Black Hole Spin Axis in Numerical Relativity

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Colliding black holes are systems of profound interest in both gravitational wave astronomy and in gravitation theory, and a variety of methods have been developed for modeling their dynamics in detail. The features of these dynamics are determined by the masses of the holes and by the magnitudes and axes of their spins. While masses and spin magnitudes can be defined in reasonably unambiguous ways, the spin axis is a concept which despite great physical importance is seriously undermined by the coordinate freedom of general relativity. Despite a great wealth of detailed numerical simulations of generic spinning black hole collisions, very little attention has gone into defining or justifying the definitions of the spin axis used in the numerical relativity literature. In this paper, we summarize and contrast the various spin direction measures available in the SpEC code, including a comparison with a method common in other codes, we explain why these measures have shown qualitatively different nutation features than one would expect from post-Newtonian theory, and we derive and implement new measures that give much better agreement.

I. INTRODUCTION

The age of gravitational-wave astronomy has arrived. In the short time since it began operation, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has detected three clear gravitational-wave events from binary black hole mergers [1–3], with many more expected to follow. After decades of effort, researchers are probing the strong-field dynamics of spacetime itself, with steadily increasing reach and precision.

Like all cutting-edge science, gravitational wave physics is a continuous conversation between observational and theoretical efforts. One theoretical technique of particular importance for exploring the strong-field dynamics of spacetime is numerical relativity, the direct computational solution of Einstein’s field equations [4, 5]. Numerical relativity can provide a picture of spacetime dynamics with no approximations other than the usual truncation error of numerical calculation, which in principle is straightforward to control.

Unfortunately, along with the exact treatment of spacetime geometry that numerical relativity provides, there also arises a great deal of ambiguity associated with the “general covariance” at the heart of Einstein’s theory. For mathematical analysis, all fields are represented in some coordinate system, however (with some technical caveats) the theory is fundamentally ambivalent about what coordinate system is used. Standard approximation techniques such as the post-Newtonian expansion [6, 7] and black hole perturbation theory [8] assume the existence of a subset of preferred coordinate systems in which deviations of the spacetime metric from its stationary state are “small.” In numerical relativity, one often makes vague statements about whether a coordinate system (a “gauge”, in this context) is “good” or “bad”, but generally very little effort goes into formalizing such statements beyond what is necessary to expect a stable evolution and sensible behavior of the evolving fields.

One of the quantities computed in numerical relativity of particular physical importance is black hole spin. The parameter space of non-eccentric binary black hole systems is seven-dimensional — described by the ratio of the holes’ masses, and the three spin components on each hole. Other parameters, such as the total mass of the system, the time of the merger, and the distance to the detector, are important for data analysis but fundamentally unimportant for source modelling as they can be altered trivially in post processing. The detections that LIGO has made thus far have claimed precise measurements of the black hole masses, but relatively rough measurements of the black hole spins and their states of alignment. Black hole spin is a phenomenon that imprints itself less strongly on gravitational waves than black hole mass, but it is a key near-term target for precision measurement as LIGO’s sensitivity improves.

A rich and increasingly relevant body of literature exists on treating binary black hole systems with arbitrarily-aligned spins in numerical relativity, exploring basic dynamical processes such as spin flips [9, 10], remnant “kicks” due to asymmetric wave generation [11–17], and of course the increasingly crucial work of numerical relativity groups at filling out “catalogs” of binary black hole waveforms [18–21] and tuning approximate waveform models to numerical results [22–26]. Beyond this, a plethora of dynamical effects associated with spin alignment have been studied, a non-comprehensive list of which would include [27–32].

While the spin axis is clearly a crucial element of modern numerical relativity simulations, with an increasingly strong connection to gravitational wave data analysis, its basic definition is somewhat vague and generally ad-hoc in numerical relativity treatments. Much of this centers on its inherent gauge ambiguity: it is defined by its alignment with the coordinate axes of the simulation, assuming an unphysical Euclidean background geometry. While the spin magnitude can be defined and practically computed in a number of gauge-invariant ways [33–36], the spin axis requires greater care and finesse. In the long run, one can hope that the physical content that is currently described with the “spin axis” might be replaced with more basic, gauge-invariant concepts such as relationships...
among horizon multipoles [37–39], for the near-term it is important to at least be specific about what is meant by “spin axis” in various codebases, and to be aware of the peculiarities of specific measures of the axis.

In particular, the definition of the spin axis used in the SpEC code [40] is nontrivial and has never been described in the literature, though multiple papers have been written which used this measure at a fundamental level. In particular, in Ref. [41] the precession dynamics in SpEC simulations were compared with expectations from post-Newtonian theory (PN). While most features agreed quite well between numerical relativity and post-Newtonian theory, the spins of the individual black holes were found to nutate in a surprising way, qualitatively different from the expectations of PN theory. In this paper, we will argue that this unexpected nutation behavior can be traced back to a peculiarity of SpEC’s default spin-axis measure (and, to our knowledge, the measures used in all recent numerical relativity calculations), and can be removed with the use of a somewhat more sophisticated measure of the spin axis.

The paper is organized as follows: in Sec. II, we lay out some mathematical preliminaries that will be useful in the further discussion. In Sec. III, we summarize existing definitions of the black hole spin axis, including the definition employed in the SpEC code. Along the way, we summarize a few of the theoretical motivations (boost invariance, centroid invariance) that led to its introduction. Then, in Sec. IV, we compare these various spin measures in the case of a nontrivially-precessing binary black hole merger, and we describe the surprising nutation features by which the SpEC spin measure differs qualitatively from PN results. In Sec. V, we employ a more straightforward technique, defining the spin axis by a quasilocal angular momentum formula using coordinate rotation generators. This straightforward method has significant theoretical drawbacks, which we will outline, but we find that the practical ambiguities are minimal, and they can be understood and mitigated through more careful analysis of the underlying mathematics. This provides a new measure of the black hole spin axis which preserves the advantageous features of SpEC’s previous measure, while agreeing much better with post-Newtonian expectations. Finally, in Sec. VI, we summarize these results and outline some prospects for future work.

II. MATHEMATICAL PRELIMINARIES

The standard techniques for computing black hole spin in the modern numerical relativity literature, including the techniques of this paper, are founded upon the following quasilocal angular momentum formula:

$$J = \frac{1}{8\pi} \oint \vec{\omega} \cdot \vec{\phi} \, dA,$$  

(1)

where the integral is carried out over a spatial two-surface normally of spherical topology (in practice, an apparent horizon), \( \vec{\omega} \) is some rotation-generating vector field, and \( \vec{\phi} \) is the normal-tangential projection of the (undensitized) canonical momentum conjugate to the spatial metric:

$$\omega_\mu = (K_{\mu\nu} - K g_{\mu\nu}) h_\mu^\rho s^\rho,$$  

(2)

where \( \vec{s} \) is the unit normal to the integration 2-surface, tangent to the spatial slice, \( h_\mu^\rho = \delta_\mu^\rho + u_\mu u^\rho - s_\mu s^\rho \) is the projector tangent to this 2-surface (\( u^\mu \) is the timelike normal to the spatial slice), \( K_{\mu\nu} \) is the extrinsic curvature of the spatial slice, and \( g_{\mu\nu} = \psi_{\mu\nu} + u_\mu u_\nu \) is the spatial metric (the spacetime metric \( \psi \) projected down to the spatial slice). The clumsy introduction of a subscript in \( \pi_0 := 3.14159... \) is due to the fact that it will eventually become convenient to use the letter \( \pi \) to denote a potential associated with momentum.

There are various justifications for this quasilocal angular momentum formula in the literature. It arises in the quasilocal charge constructions of Brown and York [42]. It naturally arises again in the formalisms of isolated and dynamical horizons [43–45], though there the “spatial slice” is often taken to be the horizon worldtube (which is spacelike for a dynamical horizon). The result is the same, though, for either slicing, so long as the rotation generator is chosen in such a way as to make \( J \) “boost invariant”, as we will discuss below. This angular momentum formula can also be shown to be equivalent to the Komar angular momentum in axisymmetric spacetimes [46].

