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Matching post-Newtonian and numerical relativity waveforms: systematic errors and a new phenomenological model for non-precessing black hole binaries

L. Santamaria,¹ F. Ohme,^{2,3} P. Ajith,^{2,3} B. Brügmann,⁴ N. Dorband,¹ M. Hannam,⁵ S. Husa,⁶ P. Mösta,¹ D. Pollney,⁶ C. Reinow,⁷ E. L. Robinson,¹ J. Seiler,⁷ and B. Kishan¹
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(Date: June 4, 2010)

We present a new phenomenological gravitational waveform model for the inspiral and coalescence of non-precessing spinning black hole binaries. Our approach is based on a frequency domain matching of post-Newtonian inspiral waveforms with numerical relativity based binary black hole coalescence waveforms. We quantify the various possible sources of systematic errors that arise in matching post-Newtonian and numerical relativity waveforms, and we use a matching criteria based on minimizing these errors; we find that the dominant source of errors are those in the post-Newtonian waveform near the merger. An analytical formula for the dominant mode of the gravitational radiation of non-precessing black hole binaries is presented that captures the phenomenology of the hybrid waveform. Its implementation in the current search for gravitational waves should allow cross-checks of other inspiral-merger-ringdown waveform families and improve the reach of gravitational wave searches.

PACS numbers: 04.80.Nc, 04.30.Db, 04.25.Nc, 04.25.de

I. INTRODUCTION

As a generalization of the classic Kepler problem in Newtonian gravity, the binary black hole (BBH) system in general relativity is of great interest from a fundamental physics viewpoint. Typically, importantly, this system has received a great deal of attention for its relevance in astrophysics and, in particular, as one of the most promising sources of detectable gravitational radiation for the present and future generations of gravitational-wave detectors, such as LIGO [1], Virgo [2], GEO600 [3], LISA [4] or the Einstein Telescope [5]. The Kepler problem can be solved exactly in Newtonian gravity and it leads to the well-known elliptical orbits when the system is gravitationally bound. In contrast, in general relativity, closed orbits do not exist and the BBH system emits gravitational waves (GWs) which carry away energy, thereby causing the black holes to inspiral inwards, and to eventually coalesce. The emitted GWs are expected to carry important information about this process, and it is one of the goals of gravitational wave astronomy to detect these signals and decode them.

No analytic solutions of Einstein's equations of general relativity are known for the full inspiral and merger of two black holes. Post-Newtonian (PN) methods can be used to calculate an accurate approximation to the early inspiral phase, using an expansion in powers of v/c (where v is the orbital velocity and c is the speed of light). As for the coalescence phase, starting with [6], the late inspiral and merger has been calculated by large-scale numerical solutions of the full Einstein field equations. Since the initial breakthrough in 2005, there has been dramatic progress in numerical relativity (NR) simulations for GW astronomy, including many more orbits before merger, greater accuracy and a growing sampling of the black hole-binary parameter space. A summary of the published "long" waveforms is given in the review [7], and a complete catalog of waveforms is being compiled at [8]; more recent work is summarized in [9]. NR results are now accurate enough for GW astronomy applications over the next few years [10] and have started playing a role in GW searches [11, 12].

Given PN and NR results, it is promising to try and combine them to produce "complete" inspiral-merger-ringdown waveforms. PN techniques in their standard formulation become less accurate as the binary shrinks, and the approximation breaks down completely somewhere prior to the merger. NR waveforms, on the other hand, become more and more computationally expensive the larger the number of cycles that one wishes to simulate: the longest published data spans 16 orbits for the equal-mass non-spinning case [12]. We therefore would hope to combine PN and NR results in the region between the points where NR simulations start and where PN breaks down. To do this it is critical to verify that the PN and NR results are in good agreement in this region and that there is a consistent PN-NR matching procedure. Much work has been done in comparing PN and NR results over the last 5-15 orbits before merger for a variety of physical configurations, such as the equal-mass non-spinning case [10, 12], the equal-mass non-precessing spin case [20], and the unequal-mass non-precessing spin case [21], and the unequal-mass spinning case [22]. The

