Directed searches for continuous gravitational waves from spinning neutron stars in binary systems

by

Grant David Meadors

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Physics)
in The University of Michigan
2013

Doctoral Committee:

Professor John Keith Riles, Chair
Professor Fred Adams
Professor Timothy McKay
Professor Stephen Rand
Professor Nuria Calvet
Research Scientist Harold Richard Gustafson

ACKNOWLEDGEMENTS

This author should give thanks far beyond a simple page. It is too soon to write something so important.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ii

LIST OF FIGURES v

CHAPTER

I. Introduction 1

1.1 Gravitational waves in astrophysics 1
1.1.1 Cosmic sources of gravitational waves 2
1.1.2 History from general relativity 6
1.1.3 Contrast with electromagnetic and particle astronomy 6
1.2 General relativity 7
1.2.1 Symmetry and action principles 7
1.2.2 Derivation of field equations 8
1.2.3 Radiation from quadrupoles 8
1.3 Astrophysical estimates 8
1.3.1 Sources: burst, continuous, inspiral and stochastic 8
1.3.2 Continuous waves from neutron stars 9
1.4 Laser Interferometer Gravitational-wave Observatories 9
1.4.1 From Weber bars to interferometry 9
1.4.2 Gravitational wave interferometry methods 9
1.4.3 Advanced observatories and beyond 11
1.4.4 Worldwide network 11
1.5 Summary 11

II. Feedforward: Auxiliary MICH-PRC Subtraction 12

2.1 Motivation and mathematics for feedforward 12
2.1.1 Auxiliary noise coherence at sensitive frequencies 15
2.1.2 Predicted and empirical correction 16
2.1.3 Filter mathematics: in-loop and out-of-loop 17
2.1.4 Estimating optimal filters 17
2.2 Prior programs 20
2.2.1 Manually-designed rational filtering 20
2.2.2 Vector-fitted filter functions 20
2.2.3 Wiener filters 20
2.3 Feedforward in-loop 20
2.3.1 Filter fitting 20
2.3.2 Real-time filtering 21
2.4 Feedforward out-of-loop 21
2.4.1 Filter fitting across science segments 22
2.4.2 Data frame generation 22
2.4.3 Post-processing diagnostics 22

2.4.4 Feedforward benefits and potential . . . 25

III. Squeezing: Quantum Vacuum Phase Noise . . . 29

3.1 Squeezing theory . . . 29
3.1.1 Quantum shot noise and radiation pressure . . . 29
3.1.2 Problems with lasers: thermal compensation . . . 29
3.1.3 Squeezing filter cavities against alternatives . . . 29
3.2 LIGO Hanford Observatory quantum vacuum squeezing . . . 29
3.2.1 Collaboration and contributions . . . 29
3.2.2 Success and Advanced LIGO prospects . . . 31

IV. TwoSpect: Binary Pulsar Searches . . . 33

4.1 Neutron stars in binary systems . . . 33
4.1.1 Binary spin-up and detectable lifetime . . . 33
4.1.2 Detection rate projections . . . 33
4.2 TwoSpect all-sky searches . . . 33
4.2.1 Two spectra: a double Fourier transform . . . 33
4.2.2 Infering neutron stars with companions . . . 33
4.3 Directed TwoSpect . . . 34
4.3.1 Target, directed and all-sky search sensitivity . . . 34
4.3.2 Enhancements enabled by directed searching . . . 34
4.4 Scorpius X-1 and results from Directed TwoSpect . . . 34

V. Exhibit: World Science Festival . . . 35

5.1 Prototypes: travelling kiosks and the Ann Arbor Hands-On Museum . . . 35
5.2 World Science Festival interferometer manufacture . . . 35
5.2.1 Laser, optics and display . . . 35
5.2.2 Aluminum baseboard . . . 35
5.2.3 Plexiglass enclosure . . . 35
5.3 Exhibitions: New York City, Portsmouth, Fort Wayne . . . 35
5.3.1 Exhibit overview . . . 35
5.3.2 World Science Festival 2010 . . . 36
5.3.3 Portsmouth and Fort Wayne . . . 36
5.4 Future LIGO outreach . . . 36

VI. Conclusion . . . 37

6.1 Cycles of science . . . 37
6.1.1 Improvements to observatories . . . 37
6.1.2 Understanding instruments . . . 37
6.1.3 Refining data . . . 37
6.1.4 Searching deep-space . . . 37
6.1.5 Reaching out, looking up . . . 37
6.2 Scientific merit: filtering and analysis . . . 37
6.2.1 Feedforward improvement to LIGO data . . . 38
6.2.2 TwoSpect directed search for neutron stars in binary systems . . . 38
6.3 Entering the advanced detector era . . . 38
6.4 Vision of a dark sky . . . 38

BIBLIOGRAPHY . . . **39**

LIST OF FIGURES

Figure

2.1	MICH noise seen as DARM/(arm gain); PRC too seen in DARM	14
2.2	Statistically-significant coherence justifies fit	18
2.3	Transfer function fit in coherent band	18
2.4	Fits for 1024 s windows in a science segment	19
2.5	Subtracted spectrum for one window	19
2.6	*Feedforward filtering pipeline*	21
2.7	*Windowing*	23
2.8	Exemplar, +1.1 Mpc (5.9% inspiral range) *(GPS 953164819 to 953165839, 2010-03-21)*	23
2.9	Best seen, +4.4 Mpc (29% inspiral range) *(GPS 955187679 to 955188191, 2010-04-13)*	24
2.10	Arithmetic (black) & harmonic (red) mean, 200 jobs: *(before-after)* (L), *(before-after)/before* (R)	24
2.11	Inspiral range vs time: LHO (L) gains 0.69 Mpc, LLO (R) gains 0.43 Mpc	26
2.12	Inspiral range *fractional gain* vs time: LHO (L) 4.13% better, LLO (R) 3.60% better	27
2.13	Webpages, window-by-window:`https://ldas-jobs.ligo.caltech.edu/ ~pulsar/feedforward/diagnos`	
3.1	Sample Figure	32
6.1	Sample Figure	38

CHAPTER I

Introduction

1.1 Gravitational waves in astrophysics

Space's metric echoes with gravitational waves. Light told the tale of the cosmos for most of history; now, the earliest epochs and secret reaches of stars might be seen in light interfering after travels transformed by gravity. General Relativity and ensuing theories of gravitation posit that accelerating quadropolar masses will radiate, much as accelerating dipolar charges do electromagnetically. In those waves we might see black holes and neutron stars colliding, supernova, the dawn of the Big Bang and rotating neutron stars – and the potential for unanticipated insights, into other objects or law of gravity, is too tantalazing to ignore. Hulse and Taylor observed a neutron star in a binary system, PSR 1913+16, with an orbit accelerating just as gravitational radiation would entail; kilometer-scale interferometers were build at the end of the last millenium to look. Laser light in these instruments travels orthogonal paths and is reflected back; shifts in the combined pattern are scrutinized for indications that gravitational waves stretched space itself. As yet, no direct detections are known. This thesis describes efforts to make that search more sensitive with quantum optics at the observatories, by filtering the data of noise and by refining a search for the promising candidate source of neutrons stars in binary systems.

Astronomy has grown from humanity's first glimpses into the night sky with the unaided eye. With every new instrument, from Galileo's telescope through radio antennae and neutrino detectors, our understanding of the cosmos has grown. Gravity pervades the universe like no other force: we must hear its tale. We know some of what to expect: astronomers have predictions for four categories of cosmic sources. We know how it would be emitted: Einstein's general relativity predicts the intensity, speed and polarization of gravitational waves. Most recently, LIGO, VIRGO, GEO600 and soon KAGRA have built gravitational wave antennae that stand on the threshold of detection. This thesis will focus on those antennae. Their sensitivity can be honed by tweaking Heisenberg's uncertainty principle with quantum optical squeezing, and even improved post-facto by feedforward filtering of recorded servo data. Neutrons stars in low-mass X-ray binary systems would live astronomically long lives, earning the attention of a dedicated Fourier-domain frequentist search. Each project is an element of a field that promises to make audible the echoes of the metric of space.

1.1.1 Cosmic sources of gravitational waves

— Cosmic origins believed to generate GW. (note: should sprinkle citations as needed, not just where it says "cite") —

Gravity's power to induce ripples in space is a matter of fact. Pulsar 1913+16, discovered by Hulse and Taylor, not only followed a pattern of orbital decay consistent with radiative loss of orbital decay to gravitational radiation – it continued to do so [57], even after Hulse and Taylor won the 1993 Nobel Prize in physics. We still may ask whether the waves are detectable on Earth. We may ask whether they appear in detectors in a way consistent with general relativity. The basic fact of their emission, however, appears settled.

Before delving into the specifics of general relativity, we might consider all the astrophysical sources we expect to emit gravitational waves. Physics prompts our search, but astronomy makes it exciting.