Because both \( \vec{\omega} \) and \( \vec{\phi} \) are defined to be tangent to the 2-surface, it is natural to write Eq. (1) in a basis that makes this explicit:

$$J = \frac{1}{8\pi} \oint \omega_A \phi^A \, dA,$$  

(3)

where capital latin letters index the 2-surface tangent bundle. In this paper we will frequently consider the manner in which quantities transform with respect to the “boost gauge” freedom. That is: the freedom to alter the slicing of spacetime near the 2-surface, while leaving the 2-surface itself fixed. For this, it is convenient to introduce a Newman-Penrose null tetrad [47], \( l^\mu, \bar{n}^\mu, m^\mu, \bar{m}^\mu \), where \( l^\mu \bar{m}_\mu = -1, m^\mu \bar{m}_\mu = 1 \), and all other dot products vanish. Furthermore, we will adapt this tetrad to the 2-surface, as in the Geroch-Held-Penrose variant of the formalism [48, 49], such that the real and imaginary parts of \( \bar{m} \) are tangent to the 2-surface, and the real null vectors \( \bar{l} \) and \( \bar{n} \) are respectively its outgoing and ingoing null normals. Finally, we fix the remaining scaling freedom in \( \bar{l} \) and \( \bar{n} \) by adapting them to the timelike normal to the slicing, \( \bar{u} \), and the spacelike normal to the 2-surface, within the slicing, \( \bar{s} \), such that:

$$\bar{l} = \frac{1}{\sqrt{2}} (\bar{u} + \bar{s}) , \quad \bar{n} = \frac{1}{\sqrt{2}} (\bar{u} - \bar{s}) ,$$  

(4)

$$\bar{u} = \frac{1}{\sqrt{2}} (\bar{l} + \bar{n}) , \quad \bar{s} = \frac{1}{\sqrt{2}} (\bar{l} - \bar{n}) .$$  

(5)

Substituting these formulas into the standard formula for the extrinsic curvature of the slicing:

$$K_{\mu\nu} = -g_{\mu\rho} g_{\nu\sigma} \nabla_\rho u_\sigma ,$$  

(6)
where \( g^\mu_\nu = \delta^\mu_\nu + u_\mu u_\nu \) is the projector to the spatial slice, it is straightforward to express the normal-tangential projection, \( \vec{\omega} \), in terms of the tetrad legs. Specifically, \( \omega_A \) represents a connection on the bundle of normal vectors to the 2-surface in spacetime:

\[
\omega_A = \epsilon^A_n \nabla_\rho n^\rho. \tag{7}
\]

While this form will be most convenient for our purposes, it is worth noting that this expression can be massaged further into standard GHP spin coefficients:

\[
\omega_A = (\beta - \beta') m_A + (\bar{\beta} - \beta) \bar{m}_A. \tag{8}
\]

The combinations of coefficients shown here are indeed the “connection coefficients” that relate the tetrad derivative operator \( \delta := m^\mu \nabla_\mu \) to the GHP derivative operator \( \bar{\sigma} \) for quantities \( Q \) of spin-weight zero and boost-weight \( \pm 1 \), namely, components of spacetime vectors normal to the 2-surface:

\[
\delta Q = \delta Q \pm (\beta - \beta') Q. \tag{9}
\]

Because \( \omega_A \) geometrically represents a connection, it is natural (and will be of practical use below) to define its corresponding curvature.

\[
\Omega = \epsilon^{AB} \nabla_A \omega_B \tag{10} \\
= -im^{[A} \bar{m}^{B]} \nabla_A \omega_B \tag{11}
\]

The scalar quantity \( \Omega \) is the imaginary part of the “complex curvature” of a 2-surface embedding, defined by Penrose and Rindler [49]:

\[
\Omega = \Im \left[ \sigma \sigma' - \rho \rho' - \Psi_2 + \Phi_{11} + \Lambda \right], \tag{12}
\]

where \( \rho \) and \( \rho' \) are the GHP coefficients representing the complex expansions of \( \vec{l} \) and \( \vec{n} \), respectively, \( \sigma \) and \( \sigma' \) are the coefficients representing the shears, \( \Phi_{11} \) and \( \Lambda \) are components of the spacetime Ricci curvature, which we will take to vanish in this paper (due to Einstein’s field equations and the assumption of vacuum), and \( \Psi_2 \) is the “Weyl scalar” that is intuitively taken to represent the non-radiative part of the spacetime Weyl tensor. (Though rigorous statements upon those lines require the choice of a special tetrad. See, for example, [50, 51].) The real part of the complex curvature, which we will not invoke here, is the familiar gaussian curvature of the 2-surface. It should be noted that \( \sigma' \) and \( \rho' \) vanish on an isolated horizon, and thus in vacuum \( \Omega \) is simply the imaginary part of \( \Psi_2 \), up to a sign. Furthermore, the quantity \( \Im \left[ \Psi_2 \right] \) in this basis is precisely the normal-normal component of the magnetic part of the spacetime Weyl tensor, \( B_{ss} = B_{ij} s^i s^j \), which is referred to intuitively as the “horizon vorticity” in Refs. [52–56].

The “boost gauge” transformation that often appears in discussion of quasilocal quantities is a transformation that leaves the 2-surface unchanged but boosts the spatial slice around it. If the timelike normal to the spatial slice, \( \vec{n} \), and the spacelike normal to the 2-surface within the spatial slice, \( \vec{s} \), are defined as in Eqs. (5), then this boost is easily described by a rescaling of the null normals:

\[
\vec{l} \mapsto \exp(a) \vec{l}, \tag{13} \\
\vec{n} \mapsto \exp(-a) \vec{n}, \tag{14}
\]

where \( a \) is some scalar on the 2-surface, representing the rapidity of the boost at each point.

Under such a transformation, it is readily seen from Eq. (7) that the quasilocal angular momentum density \( \vec{\omega} \) is not invariant, but rather transforms as:

\[
\omega_A \mapsto \omega_A - \nabla_A a \tag{15}
\]

However, because this correction term is a pure gradient, the curvature quantity \( \Omega \), defined in Eq. (10) is boost invariant.

The boost invariance of \( B_{ss} \) is even simpler to argue, since it is simply the imaginary part of the Weyl scalar \( \Psi_2 \). In terms of tetrad vectors and the spacetime Weyl tensor \( C_{\mu\nu\rho\sigma} \), \( \Psi_2 \) is:

\[
\Psi_2 = \frac{1}{2} C_{\mu\nu\rho\sigma} (l^\mu n^\nu l^\rho n^\sigma - l^\mu n^\nu m^\rho m^\sigma \bar{m}^\rho \bar{m}^\sigma), \tag{16}
\]

which is manifestly invariant under boost transformations.

III. EXISTING TECHNIQUES FOR DEFINING THE SPIN AXIS

A basic assumption underlying essentially all methods for computing black hole spin in binary systems is that the holes can in some sense, at least approximately, be considered isolated from their partners and from the dynamics of the surrounding spacetime. This intuitive idea invites appeals to the structure of the Kerr geometry, which would be expected to accurately represent a nearly isolated, uncharged, vacuum black hole. The event horizon of the Kerr geometry can be foliated by marginally outer trapped surfaces, which for a Kerr black hole would coincide with the 2-surfaces found by the “apparent horizon finder.” Furthermore, as long as the slicing of spacetime conforms to the global axisymmetry of the Kerr geometry, the apparent horizon 2-surface would then also be expected to be axisymmetric, with the axisymmetry describing a symmetry under rotations about the spin axis. Hence, under the assumption that the Kerr geometry is an accurate approximation of the spacetime near the horizon (or, quasilocally speaking, that the horizon itself is “isolated” in the sense of [43, 45]), then the axisymmetry of the horizon can be used to define the spin axis.\(^1\)

\(^1\) Note that throughout the remainder of this paper we will adopt the common parlance of numerical relativity and use the word horizon to refer to the two-dimensional marginally trapped surface computed by the code’s horizon finder.
A. Euclidean line between poles or extrema

To our knowledge, all binary black hole codes other than SpEC infer the spin axis from an axis of best approximate horizon symmetry (and an option along these lines is available in SpEC as well, as we will outline below, though it is not the default measure). Specifically, the most common technique applies methods outlined in [57], in which a Killing vector field is found on a black hole horizon (or some kind of approximation of a Killing field if an exact one does not exist) by integrating the Killing transport equations, a system of ODEs that must be satisfied by a Killing vector field along any given path.

