Systematic Parameter Errors in Inspiring Neutron Star Binaries

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The coalescence of two neutron stars is an important gravitational wave source for LIGO and other detectors. Numerous studies have considered the precision with which binary parameters (masses, spins, Love numbers) can be measured. Here I consider the accuracy with which these parameters can be determined in the presence of systematic errors due to waveform approximations. These approximations include truncation of the post-Newtonian (PN) series and neglect of neutron star (NS) spin, tidal deformation, or orbital eccentricity. All of these effects can yield systematic errors that exceed statistical errors for plausible parameter values. In particular, neglecting spin, eccentricity, or high-order PN terms causes a significant bias in the NS Love number. Tidal effects will not be measurable with PN inspial waveforms if these systematic errors are not controlled.

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Introduction.—One of the key goals of LIGO, Virgo, and other ground-based gravitational-wave (GW) detectors [1] is to measure the intrinsic parameters of coalescing neutron star (NS) binaries. The most interesting of these parameters $\theta_i$ are the individual masses $m_i$, the spin angular momenta $\mathbf{S}_i = \chi_i m_i^2 \hat{s}_i$, the orbital eccentricity $e_0$ (at a reference frequency), and the tidal deformability parameters $\lambda_i$ (which depend on the NS masses and equation of state). (Here $i = 1, 2$ labels the two bodies, $\chi_i$ are the dimensionless spin parameters, $\hat{s}_i$ are unit vectors in the spin directions, and $G = c = 1$.) Understanding how well we can extract these parameters from a noisy GW signal is especially important as we rapidly approach the operational phase of second-generation detectors.

Many studies have examined how precisely LIGO and other detectors will be able to measure the source parameters (e.g., [2] [3]). The achievable precision is ultimately determined by the signal-to-noise ratio (SNR); the corresponding statistical errors due to random noise in the detector scale like $\delta \theta_i \propto \text{SNR}^{-1} (1 + O(\text{SNR}))$ [4]. A separate but equally important issue is how accurately we can measure parameters, i.e., quantifying the systematic bias between the true and best-fit parameters, $\Delta \theta_i \equiv \theta_i^T - \theta_i^{\text{best fit}}$. This systematic error (which is SNR independent) arises from not fully understanding the detector (i.e., calibration error [5]) or from deviations between the true GW signal $h_T(\theta_i^T)$ and an approximate template waveform $h_{AP}(\theta_i^{\text{best fit}})$ used in the data analysis [3] [6] [7]. Here I investigate the latter and quantify the systematic bias induced in the intrinsic source parameters due to several potential sources of waveform template errors. The objective is to understand the costs in parameter inaccuracies if certain physical effects in binary neutron star (BNS) models are neglected.

This study focuses on the inspiral phase of BNS coalescence [which is well described by post-Newtonian (PN) waveforms [8] up to $\sim 1000$ Hz [9]]. Since the phasing of the GW signal is significantly more important for parameter estimation than its amplitude, I focus on the following sources of waveform phasing errors:

(a) High PN-order terms: For two orbiting point particles with arbitrary masses, the waveform phasing is known completely to 3.5PN order [i.e., order $(v^2)^{4-5}$ beyond the leading-order contribution]. However, unknown terms at 4PN and higher orders may significantly affect parameter accuracy. I use results from analytic BH perturbation theory [10] (in which the phasing is known to 22PN order [11]) as an approximate proxy for these unknown terms. Neglecting 4PN and higher-order terms causes systematic errors that exceed statistical ones.

(b) Spin: The predicted maximum NS spin is $\chi \sim 0.77$ [12]. NSs are observed to have dimensionless spins $\chi \sim 10^{-4} - 0.3$ [13]. While spin in BNSs is often neglected when modeling their GWs, I show below that even relatively small spins ($\chi \gtrsim 0.003$) can cause non-negligible parameter estimation bias.

(c) Eccentricity: While GW emission reduces eccentricity [14], compact objects formed in dense stellar environments could have non-negligible eccentricity in the LIGO band [15]. Neglecting small ($e_0 \lesssim 0.02$) eccentricities will not constrain the detection of GWs [16], but I show that eccentricities $e_0 \gtrsim \text{few} \times 10^{-3}$ will affect parameter estimation.

