The NINJA Project

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For the NINJA Collaboration, the LIGO Scientific Collaboration and the Virgo Collaboration

Parma Workshop on Numerical Relativity and GW, 2011
What is the NINJA project?

NINJA: Numerical INJection Analysis

Collaboration between numerical relativists and gravitational-wave astronomers

Project to test search pipelines and parameter estimation against the best available waveforms for binary black hole mergers.

The concept: Create data set(s) consisting of simulated signals injected into LIGO and Virgo interferometer's noise, run codes, compare results to injections and to each other.

Black Holes binary merger rates

**Table 4.** Compact binary coalescence rates per Mpc$^3$ per Myr$^a$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{low}}$</th>
<th>$R_{\text{re}}$</th>
<th>$R_{\text{high}}$</th>
<th>$R_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS–NS (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>0.01 [1]</td>
<td>1 [1]</td>
<td>10 [1]</td>
<td>50 [16]</td>
</tr>
<tr>
<td>NS–BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$6 \times 10^{-4}$ [18]</td>
<td>0.03 [18]</td>
<td>1 [18]</td>
<td></td>
</tr>
<tr>
<td>BH–BH (Mpc$^{-3}$ Myr$^{-1}$)</td>
<td>$1 \times 10^{-4}$ [14]</td>
<td>0.005 [14]</td>
<td>0.3 [14]</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ See footnotes in table 2 for details on the sources of the values in this table.

**Table 5.** Detection rates for compact binary coalescence sources.

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source$^a$</th>
<th>$\dot{N}_{\text{low}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{re}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{high}}$ yr$^{-1}$</th>
<th>$\dot{N}_{\text{max}}$ yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>NS–NS</td>
<td>$2 \times 10^{-4}$</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>NS–BH</td>
<td>$7 \times 10^{-5}$</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>$2 \times 10^{-4}$</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>&lt;0.001$^b$</td>
<td></td>
<td>0.01$^c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMBH–IMBH</td>
<td>$10^{-4}$</td>
<td></td>
<td>10$^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>NS–NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>NS–BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td></td>
<td></td>
<td></td>
<td>10$^b$</td>
</tr>
<tr>
<td></td>
<td>IMBH–IMBH</td>
<td></td>
<td></td>
<td></td>
<td>300$^c$</td>
</tr>
</tbody>
</table>

$^a$ See footnotes in table 2 for details on the sources of the values in this table.
NINJA-1

• Developed a format for exchanging waveforms between groups - arXiv:0709.0093

• 10 numerical relativity groups contributed binary black hole merger waveforms of their choice

• Waveforms were added to simulated colored Gaussian noise

• 9 data analysis groups analyzed the data using a variety of algorithms.
NINJA-1 Author List

Any numerical relativity group willing to contribute waveforms was welcome.

Minimal constraints were placed on the waveforms
Variety of spin, mass ratio, accuracy....
NINJA-1 Injections

• 126 injections into ~ 30 hours of data

• The starting frequency of the dominant (2,2) mode below 30 Hz

• The optimal matched filter SNR greater than 5 in at least one detector

• Longer waveforms are biased to low masses to cover mass range

\[ \left| \frac{\vec{S}_1}{m_1^2} + \frac{\vec{S}_2}{m_2^2} \right| \]
Data Analysis: Detecting Black Holes

*Un-modeled burst searches:*

- Typically coherent excess power techniques
- Don't require prior knowledge of the waveform

*Matched filter searches:*

- Require prior knowledge of the waveform (templates $h$)

\[
\langle s|h \rangle = 4R \int_{0}^{\infty} \frac{\hat{h}^*(f) \hat{s}(f)}{S_n(f)} df
\]

\[
\rho^2 = \frac{\langle s|h \rangle}{\langle h|h \rangle}
\]
# NINJA-1 Data Analysis

<table>
<thead>
<tr>
<th>Group</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEI</td>
<td>Phenomenological waveforms in LIGO/Virgo Compact Binary Coalescence (CBC) search</td>
</tr>
<tr>
<td>Birmingham</td>
<td>Bayesian Model Selection</td>
</tr>
<tr>
<td>Cardiff</td>
<td>Post-Newtonian Templates in CBC search</td>
</tr>
<tr>
<td>Cardiff, Maryland</td>
<td>EOBNR Templates in CBC search</td>
</tr>
<tr>
<td>Goddard</td>
<td>Hilbert Huang Transform</td>
</tr>
<tr>
<td>Northwestern</td>
<td>Markov Chain Monte Carlo</td>
</tr>
<tr>
<td>Syracuse</td>
<td>Extended $\eta$ PN Templates in CBC search</td>
</tr>
<tr>
<td>Umass, Urbino</td>
<td>Q-pipeline</td>
</tr>
<tr>
<td>UWM</td>
<td>PN templates in CBC search, Neyman-Pearson criteria</td>
</tr>
<tr>
<td>UWM, Umass, Urbino</td>
<td>Ringdown search</td>
</tr>
<tr>
<td>UWM, Umass, Urbino</td>
<td>Inspiral, Merger, Ringdown combined search</td>
</tr>
</tbody>
</table>
NINJA-1: Results Bottom Line

- All algorithms (matched filter to inspiral with different approximants, EOBNR, ringdown, or template-less burst algorithms) found the (loud) injections.
- The real open issue is parameter estimation.

example: burst, single IFO missed vs found
The case for NINJA-2

NINJA-1 open submission policy means these results are only qualitative: we cannot make quantitative statements about how pipelines respond to different regions of parameter space. Eg, how well does the CBC search do on spinning non precessing signals?

NR-only waveforms limited ability to test low-mass pipelines, eg, the CBC low mass $M < 25 \, M_\odot$ search?