More precisely: the method first identifies a candidate Killing vector at a point on the horizon. To do this, a three-dimensional vector space of data is constructed at the starting point. Then the Killing transport equations are used to propagate each of the basis vectors around a closed path. In so doing, the starting vectors are mapped to new vectors in the same tangent space in which they started. This mapping is linear, so one can compute corresponding eigenvalues and eigenvectors. The eigenvector with eigenvalue closest to unity is considered to be the best candidate for a Killing vector field over the whole horizon, because a true Killing vector would indeed return to itself under this transport. Once such a “best” vector is found at the chosen starting point, it is propagated to the rest of the horizon grid again using Killing transport. All published results that we are aware of that identify an approximate Killing vector (AKV) field do so using either this method or the method described below that’s used in the SpEC code. In particular, this technique is the default behavior of the QuasiLocalMeasures thorn of the Einstein Toolkit [58].

Once such a rotational Killing vector field has been constructed on the horizon, its poles (the isolated points where the computed vector field has zero norm, of which there are hopefully two) can be used to distill a kind of spin axis vector as:

\[ \hat{\chi}_{KT} := (x_2^i - x_1^i)/N, \]

where \( N \) is a normalization factor chosen to make \( \delta_{ij}\hat{\chi}_{KT}^i\hat{\chi}_{KT}^j = 1 \), and \( x_1^i \) and \( x_2^i \) (for \( i = 1, 2, 3 \)) are the global Cartesian coordinate values of the two poles. Note that this does not in itself define a “spin vector”, but rather a unit-norm “axis vector” (unit-norm in the Euclidean background space). We will use the same \( \hat{\chi} \) notation for other axis vector definitions described later in this paper. In order to define a “spin vector”, be it full angular momentum or some variant rescaled by some power of the mass, one must multiply this axis vector by an appropriate magnitude. The obvious (and ubiquitous) choice is the spin magnitude defined by Eq. (1), where \( \tilde{\phi} \) is taken to be the approximate Killing vector field.

Note also that beginning with Eq. (17) we are making essential reference to the “background” coordinates of the numerical simulation. This is an ambiguous procedure.

In principle, one could remap the spatial coordinates to achieve an arbitrary change in the \( \hat{\chi}_{KT} \) vector. This will unfortunately be a pattern in all of the spin axis prescriptions described in this paper. The spin axis vector as conventionally understood in numerical relativity is not a true geometric object, but rather defined explicitly in terms of a particular Euclidean background geometry, like the stress-energy pseudotensor of Landau and Lifshitz [39] — it transforms covariantly under global Poincaré transformations of the spatial coordinates, however a nonlinear coordinate transformation would change the underlying background geometry and thereby change the meaning of \( \hat{\chi}_{KT} \). In the numerical relativity literature, there is a general hope that the simulation coordinates — normally chosen for code stability and/or computational convenience — are nonetheless “well adapted” to the dynamics of the horizon. In practice, this naïve hope is often rewarded. For example, after a black hole merger, one would expect all fields to settle to stationary values — that is, for the coordinate time-translation vector to settle to the stationarity Killing vector of the eventual Kerr geometry. Indeed this occurs, to our knowledge, under all of the standard gauge conditions of modern numerical relativity codes. Moreover, the spatial coordinates not only adapt to the late-time stationarity, but at least in the SpEC code the time slicing even settles to conventional slicings of black-hole perturbation theory, with horizon multipoles ringing at precisely the frequencies calculated in perturbation theory [38]. Furthermore, after a black hole merger, the spacetime describing the remnant black hole is axisymmetric in simulation coordinates, even though there is no obvious reason why the coordinate gauge conditions should “find” the geometrical symmetries of the simulated spacetime. This “good behavior” of the simulation coordinates is still a somewhat mysterious phenomenon, deserving of deeper analysis. This mystery should encourage caution in the use of any background-dependent methods. But nonetheless, these are the techniques that are ubiquitous in the field, and with some practical justification.

In principle, it may be possible to describe the essential elements of the black hole spin axis in truly unambiguous language, for example using the formalism for “source multipoles” on dynamical horizons defined in Ref. [39]. Here, data on the horizon is projected against test functions that evolve on the dynamical horizon in such a way as to represent a “fixed” frame of reference, in a specific sense. We intend to explore this approach in future work, but for now we simply note that its restriction to data on the horizons themselves would cloud efforts at connecting the evolution of the two distinct holes, or of describing the relationship of spin precession to dynamics of the encompassing spacetime, as one often wishes to do in binary black hole simulations. Thus, the techniques used throughout the current paper stick with background-dependent methods as described above.

The axis vector \( \hat{\chi}_{KT} \) is not easily adaptable to the SpEC code, because the approximate Killing vector...
field constructed by the Killing transport method does not lead to a smooth vector field in the limit of an infinitely-refined grid. Many of the calculations in SpEC require smooth fields, as required by the pseudospectral numerical methods that suffuse the code. However a similar definition of approximate Killing vector fields, used ubiquitously in the SpEC code, was presented in [33, 35] (essentially the same technique was independently presented in [34]). Briefly summarizing: the approximate Killing field \( \tilde{\xi} \) is first presumed to have zero divergence on the horizon, as required by the trace of Killing’s equation:

\[
D_A \xi^A = 0, \tag{18}
\]

where \( D_A \) is the covariant derivative on the horizon 2-surface. Such a vector field can easily be constructed from a scalar potential \( \zeta \):

\[
\xi^A = \epsilon^{AB} D_B \zeta, \tag{19}
\]

where \( \epsilon^{AB} \) is the 2-surface Levi-Civita tensor. Finally, a condition is imposed on \( \zeta \) that it minimize the integrated squared shear of \( \tilde{\xi} \) over the 2-surface — that is, the remaining residual of Killing’s equation. This condition leads to a simple generalized eigenproblem for \( \zeta \) on the horizon. This eigenproblem reduces to the eigenproblem of the horizon Laplacian on a metrically-round 2-sphere, and hence \( \zeta \) can be considered a kind of generalized spherical harmonic, an idea explored further in [38]. If the horizon is not strongly deformed, the eigenfunction with the lowest corresponding eigenvalue (that is, the one corresponding to an AKV with the smallest integrated squared shear) will also align with the spin axis, when we can roughly define this axis by independent means. Hence, the vector \( \xi^A = \epsilon^{AB} D_B \zeta \) serves the same purpose as the vector defined by the Killing transport method above, though it is a smooth vector field and an “approximate” solution to Killing’s equation in a specific variational sense.

When the approximate Killing vector field \( \tilde{\xi} \) is defined in this way, its poles are the extrema of the scalar function \( \zeta \). This fact provides a natural connection of the machinery in the SpEC code to the \( \hat{\chi}_{KT} \) technique. While the approximate Killing vector field computed in SpEC is not the same vector field computed in the Killing transport method, we can nonetheless carry out an analogous procedure to define and study a very similar axis measure \( \hat{\chi}_{\zeta e} \), defined by:

\[
\hat{\chi}_{\zeta e} = (x_2 - x_1)/N, \tag{20}
\]

where again \( N \) is simply a normalization factor, but \( x_2 \) and \( x_1 \) are the coordinates of the extrema of \( \zeta \).

This procedure, while mathematically straightforward, becomes slightly tricky in SpEC, where all horizon data is resolved into a pseudospectral expansion in spherical harmonics. The high accuracy of the spectral expansion allows the code to run with rather coarse grids. In particular, in the runs presented in this paper, the spectral expansion of horizon data is resolved up to spherical harmonic order \( \ell = 15 \). This implies a typical spacing between collocation points of \( \Delta \phi = 2\pi/(2\ell + 2) \approx .2 \text{ rad} \approx 11^\circ \). In this paper, we intend to probe mutations of the spin axis to much higher precision than that. Thus, in finding extrema of \( \zeta \) (or of other functions, as we’ll discuss below), we must either employ an analytic formula to find locations of extrema purely from spectral coefficients (and we know of no such formula), or we must carry out a search procedure that probes data interpolated between the grid points of the horizon. To this end, our code first finds extrema of \( \zeta \) restricted to the coarse grid of collocation points. It then carries out a straightforward gradient-descent algorithm on the interpolated values of \( \zeta \) to locate extrema between collocation points. We have found this technique to be robust only when the extrema are not near the poles of the horizon’s spherical coordinate chart, however the simulations presented here satisfy this requirement. Because, as we will see, the use of extrema provides no particular advantage over the techniques already employed in SpEC (and provides an inferior measure of spin axis to the methods derived later in this paper), we have not attempted to improve this technique to make it more robust for general calculations.