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Tinke M. Snijders¹, Theo Vosse^{1,2}, Gerard Kempen^{1,3}, Jos J.A. Van Berkum^{1,2}, Karl Magnus Petersson^{1,3}, and Peter Hagoort^{1,3}

¹E.C. Donders Centre for Cognitive Neuroimaging, 6500 HB Nijmegen, the Netherlands; ²Cognitive Psychology Unit, Leiden University, 2311 EZ Leiden, the Netherlands and ³Max Planck Institute for Psycholinguistics, 0525 XD Nijmegen, the Netherlands

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Keywords: integration, left inferior frontal gyrus, lexeme retrieval, parsing, temporal lobe

Introduction

We hear and see thousands of words each day, and effortlessly interpret them in their context. To achieve this, several intricate processes are engaged by the brain. Whatever model of language comprehension one adheres to, all make the general distinction between retrieval and integration processes. Retrieval entails selecting the lexical representation of a word from memory. Information we have learned about single words has been laid down in long-term memory, in what psychologists usually call the "mental lexicon" (e.g., Levelt 1992). This information includes a word's form, its syntactic properties (e.g., word class, gender), and the meaning of a lexical item. In order to understand single words we have to map the input signal onto word form representations in the mental lexicon (access) and select the corresponding lexical representation (Marslen-Wilson 1987). In this way the information associated with the word form is retrieved. However, what makes language useful and creative is that words occur in all sorts of different contexts, with the varying combinations of words allowing for an infinite number of higher-level representations (von Humboldt 1836). This process of combining the retrieved single word information into higher-level representations, has been called "integration" or "unification" (Marslen-Wilson 1987).

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Hagoort et al. 1999; Sag and Wasow 1999; Kempen and Harbers 2002). Both memory and unification processes occur in parallel at the semantic (conceptual) and at the syntactic (structural) level (Jackendoff 2002). The current functional magnetic resonance imaging (fMRI) study focuses on the syntactic level. We aim to disentangle the syntactic retrieval and unification processes and identify their respective neural correlates.

Computational Model

Recently, in linguistic theories the separation between lexical items and traditional rules of grammar is fading. Increasing support has been found for lexicalist parsing models (MacDonald et al. 1994; Joshi and Schabes 1997; Jackendoff 2002). In lexicalist models syntactic properties of words needed for integration are retrieved from the lexicon (from memory), and the only remaining "rule" is unification (Jackendoff 2002). A lexicalist model that is computationally explicit is the Unification Space Model of parsing by Vosse and Kempen (2000). This model accounts for a large series of empirical findings in the parsing literature and in the neuropsychological literature on aphasia. According to the Unification Space Model, every incoming word retrieves one or more lexical frames from the "mental lexicon". These lexical frames are elementary syntactic trees, specifying the possible structural environment of the particular input word. See Figure 1 for examples of lexical frames for a noun ("light") and a verb ("be"). This parsing account is "lexicalist" in the sense that all syntactic information associated with a lexical item is retrieved from the mental lexicon rather than being supplied by grammatical rules (Vosse and Kempen 2000; for a similar account, see Collover and Jackendoff 2005).

Lexical frames that are retrieved from memory will enter the Unification Space in a sequential fashion, as new words arrive as input. Then, in Unification Space binding operations between lexical frames are performed, resulting in an incremental structural interpretation of the sentence. During the unification process lexical frames are linked, and agreement features (number, gender, person, etc.) and word order constraints are applied. Unification links are dynamic, that is, the strength of the unification links varies over time until one stable phrasal configuration results. As language is intrinsically ambiguous, often several different unification possibilities exist. In the Unification Space model, selection among alternative unification links occurs via lateral inhibition (Vosse and Kempen 2000; see Thompson-Schill 2005 on selection).

Brain Regions

With the Unification Space Model as our theoretical framework, can we identify distinct neural systems subserving

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Research output

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Recent publications

To facilitate keeping track of our latest research, here we list recent publications for the last few months only (see our [Research output](#) page for more complete listings).