(d) Tides: When BNS orbital separations are small, each star is tidally distorted by its companion. The resulting change in the gravitational potential modifies the orbital motion and corresponding GW signal. When the orbital period is much longer than the period of stellar oscillation modes that couple to tides (the adiabatic approximation [17]), the effect on the GW phasing can be parameterized by the dimensionless tidal deformation parameters $\lambda_i = \lambda_i/m_i^5$. For each star $\lambda \equiv 2 \frac{3}{2} k_2 R^5$ is defined by $\mathcal{I}_{jk} = -\lambda \mathcal{E}_{jk}$, where $k_2$ is the quadrupolar Love number, $R$ is the NS radius, $\mathcal{I}_{jk}$ is the mass quadrupole moment, and $\mathcal{E}_{jk} \equiv R_{ijk} R^{ik}$ is the quadrupolar electric-type
tidal field (i.e., the indicated Riemann tensor components of the companion’s spacetime evaluated at the star’s center) [18]. As the NS equation of state is uncertain at high densities, determining the precision with which $\Lambda_1$ can be constrained has been the focus of several studies (e.g., [17] [19]). I show that neglecting tidal interactions will cause a small parameter bias. Furthermore, the determination of $\Lambda_1$ is itself subject to large systematic bias if any of items (a)–(c) above are neglected. Tidal interactions affect the waveform phasing at 5PN and higher orders. Large parameter biases in $\Lambda_1$ arise when neglected PN terms occur at lower or comparable orders: point-particle terms are not completely known at 4PN order, while spin and eccentricity modify the phasing beginning at 1.5 and 0PN orders, respectively. The remainder of this Letter discusses the waveform models in more detail, describes the formalism for computing statistical and systematic errors, and presents the corresponding results.

Waveform model.—The GW signal is modeled using the restricted stationary phase approximation (SPA) in which the Fourier transform (denoted by tildes) of the true GW signal is expressed as a function of GW frequency $f$ via $h_T(f) = A f^{-7/6} e^{i\Psi_T(f)}$. Here $A \propto \text{SNR}$ is a constant depending on the source distance, masses, and orientation angles and does not affect our analysis. The phase is a sum of several possible contributions:

$$
\Psi_T(f) = \phi_c + 2\pi ft_c + \frac{3}{128\eta v^5} (\Delta \Psi_{\text{PP}1.5PN}^{\text{pp}} + \Delta \Psi_{\text{2PN}}^{\text{spn}} + \Delta \Psi_{\text{3PN}}^{\text{spn}} + \Delta \Psi_{\text{4PN}}^{\text{3PN}} + \Delta \Psi_{\text{5PN}}^{\text{4PN}}), \tag{1}
$$

where $\eta = m_1 m_2 / M^2$ is the reduced mass ratio, $M = m_1 + m_2$, $t_c$ and $\phi_c$ are the coalescence time and phase, and $v \equiv (\pi M f)^{1/3}$ is the PN orbital velocity parameter.

The standard 3.5PN point-particle contribution is $\Delta \Psi_{\text{3.5PN}}^{\text{pp}} = 1 + \sum_{n=2}^7 c_{\text{pp}}^n(\eta) v^n$, where the $c_{\text{pp}}^n(\eta)$ can be found in Eq. (3.18) of [7] and the 2.5 and 3PN coefficients also depend on $\ln v$.

Spin effects to 3PN order are encapsulated in the term

$$
\Delta \Psi_{\text{3PN}}^{\text{spn}} = 4 \beta_{1.5} v^3 - 10 \sigma v^4 + v^5 \ln v \left[ \frac{40}{9} \beta_{2.5} \right.
- \left. \beta_{1.5} \left( \frac{3715}{189} + \frac{220}{9} \eta \right) \right] + v^6 \left( 160 \pi \beta_{1.5} + 20 \beta_{3.0} \right). \tag{2}
$$

Here $\beta_{1.5}$ is the 1.5PN spin-orbit term [20] [21]; $\sigma = \sigma_1 s_2 + \sigma_Q M + \sigma_{self spin}$ is the 2PN spin-spin term which combines three effects [22]: the standard spin-spin interaction [21], the quadrupole-monopole term arising from corrections to the Newtonian potential caused by a spinning object’s mass quadrupole moment [23], and the self-spin interaction arising from (current quadrupole) terms in the energy flux’s multipole expansion [22]. $\beta_{2.5}$ is the 2.5PN spin-orbit term [21] and $\beta_{3.0}$ is the 3PN spin-orbit tail correction [24]. 3PN quadratic spin corrections and higher-order spin-orbit terms are not included. This analysis assumes nonprecessing spins, so all of the $\beta$ and $\sigma$ parameters are functions of $\chi_i$ and constant in time.