This method of defining a spin axis by the Euclidean line between extrema of a function can also be extended to other relevant quantities on the horizon. In particular, the quantities \( \Omega \) and \( B_{ss} \) are more directly related to quasilocal angular momentum and frame-dragging than \( \zeta \) is, and therefore might be expected to be less susceptible to tidal effects. In this paper, we will also explore quantities called \( \hat{\chi}_{\Omega e} \) and \( \hat{\chi}_{B_{ss} e} \), both defined similarly to \( \hat{\chi}_{\zeta e} \), but with \( x_1 \) and \( x_2 \) referring to minima and maxima of \( \Omega \) and \( B_{ss} \).

### B. Angular momentum vector from coordinate rotation generators

Early in the development of the modern SpEC code, we explored methods along the lines described above, but were concerned that the holes, which raise tides on one another, might deform enough that their best symmetry axis might not be determined solely by the spin axis, but also by the orientation of the tidal bulge. For this reason, we explored a more basic approach, defining the spin axis through integrals of the form of Eq. (1). Specifically, it was our hope that a spin “vector” could be defined as:

\[
J_i = \frac{1}{8\pi_0} \oint_{\mathcal{H}} \hat{\omega} \cdot \hat{\phi}_{(i)} \, dA, \tag{21}
\]

where \( \mathcal{H} \) refers to the horizon 2-surface, and the \( \hat{\phi}_{(i)} \) are the coordinate rotation vectors, which would be constructed from their corresponding one-forms:

\[
\phi_{(i)} = \eta_{ijk} \left( x^j - x^j_0 \right) \, dx^k. \tag{22}
\]

Here \( \eta_{ijk} \) represents the alternating tensor of the flat “background” geometry, a totally antisymmetric object.
with \( \eta_{123} = 1 \) in the cartesian, asymptotically-inertial coordinate system of the simulation. Throughout this paper, indices \( i, j, k \) refer specifically to the basis associated with this coordinate system, and are raised and lowered trivially with the flat metric \( \delta_{ij} \). The quantities \( x^i_0 \) represent centroid coordinates associated with the particular horizon under consideration. There are many ways to fix this centroid, a fact that we will come back to in detail in Sec. V, and they would be expected to lead to different angular momentum integrals. The most obvious one, with which we experimented the most in the early days of the SpEC code, used horizon averages of the coordinates:

\[
x^i_0 = \frac{1}{A} \oint_{\mathcal{H}} x^i \, dA.
\]  

Unfortunately, the spin measure defined in this way showed some features that do not comport with the behaviors normally associated with black hole spin. The most glaring of these was a feature in which a supposedly “nonspinning” black hole (in an equal-mass binary where neither hole initially has spin) settles (after the initial burst of junk radiation) to a hole with spin in the direction opposite to the orbital angular momentum. This much is perfectly plausible as a real, physical effect — junk radiation can be absorbed by the holes and can cause them to spin up slightly. The difficulty comes in the later inspiral, in which this small (yet numerically well resolved) initial spin, anti-aligned with the orbital angular momentum, *increases* during the ensuing inspiral. One could expect tidal viscosity effects to spin up initially nonspinning holes, but such spinup would be *aligned* with the orbital angular momentum in a system like this one. By this measure, an initially nonspinning hole appears to spin up during inspiral in the direction opposite the expectations from perturbative calculations. This phenomenon can be seen in Fig. 7, in which it can also be noted that the effect is strongly influenced by the choice of centroid \( x^i_0 \).

**C. Axis vector defined by coordinate moments**

Given the strange behaviors of \( J_i \) described in Sec. III B, and the uncertainties of choosing the centroid \( x^i_0 \), a decision was made early in the development of SpEC to de-emphasize this spin vector and to instead define the spin axis in a manner somewhat analogous to the methods of Sec. III A. However, to avoid the subtleties of rootfinding described above, we instead defined the spin axis through coordinate moment integrals of spin-related quantities on the horizon. In analogy with \( \hat{x}^i_{\Omega m} \), one could define a similar spin axis through coordinate moments as:

\[
\hat{x}^i_{\Omega m} := \frac{1}{N} \oint_{\mathcal{H}} \zeta x^i \, dA.
\]  

Or, again, under the assumption that \( \Omega \) or \( B_{ss} \) might be less susceptible to tidal effects, one could define spin axes through their moments:

\[
\hat{x}^i_{\Omega m} := \frac{1}{N} \oint_{\mathcal{H}} \Omega x^i \, dA,
\]  

\[
\hat{x}^i_{B_{ss} m} := \frac{1}{N} \oint_{\mathcal{H}} B_{ss} x^i \, dA.
\]  

These spin axis vectors are all defined as unit vectors, not as full angular momentum vectors, and thus are undefined in the case of zero spin. It therefore wouldn’t make sense to ask if they share the strange nonphysical spinup features of the \( J_i \) in Sec. III B. However, the non-normalized forms of \( \hat{x}^i_{\Omega m} \) and \( \hat{x}^i_{B_{ss} m} \) do indeed vanish (to within the estimated truncation error of the simulation) for the same equal-mass nonspinning runs.\(^2\) The three measures described here also have two other critical features, which also happen to be shared with the three measures defined in Sec. III A:

- **Centroid invariance:** If the spatial coordinates are offset by constants, \( x^i \mapsto x^i + \Delta x^i \), the spin axes \( \hat{x}^i_{\Omega m} \), \( \hat{x}^i_{\Omega m} \), and \( \hat{x}^i_{B_{ss} m} \) do not change. This is because the quantities \( \zeta \), \( \Omega \), and \( B_{ss} \) each have zero mean when integrated over the 2-surface, and thus if the \( \Delta x^i \) are constants, the additional terms integrate to zero.

- **Boost-gauge invariance:** As described in Sec. II, it is useful for theoretical reasons that the spin measure be unchanged under slicing transformations that leave the 2-surface itself fixed. For one, this invariance ensures that arguments made about the spin evaluated in the code slicing also apply to the spin as evaluated on the spacelike dynamical horizon 3-surface. All of the quantities that appear in the above moment integrals are boost-gauge invariant. \( \zeta \) is defined intrinsically to the 2-surface, so it is manifestly boost-gauge invariant. The invariance of \( \Omega \) and \( B_{ss} \) was argued in Sec. II.

The measure \( \hat{x}_{\Omega m} \) is the default measure of the spin axis used in the SpEC code, and to our knowledge has been the sole measure of spin direction in all publications of SpEC results. More precisely, SpEC outputs a “spin vector”, which is simply the “unit vector” \( \hat{x}_{\Omega m} \), multiplied by the dimensionless spin magnitude computed by approximate Killing vector methods [35].

It should be noted that boost-gauge invariance does not mean the spin direction measure is *slicing* invariant. Indeed, one would not expect an angular momentum vector to be slicing invariant [60]. If we consider a Kerr black hole, represented in, say, Kerr-Schild coordinates \( x^\mu = (t, x, y, z) \), and then reslice the spacetime using a

\(^2\) \( \hat{x}^i_{\zeta m} \) does not have a “non-normalized” form, because \( \zeta \), defined by an eigenvalue problem, has no definite scale unless some normalization condition is applied to it.
global Lorentz boost, then the shape of the horizon, represented in the boosted spatial coordinates on the boosted time slice, will be length contracted along the direction of the boost by a factor \(1/\gamma\). Since the spin axis vectors defined above (at least before normalization) are linear in the spatial coordinates \(x^i\), the components of these axis vectors along the direction of the boost are reduced by the same factor. This transformation means that the angle that the angular momentum vector makes with the direction of motion varies with spin and boost speed in precisely the same way as in special relativity and post-Newtonian theory under the Pirani spin-supplementary condition [60]. We have confirmed this transformation behavior by evaluating these spin axis measures on boosted spinning Kerr black holes in SpEC.

