PRINCIPAL REFERENCES RELEVANT TO LIGO GRAVITATIONAL-WAVE-SEARCH DATA ANALYSIS

Prepared by Kip S. Thorne, 17 October 1995

Note: The following reference list includes only a few of the most important papers directed specifically at gravitational-wave-search data analysis issues for interferometric gravitational-wave detectors. *Not* included are:

- references on data analysis more generally,
- references on extracting information from gravitational-wave signals that have been found,
- many of the references on gravitational-wave-search data analysis. (The papers listed here, however, do contain references to most of the others.)

This list was prepared for use by Caltech and MIT researchers interested in LIGO data analysis.

A. General References

A1. Kip S. Thorne, "Gravitational Waves", to be published in *Proceedings of Snowmass 94 Summer Study on Particle and Nuclear Astrophysics and Cosmology*, eds E. W. Kolb and R. Peccei (World Scientific, Singapore); Caltech preprint GRP-411.

This is an up to date overview of the field of gravitational waves, with heavy emphasis on LIGO/VIRGO. Most relevant for data analysis are Section 3 on ground based laser interferometers including projected noise spectra, and Sections 5 and 6 on gravitational wave sources in the LIGO/VIRGO frequency band.

A2. Bernard F. Schutz, "Data Processing, Analysis, and Storage for Interferometric Antennas," Chapter 16 of *The Detection of Gravitational Waves*, ed. David G. Blair (Cambridge University Press, 1991).

This slightly out of date review is the foundational paper for LIGO data analysis. It introduces and discusses most of the major issues.

A3. Lee Samuel Finn, "Detection, Measurement, and Gravitational Radiation," *Phys. Rev. D*, **46**, 5236 (1992).

This paper expounds, in a form explicitly directed at interferometric gravitational wave detectors, the Baysian statistical foundations for data analysis.

B. Searches for Stochastic Background via Cross Correlation of Data from Two Interferometers

B1. Eanna E. Flanagan, "The Sensitivity of the Laser Interferometer Gravitational Wave Observatory (LIGO) to a Stochastic Background, and its Dependence on the Detector Orientations," *Phys. Rev. D*, 48, 2389 (1993).

This paper describes the optimal data analysis algorithm for searching for a stochastic background by cross correlating the output from two different interferometers. The interferometers can be at widely separated sites and can have different orientations. References are given to previous foundational papers by Nelson Christensen and Peter Michelson.

Warning: the sliding delay function depicted in the time domain in Fig. 2 of this paper is wrong, though Flanagan correctly describes it mathematically in the frequency domain. The correct time-domain form of this function is given in an erratum by Bruce Allen:

B2. Bruce Allen, "Corrections to Flanagan's Paper on 'Sensitivity of LIGO to a Stochastic Background' ", unpublished note (18 October 1995).

C. Searches for Pulsars via FFT's with Doppler Corrections

C1. Section 16.2.3 (pages 423ff) of Ref. 2 above, by Bernard F. Schutz.

This Section describes the foundations for pulsar searches, including a conceptual formulation of a "stepping-around-the-sky" method for dealing efficiently with the Doppler corrections. Stepping around the sky has recently been implemented by one of Schutz's students, but a manuscript on the implementation is not yet available. I (Kip) recommend that we develop an implementation independently in the coming weeks.

C2. Kip S. Thorne, "Pulsar Searches by Schutz's Stepping Method," handwritten calculations, LHR→LAX, 19 August 1994.

In Reference C1 above (written in 1991), Schutz described as "impossibly great" the computational requirements for an all-sky, all-frequency search that coherently combines long stretches of data (e.g., 10^7sec). Last summer, Schutz realized that by combining stepping around the sky with a hierarchical approach to the search, the computational demands can be brought down to roughly one teraflop. Schutz has not written up anything about such hierarchical searches, but in reference C2 (my handwritten calculations after talking with Schutz), I have checked Schutz's claimed reduction in computational demands, and agree.

C3. Theocharis Apostolatos, "Number of Patches of the Sky to Look for Pulsars," handwritten notes, 8 September 1994

In Schutz's original manuscript (Ref. C1), he seriously overestimated the number of patches on the sky that must be given different Dopppler corrections. In Ref. C2, I caught his error and did a crude reestimate. These handwritten notes by Apostolatos do a careful reestimate. They bring down the number of independent patches by a factor ~ 1000 from Schutz's original estimate. This contributes in a major way to reducing the computational requirements to ~ 1 teraflop.