Gravitational waves (henceforth also abbreviated GW) searches presently focus on four distinct types of cosmic sources. This thesis concentrates on continuous waves, which are sine waves – perhaps modulated by orbital motion, spin-up or spin-down. Continuous waves are most likely to be detectable from neutron stars. Given a sufficiently large ellipticity, which might be on the order of $\epsilon \approx 10^{-6}$ [CITE] or smaller for a neutron star rotating on the order of 1 kHz, a deformation of the crust would radiate sufficient gravitational radiation to be a plausibly-detectable source. Indeed, the radiation would rapidly deplete the rotational energy of the neutron star [CITE], which is why binary systems, where the neutron star could be recycled and spun-up by a partner, prove a promising target [CITE]. Scorpius X-1 offers a canonical case, although our discussion of the TwoSpect analysis will elaborate the abundance of other low-mass X-ray binary (LMXB) systems of interest. Given the paucity of information on the interiors of collapsed stellar remnants, direct detection of gravitational waves from neutron stars could prove informative. We might infer details favoring one equation of state [CITE], might extract parameters suggesting the existence of quark stars or gravitars [CITE], and will have an unparalleled peek into the interior of the densest stable three-dimensional objects in the universe. Their simple waveforms might even facilitate the calibration of other types of gravitational wave data [CITE]. From any source, continuous waves are a conceptually-elegant and astronomically-enticing target.

Yet other sources of gravitational waves, as will be discussed in more detail later, have a comparable pull on our attention. Oft discussed, inspirals or compact binary coalescences occur when two stellar remnants draw nearer in their orbits, radiating gravitational radiation and finally merging in a titanic release of energy. While sometimes invisible – the merging of black holes in short-hard gamma ray burts (GRBs) proving an exception – these events compete eagerly with supernovae as the most explosive in the modern universe. Were we to detect them directly with gravitational waves, we would see their waveforms, which in turn can be predicted through post-Newtonian approximation and numerical relativity. As the amplitude would diminish linearly with distance, we would then have standard candles or 'sirens' by which to calibrate and measure the universe. Advanced LIGO may prove sensitive to neutron star-neutron star and stellar mass black hole-neutron star mergers, and, if low-frequency sensitivity is sufficient and the sources exist, to intermediate-mass black holes. Space-based observatories such as the longsuffering Laser Interferometer Space Antenna (LISA), the DeciHertz Gravitational-wave Observatory (DECIGO), Big Bang Observer (BBO) and proposed others could detect supermassive black hole mergers. If fortunate, they would see a low-frequency noise floor due not to seismic vibration, as in LIGO, but to white dwarf binaries throughout the galaxy. Since the waveforms are well-predicted, we could even investigate deviations from general relativity, perhaps seeing new physics in the ringdown of black holes.

Physical insight could also come from burst searches. Bursts share with inspiral searches the property of looking for a single event, as opposed to a source spread over duration. Burst is a somewhat general term, and analyses for them can sometimes be applied to inspiral or detector characterization tasks as well, yet the immediate focus lies with supernovae and perhaps gamma-ray bursts. Because the waveform is unknown, burst searches rely significantly more on the coincidence between multiple detectors to distinguish signal from noise. Just as with neutrino observations of supernova 1987A, the burst program would hope for a fortuitously nearby cataclysm to be seen simultaneously – or nearly so, the time of flight indicating a direction – in a global gravitational-wave detector network. Due to the versatility of this method, some researchers have proposed looking for non-general relativitic terms, such as longitudinal polarization in addition to plus and cross orthogonal polarization. Any detection would be quiet exciting for probing systems still mysterious with electromagnetic and neutrino measurements, and it would help, in conjunction with multi-messenger coordinated searches with those observatories, to ascertain at precisely what speed gravity travels through space-time and to what extent it is attenuated or altered.

The background of space-time itself may itself how interesting physics and gravitational wave signatures. Searches for the stochastic gravitational wave background look not for events but for many months of correlated signals between networks of detectors. In doing so, they hope in particular to see the earliest turbulence of the universe – long before the cosmic electromagnetic background, now microwaves, was emitted 380000 years after the Big Bang, gravitational waves were travelling unimpeded. While the opacity of the infant cosmos conflates electromagnetic signals from different times and places, the transparency of the universe to gravity means that we might see the inflationary epoch or earlier, the Planck time, in gravitational waves. Unfortunately, this signal is thought to be far below the sensitivity of existing detectors. While LIGO did set a new upper limit on the energy density of gravitational waves, measured as a fraction, Ω_{gw} of the critical closure density of the universe [55], the inflationary background at LIGO frequencies is predicted to be about ten orders of magnitude lower. Alternative theories, such as ekpyrotic/cyclic universes, make other predictions, so an anomalously high stochastic background could prove cosmologically significant.

All gravitational waves searches look for something. While the most exciting possibility remains that we will see the unexpected, we think that our present divisions will permit serendipity while efficiently categorizing the computational challenges we do expect. Continuous wave and inspiral methods both search against waveform templates; burst and stochastic have no template and rely on correlation and coincidence. Continuous wave and stochastic analyze weeks, months, even years of data in search of persistant features; inspiral and burst look for transient events. In the abstract dimensions of search groups, we are complete. Our blind spots are in what data we provide to those groups – in the focus on audio frequencies of tens to a few thousand Hertz at present – blindness that will in time be rectified by CMB polarization, pulsar-timing and space-based interferometry for low frequencies and possibly by atom interferometry for high frequencies. To appreciate our choice of focus in these nascent days of the field, we must turn back a century to understand its origins in Einstein's mathematics.

1.1.2 History from general relativity

Historical brief of Einstein.

It all began in 1915. In 1916, Einstein predicted gravitational waves, although he got some things wrong. Probably good to consult Gravitation [44] and Sean Carroll [17] as well as proper history books.

1.1.3 Contrast with electromagnetic and particle astronomy

Contrast with electromagnetism, compare with radio/X-ray/et cetera astro. Can make analogy to radio waves and make note of the ease with which one can operate a small radio telescope, as I did in my thesis [42], compared the the difficulty of gravitational wave detection. Muons from space were detected long ago, as in C.D. Anderson's 1949 paper on what was then called the mesotron, [35]. Compare with neutrinos as in the John Bahcall review paper [11], which were a well-established field by the turn of the millenium, including the detection of supernova 1987A. Might be worth comparing to the focus in new neutrino detectors that I had in my research and development work on them [14], [40]. Even with those detectors, however, astrophysically-oriented detectors could be cross-referenced against terrestrial generators. Bahcall's search for solar neutrinos, which were theoretical in 1964, [10], at least had the certainty that neutrinos had been detected from the Savannah River nuclear reactor. Yet when those solar neutrinos were detected, it a significant confirmation of nuclear theory. General relativity has been established by the 1913+16 pulsar [57] and would likely be much boosted by direct detection, and it might reach surprising new insights, analogous to neutrino oscillation found by looking at the solar neutrino spectrum.

1.2 General relativity

General relativity (the mathematics). The ideal reference here is Sean Carroll's lecture notes on general relativity, [17], although I should also cite Will Farr's thesis if it is elegant. Farr is good for citing things like the Palatini action. Of course, I should also "dig down" and cite the original sources that they reference too, where applicable. Can also cite Misner, Thorne and Wheeler [44].

1.2.1 Symmetry and action principles

Like electricity and magnetism, GR is the product of symmetry, action. This is the right place for [17].

1.2.2 Derivation of field equations

Derive field equations as extremized curvature.

It's all about the Ricci tensor and the Einstein-Hilbert action. This might be the right place for [?] and other sources.

1.2.3 Radiation from quadrupoles

Predict power from rotating quadrupole. Might also be a good place to invoke Vladimir's thesis [20] as well as original primary sources. Note that just as light travels at the speed of light, which is measureable [45] and which can be derived from electromagnetic theory [30], so we think that gravity should travel at the speed of light. Note that this radiation should not be affected by the interstellar medium. I think that Ostriker is the source to reference on the ISM [16], [38].

1.3 Astrophysical estimates

Astrophysical estimates and predictions.

1.3.1 Sources: burst, continuous, inspiral and stochastic

Describe the four types of sources: burst, continuous, inspiral and stochastic.

Mostly above, but clarify exact how much we should see. Cite the 2009 Nature stochastic paper et al [55]. The importance to early universe cosmology was initially handled by Maggiore [36]. Before that, of course, once can reference the Allen and Romano methods paper [9], anything interesting from Nick Fotopoulos's thesis [25], and the various mid-2000s stochastic work that I was familiar with [3], [2]. Note the interesting meaning of anisotropies [8] and point out how not only Stefan's radiometer search can find them but how it can be adapted to many other purposes, such as spherical harmonics, which is useful for the cosmic microwave background [46] and was briefly my work [41] and the Scorpius X-1 search; Stefan's canonical radiometer reference is in Classical Quantum Gravity [13].

1.3.2 Continuous waves from neutron stars

Continuous – specifically, binary neutron stars and rate predictions. Describe archetypical search methods as in the Abbott et al paper [6] and the most interesting to date, Vladimir's PowerFlux [5]. Discuss earlier results from the earliest period [1] and an early search for Scorpius X-1 [4]. Reinhard Prix is probably another good source [47].

Rates go in here.

1.4 Laser Interferometer Gravitational-wave Observatories

LIGO observatories. The most fun part to write. Cite Nergis Mavalvala [37], Stefan Ballmer [12], Rana Adhikari [7], Nicolas de Mateo Smith-Lefevbre [51] and, of course, Peter Saulson [50].

1.4.1 From Weber bars to interferometry

History lesson: Weber bars progress to interferometers. Use Saulson, but Nic's thesis has links to some of the original sources [50], [51].

1.4.2 Gravitational wave interferometry methods

Michelson was one of the first to use interferometers [43]. He is famous for having done so to try to measure the velocity of the Earth with respect to the luminerferous ether and finding it to be unmeasurable.