- July 2011
- June 2011
- May 2011
- April 2011
- March 2011
- February 2011
- January 2011
- December 2010
- November 2010
- October 2010
- September 2010
- August 2010

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Biennial research reports and annual reports

Below are the research reports of our institute, in pdf. Note that as of 2007, the institute has switched to a bi-annual format with selective publication lists only. Full publication lists are generated automatically from our publications database.

Reports

- Research Report 2009 - 2010 (2MB)
- Research Report 2007 - 2008 (2 MB)
- Annual Report 2006 (18 MB)
- Annual Report 2005 (22 MB)
- Annual Report 2004 (30,2 MB)
- Annual Report 2003 (2,7 MB)
- Annual Report 2002 (5,2 MB)
- Annual Report 2001 (14,5 MB)

Publications ordered by year

- 2011 publications
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- 2009 publications
- 2008 publications
- 2007 publications

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Research projects

Virtually all of our current research is organized in the Institute Projects listed below (with many of them involving multiple research groups):

Categories across language and cognition

This project is concerned with the nature of categories and concepts in language, in non-linguistic perception and cognition, and the relationship between them.

Coordination of cognitive systems

This project investigates the relationship between language comprehension and production and other cognitive processes, including attention, vision, and working memory.

Individual differences project

The project aims to describe how people are similar and how they differ in their ways of speaking and understanding spoken language and to explain how these differences arise.

Language and genetics project

Research on the complex interplay between genes and language at different levels and time scales.

Mechanisms and representations in comprehending speech

Research on theoretical issues in speech comprehension.

Interactional foundations of language

This project investigates language in its primordial context – face-to-face conversational interaction – the context in which language is learnt, and predominantly used.

Language in action

Cognitive neuroscience research on the architecture of the language system as it operates in rich social, physical, or discourse contexts.

Unification

Research on how different sources of information (retrieved from memory or provided by sensory input) are unified with language into an interpretation (comprehension) or message (production).

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Research departments and research groups

Our institute's primary organisational units are the research departments listed below:

Individual differences in language processing department

Why are some people better with words than others?
Director: Antje Meyer.

Language acquisition department

How do we learn a first, second or third language?
Director: Wolfgang Klein.

Language and cognition department

What is the relationship between language and general cognition?
Director: Stephen Levinson.

Language and genetics department

Which genes underlie human language, and how do they explain its evolution and variability? How does the genome help build a language-ready brain?
Director: Simon Fisher.

Language comprehension department

How do we understand spoken language?
Director: Anne Cutler.

Neurobiology of language department

How does the brain support language?
Director: Peter Hagoort.

Other research groups funded by the MPG:

Adaptive listening group

How do listeners understand language spoken with a foreign accent?
Headed by: Andrea Weber.

Communication before language group

How do infants communicate before they have language?
Headed by: Ulf Liszkowski.

Comparative cognitive anthropology group

How much does human cognition vary across cultures?
Headed by: Daniel Haun

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MPI Dissertation series

Since 1997, Ph.D.'s of the Max Planck Institute for Psycholinguistics have their theses appear in a series. This MPI Series in Psycholinguistics enables the Institute to make the quality and diversity of its research more visible to the outside world. Here is a list of theses that have appeared so far. Note that the following titles are unpublished dissertations. Anyone interested in a copy is advised to contact the author of the dissertation in question (or, if that fails, the library).

1. *The electrophysiology of speaking. Investigations on the time course of semantic, syntactic and phonological processing*
Miranda van Turenout
1997
2. *The role of the syllable in speech production. Evidence from lexical statistics, metalinguistics, masked priming and electromagnetic midsagittal articulography*
Niels O. Schiller
1997
3. *Lexical access in the production of ellipsis and pronouns*
Bernadette M. Schmitt
1997
4. *The open-/closed-class distinction in spoken-word recognition*
Alette Haveman
1997

