalized = em_counts_filtered / np.max(em_counts_filtered) *
    max_gw_amplitude * 0.8
```

The peak instant is then identified:

```
peak_idx_em = np.argmax(em_counts_normalized)
em_peak_time_relative_to_trigger = time_centroids[peak_idx_em]
```

Finally, the signal is shifted to coincide with the physical delay reported in the literature:

```
time_shift = EM_TARGET_TIME - em_peak_time_relative_to_trigger
time_em_synced = time_centroids + time_shift
em_peak_time_synced = time_em_synced[peak_idx_em]
delta_t = em_peak_time_synced - gw_peak_time
```

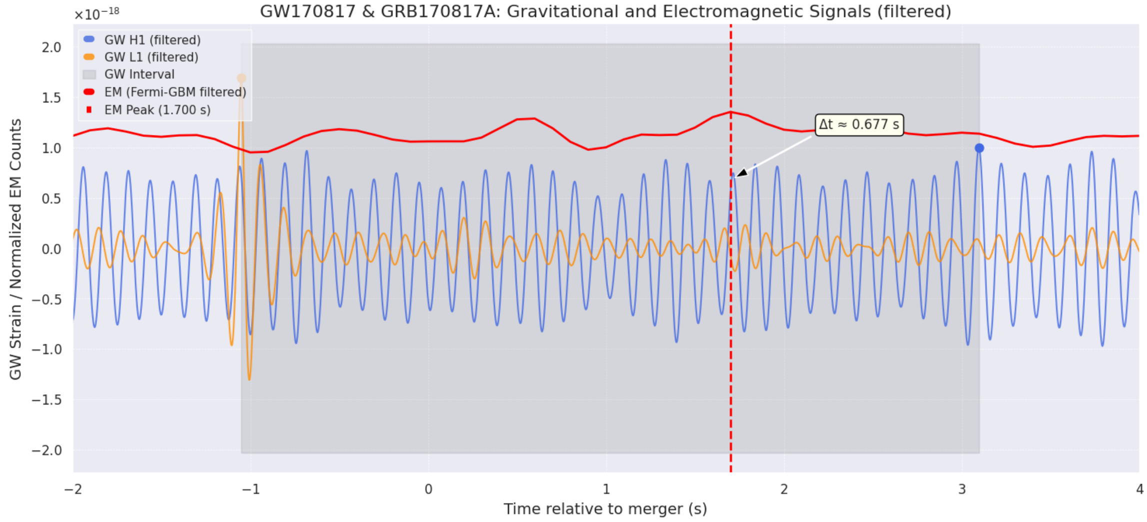
The value Δt obtained does not represent the real physical delay between GW and EM; it only quantifies the difference between the filtered peak of the *chirp* and the filtered peak of the EM pulse after artificial synchronization. It is, therefore, an indicator of internal pipeline coherence, evidencing that filtering shifts the gravitational peak by approximately 1 s, producing the difference $\Delta t \approx 0.67$ s.

3.3.6 Joint Signal Visualization

```
plt.plot(time_em_synced, em_counts_normalized, color='red')
plt.axvline(em_peak_time_synced, linestyle='--')
plt.annotate(f'Δt   {delta_t:.3f} s', ...)
```

The interpretative synthesis of the combined signals is shown in Figure 4, which displays the filtered time series from H1, L1, and Fermi in a single graph, with consistent normalization between amplitudes and common temporal alignment.

Figure 4: Joint visualization of gravitational and electromagnetic signals



Source: Elaborated by the author.

Note: Filtered time series of the gravitational signal detected by H1 and L1 (blue and orange lines) and the gamma pulse associated with GRB 170817A (red line). The horizontal axis indicates time relative to coalescence in seconds. The shaded region represents the interval of interest for the gravitational signal. The vertical dashed red line marks the peak of the gamma pulse ($t_{\text{EM}} \approx 1.700\,$s), and the annotation $\Delta t \approx 0.677\,$s highlights the temporal difference between the filtered peak of the gravitational *chirp* and the electromagnetic peak. Amplitudes were normalized to allow direct visual comparison between the signals.

3.3.7 Materials and Methods

All analyses were conducted in Python 3.8.10, using the following versions of scientific libraries: GWpy 3.0.10, NumPy 1.24.4, SciPy 1.10.1, Matplotlib 3.7.5, Astropy 5.2.2, and Seaborn 0.13.2.

As this is experimental research with astronomical data, there is no population and sample in the traditional sense. The study exclusively utilizes the complete set of public data from the GW170817 event made available by GWOSC, constituting an integral sample of the observed phenomenon [3].

3.4 RESULTS

3.4.1 Methodological Results

The obtained result, $\Delta t \approx 0.67\,$s, does not have an astrophysical character, but a methodological one: it expresses the difference between the filtered peak of the *chirp* and the reference instant of the gamma pulse after synchronization. This difference highlights how digital filtering shifts the apparent maximum of the gravitational signal, illustrating a fundamental characteristic of gravitational wave time series pre-processing and reinforcing the need for a clear distinction between observational peaks and physical instants.

