# Measuring Kerrness in Binary Black Hole Simulation Ringdowns

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## Introduction

The first detection of gravitational waves originating from a binary black hole merger [1] has provided a significant confirmation of the predictions of general relativity and has opened the door to many more such tests and observations of black holes.

Numerical relativity is the field which concerns the simulation and evolution of spacetimes by solving Einstein's equations. Its role in LIGO includes correlating observed gravitational waveforms with the local properties of their sources [8].

One challenge in numerical relativity is the effect of the choice of coordinates on behavior and quantities of interest [6]. Because of this, it is often useful to consider invariants which are independent of basis.

Furthermore, numerical studies of binary black hole mergers frequently assume a perturbed Kerr spacetime during ringdown [6]. Although simulations have been run which show that the remnant spacetime resulting from a binary black hole merger is a Kerr black hole at the final moment of the simulation [7] [5], the point at which the assumption of a perturbed Kerr spacetime becomes valid has not been established in previous analysis.

We define Kerrness as a measure of deviations from the Kerr spacetime, and we seek to explore invariant measures of Kerrness, including established measures such as speciality indices [3] and newly proposed measures such as those proposed by Gómez-Lobo [4] and Bäckdahl and Valiente Kroon [2]. In studying these invariants, we seek both to validate that they are appropriate measures of Kerrness through simulations and to use them to more quantitatively define when a remnant spacetime can be considered adequately close to Kerr.

## Objectives

We aim to explore the use of invariants such as speciality indices and the measures of "Kerrness" proposed by Gómez-Lobo (and Bäckdahl, as time permits) to determine the deviations of a spacetime from Kerr. In particular, we wish to better understand the point at which it is valid to assume a perturbed Kerr spacetime resulting from a binary black hole merger.

We will first verify that these measures of Kerrness behave sensibly on a single black hole simulation, both to validate the metrics themselves and as a proof of concept that they have been implemented correctly in the simulation code.

Once this verification has occurred, we aim to compute these measures of Kerrness on binary black hole ringdown simulations.

As time permits, we may simulate the emission of a ray of light which travels from the local vicinity of the merger to an observer at future null infinity. By beginning the ray's travel when some threshold in the value of the metric under consideration is met, it may be possible to correlate the local behavior with the observed gravitational waveform.

# Approach

The project will involve writing code to run various simulations, running the simulations, and analyzing the results.

Implementation of the simulations will be done predominantly in C++ using the SpEC (Spectral Einstein Code) numerical relativity framework. The SpEC framework implements various subroutines for solving elliptic and hyperbolic equations, as well as other utilities involved in studies of general relativity [6].

One challenge will be the timing of running and analysis of more computationally involved binary black hole simulations, as some of these may take days or weeks to complete. In order to optimize time spent toward simulation and analysis, organization and planning of tasks will be key; the tentative project schedule shows the current prospective timeline for simulation and analysis of several of the invariants under investigation.

Simpler simulations, such as that of a single black hole, which require fewer computational resources will be performed first in order to gain familiarity with running computational jobs. In addition, the single black hole simulations will be run using Kerr initial data, which will allow for preliminary validation of the Kerrness measures. After analysis of Kerrness measure performance at this stage, they may be applied to binary black hole simulation volume data [6].

Simulations involving the speciality indices will be run first as an exercise since the SpEC framework already implements most of what is required to run this. Afterwards, the more advanced measures of Kerrness will be run.

Many of the simulations will require significant computational resources and running time, and so these will be run on the zwicky machine provided by the Caltech Center for Advanced Computing Research (CACR).

Simulations will be run at various resolutions to confirm convergence properties.

Analysis of the simulations will involve the SpEC framework and writing scripts for automation and plotting. In addition to libraries for running simulations, the SpEC framework contains utilities for the analysis of data, and these will be used in conjunction with the scripts.

# Tentative Project Schedule

- Week 1: Become familiar with SpEC and set up computing environment for developing simulations. Practice running simulations by running a simulation of a single black hole and compute speciality index.
- Week 2: Continue setting up computing environment as necessary. Begin running binary black hole ringdown simulation and compute speciality index.
- Weeks 3 - 4: Code compute item for Kerrness measure proposed by Gómez-Lobo. Analyze results of simulations pending success thus far.
- Weeks 4 - 5: Begin writing compute item for Kerrness measure proposed by Bäckdahl and Valiente Kroon. Analyze results of previous simulations which have finished.
- Weeks 6 - 7: Continue writing compute item described in goals for week 4 - 5. Addition of the simulation of a ray of light traveling to future null infinity as time permits.
- Weeks 8 - 9: Analyze binary black hole ringdown simulation output.
- Week 10: Final analysis of results, preparation of final report and presentation

# References


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