Why GW interferometers work. Null measurements, a zeroed operating point. The specifics are best handled by Saulson [50]. The idea of a Pound-Drever-Hall lock is most elegantly explained by Black [15]. Rai Weiss may have some neat details, possibly historical, albeit that it is in a presentation [58]. The details of Fabry-Perot cavities in LIGO are handled by Rakhmanov, Savage et al [49], [48]. The motivation for the evolution to Enhanced LIGO and its DC readout methods is covered well in the corresponding CQG article [26] and specific details of its construction and operation are in Tobin Fricke's thesis [27].

Interferometer theory

GW interferometry theory: differential arm motion, key noise sources. Again, the main source is Saulson [50], although we also need another source in the Advanced Detector Era.

Observatory operation

Operating LIGO: controls, Detector Characterization. One of the first sources from initial LIGO to read up on is a paper by Fritscel, Bork, Mavalvala et al [28]. Initially this system made a detection based on heterodyne readout using gravitational wave sidebands, which, among other troubles, could be unequal in the recycling cavity [39].

Detector characterization DetChar methods: omega scans, line hunting and glitches

Feedforward filtering Example of feedforward: 60 Hz magnetometer. The only source that mentions this is, I think, Nic's thesis [51]. Yet the most pertinent example is one that has long been applied to LIGO: MICH and PRC feedforward. The specific needed are mention in the thesis of Adhikari [7] and Ballmer [12], but immediately before Keita Kawabe and I began our project, these parameters had been tuned by Jeff Kissel [33]

Phase camera Future devices: overview of phase camera with Vladimir. Vladimir's thesis definitely talks about it [20]. We can discuss the fundamentals behind the need for angular stabilization and control from Nergis Mavalvala's thesis [37], but we can refresh it with a modern reference from Kate Dooley's thesis [22].

1.4.3 Advanced observatories and beyond

Advanced LIGO and beyond – squeezing and prospects?

1.4.4 Worldwide network

Allies: LIGO India, KAGRA, Advanced VIRGO, Einstein Telescope, LISA

1.5 Summary

Summary: strong motivation and instruments, need to find evidence of GW.

CHAPTER II

Feedforward: Auxiliary MICH-PRC Subtraction

2.1 Motivation and mathematics for feedforward

LIGO, the Laser Interferometer Gravitational-wave Observatory [Hanford, Washington and Livingston, Louisiana] measures the differential length of 4-km Michelson arms with Fabry-Perot cavities. Length changes could indicate strain caused by astrophysical sources of gravitational waves. Fundamentally limited by seismic noise, thermal suspension noise, and laser shot noise in different frequency bands, a LIGO interferometer's sensitivity can also be degraded by additional relative motion of the inner arm cavity mirrors due to imperfectly-servoed Michelson motion. In this project we seek to subtract the effects of this residual motion by feedforward correction of the gravitational-wave data channel. We divide data from LIGO's sixth science run into 1024-second time windows and numerically fit a filter representing the frequency-domain transfer function from Michelson servo noise to gravitational wave channel for each window. Finally, the Michelson servo channel is processed through the filter and is subtracted from the gravitational-wave signal channel. The algorithm used in this procedure will be described with a preliminary assessment of the achievable sensitivity improvement.

Before delving into the details of the algorithm, a primer on the motivation and mathematics should follow. LIGO and its predecessors have long relied on servo control using feedforward and feedback to stabilize interferometers. At the 40 meter interferometer at Caltech, an early experiment to subtract noise post-facto was attempted (Bruce Allen? Find earliest citation – Keith or Rana would know). Yet most schemes in the modern era have relied on realtime methods. Fundamental noise sources would be unapproachable if we did not.

LIGO by design should be limited only by fundamental, physical sources of noise. Initial and Enhanced LIGO are bound at low frequencies by seismic noise, at its middle and most sensitive frequencies by thermal noise from its suspensions, and at its highest frequencies by laser shot noise. Advanced LIGO, if commissioning succeeds, will be purely quantum mechanically limited: radiation pressure will dominate the low frequencies and shot noise the high. These sources can only be ameliorated with better hardware. Yet we have reason to suspect that the real instruments are not so perfect: some noise remains that is both caused by and can be fixed by better software – in particular, better servos.

Myriad LIGO systems are servoed, from laser frequency to mirror position. The entire aim of these servos is to provide a more sensitive measurement of differential arm motion, which directly corresponds to *h(t)*, the gravitational wave signal. Some servos affect *h(t)* more directly than others. The differential arm motion of the outer mirrors is itself refered to as $DARM$, and the three other motions of the mirrors have a special importance as well: $CARM$, the common outer arm motion, $MICH$, the differential "Michelson" motion of the inner mirrors, and PRC, the "power recycling cavity" common motion of the inner mirrors.

The four LIGO mirror test masses (TM) are named by arm (X or Y) and inner (I) vs end (E) of the Fabry-Perot cavities. LIGO controls four length degrees of

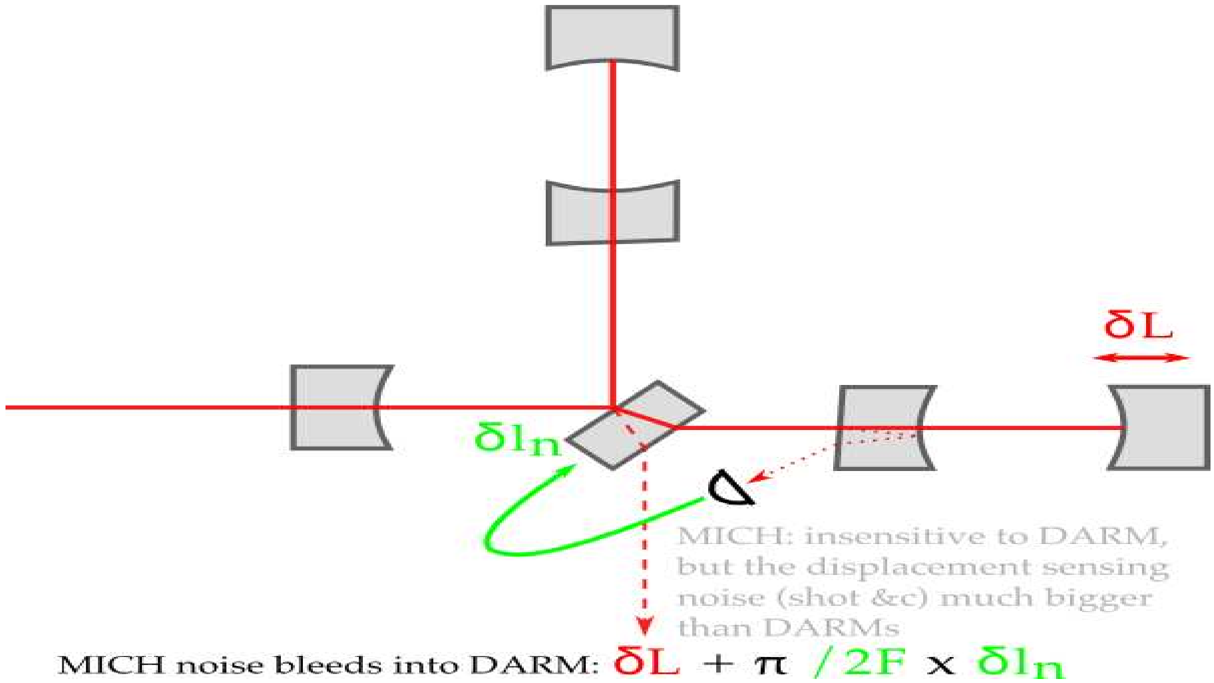

Figure 2.1: MICH noise seen as DARM/(arm gain); PRC too seen in DARM

freedom.

$$CARM = L_+ = \frac{L_y + L_x}{2},$$

$$DARM = L_- = L_y - L_x,$$

$$PRC = l_+ = \frac{l_y + l_x}{2},$$

$$MICH = l_y = l_y - l_x,$$

$$L_y \equiv d(ETMY - ITMY),$$

$$L_x \equiv d(ETMX - ITMX),$$

$$l_y \equiv d(ITMY - RM),$$

$$l_x \equiv d(ITMX - RM).$$

In initial LIGO, for historical interest, but not precisely so in enhanced or advanced LIGO,

$$\aleph \equiv 4J_0(\Gamma)J_1(\Gamma)P\cos\omega_m t,$$

$$[L_- \to AS_Q] = -\aleph g_{cr} t_s b r'_c \frac{1}{1+if/f_c} k\delta L_-,$$

$$[l_- \to AS_Q] = \aleph g_{cr} t_{sb} r_c \frac{1}{1+if/f_c} k\delta l_-.$$

Conclusion about MICH-DARM coupling: Noisy MICH resembles DARM *sans* arm gain.

$$r'_c = \pi/(2F) \approx 137 r_c$$

2.1.1 Auxiliary noise coherence at sensitive frequencies

DARM is coherent with MICH and PRC, as can be seen in figures (ADD LABELS), in the most sensitive band for gravitational wave detection. Coherence is the frequency-dependant analog of statistical correlation: on a scale of 0 to 1, it represents the normalized fraction of a frequency bin in the spectrum of one channel that is in a constant phase and amplitude relation with the corresponding frequency bin in the spectrum of another channel. It thus represents the degree of linear coupling between those channels. Channels that have a low value of coherence across their spectrum can be viewed as relatively linearly indepedent of one another.