Also, while the technique outlined here to define \(\hat{\chi}_{\Omega m}\) through coordinate moments may seem ad-hoc, it actually arises from Eq. (1) in a straightforward manner. On a sphere of radius \(r_0\) in Cartesian coordinates in a Euclidean geometry, the rotation vectors on can be rewritten as:

\[
\phi_A^{(i)} = r_0 \epsilon_A B D_B x^i, \tag{27}
\]

where the three coordinates \(x^i\) are treated as scalars with regard to the covariant derivative \(D\) on the 2-surface. If we use this vector field to evaluate the quasilocal angular momentum using Eq. (3), then an integration by parts gives:

\[
J^{(i)} = \frac{r_0}{8\pi} \int \omega_A^{AB} D_B x^i \, dA, \tag{28}
\]

\[
= \frac{r_0}{8\pi} \int x^i \epsilon^{BA} D_B \omega_A \, dA, \tag{29}
\]

\[
= \frac{r_0}{8\pi} \int x^i \Omega \, dA. \tag{30}
\]

In practice, of course, the horizon is not a round sphere embedded in Euclidean space, so this is simply a motivating argument, not any kind of derivation. But this argument, along with the centroid and boost-weight invariance of \(\hat{\chi}_{\Omega m}\), were the main motivating factors that led to its adoption as the default measure of spin axis in SpEC.

IV. DISCREPANCIES BETWEEN THESE MEASURES, AND WITH POST-NEWTONIAN RESULTS

The previous section outlined six different options for defining the spin axis in numerical relativity, each about equally well motivated. All involve scalar quantities on the horizon (specifically, the scalar curvature, \(\Omega\) of the horizon’s normal bundle, which very naturally distills the boost-invariant information from the quasilocal angular momentum density; the normal-normal component of the magnetic part of the Weyl tensor, \(B_{ss}\), called the “horizon vorticity” in Ref. [52], which equals \(\Omega\) when the horizon is stationary, and can be easily related to differential frame dragging; and the potential \(\zeta\) associated with an approximate symmetry of the horizon). Further, these scalar quantities could be distilled into an “axis” either by taking integral moments over the horizon with respect to the background Cartesian coordinates, or by tracing a coordinate line between their extrema. The SpEC code, by default, uses moments of \(\Omega\), while most non-SpEC papers trace a line between the poles of the approximate symmetry vector (a technique that we will model here with lines between the extrema of \(\zeta\)).

Given the many options for defining the spin axis, it would be helpful to calculate the discrepancies among these measures in a representative case, as a rough measure of how well they might be trusted as measures of the specific physical quantity that they are all meant to represent.

We consider a merger of particular physical interest because it involves particularly simple though nontrivial mutation properties, and because these mutations were found (using the standard measure from the SpEC code, \(\chi_{(1)}m\)) to display features that are qualitatively inconsistent with expectations from Post-Newtonian theory [41]. The case is a low-eccentricity inspiral of black holes with mass ratio 5:1, in which the less massive hole is non-spinning and the more massive hole has spin magnitude \(0.5\), where \(m_1\) is the mass of this larger hole, \(5/6\) the total mass \(m\) of the system, with initial spin direction (according to the \(\hat{\chi}_{\Omega m}\) measure) tangent to the initial orbital plane. This simulation was referred to as q5_0.5m in Ref. [41], and further details can be found at [19] where this configuration is numbered 0058, though for this study we reran the simulation to add the new spin measures.

In Figures 1 – 4, we summarize the discrepancies between these measures.

Figure 1 shows the difference between an axis determined by the line between extrema and an axis determined by coordinate moments. Curves are shown comparing these measures for the three scalar quantities \(\zeta\), \(B_{ss}\), and \(\Omega\), though the latter two curves overlap to the eye. The fact that the measures differ more for \(\zeta\) and for \(B_{ss}\) than for \(\Omega\) implies that \(\Omega\) and \(B_{ss}\) have higher multipolar structure. Indeed, the \(\zeta\) quantity is considered in Ref. [38] to define a pure dipole, in a spectral sense, that would be expected to agree reasonably well with a coordinate dipole, for which the moment measure and extremum measure would be expected to agree exactly.

Figure 2 shows the differences between using \(B_{ss}\) and \(\Omega\), either via moments or extrema. The agreement is remarkably good, implying that the pre-merger dynamics are not strong enough to cause \(\Omega\) and \(B_{ss}\) to substantially differ from one another. In fact, when analyzing any such small quantities, one must be careful to account for numerical truncation error. The SpEC code uses a rather elaborate system of adaptive mesh refinement, so detailed convergence analysis is not straightforward. The situation for the calculations in this paper is even more complicated, as many of our calculations involve calculus on the horizon itself, which is itself resolved to some
FIG. 1: Angle (in the Euclidean background space) between spin axes defined using coordinate moments and using line between extrema. The data for the horizon vorticity $B_{ss}$ (green curve) and the closely related curvature $\Omega$ of the normal bundle (red curve), overlap so precisely that only one can be seen in this figure. For all three scalars, agreement is to within a degree throughout the inspiral. For reference, the orbital period in the early inspiral is approximately 400m.

FIG. 2: Angle (in the Euclidean background space) between spin axes defined using $B_{ss}$ and $\Omega$, either using coordinate moments or a line between extrema. The measures agree remarkably well, a sign that $B_{ss}$ is very nearly equal to $\Omega$, as one would expect for holes that are not undergoing strong dynamical processes. In fact, the measures agree to within a hundredth of a degree right up to the formation of the common horizon. It should be noted that all axis measures described in this paper, including these ones, differ from one another in our two highest resolution runs by angles of order 0.05°, significantly more than either of these discrepancies, shown here evaluated at the highest resolution. Thus, even these differences could be largely due to numerical truncation error.

finite spectral order. As a rough measure of numerical truncation error, we simply measure the angle between the two highest-resolution calculations of any given axis measure. We find that all axis measures differ in our two highest resolutions of this simulation by angles of order 0.05°. The errors in each of these very different axis measures depends on time in a visually similar way, suggesting that the dominant source of this truncation error is in the finding of the horizon itself rather than the calculations carried out upon it. Still, we find it prudent to ignore variations of any of these axis measures at a level significantly less than 0.05°. Therefore we consider the measures based on $B_{ss}$ and $\Omega$ to be identical to within numerical truncation, though theoretically they could differ.

As a final comparison, we show the discrepancy between a spin axis determined by the symmetry generator $\zeta$ and the normal-bundle curvature $\Omega$, either via coordinate moments or extrema. Here, the moment measures agree much better (differences of order .05°) than the extremum measures (differences of order 1°). The greater variation in extremum measures is again due to the fact that $\Omega$ has more non-dipolar structure than $\zeta$. This non-dipolar structure is largely filtered out from the coordinate moments.

As a final comparison, we show the discrepancy between the default measure of spin axis in SpEC with our model of the standard non-SpEC measure (the line between rotation poles, which we model as the line between extrema of $\zeta$). The discrepancy is within half a degree for much of the inspiral, implying that both measures would be essentially equally “good” for rough measurements of the
spin axis and its secular precession, but likely neither is trustworthy for the finer nutation features that motivate the current work.

To further explore the variation in these axis measures, we repeat a procedure from Ref. [41] that allows us to trace out the finer nutation features without the distraction of the secular precession. The method is based around the idea of a “coprecessing” frame. We begin by computing a running average of any given spin axis vector \( \hat{\chi} \), averaging over a few orbital periods (which would be expected to agree with the mutation period) to define a slowly, steadily rotating vector \( \hat{e}_1 \). We then compute the time derivative of this steadily rotating vector and normalize it to define another basis vector \( \hat{e}_2 \). We then complete the triad with a simple cross product: \( \hat{e}_3 = \hat{e}_1 \times \hat{e}_2 \). The nutation, referring to the variation in spin axis that occurs within the window of time averaging, would be represented by the quantities \( \hat{\chi} \cdot \hat{e}_2 \) and \( \hat{\chi} \cdot \hat{e}_3 \). Figures 5 and 6 apply this technique to plot the nutation about the slowly-varying orbit-averaged precession axis. In both cases we also include the mutation expected from a post-Newtonian calculation, which we compute using equations available in Ref. [41]. The post-Newtonian calculations tell us to expect purely vertical nutations (that is, nutations purely perpendicular to the direction of the averaged precession of the spin axis) with amplitude of approximately 0.5°. The moments of \( \zeta \), \( \Omega \), and \( B_{ss} \) all roughly agree with this “vertical” nutation expected from post-Newtonian theory, yet they add a horizontal component (that is, \( \hat{\chi} \cdot \hat{e}_2 \)) which does not vanish as expected, and indeed exceeds the vertical nutation by approximately a factor of five. The measure involving extrema of \( \zeta \) (our model of the standard non-SpEC axis measure) shares this unphysical horizontal nutations as well as drastically enlarged vertical nutations.

These quantities.