Real detector noise is not Gaussian, there are loud glitches that can produce numerous triggers that can reduce the significance of real signals or mask them entirely. It is important to know how well a pipeline works in the presence of such glitches.

Closing the loop between search and parameter estimation: how well do parameter estimation techniques work with candidates from these searches?

Low mass vs high mass CBC / high mass matched filter vs burst
NINJA-2

* Use real noise through LSC/Virgo MOU  (simulated noise for test runs).

* More waveforms, more injections (~127 in NINJA-1).

* PN-NR stitching to cover mass down to $\approx 10 M_\odot$

* Accuracy requirements:

  $\geq 5$ usable orbits before merger

  GW stitching @ $M\omega_{2,2} \leq 0.075$

  Hybrid WF usable for LIGO/Virgo down to $10 M_\odot$ at 20Hz,

  NR(2,2) amplitude accuracy below 5%

  NR(2,2) accumulated phase error below 0.5 radian

  Highest PN order available for phase and amplitude for hybridisation

* All spherical Harmonic modes welcome (only $l = |m| = 2$ required).
NINJA-2: Waveform Parameters

Contributing Groups: BAM, FAU, GATech, Llama, LEAN, SpEC, RIT, UIUC

Mass Ratio ($q = m_1/m_2$)

Spin
- NINJA-2: 43 of ~60 waveforms have spin, values up to 0.95
- No precession. Stay tuned for NINJA-3!

Modes
- NINJA-2: 22 submissions have higher-order modes
Examining NINJA-2 Submissions

Unlike NINJA-1, there has been extensive checking and cross-testing of the NR submissions prior to creating the data sets.

PN coefficients and codes have been tested against each other by many people.

We have also looked at waveforms in the time and frequency domains, as well as overlaps between waveforms with identical parameters.
Examining NINJA-2 Submissions

Equal-mass, nonspinning waveform. The waveform looks continuous in both time and frequency domains, no features due to the hybridization are visible.
Comparing NINJA-2 Submissions

Comparison between hybrid equal-mass, non spinning submissions.
NINJA-2 Data Sets

Two 1-week test sets in simulated Gaussian noise to shake out bugs in the injection software and procedures and do preliminary pipeline tests. These were split into mass ranges; low (10-40 M$_\odot$), high (25-100 M$_\odot$), burst/ringdown (80-350 M$_\odot$).

- One 2-month production set in simulated Gaussian noise (first attempt found remaining bugs!)

- Masses uniform from 10-350 M$_\odot$.

- Different injection densities over different weeks.

- Uniformly distributed in network SNR between 6-130 for most weeks, in 1/(network SNR) for densest period.
NINJA-2 Data Sets
## NINJA-2 Data Analysis: Detection

<table>
<thead>
<tr>
<th>Group</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiff/Syracuse</td>
<td>Low mass standard pipeline</td>
</tr>
<tr>
<td>GSTLAL</td>
<td>Matched filter, inspiral, merger, and ringdown spin aligned templates</td>
</tr>
<tr>
<td>Urbino</td>
<td>Matched filter with PhenSpin (inspiral, merger, ringdown) templates</td>
</tr>
<tr>
<td>UMass</td>
<td>Burst search with Omega pipeline</td>
</tr>
<tr>
<td>Washington State</td>
<td>CBC High mass with Coherent Stage</td>
</tr>
<tr>
<td>AEI Hannover/ UF waveburst</td>
<td>Burst search with coherent WaveBurst</td>
</tr>
<tr>
<td>UMD</td>
<td>CBC high mass EOBNRv2 templates</td>
</tr>
<tr>
<td>AEI/RIT</td>
<td>Matched filter searches using spinning phenomenological templates</td>
</tr>
<tr>
<td>Group</td>
<td>Analysis</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Northwestern/MIT</td>
<td>Parameter estimation with LALInference</td>
</tr>
<tr>
<td>inspnest</td>
<td>Parameter estimation and model selection with nested sampling</td>
</tr>
<tr>
<td>Cambridge</td>
<td>Parameter estimation with MultiNest (nested sampling)</td>
</tr>
</tbody>
</table>
Preliminary results

Several analyses have been run on the test weeks:

- CBC low mass
- CBC high mass
- Omega, Omega chirplet (also run on the full 2 month set!)
- Coherent WaveBurst (also run on the full 2 month set!)
- Ringdown
- gstlal/IMRSA
- Bayesian parameter estimation and model selection with lalapps_inspnest
- PhenSpin
Preliminary results: CBC low mass

Found/missed and SNR recovery before coincidence
Preliminary results: PhenSpin

Analysis run by Riccardo Sturani, University of Urbino

Found/missed and SNR recovery, ~720 templates

Found/missed and SNR recovery ~7000 spinning templates
Preliminary results: gstlal

Found/missed, SNR and spin recovery before coincidence
Preliminary results: Omega

Analysis run by Satya Mohapatra, Umass Amherst

Found/missed before coincidence
2-month data set
Preliminary results: Coherent WaveBurst

Analysis run by Giulio Mazzolo, AEI

Found/missed before background tuning
First 6 weeks of full run
Status and Next Steps

NINJA-1 was a big success!  
(Benjamin Aylott et al 2009 CQG 26 165008, arXiv:0901.4399)

NINJA-2 is well on the way:

• 2-month data set with previous generation of waveforms is being distributed to analysts, runs have begun.

• All final waveform submissions have been submitted and verified.

• Subsequent runs will be done by injecting waveforms “on the fly,” analysis code will add injections to noise as it runs. This code is ready to be distributed.

• MoU between the NINJA collaboration and the LIGO and Virgo collaborations has been signed! This will allow NINJA-2 to use real detector noise.
NINJA-2 Waveforms