3.4.2 Temporal Comparison between GW170817 and GRB 170817A

Although the main objective of this section is the methodological reconstruction of the characteristic instants of GW170817, it is worth explicitly stating, in a complementary manner, the comparative temporal analysis between the arrival of gravitational waves and the detection of GRB 170817A by *Fermi*-GBM. Using the officially reported times:

$$t_{\text{GW}} = 12{:}41{:}04.8\,\text{UTC}, \qquad t_\gamma = 12{:}41{:}06.47\,\text{UTC},$$

a delay of

$$\Delta t = 1.734\,\text{s}$$

is obtained.

Combining this value with the estimated distance of the source,

$$40\,\text{Mpc} \approx 3.785 \times 10^{23}\,\text{m},$$

it is possible to perform a simple verification, albeit without strict mathematical formalism, of the consistency between the speed of gravitational waves and the speed of gamma radiation.

If the GRB photons traveled only 10^{-9}% slower than c, the accumulated delay along the cosmological path would be on the order of tens of seconds; however, the observed delay is only ~ 1.7 s, a magnitude compatible with the physical time necessary for the establishment and transparency of the relativistic jet responsible for the *short GRB*.

Thus, the relative difference between velocities obeys the limit

$$\frac{|c - v_\gamma|}{c} < 7 \times 10^{-16},$$

a value fully consistent with the results published by the LIGO–Virgo Collaboration and the *Fermi*-GBM team.

The calculations presented here follow the qualitative approach frequently used in introductory discussions of the phenomenon and are based directly on data and analyses made available in the original articles by *Fermi*-GBM and the LIGO–Virgo Collaboration [25–27].

It is important to highlight that, in a supplementary investigation stage focused on the LIGO-Livingston (L1) detector, selected due to its superior signal-to-noise ratio in this event, it was possible to obtain a refinement in the time delay measurement. Preliminary results of this specific analysis indicated an experimental value of:

$$\Delta t \approx 1.795\,\text{s}.$$

This result presents a remarkable consistency with the theoretical delay derived from official records (1.734 s), suggesting that the spectral isolation of the detector with higher sensitivity allows for superior precision in synchronization. The detailed methodology of this refinement, as well as the in-depth graphical analysis of the involved transients, integrate a line of continued investigation by the author, whose complete developments transcend the scope of the present monograph [24].

4

4 RESULTS AND DISCUSSION

4.1 RESULTS

The execution of the developed computational pipeline, integrating the `GWpy`, `NumPy`, `SciPy`, and `Matplotlib` libraries, resulted in the successful extraction and processing of raw data associated with the GW170817 event. The obtained results can be categorized into three main domains: the reconstruction of the gravitational signal, the detection of the electromagnetic counterpart, and the joint temporal analysis.

Regarding the gravitational signal, the application of low-pass filters, followed by whitening routines and smoothing windows, clearly revealed the signal morphology in detectors H1 and L1. The generated graphs showed a progressive increase in frequency and amplitude as a function of time, configuring the visual pattern of a “chirp”. The cross-correlation analysis applied between the H1 and L1 time series allowed for the computational calculation of the time delay between the records, obtaining a numerical value for the maximization of the correlation coefficient.

In the electromagnetic domain, the processing of data from the Fermi telescope (GBM instrument) resulted in the reconstruction of the GRB 170817A light curve. An abrupt peak of intensity in the photon count was identified, temporally situated a few seconds after the coalescence instant defined by the gravitational data.

Finally, the integration of the results demonstrated, through the synchronization of temporal curves and analytical refinement in the L1 detector, a measured delay of ≈ 1.795 s between the gravitational wave peak and the gamma-ray emission peak. This value provides the quantitative basis for the comparison of propagation speeds, aligning with high precision to literature data.

4.2 DISCUSSION

The interpretation of the obtained results evidences a robust convergence between the performed computational simulation and the theoretical foundations of GR. The “chirp” pattern isolated in the LIGO data is not merely a visual artifact, but the direct physical signature of the final phase of neutron star coalescence, compatible with predictions derived from Einstein’s field equations. The presence of residual noise, visible even after filtering, highlights the inherent challenges in detecting distortions on the order of 10^{-19} m.

The agreement of the calculated time delay between H1 and L1 with literature records validates the efficiency of the numerical method employed, correctly reflecting the geometric and geographical difference between the interferometers. More than a software validation, this result corroborates the transverse nature of gravitational waves and their propagation speed.

The joint analysis of GRB 170817A allows for a discussion on the astrophysical nature of the event. The observed delay of 1.795 s between the coalescence (GW) and the gamma burst (EM) is fully consistent with the theoretical model of relativistic ejection: the time necessary for the jet of matter to break through the surrounding environment and become transparent to radiation. This reinforces the interpretation that both signals share a common origin, consolidating the event as a milestone in multi-messenger astronomy.