Eccentricity corrections to the SPA phase are included at leading order in eccentricity via an extension of the approach in [20] to 2PN order [27].

$$
\Delta \Psi_{\text{2PN}}^{\text{ecc}} = \frac{2355}{1462} \eta_0 \left( \frac{v_0}{v} \right)^{19/3} \left[ 1 + v^2 \left( \frac{299 076 223}{81 976 608} + \frac{18 766 963}{292 736} \eta \right) \right] + v^4 \left( \frac{16 237 683 263}{3 330 429 696} + \frac{24 133 060 753}{971 375 328} \eta + \frac{1 562 608 261}{69 383 952} \eta^2 \right) + v^6 \left( \frac{847 282 939 759}{82 632 420 864} - \frac{718 901 219}{368 894 476} \eta - \frac{3 697 091 711}{105 398 496} \eta^2 \right) - \eta \left( 1 + 4 \eta \left( 1 + 9 \eta - 11 \eta^2 \right) \right). \tag{3}
$$

The relative 1PN $[O(v^2)]$ correction [28] can be written in terms of $\Lambda$ and another parameter $\delta \Lambda$ [29]. For equal-mass NSs and $\lambda_1 = \lambda_2 = \lambda$, $\Lambda \rightarrow \lambda$ and $\delta \Lambda \rightarrow 0$. This ($\Lambda$, $\delta \Lambda$) parametrization is advantageous because the $\delta \Lambda$ contribution is very small ($\delta \Lambda / \Lambda \sim 0.001$) and can be ignored. This reduces the number of parameters needed and improves their measurement precision. The parameters $\lambda_i$ span a range $\sim 60$–1600 for $1.4M_\odot$ NSs and can reach values as large as 4400 for $1.2M_\odot$ NSs [19].

The test-mass limit contributions have the form

$$
\Delta \Psi_{\text{6PN}}^{\text{tm}} = \sum_{n=8}^{12} c_{\text{tm}}^n v^n, \quad \text{where } c_{\text{tm}}^n \text{ are independent of } \eta \text{ but can be quadratic functions of } \ln v. \text{ These coefficients are derived to 6PN order [29] [30] using the results}
$$

\[ -\sqrt{1 - 4\eta(1 + 9\eta - 11\eta^2)}(\lambda_1 + \lambda_2). \]
TABLE I. Contributions to the PN coefficients $c_n^{pp}(\eta)$ in the SPA phase $\Delta \Psi_n^{3PN}(f)$. Columns list the PN order, the $\eta = 0$ contribution to the coefficient, the equal-mass limit, and the fractional contribution of the $\eta$-dependent piece (which is < 35\% except for the 3PN piece). Logarithmic terms are evaluated at $v = 0.351 (f = 1000 \text{ Hz for two } 1.4\, M_\odot \text{ NSs).}$

| PN coeff. | $c_n^{pp}(0)$ | $c_n^{pp}(0.25)$ | $1 - \frac{c_n^{pp}(0)}{c_n^{pp}(0.25)}$ |
|-----------|---------------|-----------------|-------------------------------------|
| 1PN       | 4.91          | 6.44            | 0.259                               |
| 1.5PN     | -50.3         | -50.3           | 0                                   |
| 2PN       | 30.1          | 46.2            | 0.349                               |
| 2.5PN     | -504          | -487            | -0.0366                             |
| 3PN       | 63.2          | -763            | 1.08                                |
| 3.5PN     | 954           | 1131            | 0.157                               |

FIG. 1. (color online). Contribution of the last four terms evaluated at $v < c$ as a proxy for the (unknown) full PN coefficients $\eta$ ing that the total coefficient’s value.

The following five scenarios were considered:

(i) To study the effect of varying the PN order we choose $\Psi_T \propto \Delta \Psi_{3,5PN}^{pp} + \Delta \Psi_{6PN}^{pp}$. The same expression for $\Psi_{AP}$ is used except the PN series is quentumly truncated at increasing powers of $v$ (from 1PN to 5.5PN).

(ii) Neglecting NS spin is modeled by choosing $\Psi_T \propto \Delta \Psi_{3,5PN}^{pp} + \Delta \Psi_{3PN}^{spin}$ and $\Psi_{AP} \propto \Delta \Psi_{5PN}^{pp}$ while varying $\chi_i$ (assumed to be equal for each NS).