V. ANOTHER LOOK AT COORDINATE ROTATION GENERATORS

It should not be particularly surprising that the spin axis measures defined in Sec. III behave in a qualitatively different fashion than the spin of post-Newtonian theory. Even aside from the subtle questions of gauge ambiguity, a much larger issue is that there simply is no reason that the axis of approximate horizon symmetry (defined either by poles or by moments), or the same axes defined by horizon vorticity, should behave dynamically in the same manner as the spin defined in post-Newtonian theory. They are simply different quantities, intuitively expected to agree in some vague approximate sense, but not with the kind of precision that is available in modern numerical relativity codes.

In order to bring the discussion back to concepts directly associated with angular momentum, we return to the quasilocal formula in Eq. (21). Again, this spin measure was explored in the early days of the SpEC code, but abandoned. It was abandoned in part because it did not satisfy the useful technical conditions of centroid invariance or boost-gauge invariance, but a more direct reason was the nonphysical behavior it exhibited in binaries of small spin. This behavior, in a simple simu-
lution of an equal-mass non-spinning inspiral, can be seen in Fig. 7. The holes are nonspinning according to the well-defined spin magnitude computed using approximate Killing vectors [33–35]. After the initial ringing, a small but well-resolved spin in the $−z$ direction arises (that is, in the direction opposite the orbital angular momentum). More troublingly, this nonzero spin grows over the course of the inspiral, still in the direction opposite the orbital angular momentum. This spinup is opposite (and much stronger than) what would be expected from tidal spinup.

Figure 7 includes curves showing two choices of centroid. The blue curve uses the centroid computed directly from the coordinate shape, assuming no spatial curvature:

$$x_{0,\text{flat}}^i = \frac{1}{A_0} \oint_{\mathcal{H}} x^i dA_0,$$

where $dA_0$ refers to the surface area element inferred on the horizon 2-surface $\mathcal{H}$ from the flat background geometry. The green curve shows the spin computed similarly, but fixing the centroid using the physical curved-space geometry:

$$x_{0,\text{curved}}^i = \frac{1}{A} \oint_{\mathcal{H}} x^i dA.$$

Figure 7 not only shows the unphysical apparent spinup, it also clearly shows that this unphysical spinup is strongly dependent on the choice of centroid. Thus, by fixing the centroid in a reasonable way, one might hope to cure this apparent spinup.

FIG. 7: Component of spin, on either black hole, along direction of orbital angular momentum, in a binary of equal-mass initially nonspinning black holes. When the spin is measured using the simple coordinate rotation vectors of Eq. (22), the holes spin up in the direction opposite expectations from perturbation theory. This spinup, while small, is well resolved by the code. Moreover, this spinup is strongly influenced by the choice of the coordinate centroid defining the rotation vectors. When the boost-fixed coordinate spin defined in Eq. (43) is used, the spin remains zero to well within the accuracy of numerical truncation throughout the entire inspiral (including a sharp but numerically unresolved spinup after the formation of the common horizon).

A. Hodge decomposition and boost-fixed coordinate spin

To clarify these issues, let us decompose the $\bar{\omega}$ quantity into two scalar potentials on the horizon:

$$\omega^A = D^A \pi + \epsilon^{AB} D_B \varpi. \quad (33)$$

If we know the vector $\bar{\omega}$, then the potentials $\pi$ and $\varpi$ can be readily computed through a Poisson equation on the 2-surface:

$$D^2 \pi = D_A \omega^A = \Pi, \quad (34)$$
$$D^2 \varpi = \epsilon^{AB} D_A \omega_B = \Omega. \quad (35)$$

Note that because the sources, $\Pi$ and $\Omega$, are pure derivatives, they integrate to zero on the 2-surface, the necessary condition for them to lie within the image of the horizon Laplacian operator, and thus for solutions for solutions $\pi$ and $\varpi$ to exist. These potentials are defined only up to a constant, but the constant is irrelevant in reconstructing $\omega^A$, and hence the spin. (In SpEC, these potentials can be computed, and the constant is fixed by the condition that $\pi$ and $\varpi$ integrate to zero.)

Note that because $\Omega$ is boost-gauge invariant, the potential $\varpi$ defined by Eq. (35) is also boost-gauge invariant. The other potential, $\pi$, is not boost-gauge invariant, and
for interesting physical reasons. Under a boost-gauge transformation, $\tilde{t} \rightarrow e^{\tilde{t}}, \tilde{n} \rightarrow e^{-\tilde{n}}, \tilde{\omega}$ transforms as:

$$\omega^A \rightarrow \omega^A - D^A a,$$

$$D^A \pi + \epsilon^{AB} D_B \pi \rightarrow D^A \pi + \epsilon^{AB} D_B \pi - D^A a,$$  

and hence we can infer that, up to an additive constant, $\pi \rightarrow \pi - a$.

Now, return to the quasilocal angular momentum formula. Substitute the above scalar decomposition, and integrate by parts:

$$J = \frac{1}{8\pi_0} \oint_{\Sigma} (D^A \pi + \epsilon^{AB} D_B \pi) \phi_A dA,$$  

$$8\pi_0 J = -\oint_{\Sigma} \pi (D^A \phi_A) dA + \oint_{\Sigma} \epsilon^{AB} D_A \phi_B dA.$$  

The first integral is not boost-gauge invariant, while the second integral is. We could choose to fix boost gauge with the condition $\pi = 0$, which is always accessible given the transformation law for $\pi$. This fixing of boost-gauge was employed by Korzynski [61] in a different but related approach to quasilocal black hole spin (involving conformal Killing vectors on the horizon, rather than the global coordinate rotations considered here). But there is another way to think about the condition in the current context.

The offending boost-dependent term in Eq. (39) also involves the quantity $\nabla A \phi_A$, the divergence of the rotation generator. If $\phi$ were a true Killing vector on the 2-surface, then this divergence would vanish simply due to the trace of Killing’s equation.

As a simple motivating case, consider a metrically-round 2-sphere embedded in truly Euclidean 3-space. The Killing vector fields that generate rotations about the center of this sphere are tangent to it and thus also Killing vectors of the surface. One can show (using arguments along the lines outlined below) that the vector fields that generate rotations about a point offset from the center of the sphere, when projected down to the surface, have nonzero surface divergence. Furthermore this surface divergence is linear in the offset vector. Hence, in Euclidean space, one can fix the centroid ambiguity by insisting that the rotation generator has zero divergence.

On an arbitrary 2-surface, in curved or flat geometry, it is no longer true that simple translation of background-coordinate rotation generators can always render the projected field divergence-free. However one can always project out the “divergence-free part” of $\phi$, using a Hodge decomposition analogous to that already employed for $\omega$:

$$\phi_A = D_A a + \epsilon_A^B D_B \beta,$$  

$$\beta = D^{-2} (\epsilon^{AB} D_A \phi_B),$$  

$$\phi_A^{DF} = \epsilon_A^B D_B \beta.$$  

Such a projection might be considered a “generalized” translation of the coordinate rotation generator.

Either viewpoint (fixing boost-gauge to render $\pi = 0$, or deforming the rotation generator to remove its divergence while preserving its curl) leads to the following very simple gauge-fixed coordinate spin vector:

$$J_{ij} := \frac{1}{8\pi_0} \oint_{\Sigma} \epsilon^{AB} D_A \phi_B^{i} dA,$$  

where $\phi^i_A$, for $i = 1, 2, 3$, are the three standard coordinate rotation generators. We refer to this quantity as the “boost-fixed” coordinate spin vector, though we will show below that it is also invariant under changes of the coordinate centroid that defines the rotation generators $\phi^i_A$.