For the coherence between MICH and DARM, values of up to 0.1 were seen in the band of a few hundred Hertz before Keita Kawabe and I implemented the realtime version of our version. The PRC-to-DARM coherence was several times smaller and thus deemed insignificant. When we implemented our filter, the MICH values diminished several-fold (ADD SCREENSHOT?), demonstrating the filter's efficacy.

In the post-facto work, we had to design a system that could effectively fit a filter in the most-coherent band across many different segments. We surveyed S6 LIGO science segments until focusing on the 80 to 400 Hz (DOUBLE CHECK) band as the most coherent for both MICH and PRC coupling into DARM, or rather, its calibrated counterpart, Hoft. Note that coherence is, ideally, transitive. Since Hoft is simply DARM passed through a linear filter, the coherence between any channel and Hoft should be, to within numerical precision, identical to the coherence between that channel and DARM. We then decided to fit heavily in this region. As referenced by Greg Mendell (cite his 2013 March LVC talk if necessary), the statistical significance of a transfer function – and thus our measure of the coupling from noise into signal – is assessed through coherence. By fitting only in regions where the coherence was typically greater than 0.03 (CHECK: is this about the right number?), we verified that the uncertainty in our transfer function was no greater than (CHECK: what is the number?). Outside this band we both deweighted the fit to the transfer function and pre-processed the transfer function, surpressing it by factors of $(f/f_{\text{knee}})^{\alpha}$, where $\alpha = 8$ at low frequencies and -8 at high. Both the deweighting and the pre-processsing must be carefully-tuned to avoid monopolizing a scarce set of free parameters, the poles and zeros that float to fit the transfer function.

By minimizing the transfer function and thus our fitted filter where it would be incoherent, we avoid adding noise.

2.1.2 Predicted and empirical correction

Manual, constant correction long applied, known *a priori* cause.

Draw on Stefan Ballmer/Rana Adhikari and trace down the origin of the MICH and PRC estimates, possibly reiterate with citation. Emphasize that it is frequency-independent, flat, whereas the observed residual coherence is not perfectly flat.

2.1.3 Filter mathematics: in-loop and out-of-loop

Mathematics of in-loop/out-of-loop filtering.

Discuss servos, including the usual terminology of plants, gain. Principle references: Saulson [50], Luca Matone's lectures, possibily some EE texts such as Horowitz and Hill.

We should also quote Jeff Kissel's thesis [34], which in chapter 3 has an extensive discussion of DARM, its calibration and response function, the actuation and sensing functions, filters and plants.

2.1.4 Estimating optimal filters

Transfer functions to second-order systems.

Transfer functions are frequency-domain fit to 32-pole ZPK (zero-pole-gain) filters, applied in time domain.

Frequency domain subtraction filtering.

$$T_{xy}(f) = \frac{P_{yx}(f)}{P_{xx}(f)},$$

$$P_{yx}(f) = \int_{-\infty}^{+\infty} \left(\int_{-\infty}^{+\infty} y^*(\tau) x(t+\tau) d\tau \right) e^{i2\pi f t} dt,$$

$$g_c(f) = T_{sn}(f),$$

$$\hat{s}(f) = (s + g_s \times n)_m(f) - g_c(f) \times n_m(f).$$

Where $\hat{s}$ is the post-filter signal, s is the pre-filter signal, n is the noise, g_s is the transfer function coupling noise into signal, g_c is the estimated feedforward filter decoupling noise from signal, and the subscript m indicates an observable or measurable quantity.

Sample feedforward from LIGO Hanford Observatory

2010-03-21T0000Z: MICH on left, PRC on right.

