

# Supplement to Attachment A, Report to NSF

**LIGO-M010187-00-M**

**Organization** Carleton College Relativity Group (CCRG)

**Report Date** 2001

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## Activities:

We have been extremely busy with LIGO related research. A description of our activities is presented below.

- 1) Demonstration of the Markov chain Monte Carlo (MCMC) technique for binary inspiral parameter estimation.

Nelson Christensen worked with Dr. Renate Meyer (Dept. of Statistics, University of Auckland) on the development and testing of a Gibb's sampler program. This program was designed to take LIGO-like data and search for a gravity wave signal from the inspiral of a pair of compact objects (neutron stars, black holes). The signal templates used were 2.5 post-Newtonian order, and involved five parameters. We demonstrated that the MCMC technique did in-fact work. In addition to finding the parameter values for the signal we were able to also produce summary statistics, including probability distribution functions for the parameters. We studied some of the issues that pertain to the optimization of the efficiency of the program. The results of this research were written-up as a paper that is in the final stages of review with Physical Review D (Using Markov chain Monte Carlo methods for estimating parameters with gravitational radiation data, Nelson Christensen and Renate Meyer, see also gr-qc/0010052). A significant amount of time was invested in ensuring that we effectively sampled the parameter space. Our final program is a combination of a Gibb's sampler and another technique, simulated annealing.

- 2) Detector Characterization for LIGO E2 Engineering run.

Nelson Christensen was part of a LIGO detector characterization investigation led by Prof. Keith Riles (Dept. of Physics, University of Michigan). Nelson Christensen was the leader of a sub-group investigating correlations between LIGO interferometer signals and signals from environmental monitors. Tom Robinson, a Carleton College undergraduate, and Assoc. Prof. Adrian Ottewill (University College Dublin) also collaborated on this work.

The sub-group examined data from the LIGO (Hanford) E2 engineering run. We computed numerous correlations between interferometer control channels and environmental monitors in order to decipher sources of noise. In addition, we also used higher order statistics, such as the bicoherence, in order to look for non-linear up-conversion of noise in the interferometer output. Numerous correlations were observed, as well as a few places where LIGO noise was coherently couple at differing frequencies. A LIGO technical report was written (E2 Correlations, LIGO Technical Document LIGO-T010017-00-Z, N. Christensen, T. Robinson, A. Ottewill), and Nelson Christensen presented the results in a talk at the LIGO Scientific Collaboration (LSC) meeting in Baton Rouge in March 2001.

Our group (now expanded to also include Steve Penn, Syracuse University) will continue to analyze data and search for noise correlations in further LIGO engineering run data. We are presently examining data from the E3 run. Nelson Christensen will continue as the leader of this sub-group.

### 3) Inspiral Upper Limit Group

Nelson Christensen is an active member in two of the LSC's groups dedicated to using LIGO data to set upper limits on astrophysical sources. One of these is the Inspiral Upper Limit Group. Christensen is concentrating his efforts in two specific sub-group activities.

#### a) Detector Characterization Sub-Group

Nelson Christensen is the leader of the Detector Characterization Sub-Group, and is working with seven other LSC members on this effort. The sub-group is conducting extensive studies on numerous environmental monitor channels in order to quantify when environmental events influence the quality of the interferometer output data. We are charged with developing code in order to present veto flags for the data. This effort has been going since December 2000, with the intent to have the code completed for the LIGO scientific run in September 2001. Nelson Christensen presented a talk on this work at the LSC meeting in Baton Rouge, March 2001.

#### b) Multiple Interferometers and Statistics Sub-Groups

Nelson Christensen is also a member of the Multiple Interferometers and Statistics Sub-Groups. His primary responsibility will be to develop a Metropolis-Hastings MCMC code in order to estimate parameters and produce summary statistics for events recorded by the binary inspiral template search. This will be the natural extension of the MCMC effort already conducted. This work commenced in February of 2001, and the code is under development at present. Carleton College undergraduate Tom Robinson is also working on this effort, and it will be his primary research activity for the summer of 2001.

