Proposal to the LSC
for a
Prototype Implementation
of a
Binary Inspiral Search
Based on the Fast Chirp Transform

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1 Scientific and Technical Motivation

Binary inspiral searches are one of the major categories of LIGO data analysis. Conventional approaches to binary inspiral searches involve "templates" which are used in a matched filter analysis to provide optimal sensitivity for the detection of GW from binary inspiral. We propose to develop an alternative approach based on the recently formulated Fast Chirp Transform (FCT) technique of Jenet and Prince (see Appendix).

The FCT approach does not require the explicit generation of individual gravitational wave templates, but rather is a parametrized search technique which can be used to completely search the space of physical waveforms. In many ways it is more flexible than the template search approach and may also be computationally more efficient. The FCT is also advantageous in that it will use a single highly-tested routine for all searches. That is, analogous to the Fast Fourier Transform (FFT), a "Numerical-Recipes Style" generic FCT routine is being developed which will be applicable to a broad range of problems, not only in GW astrophysics, but in other areas of signal-processing as well. This proposal describes an effort to apply the FCT to binary inspiral detection and to thoroughly test the approach by comparing it to conventional template-based approaches.

We expect that there will be a range of applications for which template-based approaches are optimal and a range of applications where FCT-based approaches are optimal. Cross-comparison of the two techniques will prove invaluable for test and validation.

2 Character of the Proposed Work

The proposed work will include:

A "proof of principle" component. The proposed work has the goal of demonstrating that FCT techniques can be used to undertake matched filter searches for binary inspiral with performance comparable to or better than conventional methods, with the additional advantage of considerably more flexibility and robustness.

A prototype development activity. The work will develop prototype techniques for FCT analysis, testing them first on existing 40m data and simulated data, for comparison to conventional techniques. Prototyping will take place using simple-exact FCT implementations before moving to fast-approximate methods. Because generic, well-tested FCT implementations are expected to be developed quickly, the prototype phase is expected to be short.

A LAL software development activity. A LAL suite of code will be developed to support binary inspiral searches using FCTs. In addition, generic C and C++ FCT implementations will be developed.

Support of LDAS/LSC mock data challenges. Given successful results from the "proof of principle" and prototyping efforts, it is expected that FCT binary inspiral search implementations will be available for the Science Analysis MDC.

3 Technical Approach

The focus of the work will be development of code to support the application of FCTs for binary inspiral searches. Work already in progress will result in the implementation of generic FCT routines ("Numerical-recipes-like") that will be used as the computational core of the binary inspiral search package. This includes development of efficient, parallel FCT implementations written in C and C++. The work proposed here includes aspects specific to binary inspiral, such as: use of the FCT for different waveform expansions (e.g. PN and P-Approximant) and optimum decomposition of the FCT binary inspiral search for LIGO Beowulf configurations.

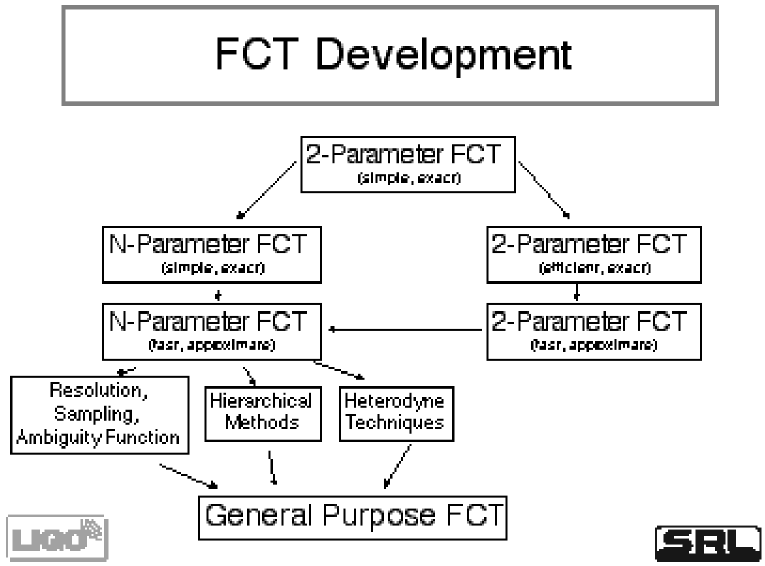

Figure 1: Flow Plan for FCT Development

Figure 2: FCT of Quadratic Chirp. The signal has phase evolution of the form: $\phi(t) = 2\pi(f_0 t + (1/2)\dot{f}t^2$. The horizontal axis is the starting frequency, f_0, and the vertical access is $\dot{f}$. The true $\{f_0, \dot{f}\}$ of the signal is at the location of the center of the "bowtie" PSF in the figure.

3.1 Generic FCT Implementation

Figure 1 shows how the development of the FCT implementations is planned to proceed.

Two-Parameter FCT Development. Simple-exact implementations for 2-parameter FCTs have already been written in IDL and C++. Figure 2 shows the results of a 2-parameter FCT.

Fast-approximate 2-parameter implementations have been written and are being tested. Two-parameter FCT implementations test many of the basic features of FCT, and can be used for testing concepts such as oversampling, and evaluation of ambiguity functions. Simple-exact and fast-approximate methods can be easily compared with respect to sensitivity and fidelity of the matched filter operation. The two-parameter FCT development is assumed, and is not being proposed as part of this effort.

Two-parameter FCTs can be tested in the context of gravitational waves by looking for Newtonian-chirp signals in existing 40m data. Such tests are planned as part of this proposal effort.