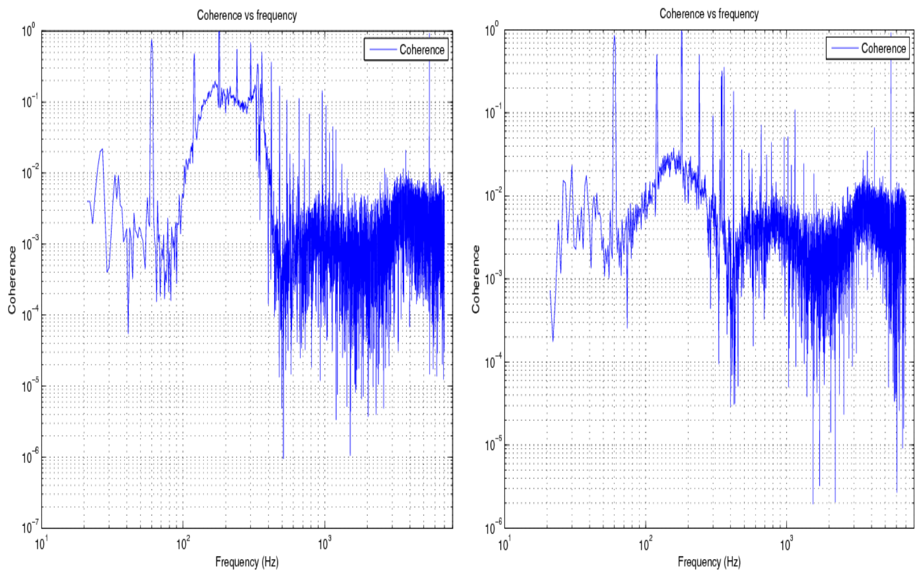

Figure 2.2: Statistically-significant coherence justifies fit

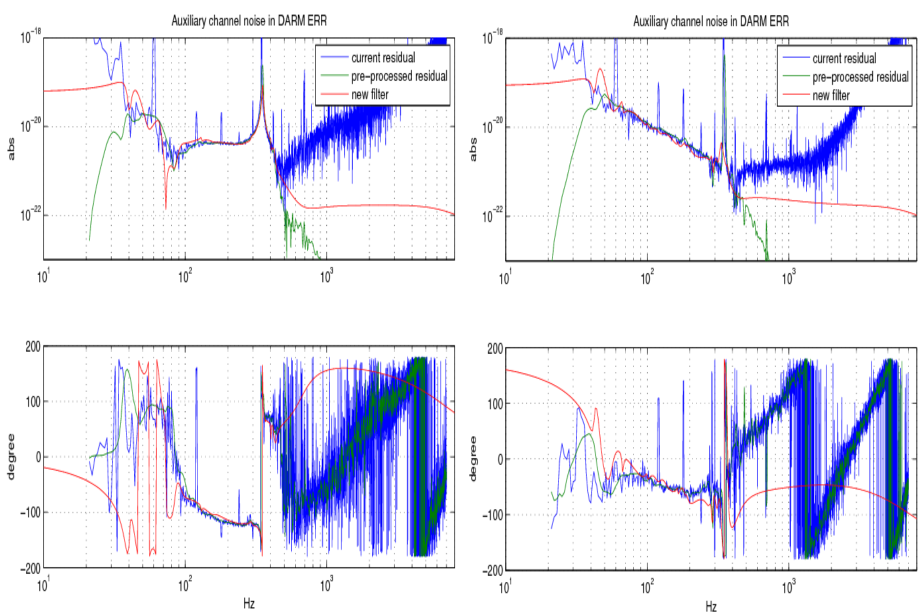

Figure 2.3: Transfer function fit in coherent band

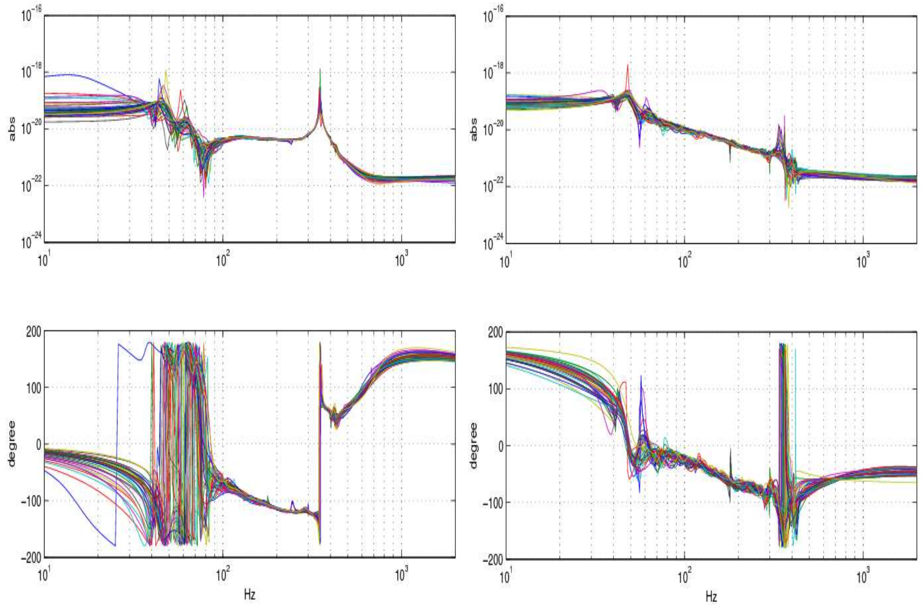

Figure 2.4: Fits for 1024 s windows in a science segment

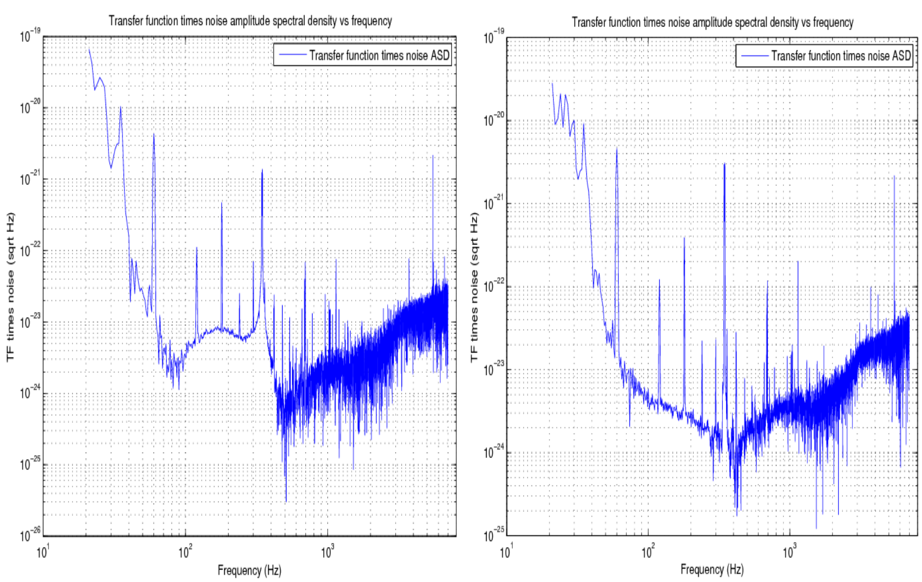

Figure 2.5: Subtracted spectrum for one window

2.2 Prior programs

Keita's and Rana's prior programs.

2.2.1 Manually-designed rational filtering

Keita's by-hand rational-filter

2.2.2 Vector-fitted filter functions

Rana and Jenne's and Dani's work with vectfit.

2.2.3 Wiener filters

Rana and Jenne's 40 m Wiener filtering attempts and why that fails here. Klimenko?

Wiener filtering searches for an optimal filter of a particular kind: it minimizes the squared error. That error can be the difference between the estimated signal and the time-delayed signal. However, the error is over the entire spectrum. For our problem, we would have to band-pass the spectrum into many sub-spectra, then evaluate the error over those, or else the estimation would be overwhelmed by the power at low-frequencies. The coherence at low-frequencies is low, so basing a filter on those, especially at the expense of higher frequencies, would be unjustified and futile.

2.3 Feedforward in-loop

Feedforward program structure: in-loop.

2.3.1 Filter fitting

Matlab: obtain frame data, fit, integrate existing filters, export.

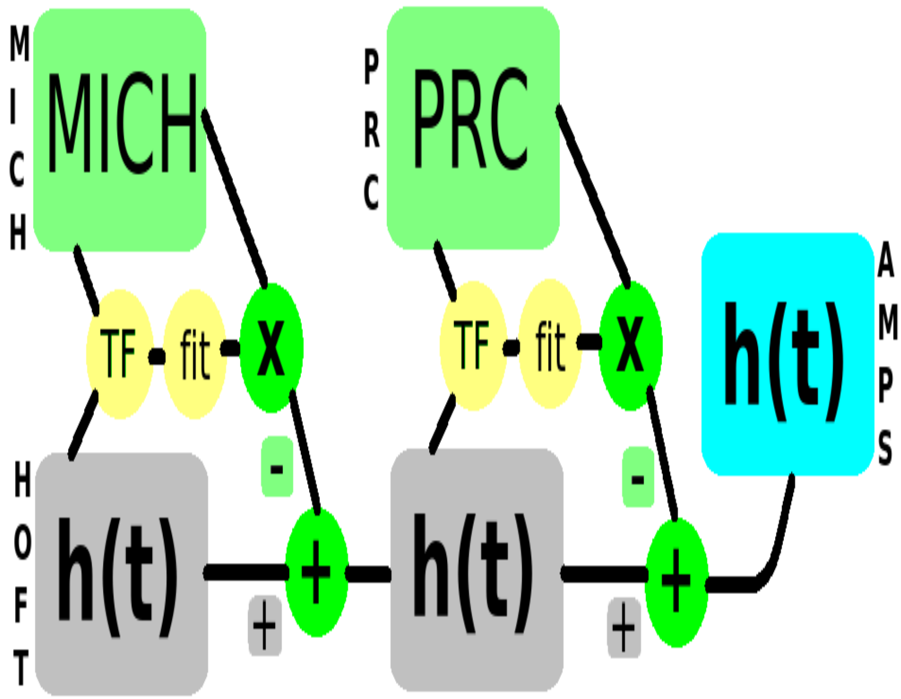

Figure 2.6: *Feedforward filtering pipeline*

2.3.2 Real-time filtering

Foton: real-time SOS filtering.

2.4 Feedforward out-of-loop

Read in Hoft (calibrated DARM), MICH, PRC, write out AMPS (clean calibrated DARM). Code in LIGO SVN:

`matapps/packages/detchar/`

`AMPS/trunk/aletheia.m`

A critical point: we use the entire set of data for a window to produce a filter, then apply that filter back to the entire set of data. Those familiar with a machine learning view may worry that this is overfitting, that we are not training the data. But that worry really is not justified. The concept of training and over-fitting are valid in the frequency-domain aspect of this work, where we take steps to correct it, such as the pre-processing of the spectrum shape and the post-processing vetos. But in the time-domain, overfit should we restrict the filter-training to a subset of the data? That might make sense if we assumed the data to be stationary and were going to let it run into the future, or if we wanted to learn something scientific about the meaing of the filter coefficients. None of those assumptions hold. We assume the data to be non-stationary, although a complaint could be made that we are unsure about the timescales of non-stationarity. We do not let the filter run arbitrarily into the future, but explicitly window it. Finally, we do not have ambitions to extract scientific meaning from the filter coefficients, although that may change – even if we did go down that route, it would probably be based more on the original spectra than on the fit to them.

2.4.1 Filter fitting across science segments

Matlab: obtain frame data, fit, window across science segments.

One job per science segment, filters are calculated for 1024 s windows; 50%-overlapping Hann windows merged, AMPS h(t) frames written. Code in LIGO SVN: `matapps/packages/detchar/`
`AMPS/trunk/eleutheria.m` Feedforward program structure: out-of-loop.

2.4.2 Data frame generation

Matlab: write frame files on cluster.

2.4.3 Post-processing diagnostics

LIGO Hanford h(t) spectrum after filtering MICH & PRC:
noise floor in bucket falls quiet, freeing inspiral range.

Matlab/Python/C: diagnostics – combs, SFTs, range and data consistency.

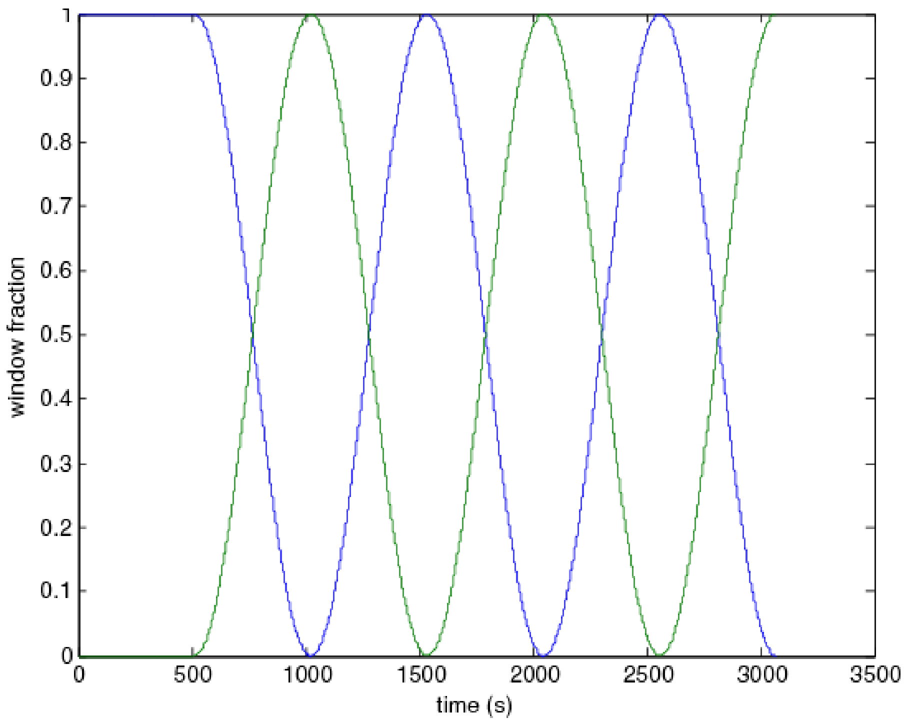

Figure 2.7: *Windowing*

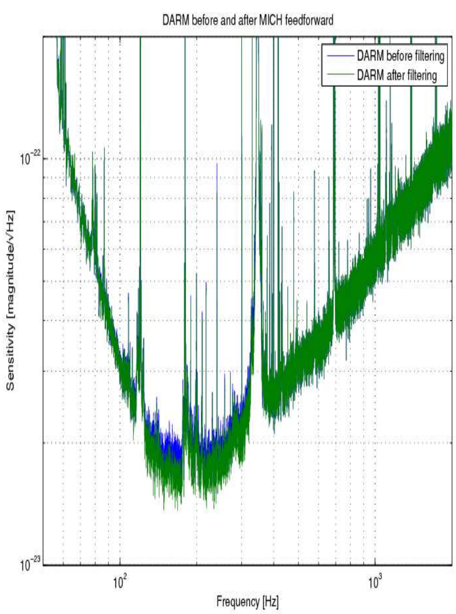

Figure 2.8: Exemplar, +1.1 Mpc (5.9% inspiral range) *(GPS 953164819 to 953165839, 2010-03-21)*