- person webpages
- **our dissertation series webpage**

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in press

- 1 **Ahn, S.-J., Badenes-Pérez, F. R., Heckel, D. G.** (in press). A host-plant specialist, *Helicoverpa assulta*, is more tolerant to capsaicin from *Capsicum annuum* than other noctuid species. JOURNAL OF INSECT PHYSIOLOGY. doi:10.1016/j.jinsphys.2011.05.015. [HEC195] [PubMan](#)
- 2 **Beyaert, I., Köpke, D., Stiller, J., Hammerbacher, A., Yoneya, K., Schmidt, A., Gershenzon, J., Hilker, M.** (in press). Can insect egg deposition 'warn' a plant of future feeding damage by herbivorous larvae? PROCEEDINGS OF THE ROYAL SOCIETY OF LONDON SERIES B-BIOLOGICAL SCIENCES. doi:10.1098/rspb.2011.0468. [GER169] [PubMan](#)
- 3 **Bomble, F. W., Joußen, N., Schmitz, B. G. A., Wolgarten, H.** (in press). Seltene und kritische Gefäßpflanzen im Nationalpark Eifel (Rare and critical vascular plants in the Eifel National Park). DECHENIANA. [HEC196] [PubMan](#)
- 4 **Camehl, I., Sherameti, I., Seebald, E., Johnson, J., Oelmüller, R.** (in press). Role of defense compounds in the beneficial interaction between *Arabidopsis* and *Piriformospora indica*. In R. Oelmüller, G. Kost, S. Tripathi, A. Varma (Eds.), SEBACINALE: FORMS, FUNCTIONS AND BIOTECHNOLOGICAL APPLICATIONS. [IMPRS006] [PubMan](#)
- 5 **Freitag, M., Beszteri, S., Vogel, H., John, U.** (in press). Induced toxicity and pecketeptide synthase gene expression following physiological shock in the toxigenic *Pyrenopeziza parvum* (Pyrenopezizaceae). EUROPEAN JOURNAL OF PHYCOLOGY. [HEC192] [PubMan](#)