C4. Bernard F. Schutz, "An Approximate Fast Fourier Transform," handwritten notes, probably early 1994.

In these notes Schutz describes a fast method of doing approximate Fourier transforms of very long data sets (such as those for pulsar gravity wave searches), using parallel processors.

C5. T. M. Niebauer, A. Rüdiger, R. Schilling, L. Schnupp, W. Winkler, and K. Danzmann, "A Pulsar Search Using Data Compression with the Garching Gravitational Wave Detector," *Phys. Rev. D*, 47, 3106 (1993).

This is a detailed paper on the most recent and extensive search for pulsars that has been carried out using interferometric gravitational wave detectors.

C6. Jeff Livas, unpublished PhD thesis (MIT 1987).

This thesis describes (among other things) two searches for pulsars carried out with the MIT prototype: (i) An all-sky search with a FFT involving 2×10^7 points, in which a Cray 2 computer was used to search for peaks in the spectrum that exhibited FM and AM modulations due to the motion of the Earth; and (ii) A search in the galactic center region in which Doppler corrections were applied in the time domain before doing the FFT. [Other pulsar searches, using 40m data, are described in the unpublished PhD theses of Mark Hereld (Caltech, 1983), and Mike Zucker (Caltech, 1989).]

D. Searches for Inspiraling, Compact Binaries via the Method of Matched Filters

D1. Theoretical Waveforms as a Foundation for Search Templates

Note: The references in this section describe theoretical waveforms that will constitute a foundation for the binary search templates, as I envision them. People unfamiliar with these references might wish to skip over them in a first study of the LIGO data analysis literature, and simply assume that the relativists will provide the necessary waveforms, based on these references and others.

D1a. Luc Blanchet, Thibault Damour, Bala R. Iyer, Clifford M. Will, and Alan G. Wiseman, "Gravitational Radiation Damping of Compact Binary Systems to Second Post-Newtonian Order," *Phys. Rev. Lett.*, **74**, 3515 (1995).

This is the most recent publication in a long series directed at computing, to high post-Newtonian order, the waveforms from binary inspiral. It indicates the status of the effort as of last winter (much progress has been made since then), and gives a feeling for the magnitudes of post-Newtonian effects. Alan Wiseman is in the process of preparing, for archiving on the WWW, analytic formulae for the inspiral waveforms accurate through post^2-Newtonian order (4 orders in v/c beyond the leading order radiation reaction). Those waveforms will be a key foundation for our search templates.

D1b. Theocharis A. Apostolatos, Curt Cutler, Gerald Jay Sussman, and Kip S. Thorne, "Spin-Induced Orbital Precession and its Modulation of the Gravitational Waveforms from Merging Binaries," *Physical Review D*, **49**, 6274 (1994).

The Blanchet-Damour-Iyer-Will-Wiseman work (Ref. D1a) ignores the spins of the binary's bodies, or assumes that they are aligned with the orbital angular momentum vector. As Ref. D2c below shows, in searches for most binaries this is probably a good approximation, but for some it is not: Certain important nooks and crannies of binary parameter space can be searched well only with templates that take account of the orbital precession induced by large spins that are not aligned with the orbital angular momentum. This reference, and a similar one by Larry Kidder ["Coalescing Binary Systems of Compact Objects to Post$^{5/2}$-Newtonian Order. V. Spin Effects," *Phys. Rev. D*, **52**, 821 (1995)], derive and discuss the details of that orbital precession and its influence on the inspiral waveforms.

D1c. Hideyuki Tagoshi and Misao Sasaki, "Post-Newtonian Expansion of Gravitational Waves from a Particle in Circular Orbit around a Schwarzschild Black Hole," *Prog. Theor. Phys.*, **92**, 745 (1994).

This paper, together with others by Tagoshi and colleagues, derives analytic formulae for the inspiral waveforms in the limit of extreme mass ratio, to far higher post-Newtonian order than has be done for arbitrary mass ratios by Blanchet et. al. We may want to include these higher-order terms in our search templates, thereby improving them slightly.