B. Behavior under changes of coordinate centroid

Consider the rotation generator $\phi_i$ associated with the three dimensional background Euclidean space. Again, the index $i$ labels the particular generator, and references a Cartesian basis in the background geometry. This vector field can also be represented in terms of the Cartesian coordinates and a conventional tensor index $a$:

$$\phi_{ia} = \eta_{ijk} (x^j - x_0^j) \partial_a x^k,$$  

where again $x_0^j$ refers to the three components of the center point of the rotation (the centroid), taken to be constant with regard to the spatial derivative $\partial_a$. This representation of the rotation generator is convenient because projecting to the 2-surface is as simple as changing the derivative operator to a derivative tangent to the surface:

$$\phi_{iA} = \eta_{ijk} (x^j - x_0^j) D_A x^k.$$  

Note that for convenience of later notation we have changed the derivative operator on the surface to the surface covariant derivative $D$. However because the individual coordinates $x^k$ are treated here as three independent scalars, $D_A$ coincides with $\partial_A = e^a_A \partial_a$. The divergence of $\phi^i$, on the 2-surface, is simply:

$$D^A \phi_{iA} = \eta_{ijk} D^A x^j D_A x^k + \eta_{ijk} (x^j - x_0^j) D^2 x^k.$$  

The first term on the right hand side vanishes because $\eta_{ijk}$ is antisymmetric in the $j$ and $k$ indices, while $D^A x^j D_A x^k$ is symmetric in these indices. What remains is:

$$D^A \phi_{iA} = \eta_{ijk} x^j D^2 x^k - \eta_{ijk} x_0^j D^2 x^k.$$  

In a similar manner, one can calculate the curl of $\phi_{iA}$, and the result is remarkably simple, and independent of the center coordinates $x_0^j$:

$$\epsilon^{AB} D_A \phi_{iB} = \eta_{ijk} \epsilon^{AB} D_A x^j D_B x^k.$$  

(48)
Substituting these results into Eq. (39), one finds a remarkable and familiar result:

\[ J_i = J_{0i} + \gamma_{ijk} x^j_0 p^k, \]

(49)

where:

\[ J_{0i} = -\gamma_{ijk} \int \pi x^j D^a x^k \, dA \]

\[ + \gamma_{ijk} \int \pi \epsilon^{AB} D_A x^j D_B x^k \, dA, \]

(50)

\[ p^k = \int \pi D^2 x^k \, dA = \int \Pi x^k \, dA. \]

(51)

The object \( p^k \) is naturally associated with quasilocal linear momentum. A closely-related idea was explored in Ref. [62], though here it has arisen naturally from the transformation properties of angular momentum. Under this consideration, an offset \( \Delta \vec{x} \) in the reference coordinates is found to lead to the same change, \( \Delta \vec{x} \times \beta \) as in Newtonian physics. The potential \( \pi \) is not boost-gauge invariant because it represents, in this formalism, a surface density of linear momentum, which must vanish if one boosts to a slicing in which the horizon is at rest.

As a final note, recall the “boost-fixed” coordinate spin defined in Eq. (43). That quantity equals the angular momentum in Eq. (49) when \( \pi = 0 \), in which case dependence on \( x^0_0 \) disappears. Therefore \( J_{bf} \) is independent of the choice of centroid.

C. Associated ambiguity of the spin axis

We began this section with a demonstration that the simple “coordinate spin” vector of Eq. (21) is at least slightly dependent on the choice of centroid for the coordinate rotation generator. The elaborate derivations of Sec. V B demonstrated that this dependence is directly analogous to a translation ambiguity that exists even in Newtonian physics, an ambiguity present in post-Newtonian theory as well, in which the spin “vector” is defined only after a certain “spin supplementary condition” has been imposed [60]. It is extremely tempting to generalize the standard spin supplementary conditions of post-Newtonian theory to the context of full numerical relativity. We intend to pursue this path in future research, however such a generalization would necessarily involve quasilocal energy, a concept that has been very well studied (the approach of Brown and York [42], in particular, is directly related to the angular momentum arguments treated here). However quasilocal energy is famously a much more subtle concept than the simple angular momentum constructions employed here, so we must consider this extension beyond the scope of the current work.

Instead, here we simply view the centroid ambiguity as another inherent ambiguity of the coordinate spin angular momentum. This ambiguity can be fixed by choosing particular centroids such as those defined in Eqs. (31) – (32), or by employing the boost-invariant measure defined in Eq. (43). The results shown in Fig. 7 might be taken to imply that a small (though non-oscillating) discrepancy might exist between \( z \)-components of the coordinate spin measures using the flat- or curved-space centroids. However, as seen in Fig. 8, the discrepancies are quite small in this case. In fact, the true discrepancies do not appear to even be resolved beyond the estimated truncation error of our highest-resolution runs. On a practical level, it is encouraging that these measures do not quite differ by more than our estimated truncation error of 0.05°, implying that each would be equally “good” except in extremely high-precision simulations. On a theoretical level, however, it is disappointing that the discrepancies which should exist according to the discussion in Sec. V B cannot be clearly seen.

The mutation features of these axis measures can be seen again using “copercesing frame” diagrams analogous to Figs. 5 and 6. All three of our coordinate spin measures (which, again, differ by amounts roughly equal to our estimated truncation error, and hence may not be fully resolved) are shown in Fig. 9. Nonetheless, one fact is quite clear: the wild mutations seen with the earlier measures have been reduced by approximately two orders of magnitude.

As a final demonstration of the improved behavior of these coordinate spin axes, we repeat the kind of fit to post-Newtonian theory carried out in Ref. [41]. We solve the same post-Newtonian equations as in that research, though we note that while this reference includes an extremely convenient compilation of orbital, spin-orbit, and spin-spin terms from a variety of sources, it currently includes a few typographical errors. The quantity \( \gamma \) should read:
FIG. 9: Nutation in a coprecessing frame of the larger hole in the same $q = 5$, $\chi_1 = .5$, $\chi_2 = 0$ simulation shown also in Figs. 5 and 6. The spin axes are now defined through the “boost-fixed” coordinate spin, $\vec{J}_{bf}$, as well as the quasilocal angular momentum computed from standard coordinate rotation generators with $x^0_i$ set to either the flat-space centroid, Eq. (31), or the curved-space centroid, Eq. (32). For comparison, we have also included the nutations of the SpEC-default spin axis, which uses moments of $\Omega$, and the axis defined by extrema of $\zeta$ (that is, the poles of the Approximate Killing Vector). The distinctions between the coordinate-spin nutations may not be fully resolved, however each of them agrees far better with post-Newtonian expectations. In particular, for the spin computed using the flat-space centroid, as well as $\vec{J}_{bf}$, the unphysical horizontal nutation amplitude has been reduced by two orders of magnitude.

\[
\gamma = x \left\{ 1 + \frac{3 - \nu}{3} \right\} + \frac{35\sigma_l + 5s_l}{3} x^{3/2} + \frac{12 - 65\nu}{12} x^2 + \left[ 1 + \nu \left( -\frac{2203}{2520} - \frac{41\pi^2}{192} \right) + \frac{229\nu^2}{36} + \frac{\nu^3}{81} \right] x^3 + \left( \frac{60 - 127\nu - 72\nu^2}{212} - \frac{18 - 61\nu - 16\nu^2}{36} \sigma_l \right) x^{7/2} + x^2 \left( s_{0}^2 - 3(s_0 \cdot \vec{\ell})^2 \right),
\]

and the quantity $b_7$ should read:

\[
b_7 = \left( \frac{476645}{6804} + \frac{6172}{189} - \frac{2810}{27} \nu^2 \right) s_l + \left( \frac{9535}{336} + \frac{1849}{126} - \frac{1501}{36} \nu^2 \right) \sigma_l + \left( -\frac{16285}{504} + \frac{214745}{1728} \nu + \frac{193385}{3024} \nu^2 \right) \delta \sigma_l \pi.
\]

We keep all terms in these expressions and the rest of the post-Newtonian expressions given in Ref. [41], and handle the evolution of the $x$ parameter using the simple TaylorT1 approximant. We match by minimizing the same integral as in that paper, an integral of:

\[
\mathcal{S} := \langle (\angle L)^2 \rangle + \langle (\chi_1)^2 \rangle + \langle (\Delta \Omega)^2 \rangle,
\]

where $\angle L$ is the angle (in radians) between the orbital angular momentum axis of the PN solution and that computed from coordinate trajectory data in the numerical relativity solution; $\angle \chi_1$ is the angle between PN and NR spin axes, and $\Delta \Omega := (\Omega_{PN} - \Omega_{NR})/\Omega_{NR}$, where $\Omega_{PN} = x^{3/2}/\mu$ and $\Omega_{NR}$ is the angular velocity of the
We attribute the failure to find better agreement in the text, where the integration window of the fit extends from $t = 4000m$ to $t = 5500m$. The uppermost curve shows the discrepancy with $\hat{\chi}_{\zeta e}$, our model of a standard axis measure defined by a line between poles of the approximate horizon symmetry. The intermediate curve represents the standard axis measure in the \textsc{SpEC}, $\hat{\chi}_{\Omega m}$, which also differs from the best-fit post-Newtonian spin axis by approximately a half degree throughout the inspiral, due to the wild horizontal oscillations visible in Fig. 6. The bottom curve shows the best fit to our boost-fixed coordinate spin axis defined in Eq. (43). The other coordinate-spin axes defined in Sec. V overlap visually with this curve.