http://www.ice.mpg.de/ext/publ_ice.html



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Profile

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Email: ABE.Fujio@nims.go.jp

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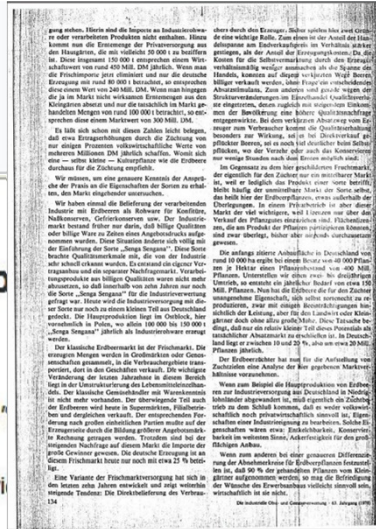
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Barrens
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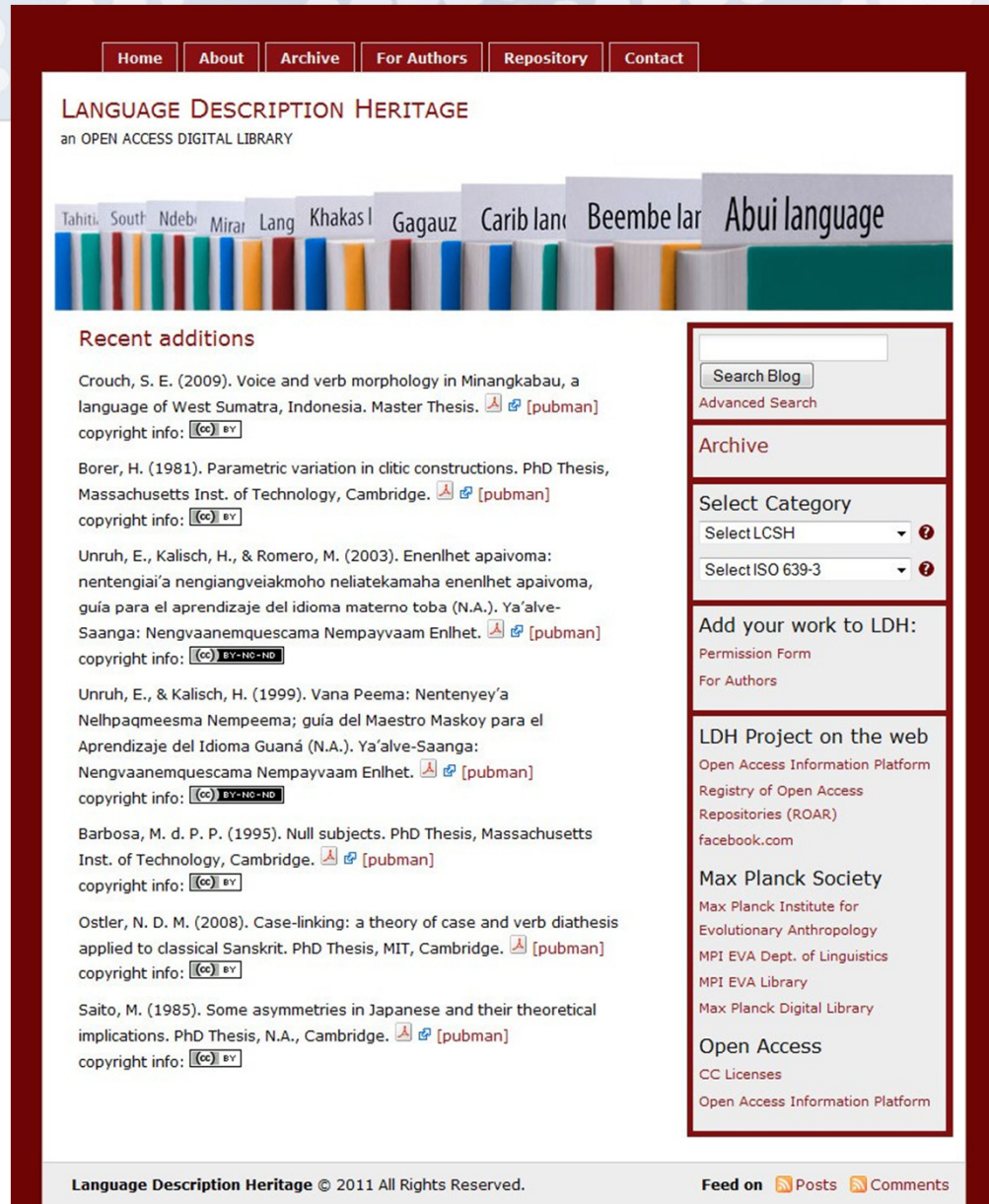
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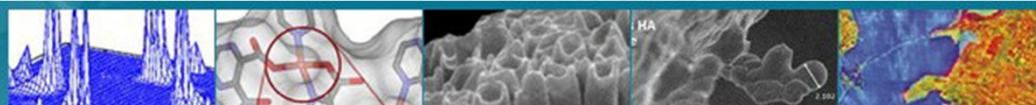
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Todoroki, Shin-ichi

Senior Researcher

Optronic Materials Center

National Institute for Materials Science



About

Working on optical fibers being exposed to high power laser beam.
Interested in digital publishing using free software, including writing light essays.

Completed my PhD in engineering at Kyoto University in 1993.

See also

My homepage @ geocities.jp

My essays @ scribd.com

My video works @ youtube.com

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- 2010.03.11 [第1回 有機・ナノ冶金融合都市鉱山型新レアメタル抽出技術](#)
- 2010.03.01 [ベッセマー+200研究会 1](#)

LECTURES

- 2011.03.02 [日本ICAA学会第9回研究発表会\(資源リスクとサステイナブル\)](#)
- 2011.01.28 [日本学術振興会第166委員会 透明機能性物・電子材料\(新型\)](#)
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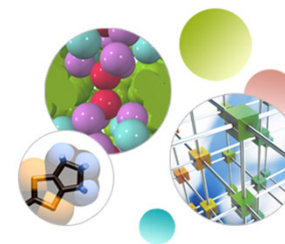
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Q 検索

研究情報の選及を目指して

本サイトは、導伝性にすぐれた単一分子性物質や有機超電導物質の探索と構造機能の解明に関する研究についてのデジタルアーカイブです。研究者自らが電子的に保存し、社会に公開すると共に、積極的に情報発信するライブラリーとして研究情報の選及を目指しています。



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Thank You!

Martin Boosen

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