### 4) Stochastic Background Upper Limit Group

Nelson Christensen is a member of the LSC's Stochastic Background Upper Limit Group. Christensen is part of the detector characterization effort, with the goal being to identify possible sources of correlated noise between the two LIGO detector sites. This correlation effort makes use of correlation code already being used in the other correlation studies. Nelson Christensen is working with Peter Fritschel (M.I.T.) and Mike Landry (LIGO-Hanford) on this effort. We are concentrating our search on seismic, magnetic and voltage line noise.

There is much overlap in interest between the Keith Rile's detector characterization group and the Upper Limit detector characterization sub-groups. As such, Nelson Christensen is working in close consultation with a number of LSC members on detector characterization.

### 5) Cosmic Microwave Background Parameter Estimation

In a somewhat tangential effort, Nelson Christensen was approached by Lloyd Knox (U.C. Davis) about using MCMC techniques for cosmological parameter estimation from measurements on the cosmic microwave background anisotropy spectrum. We conducted a study and wrote a paper (submitted to *Classical and Quantum Gravity*, *Bayesian Methods for Cosmological Parameter Estimation from Cosmic Microwave Background Measurements*,

Nelson Christensen, Renate Meyer, Lloyd Knox, Ben Luey. See also *astro-ph/0103134*). In our effort to develop the of Metropolis-Hastings code we actually solved a number of problems that are directly related to what we will need to do for the Metropolis-Hastings code we are developing for parameter estimation in the LSC's Inspiral Upper Limit effort.

**Educational Activities:** This grant is an RUI, so research at an undergraduate institution implies that undergraduates will be involved. A very talented undergraduate is immersed in this project. Tom Robinson is a junior physics/math major at Carleton College. Tom is learning much about physics, statistics and data analysis as a consequence of this grant. Tom has been part of the team that has been analyzing the data from the E2 engineering run. In addition, Tom is working with Nelson Christensen on the development of parameter estimation code that will run on LIGO's data acquisition system. Tom will continue this research over the summer of 2001, with this grant supporting him.

Another student, Ben Luey, a junior physics major at Carleton College, has benefited indirectly from this grant. Christensen has developed an MCMC program for estimating cosmological parameters from cosmic microwave background data. This program is very similar to what we are currently writing for LIGO. Luey and Robinson have both learned much as a result of the data analysis research conducted at Carleton College.

#### Findings:

The research that was conducted NSF grant has resulted in numerous findings.

Renate Meyer and Nelson Christensen have collaborated on the development of Markov chain Monte Carlo (MCMC) code that can be used to estimate the parameters that created a binary inspiral gravity wave signal detected by LIGO. In our publication we describe how the 2.5 post-Newtonian templates are implemented. We concentrated on the basic five-parameter problem (two masses, signal amplitude, signal time and signal phase). We succeeded in deciphering a signal from noise, and generating summary statistics for the detection. We developed a method, similar to simulated annealing, for effectively sampling the phase space of parameters. The statistical ability to estimate compact binary system parameters were observed as a function of signal-to-noise ratio. We studied and discovered techniques for optimizing the speed of the code. We believe that this is a tremendous success.

We have produced a new method for sampling the parameter space. In addition, the generation of summary statistics is something that outside of the ability of other

parameter estimation techniques. We are presently working on the expansion of this technique to include further parameters. We have now included the spin of the compact objects. We hope to write up the results of this study soon. Suffice it to say, MCMC works, and continues to work as we increase parameter number. MCMC may offer the only hope for parameter estimation with inspiraling compact binaries when all spin and eccentricity parameters are included.

The detector characterization work has also contributed a number of findings to the knowledge pool of LIGO. Christensen, Robinson and Ottewill have searched for correlations between the LIGO interferometer control signals and environmental monitors. Our results were presented as a talk at the LSC meeting in Baton Rouge (March 2001) and through a LIGO technical document ("E2 Correlations." LIGO Technical Document LIGO-T010017-00-Z, N. Christensen, T. Robinson, A. Ottewill). We observed how noise is coupled into the LIGO interferometers through the mode cleaner and the laser. Numerous correlations with microphones and accelerometers were observed. 60 Hz noise and correlations were also seen. In addition, higher order statistics revealed that a noisy region in the interferometers power spectral density is coherently coupled to seismic noise at around 25 Hz. These correlation studies are continuing with the data from Hanford and Livingston.