NR solution, again computed using coordinate trajectory data. The angled brackets $\langle \cdot \rangle$ refer to a coordinate-time integration, in this case carried out from $t = 4000m$ to $t = 5500m$, in rough agreement with the window used in Ref. [41].

The discrepancy of three numerical-relativity axis measures, versus best-fit post-Newtonian values, is shown in Fig. 10. The spin measure defined in (43) (and the standard angular momentum with coordinate rotation generators, using our two considered centroids, not shown) improves on the two standard axis measures in modern Numerical Relativity literature by an order of magnitude. We attribute the failure to find better agreement in the bottom curve, particularly within the matching window itself, to our marginal numerical resolution of this spin axis measure.

\section{VI. DISCUSSION}

The research presented here was motivated by two particular goals. The first, more modest, was to simply present formally the default definition of spin axis currently employed in the \textsc{SpEC} code, how it relates to the other current standard and other similarly well-motivated measures. The second goal was to explain and resolve the unphysical nutation features discovered in Ref. [41], which clouded otherwise very strong agreement with post-Newtonian results.

On the first point, we have formally defined, in Eq. (25), the axis measure $\hat{\chi}_{\Omega m}$ that defines the spin axis in all currently published \textsc{SpEC} results, and which indexes the simulations catalogued at [19]. Specifically this measure defines the spin axis through coordinate moments of a scalar quantity $\Omega$ defined on any 2-surface in spacetime, mathematically a scalar curvature of the normal bundle of the embedding of the 2-surface in spacetime. Though it may seem mathematically obscure, this quantity has a long history in \textsc{SpEC}, and in the general formalism of quasilocal spin. It is also used in \textsc{SpEC}'s standard measure of spin magnitude as well as higher current multipoles [33–35, 38], as well as a measure of horizon extremality [36, 63]. It is also very closely related (though not mathematically identical) to the normal-normal component of the magnetic part of the spacetime Weyl tensor, $B_{ss}$, which is related to differential frame-dragging at the horizon and referred to as horizon vorticity in [52–56]. Though the quantity $\Omega$ is intricately related to black hole spin, the use of its coordinate moments as a measure of spin axis was largely an ad-hoc practical decision, with little theoretical justification.

The other standard measure of spin axis in the current numerical relativity literature is the Euclidean line connecting the poles of an approximate symmetry of the horizon. The approximate symmetry in this context is a vector field computed over the horizon's coordinate grid via integration of Killing transport equations. A direct implementation of this technique would be difficult in \textsc{SpEC}, so we have instead considered the line connecting poles of \textsc{SpEC}'s standard approximate Killing vector, defined via a scalar potential $\zeta$ that satisfies a certain eigenproblem derived from the squared residual of Killing’s equation [33–35]. This axis measure, $\hat{\chi}_{\zeta e}$, while not precisely the same as the measure used in other codes, is directly analogous and so we treat it as a model of the standard measure in other codes.

While we have not carried out a systematic comparison of these standard spin measures, in Fig. 4 we have given the first direct comparison of these spin measures in a non-trivially precessing binary black hole simulation, showing that over the course of the inspiral these measures agree to within approximately a degree over the course of the inspiral. This is an encouraging sanity check for general purposes, implying that the distinction is likely unimportant for calculations requiring only a coarse measure of the spin axis. At the same time, though, it implies that the features of spin nutation, which in this case oscillate by significantly less than a degree, cannot be expected to be measured accurately by these ad-hoc measures. We have also explored other similar variants, such as using a line between extrema of $\Omega$ and $B_{ss}$, or coordinate moments of the symmetry potential $\zeta$, finding that extrema of $\Omega$ and $B_{ss}$ vary even more wildly, likely due to their
higher multipolar structure.

With regard to the second goal of this paper — explaining and mitigating the unphysical nutations discovered in Ref. [41] — the previous considerations have motivated our view that these mutations were due to the corruption of these ad-hoc axis measures by the tidal structure, present in black hole inspiral, that these ad-hoc measures nonetheless completely ignore.

To probe spin axis in a more dynamically-meaningful way, we have returned to the quasilocal spin angular momentum measure defined in Eq. (21). Employing this formula in this context requires us to make some background-dependent decision of what to use for the rotation generators \( \hat{\phi}_i \). The simple application of coordinate rotation generators, while not mathematically elegant, is no less geometrically meaningful than the ad-hoc measures currently employed. There are, however, two reasons to hesitate before using Eq. (21) with coordinate rotation generators, reasons that are not shared by the ad-hoc measures in current use: the resulting spin axis will not necessarily be boost-gauge invariant, and more troublingly, it will depend on the centroid used to define the coordinate rotation. This latter concern, however, suffuses the treatment of spin even in Newtonian and post-Newtonian physics, in which a spin-supplementary condition must be imposed to specify what precisely one means by the spin vector. With coordinate rotation vectors as defined in Eq. (22), the quasilocal spin vector can be written in a form directly analogous to the spin tensor used in post-Newtonian theory:

\[
S_i = \frac{1}{8\pi_0} \oint_{\mathcal{H}} \eta_{ijk} \left( x^j - x^j_0 \right) \omega^k \, dA
\]

\[
S^{jk} = \frac{1}{8\pi_0} \oint_{\mathcal{H}} \left( x^j - x^j_0 \right) \omega^k \, dA,
\]

where \( \omega^k := e^k_A \omega_A \). In post-Newtonian theory, the spin-supplementary condition, which fixes the worldline of the centroid \( x^j_0(t) \), is generally stated as a condition on the spacetime spin tensor, such as \( S^{\mu
u}u_\nu = 0 \) where \( \vec{u} \) is, say, the 4-velocity of the spinning body. The appearance of a spin tensor in our formalism raises the tantalizing possibility of enforcing spin-supplementary conditions of post-Newtonian theory in the numerical relativity context. Unfortunately to do so we would also need to define the space-time components \( S^{0i} \) of our numerical relativity spin tensor, and to do so would require implementation of a quasilocal energy density measure, which we intend to pursue in future work.

Instead, we have simply treated the ambiguity of the centroid \( x^j_0 \) as precisely that, an ambiguity of the formalism. And we have fixed this ambiguity in two ways, by setting \( x^j_0 \) to the coordinate center of the horizon, Eq. (31), and to the geometric center of the horizon, Eq. (32).

This coordinate spin measure, using either centroid, also suffers from the boost-gauge ambiguity, which might be considered less severe a problem here than in other contexts considering that so much gauge ambiguity is already being fixed by the coordinates of the simulation. Nonetheless, we have also employed a Hodge decomposition of the quasilocal angular momentum density \( \omega_A \) to distill its boost-invariant component \( \epsilon_A^B D_B \omega \) to define a coordinate spin measure \( \vec{J}_{bf} \), Eq. (43), that turns out to be both boost invariant and centroid invariant (or, rather, boost-fixed and centroid-fixed, depending on one’s point of view).

These three measures of spin angular momentum should differ from one another, and indeed they do differ in the results we have presented, however they do so by less than our estimated truncation error of approximately 0.05°, so we cannot claim with certainty to have resolved the difference between them. The good news, however, is that none of the three suffers from the drastically unphysical nutations discovered in Ref. [41], agreeing better with best-fit post-Newtonian solutions by an order of magnitude. We have reason to believe that this agreement will become even better (and the distinction between these spin axes will be numerically resolved) in higher-resolution runs. We are currently carrying out these higher-resolution runs and will report on them in future work.

We note that the improved physical behavior of, say, our \( \vec{J}_{bf} \) quantity may imply improved behavior in analytical and surrogate models matched to numerical relativity results. We encourage further analysis along these lines.

Finally, we note that in describing the dependence of our spin axis measures on the choice of coordinate centroid, we were naturally led to a measure of quasilocal linear momentum, in Eq. (51). Quasilocal linear momentum is not a new concept, and it has been studied before even in the numerical relativity literature [62]. However the fact that this particular measure has arisen directly from considerations of the transformation properties of our spin angular momentum encourages us to explore it further in the future. It could conceivably be a useful measure in analyzing (and reducing) orbital eccentricity and junk radiation, and it might behave in interesting ways in high-speed collisions or collisions of nearly extremal holes.

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