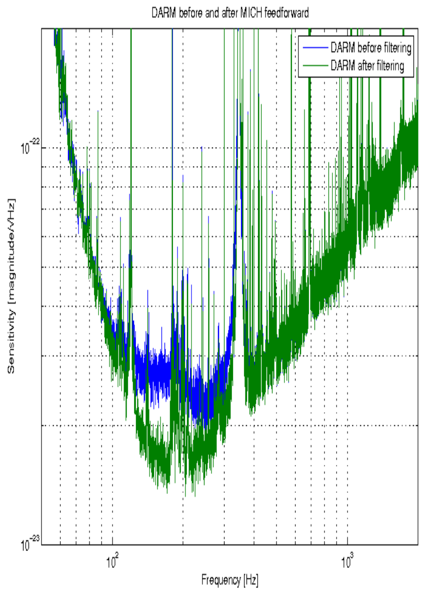

Figure 2.9: Best seen, +4.4 Mpc (29% inspiral range) *(GPS 955187679 to 955188191, 2010-04-13)*

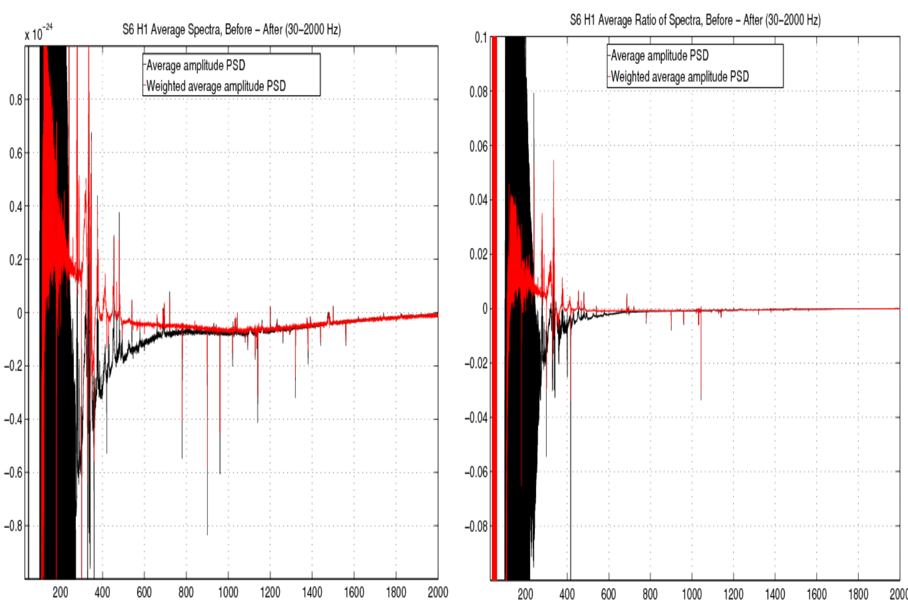

Figure 2.10: Arithmetic (black) & harmonic (red) mean, 200 jobs: *(before-after)* (L), *(before-after)/before* (R)

Many post-processing diagnostics, injections included. We tested the syncronization, before and after, with ringdown and sine-gaussian burst injections, and additionally we looked for any evidence of a frequency comb at the windowing frequency. No problems were found.

This is probably the optimal place to talk about the work that Ian Harry and maybe James Clark, David Keital and Karl Wette are doing, as well.

2.4.4 Feedforward benefits and potential

Fine tuning, how data improves, potential for future.

Inspiral range, the distance at which coalescing neutron stars are likely to be detected, increases for both LIGO observatories when data from science run 6 is filtered. *Post facto* feedforward noise subtraction improves performance.

1 . Feedforward subtracts noise using Vectfit to fit a transfer function between noise & signal

2 . h(t) is filtered with MICH & PRC, range improves 4 % (volume 12 %), minimum strain about ten percent better.

3 . AMPS frames for S6 LHO & LLO exist at CIT: `/archive/frames/S6/pulsar/feedforward`

4 . The *best* h(t) & inspiral range of any site/time till Advanced LIGO is on these frames

5 . Advanced LIGO could use such methods to characterize MICH & PRC changes, fix quickly, even *post facto*

References: LIGO optical pathlength definitions via Adhikari [7] and [12]; Vectfit developed by Gustavsen et al [21], [31], [32]. Remember to note that Tobin Fricke

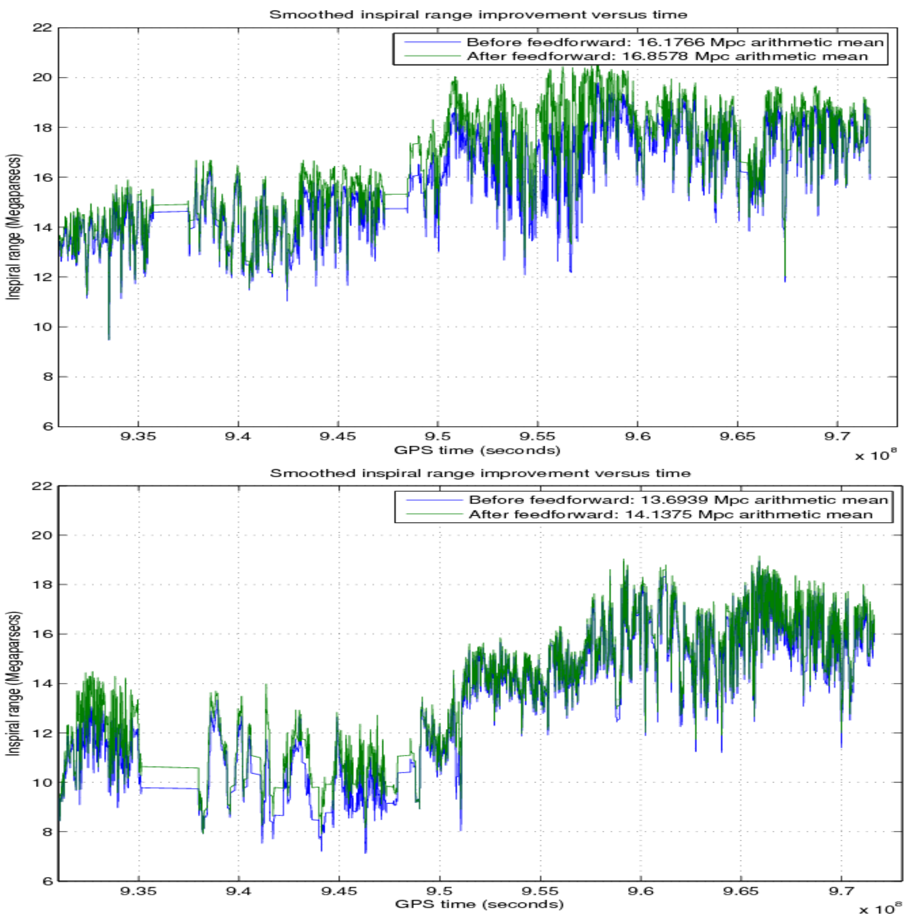

Figure 2.11: Inspiral range vs time: LHO (L) gains 0.69 Mpc, LLO (R) gains 0.43 Mpc

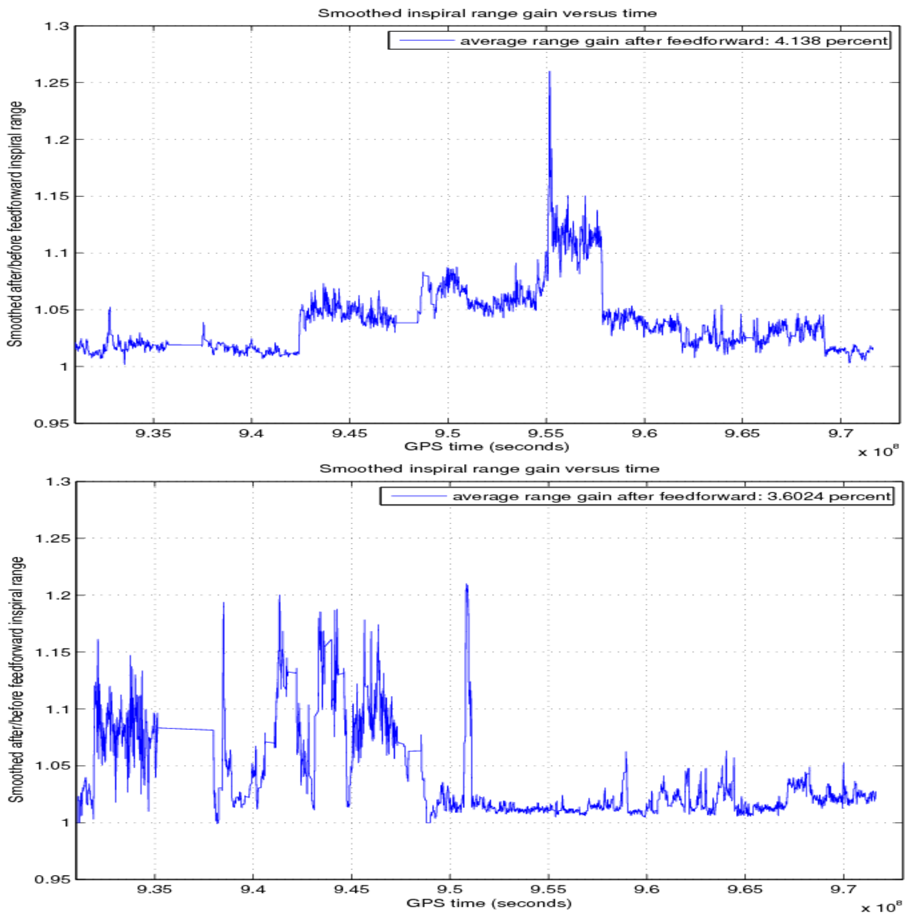

Figure 2.12: Inspiral range *fractional gain* vs time: LHO (L) 4.13% better, LLO (R) 3.60% better