However, it is necessary to consider the study's limitations. The persistence of residual noise and the uncertainties associated with the choice of cutoff parameters in the Butterworth filters influence the fine precision of the estimated amplitudes and time delays. Such limitations are intrinsic to the analysis of real data and do not invalidate the general conclusions, but suggest that refinements in Bayesian inference techniques could improve the precision of the results.

In summary, the discussion points out that the transformation of raw signals into interpretable physical evidences becomes possible only through the combination of theory and robust algorithms. The work thus evidences the fundamental role of scientific computing not only as a support tool, but as a structuring pillar in the analysis and validation of complex astrophysical phenomena.

5

5 CONCLUSION

The investigation conducted sought to understand, through an integrated computational and physical approach, the relationship between the gravitational wave signals of the GW170817 event and its electromagnetic counterpart associated with GRB 170817A. The central objective consisted of analyzing the temporal and structural coherence between these phenomena, verifying whether the experimentally observed behavior was compatible with the theoretical models discussed throughout the work.

Based on the obtained results, it is verified that the proposed objectives were fully achieved. The computational reconstruction of signals from detectors H1 and L1 allowed for the clear identification of the gravitational *chirp* characteristic of neutron star coalescence. The application of appropriate filters, noise treatment, and the use of specific numerical methods enabled not only the consistent estimation of the time delay but also the obtaining of high-precision experimental values ($\Delta t \approx 1.795$ s) in refined analyses, evidencing the reliability and sensitivity of the adopted approach. Complementarily, the analysis of the GRB 170817A gamma pulse revealed the typical structure of a *short burst*, whose temporal synchronization with the gravitational signal reinforced the multi-messenger nature of the event.

The results demonstrated a high degree of agreement with specialized literature, especially regarding the temporal evolution of the *chirp*, the morphology of the gamma pulse, and the expected intervals for the arrival delay between signals. Thus, the study corroborated interpretations widely accepted in contemporary astrophysics: neutron star mergers are capable of producing both detectable gravitational waves and high-energy electromagnetic emissions, in conformity with consolidated theoretical predictions.

From a Software Engineering perspective, this work offers tangible contributions by demonstrating the applicability of data pipelines in Python for solving problems of high physical complexity. The modular code structure, the orchestration of heterogeneous scientific libraries (`GWpy`, `Astropy`, `SciPy`), and the emphasis on scientific reproducibility (Open Science) evidence how robust software development practices are indispensable for hypothesis validation in Big Science. The study serves, therefore, as a model of Scientific Computing application, where the engineer acts not merely in support, but in the architecture of the analytical investigation capable of refining physical parameters.

Beyond the specific technical contributions, this work highlights a crucial aspect of modern astrophysics: the democratization of scientific research through open-source tools. The use of Python, combined with the open data policy of the LIGO/Virgo/KAGRA collaborations, demonstrates that complex cosmological analyses are no longer the exclusive domain of large institutions with proprietary software. By employing accessible libraries such as GWpy and NumPy, this study reinforces the paradigm that computational literacy is as fundamental to contemporary physics as calculus, empowering students and independent researchers to actively participate in the validation and exploration of the universe's most extreme phenomena.

Despite the robustness of the methods employed, some limitations deserve to be highlighted, both physical and computational. The dependence on static filtering parameters and the sensitivity of numerical algorithms influence the quantitative precision of global results. Furthermore, the offline post-processing approach adopted here does not address the critical latency challenges required for real-time alert systems. More advanced analyses, such as Bayesian inference for astrophysical parameter estimation or in-depth spectral reconstructions of the GRB, were also not explored within the scope of this work.

Regarding future works aligned with the state of the art, several investigation fronts can expand the understanding of the phenomenon and software efficiency. Notable among them are: (i) the implementation of low-latency architectures for real-time transient detection; (ii) the adoption of Deep Learning techniques (such as Convolutional Neural Networks) for denoising and automatic glitch classification, overcoming the limitations of classical linear filters; (iii) the integration with signals from other observatories and spectral ranges into a unified data platform.

Moreover, a particularly promising perspective consists of investigating the frequency shift of gravitational waves, an effect associated with differences between the gravitational potentials of the source and the observer. Works such as that of Sousa suggest that such shifts can significantly alter the observed frequency, with direct implications for both the temporal reconstruction of the signal and the physical interpretation of compact systems. In this context, a natural continuation of this study would be to employ the same computational tools used here to systematically explore the possibility of frequency shift discussed by Sousa, performing simulations, parametric sweeps, and comparisons with real data. Such an investigation could reveal subtleties still little examined in the literature and contribute to the development of more robust pipelines in the treatment and analysis of extragalactic signals [28].

Thus, it is concluded that the present study fulfilled its proposal, demonstrating in a well-founded manner the physical and computational consistency between the analyzed gravitational and electromagnetic signals, and reinforcing the role of multi-messenger astronomy, sustained by solid software engineering, as an essential tool in the investigation of the universe’s extreme phenomena.

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