(iii) To neglect eccentricity we choose $\Psi_T \propto \Delta \Psi_{3,5PN}^{pp} + \Delta \Psi_{6PN}^{tidal}$ and $\Psi_{AP} \propto \Delta \Psi_{3,5PN}^{pp}$ varying $e_0$.

(iv) To neglect tidal interactions we choose $\Psi_T \propto \Delta \Psi_{3,5PN}^{pp} + \Delta \Psi_{6PN}^{tidal}$ and $\Psi_{AP} \propto \Delta \Psi_{3,5PN}^{pp}$ while varying $\lambda_i$ (also set equal for each NS).

(v) Last, we consider the neglect of spin, eccentricity, or high-PN-order terms on the tidal deformation measurable. We choose $\Psi_T \propto \Delta \Psi_{3,5PN}^{pp} + \Delta \Psi_{6PN}^{tidal}$ and $\Psi_{AP} \propto \Delta \Psi_{3,5PN}^{pp}$ and $\Psi_{tidal}$ while varying $\lambda_i$. Here, $X$ refers to the spin, ecc., or tm terms in Eq. (1). We set $\delta \hat{\Delta} = 0$, and $\hat{\Delta}$ is added as a parameter to $\Gamma_{ab}$ with prior $\sigma_{\hat{\Delta}} = 5000$.

Results.—Figure 2 summarizes the most important results of this study, focusing on the fractional errors in the reduced mass ratio. Figure 2(a) shows the statistical and systematic errors for case (i). Here we see that using an approximate 3.5PN template results in a systematic error that is double the statistical error, $\Delta \eta/\eta \approx 2.1$ (aLIGO). Figure 2(a) suggests that decreasing the systematic error on the masses below the statistical errors will require 4PN order waveforms. For ET, waveforms
will likely need to be known to at least 6PN order. Figure 2(b) shows error estimates for case (ii) as a function of the NS spin parameter. Here we see that dimensionless spins as small as $\chi_s \approx 0.003$ ($10^{-4}$) can cause systematic errors to exceed statistical errors for aLIGO (ET). Figure 2(c) shows error estimates for case (iii) as a function of the orbital eccentricity at 10 Hz. Here we see that neglecting eccentricity causes systematic errors that exceed statistical errors if $e_0 \gtrsim 0.002$ ($0.0005$) for aLIGO (ET). While systematic errors in $M_{\text{ch}}$ can also exceed statistical ones, in nearly all cases both errors are $\approx 1\%$.

For case (iv) $\Delta \eta/\eta < 3\%$ but exceeds $\delta \eta/\eta$ for $\lambda_s > 320$ [39]. For case (v) [Fig. 2(d)] we see that the unknown 4PN and higher point-particle terms nearly always introduce a systematic bias in $\Lambda [\Delta \Lambda/\delta \Lambda \sim 1.1$ (16)] for aLIGO (ET), making that parameter unmeasurable with existing PN waveforms. This plot also indicates that spins $\chi_s \gtrsim 0.03$ or eccentricities $e_0 \gtrsim 0.003$ yield $\Delta \Lambda > \delta \Lambda$ (aLIGO). This poses difficulties for attempts to infer information about the distance-redshift relation from BNS inspirals [39]. Note that the statistical errors $\delta \Lambda/\Lambda \sim 20\%-60\%$ for aLIGO are themselves large.

Statistical errors for ET are smaller by a factor $\sim 10$ (largely due to higher SNR). Because systematic errors are SNR independent, understanding waveform errors is especially critical for third generation detectors like ET.

**Conclusions.**—Several plausible theoretical waveform errors were considered, and the corresponding systematic biases were evaluated and found to be important in many cases. Correcting these biases will be essential for accurate parameter extraction from expected aLIGO observations. In particular the following suggestions are recommended: (1) standard PN waveforms should be developed to 4PN order to improve mass accuracy, and to 5PN order to reduce biases on equation-of-state constraints; (2) while their dimensionless spins are much smaller than for black holes, NS spin effects should not be neglected in parameter estimation studies; (3) although eccentricities of known binary pulsars will be smaller than $e_0 \lesssim 10^{-5}$ at 10 Hz, eccentric templates will be needed if astrophysical scenarios predict $e_0 \gtrsim 10^{-3}$. Further investigations of these issues are in progress [29].

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