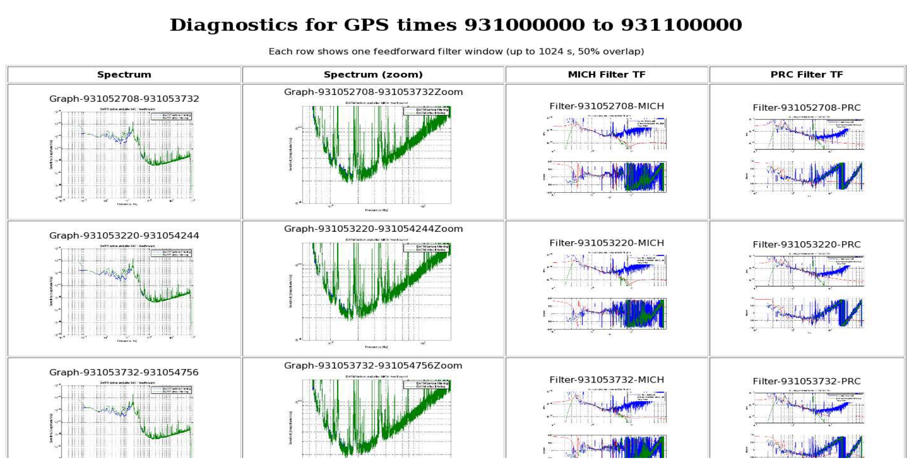

Figure 2.13: Webpages, window-by-window:
`https://ldas-jobs.ligo.caltech.edu/ ˜pulsar/feedforward/diagnostics`

wrote the function that applies the ZPKs as a SOS section-order-sections filter to the actual data, filterZPKs.m.

CHAPTER III

Squeezing: Quantum Vacuum Phase Noise

3.1 Squeezing theory

Squeezing theory.

3.1.1 Quantum shot noise and radiation pressure

Carlton Caves, quantum shot noise and radiation pressure.

3.1.2 Problems with lasers: thermal compensation

Experience (some firsthand) with thermal compensation.

3.1.3 Squeezing filter cavities against alternatives

3.2 LIGO Hanford Observatory quantum vacuum squeezing

Quantum vacuum squeezing at LIGO Hanford Observatory. Naturally, a great deal of description and background will come from Sheila Dwyer's thesis [24] and Sheon Chua's thesis [18].

3.2.1 Collaboration and contributions

Contributions: table, in-vacuum installation, electronics, range est.

Optical table support assembly

Table legs (me) and results of Sheon and Robert's shakers.

Here might be good place to put old AutoCAD drawings to use.

Faraday isolator measurement

Faraday isolator measurement (me with Keita, Matt, Lisa).

What were the results of the measurement? Show e-log entries, comment on in-and-out-of-vacuum performance and what it says about the need for low loss to be a top priority in future squeezing efforts.

In-vacuum installation

In-vacuum Faraday and baffle installation with "".

Show pictures of the installation, connect to the issues with stray and perhaps backscattered light.

Discuss the repair of the output mode cleaner, which is mentioned (citation 50) in Nic's thesis [51]. The technical report corresponding to it is by Waldman and Chua [56].

Data digitization

Electronic cabling and analog-to-digital converter installation.

May want helpful diagram.

Figures of merit: inspiral range

Range estimation after squeezing

From the improved shot noise, we can see that squeezing at high frequencies bought enhanced LIGO a megaparsec of inspiral range. This number is impressive in several respects: our goal was to acheive a squeezing factor of perhaps as much as 3 dB, but to do it in the shot noise-limited region, at high frequencies, where the inspiral range equations (MATH: add the inspiral range equation if not already shown for feedforward!) count for much less. Morever, that range figure reflects the acheivement of squeezing down to 150 Hz (CITE: can we use this number?), which is the lowest yet achieved for a gravitational wave interferometer.

3.2.2 Success and Advanced LIGO prospects

Results and hopes for aLIGO+ squeezing.

The squeezer group has a paper pending in review for Nature, written by Lisa Barsotti, in which we discuss our acheivement of perhaps 2 dB worth of squeezing (need to cite and check whether it is OK to use this number) [52]. It builds on the previous success of GEO600 in squeezing [54].

Discuss Sheila Dwyer's [23] and Sheon Chua's [19] papers, since I am an author on both of them. We have a preliminary understanding now of at least two major problems: the quadrature phase noise fluctatuations and backscattered light. Backscattered light can be resolved in several ways. Phase noise must be progressively improved, as Sheila discusses, because we can hope to acheive the mature filter cavity design proposed below.

Discuss Lisa Barsotti's talk about the future prospect for LIGO using filter cavities, work that Tomoki Isogai is doing. With filter cavities, we can acheive frequency-dependent squeezing, having the best of both works by reducing quantum radiation pressure noise at low frequencies and shot noise at high, by using the filter cavity to produce a squeezed vacuum with a squeeze angle that varies as a function of frequency. Though as yet this filter cavity has yet to be constructed, it is in the works at MIT.

The following is an example of using the commands *ref* and *label*. With these commands theorems, chapters, sections and figurres can be labeld with names in the tex file and then refered to by these names in later tex files. In chapter I we saw section **??** or theorem **??**.

Lastly, here is how to include a figure. First generate an encapsulated postscript file in xfig, adobe illustrator or some other program. The specific commands are found in *chap2.tex*.

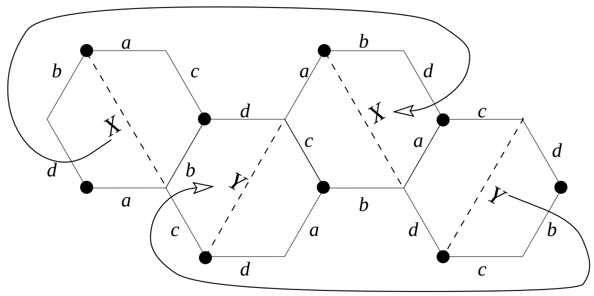

Figure 3.1: Sample Figure

CHAPTER IV

TwoSpect: Binary Pulsar Searches

4.1 Neutron stars in binary systems

Astrophysical prospects for binary pulsar detection.

4.1.1 Binary spin-up and detectable lifetime

GW pulsar lifetime alone vs companion.

4.1.2 Detection rate projections

aLIGO rate projections.

4.2 TwoSpect all-sky searches

TwoSpect methods as-is. These are described in detail in Evan Goetz's thesis [29]. Note that the code is located on the web freely accessible in the LALApps repository [53].

4.2.1 Two spectra: a double Fourier transform

'Two spectra' – FFT of periodograms reveals modulation of sine waves.

4.2.2 Infering neutron stars with companions

Infer whether modulation is due to a companion star.

4.3 Directed TwoSpect

TwoSpect improvements myself (to do).

4.3.1 Target, directed and all-sky search sensitivity

Targeted (known object) vs directed (region)vs all-sky (everything).

4.3.2 Enhancements enabled by directed searching

Modifications for directed search.

4.4 Scorpius X-1 and results from Directed TwoSpect

Preliminary results of a directed search (possibly simulation-only).

CHAPTER V

Exhibit: World Science Festival

5.1 Prototypes: travelling kiosks and the Ann Arbor Hands-On Museum

Prototypes: Ann Arbor Hands-On Museum and travelling kiosk.

5.2 World Science Festival interferometer manufacture

World Science Festival interferometer in isolation.

5.2.1 Laser, optics and display

Laser and optics (and display).

5.2.2 Aluminum baseboard

Aluminum base plate.

5.2.3 Plexiglass enclosure

Plexiglass, many lessons learned.

5.3 Exhibitions: New York City, Portsmouth, Fort Wayne

World Science Festival interferometer installed.

5.3.1 Exhibit overview

NYC exhibit overview: design, walls, kiosks, displays, interactivities.

5.3.2 World Science Festival 2010

Success in WSF 2010.

5.3.3 Portsmouth and Fort Wayne

Secondary installations and future outreach potential.

5.4 Future LIGO outreach

Future LIGO outreach? How to explain a new astronomy.

CHAPTER VI

Conclusion

6.1 Cycles of science

How it all fits together.

6.1.1 Improvements to observatories

Enhancements like enhanced/advanced LIGO and squeezing.