The MCMC code developed for cosmological parameter estimation with data from cosmic microwave background observations provided a very important development of MCMC methods. In our publication (Bayesian Methods for Cosmological Parameter Estimation from Cosmic Microwave Background Measurements, submitted to Classical and Quantum Gravity, Nelson Christensen, Renate Meyer, Lloyd Knox, Ben Luey 2001, see also astro-ph/0103134) we describe how one can use a Metropolis-Hastings method to implement the MCMC search even though the likelihood function can not be displayed in closed form. A numerical generation of the likelihood is coupled to our routine. This will be exactly what we will need to do with complicated binary inspiral templates that include eccentricity, mass spin, and also account for final plunge and black hole formation. The findings from this study are currently being implemented in our gravity wave code.

### Research and Training

This project has furthered Nelson Christensen's ability in his study of statistical methods as applied to LIGO. Christensen has been exposed to LIGO analysis packages, namely the Data Monitor Tool (DMT) for detector characterization and the LIGO Analysis Library (LAL) for implementing templates into the Metropolis-Hastings code. The use of all of these techniques will prove to be extremely valuable as he continues to work with the LIGO detector and its data.

Tom Robinson, Carleton College undergraduate, has acquired the same training with these analysis tools. In addition, Robinson is learning much about experimental physics, gravitation and astrophysics along the way. This RUI is an extremely valuable

educational resource for students who will be our countries next generation of active scientists. LIGO is a great educational resource for Tom Robinson, and students to come.

## Outreach

Nelson Christensen runs a week long training session for high school AP physics teachers. All of these teachers hear about the excitement and potential of the LIGO project. Christensen is scheduled to speak to a high school physics class (Century High School, Rochester, Minnesota) in April of 2001.

## Contributions within Discipline:

How have your findings, techniques you developed or extended, or other products from your project contributed to the principal disciplinary field(s) of the project? Please enter or update as appropriate.

MCMC techniques have been revolutionary in computational statistics over the last 10 years. These methods are only now entering the physics world. The results of Christensen and Meyer are becoming noticed and appreciated in the LIGO community. Christensen is part of the LIGO Scientific Collaboration's Inspiral Upper Limit team. Christensen has been charged with the responsibility to develop the MCMC code necessary to produce the statistics associated with a candidate event. There is no competing method for producing the statistics, and the LIGO researchers have recognized the potential for MCMC.

Some in the LIGO community recognize that MCMC methods provide hope for when the number of parameters contributing to a binary inspiral signal is allowed to increase. At this point in time there are no other methods that one can reasonably expect to be extended from five to eleven parameters.

How have your findings, techniques you developed or extended, or other products from your project contributed to disciplines other than your own (or disciplines of colleagues and associates not covered under "Contributions within Discipline")? Please enter or update as appropriate.

Lloyd Knox (U.C. Davis) became aware of the MCMC parameter estimation work by Christensen and Meyer. Through conversations and discussions it became apparent that the MCMC methods we have applied to gravity wave parameter estimation would also be extremely valuable to cosmological parameter estimation for data from cosmic microwave background observations. We conducted a study, demonstrated the technique and wrote a paper. The number of cosmological parameters needed to explain the data is very large, so MCMC methods could prove very useful.

How have results from your project contributed to human resource development in science, engineering, and technology? Please enter or update as appropriate.

This project is quite visible within the Physics and Astronomy Department at Carleton College. With about 20 majors a year, a number of young students are being exposed to excitement of LIGO's science. Carleton has a large number of women physics majors, and we are constantly striving for gender equality in physics. This project further supports Carleton's success.

High school teachers are exposed to this science when they come to the AP Physics camp for a week each June. Christensen lectures on a number of topics for this workshop. Under the category of "Hot Experimental Projects" LIGO is at the top. These high school teachers are hearing about the fun and exciting science we are doing. Their students then hear about it.

How have results from your project contributed to physical, institutional, and information resources for research and education (beyond producing specific products reported elsewhere)? Please enter or update as appropriate.

This project provides computational resources to Carleton College's Physics and Astronomy Department. This, and the unique data analysis work that we do, further strengthens Carleton College. Students are also exposed to the unique computing capabilities of the LIGO labs. Through memoranda of understandings with LIGO are students can (and have) actually used some extremely sophisticated computing resources.

What I am doing next year:

Publications

Talks