D2. Construction of Discrete Families of Search Templates from Theoretical Waveforms and Estimates of Computational Requirements

D2a. Benjamin J. Owen, "Search Templates for Gravitational Waves from Inspiraling Binaries: Choice of Template Spacing," manuscript in preparation for submission to *Phys. Rev. D.*

In this paper Ben sketches the two different search strategies that one might pursue: a one-pass search, and a hierarchical search; and he then develops the foundations for selecting, from a continuous family of theoretical waveforms, a discrete family that can function as the templates for a one-pass search or for the final stage of a hierarchical search. He also estimates the computing power required in a one-pass search, both for initial LIGO interferometers and advanced interferometers.

D2b. Sanjeev V. Dhurandhar and B. S. Sathyaprakash, "Choice of Filters for the Detection of Gravitational Waves from Coalescing Binaries. II. Detection in Colored Noise," *Phys. Rev. D*, **49**, 1707 (1994).

This paper (which is a foundation for Ben's Ref. D2a) provides foundations for selecting the coarsely-spaced discrete families of templates that might be used in early stages of a hierarchical search. The paper does not refer at all to the concept of a hierarchical search; it is only in retrospect that we recognize this as its principal value.

D2c. Theocharis A. Apostolatos, "Search Templates for Gravitational Waves from Precessing, Inspiraling Binaries," *Phys. Rev. D*, **52**, 605 (1995).

This paper and others referenced therein provide a foundation for choosing the continuous families of (approximate) theoretical waveforms that will be used in constructing the discrete search templates [as discussed in Refs. D2a and D2b]. These papers compute the (noise weighted) correlation between approximate waveforms of various sorts, and more highly accurate inspiral signals. These computations (which are all summarized in Ref. D2c) tell us that in a one-pass search and in the final stage of a hierarchical search, it will be necessary to use the high-order post-Newtonian waveforms of refs. D1a and D1c; and for certain nooks and crannies of parameter space, we must include modulation due to spin-induced precession (Ref. D1b).

D3. Some Technical Aspects of the Binary Searches

Note: I have not studied the following papers in any detail, so I don't know how useful they will be. However, they are the only papers I know thus far (except for Schutz's general review, Ref. A2 above) that deal with technical aspects of carrying out binary searches in LIGO/VIRGO.

D3a. B. S. Sathyaprakash and Sanjeev V. Dhurandhar, "A Parallel Algorithm for Filtering Gravitational Waves from Coalescing Binaries," *J. Comp. Phys.*, **109**, 215 (1993).

D3b. Sanjeev V. Dhurandhar and Bernard F. Schutz, "Filtering Coalescing Binary Signals: Issues Concerning Narrow Banding, Thresholds, and Optimal Sampling," *Phys. Rev. D*, **50**, 2390 (1994).

D3c. Lee Samuel Finn, paper in preparation.

This long awaited paper (which is presumably nearing completion) is expected to discuss searches that make simultaneous use of the data from all the available interferometers — instead of searching separately in each interferometer's data train and then comparing candidate signals.

D4. Past Searches for Inspiraling Binaries

D4a. Sheryl Smith, "Algorithm to Search for Gravitational Radiation from Coalescing Binaries," *Phys. Rev. D*, **36**, 2901 (1987).

This search used the Caltech 40 meter interferometer and templates based on Newtoninan-order waveforms; and it implemented the trick of tranforming the data's time series into a form where, instead of cross correlating with theoretical templates, one could do a simple FFT of the data. Such a trick will probably not be helpful in LIGO, where the search templates will involve at least two nontrivial parameters (the masses of the binary's two bodies).

D4b. Aaron D. Gillespie, "Thermal Noise in the Initial LIGO Interferometers," unpublished PhD thesis (Caltech, 1995), Chapter 7.

This chapter describes Gillespie's search for inspiraling binaries in 40m data taken last autumn. He found a set of "signals" that exceed the interferometer's Gaussian noise, and that presumably are due to non-Gaussian features of the noise. It is important for us to explore their nature.

E. Searches for Nonaxisymmetric Supernovae and other Sweeping Sinusoids Using Wavelet and Other Time-Frequency Techniques

Note: I do not know of any references dealing with this type of gravity-wave search. The following reference describes much of our present knowledge of the signals:

E1. Dong Lai and Stuart L. Shapiro, "Gravitational Radiation from Rapidly Rotating Nascent Neutron Stars," *Astrophys. J.*, **442**, 259 (1995).

See also Sec. 6.1 of Ref. A1.