N-Parameter FCT Development. To carry out binary inspiral searches using P-Approximant or PN-expansions, multi-parameter FCTs will need to be calculated, with at least 3 parameters (and heterodyning for order higher than 1PN) required for spinless binaries, and more parameters for searches for binaries with spin. The N-parameter FCT development is reasonably straightforward and prototype coding has begun. A simple, exact N-parameter FCT has been developed and will be used as a reference. A fast, exact N-parameter FCT will follow. Later, a prototype fast-approximate N-parameter FCT will be implemented using experience gained from the 2-parameter fast-approximate FCT. In addition, there are sampling issues that affect the computational efficiency of the FCT. These are analogous to the issues of template spacing for template searches. Also, FCTs lend themselves to hierarchical methods, and these will be developed to achieve optimal computational efficiency.

The development of the simple N-parameter FCT is assumed and is not part of the proposed effort. However, enhancements to the N-parameter FCT needed for GW detection, such as hierarchical methods and ambiguity function evaluation, will be part of the proposed effort.

Generic FCT Routine. The generic FCT routine will take as inputs pointers to a set of non-linear functions that define the expansion of the phase of the waveform, a specification of the range for the conjugate parameters corresponding to the non-linear functions, and the sample spacing. The output will be an approximation to the Discrete Chirp Transform (DCT) appropriately sampled.

3.2 Application to Binary Inspiral

Optimal Expansions for Searches. The development of FCTs was motivated by the desire to efficiently evaluate matched filter expressions involving waveforms derived using PN-expansions. We will develop prototype implementations first for 1PN and then more generally for higher order (2PN and higher).

FCTs are not limited to PN-derived waveforms. In particular, P-Approximants have been shown to have many advantages. In discussions with Tibault Damour in January, 2000, an approach to using the FCT with waveforms derived from P-Approximants was suggested. Further work is needed to show that waveforms can indeed be derived using P-Approximants that lend themselves to matched-filter evaluation with FCTs. Also, as shown by Damour, Iyer and Sathyaprakash, cutoffs in the waveform must be treated carefully. The implications of this for FCT approaches requires further study.

More generally, there is the question of use of other expansions for investigation of chirps with FCTs. Other expansions may be useful for characterizing and removing chirp-like instrumental signals from the data.

Optimal Parallel Algorithm Decomposition for LIGO Beowulf Systems. While the FCT is clearly highly parallelizable, the optimum parallel decomposition for LIGO Beowulf architectures has not yet been thoroughly investigated. The problem could be decomposed in time, or in parameter search range. Such optimization considerations must wait for the development of the fast-approximate FCT implementations and the consequent scaling of the computational efficiency of such fast-approximate implementations.

3.3 Testing

Testing of the FCT for binary inspiral will take place in stages: (1) Use of computed binary inspiral waveforms w/o noise, (2) Use of computed waveforms with simulated noise, (3) Use of computed waveforms with 40m noise, and (4) Use of computed waveforms with LIGO IFO data from the commissioning period. The principal results of the testing will be recovered power versus false event rate.

4 Deliverables

The proposed effort will produce a hierarchical binary inspiral search code for LIGO analysis suitable for LDAS MPI execution, together with LAL compliant components. The search code will use as its "engine" a generic N-parameter FCT code implementation.

Several papers are expected to result from this work: an initial paper comparing the FCT methods to template methods using 40m data; a paper describing an enhanced FCT-based algorithm for binary inspiral detection including hierarchical and parallel computing approaches; and a paper describing the application of the enhanced FCT algorithm to LIGO data. All co-proposers are expected to be co-authors on these three papers.

5 Required Resources

Software. The FCT is based on efficient use of a standard FFT implementation. We assume the availability of FFTW for both LDAS and LAL. We also assume the availability of simple generic 2- and N-parameter FCT implementations.
Hardware. Availability of a Beowulf cluster is required for testing of the parallel FCT code. Otherwise, no special hardware is required.
Data. Data from the 1994 40m run will be used for initial testing. Engineering IFO data from the LIGO sites will be used for later testing.
Personnel. The FCT implementation and test will be carried out initially by 1.5 FTE postdoc and 1 undergraduate student (Philip Charlton, Jeff Edlund, and Rick Jenet, LIGO Lab/Caltech LSC). Starting in late Fall 2000, a new postdoc (Linquing Wen, LIGO Lab) will join the effort, replacing Rick Jenet. Design of the binary inspiral search using FCTs and the specification of the testing program will be undertaken by a collaboration of LSC members consisting of the co-proposers and others wishing to join the effort. We expect that this will require 1 to 1.5 equivalent FTEs from the LSC spread over several individuals.

The effort is open to all interested LSC members. Several working groups will be formed and each LSC participant will be expected to join one or more working groups. The working groups are:

1. Ambiguity functions and hierarchical methods for the FCT
2. Alternate/non-PN expansions
3. Application of FCT to CW searches
4. Code implementation for binary inspiral searches based on the FCT
5. Testing/performance

6 Work Plan

- N-Parameter Algorithm for 2PN chirps: Charlton, Edlund, Lazzarini (9/1/00)
- Use of FCT for non-PN expansions: Sathyaprakash (9/15/00)
- Resolution, Sampling, Ambiguity Function Issues: T. Creighton, Hughes, Jenet, Sathyaprakash, Prince (10/1/00)
- Hierarchical Methods: Blackburn, Dhurandhar, Finn, Jenet, Lazarini (10/15/00)
- Application to CW searches: Anderson, Brady, Dhurandhar (schedule TBD)
- Testing/Performance of FCT GW Code: Anderson, Charlton, Finn, Lazzarini, Wen (ongoing)
- General FCT GW Code (Single Processor): Anderson, J. Creighton, Edlund, Wen (1/15)
- GW FCT parallelization and MPI version: J. Creighton, Blackburn, Charlton, Edlund, Wen (3/01)

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