6.1.2 Understanding instruments

....necessitate detector characterization, like scans and filters

6.1.3 Refining data

....automated feedforward filters yield own enhancements

6.1.4 Searching deep-space

...TwoSpect and other searches benefit

6.1.5 Reaching out, looking up

...Outreach makes research accessible to public.

6.2 Scientific merit: filtering and analysis

Core projects.

6.2.1 Feedforward improvement to LIGO data

Evaluate success of feedforward.

6.2.2 TwoSpect directed search for neutron stars in binary systems

...and TwoSpect-directed.

6.3 Entering the advanced detector era

Advanced LIGO: how much better can we do?

6.4 Vision of a dark sky

Why GW astronomy at all? What could be out there?

The following is an example of using the commands *ref* and *label*. With these commands theorems, chapters, sections and figurres can be labeld with names in the tex file and then refered to by these names in later tex files. In chapter I we saw section **??** or theorem **??**.

Lastly, here is how to include a figure. First generate an encapsulated postscript file in xfig, adobe illustrator or some other program. The specific commands are found in *chap2.tex*.

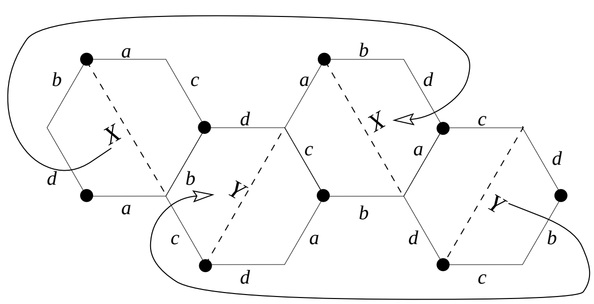

Figure 6.1: Sample Figure

BIBLIOGRAPHY

BIBLIOGRAPHY

[1] B. Abbott, R. Abbott, R. Adhikari, A. Ageev, B. Allen, R. Amin, S.B. Anderson, W.G. Anderson, M. Araya, H. Armandula, and et al. Analysis of LIGO data for gravitational waves from binary neutron stars. *Phys. Rev. D*, 69:122001, 2004.

[2] B. Abbott, R. Abbott, R. Adhikari, J. Agresti, P. Ajith, B. Allen, R. Amin, S.B. Anderson, W.G. Anderson, M. Arain, and et al. Upper limit map of a background of gravitational waves. Technical Report astro-ph/0703234v1, arXiv, 2007-03-09.

[3] B. Abbott, R. Abbott, R. Adhikari, J. Agresti, P. Ajith, B. Allen, R. Amin, S.B. Anderson, W.G. Anderson, M. Araya, and et al. Searching for a stochastic background of gravitational waves with LIGO. Technical Report astro-ph/0608606v1, arXiv, 2006-08-28.

[4] B. Abbott and et al. Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run. *Phys. Rev. D*, 76(8):082001, 2007.

[5] B. Abbott et al. *Phys. Rev. Lett*, 102(111102), 2009.

[6] B.l Abbott et al. *Phys. Rev. D*, 76(082001), 2007.

[7] R. Adhikari. *Sensitivity and Noise Analysis of 4 km Laser Interferometric Gravitational Wave Antennae*. PhD thesis, Massachusetts Institute of Technology, 2004.

[8] B. Allen and A.C. Ottewill. Detection of anisotropies in the gravitational-wave stochastic background. *Phys. Rev. D*, 56(2), 1997.

[9] B. Allen and J.D. Romano. Detecting a stochastic background of gravitational radiation: signal processing strategies and sensitivities. *Phys. Rev. D*, 59:102001, 1999.

[10] J.N. Bahcall. Solar neutrinos. i. theoretical. *Phys. Rev. Lett.*, 12(11):300, 1964.

[11] J.N. Bahcall. Astrophysical neutrinos: 20th century and beyond. *Nucl. Phys. B (Proc. Suppl.)*, 91:9, 2001.

[12] S. W. Ballmer. *LIGO interferometer operating at design sensitivity with application to gravitational radiometry.* PhD thesis, Massachusetts Institute of Technology, 2006.

[13] S.W. Ballmer. A radiometer for stochastic gravitiatonal waves. *Class. Quantum Grav.*, 23:S179, 2006.

[14] C. Beal and R.M. Wilson. A report on the research and development of the e-bubble collaboration. Web: http://www.nevis.columbia.edu/reu/2005/ebub.pdf, August 2005.

[15] E. Black. Notes on the pound-drever-hall technique. Technical Report T980045-00-D, Laser Interferometer Gravitational Wave Observatory, April 1998.

[16] J.A.R Caldwell and J.P Ostriker. *ApJ*, 251(61), 1981.

[17] S.M. Carroll. Lecture notes on general relativity. Technical Report gr-qc/9712019v1, arXiv.

[18] Sheon S. Y. Chua. *In preparation*. PhD thesis, Australian National University, In preparation.

[19] S.S.Y. Chua, S. Dwyer, L. Barsotti, D. Sigg, R.M.S. Schofield, V.V. Frolov, K. Kawabe, M. Evans, G.D. Meadors, M. Factourovich, R. Gustafson, N. Smith-Lefebvre, C. Vorvick, M. Landry, A. Khalaidovski, M.S. Stefszky, C.M. Mow-Lowry, B.C. Buckler, D.A. Shaddock, P.K Lam, R. Schnabel, N. Mavalvala, and D.E. McClelland. Impact of backscattered-light in a squeezing-enhanced interferometric gravitational-wave detector. In preparation.

[20] V. Dergachev. *An all-sky search for continuous gravitational waves*. PhD thesis, University of Michigan, 2009.

[21] D. Deschrijver et al. *IEEE Microwave Wire. Comp. Lett.*, 18(6), 2008.

[22] Katherine Laird Dooley. *Design and performance of high laser power interferometers for gravitational-wave detection*. PhD thesis, University of Florida, 2011.

[23] S. Dwyer, L. Barsotti, S.S.Y. Chua, M. Evans, M. Factourovich, D. Gustafson, T. Isogai, K. Kawabe, A. Khalaidovski, P.K. Lam, M. Landry, N. Mavalvala, D. McClelland, G.D. Meadors, C.M. Mow-Lowry, R. Schabel, N. Smith-Lefebvre, M. Stefszky, C. Vorvick, and D. Sigg. Squeezed quadrature fluctuations in a gravitational wave detector using squeezed light. In preparation.

[24] Sheila E Dwyer. *Quantum noise reduction using squeezed states in LIGO*. PhD thesis, Massachusetts Institute of Technology, February 2013.

[25] Nickolas Fotopoulos. Searching for stochastic gravitational waves using co-located interferometric detectors. Master's thesis, Massachusetts Institute of Technology, September 2006.

[26] T.F. Fricke, N.D. Smith-Lefebvre, R. Abbott, R. Adhikari, K.L. Dooley, M. Evans, P. Fritschel, V.V. Frolov, K. Kawabe, J.S. Kissel, B.J.J. Slagmolen, and S.J. Waldman. DC readout experiment in Enhanced ligo. *Classical and Quantum Gravity*, 29(6):065005, 2012.

[27] Tobin Thomas Fricke. *Homodyne detection for laser-interferometeric gravitational wave detectors*. PhD thesis, Louisiana State University, December 2011.

[28] Peter Fritschel, Rolf Bork, Gabriela González, Nergis Mavalvala, Dale Ouimette, Haisheng Rong, Daniel Sigg, and Michael Zucker. Readout and control of a power-recycled interferometric gravitational wave antenna. *Appl. Opt.*, 40(28):4988–4998, 2001.

[29] Evan A. Goetz. *Gravitational wave studies: detector calibration and an all-sky search for spinning neutron stars in binary systems*. PhD thesis, University of Michigan, 2010.

[30] D.J. Griffiths. *Introduction to Electrodynamics*. Prentice Hall, Upper Saddle River, N.J., third edition, 1999.

[31] B. Gustavsen. *IEEE Trans. Power Delivery*, 21(3), 2006.

[32] B. Gustavsen and A. Semlyen. *IEEE Trans. Power Delivery*, 14(3), 1999.

[33] J. Kissel. Mich and prc coupling into darm. Web: http://ilog.ligo-wa.caltech.edu/ilog/pub/ilog.cgi?group=detector&date_to_view=06/16/2009&anchor_to_scroll_to=2009:06:16:23:51:59-kissel, June 2009.

[34] Jeffrey S. Kissel. *Calibrating and improving the sensitivity of the LIGO detectors*. PhD thesis, Louisiana State University, December 2010.

[35] R.B. Leighton, C.D. Anderson, and A.J. Seriff. The energy spectrum of the decay particles and the mass and spin of the mesotron. *Phys. Rev.*, 75(9):1432, 1949.

[36] M. Maggiore. Gravitational wave experiments and early universe cosmology. Technical Report gr-qc/990901v4, arXiv, 2000-02-06.

[37] N. Mavalvala. *Alignment issues in laser interferometer gravitational-wave detectors.* PhD thesis, Massachusetts Institute of Technology, 1997.

[38] C.F. McKee and J.P. Ostriker. *ApJ*, 218(148), 1977.

[39] G.D. Meadors. Study of the LHO 4K recycling cavity sideband and carrier response to excitation and perturbations. LIGO technical report: LIGO-T050276-00-I (advisor: Richard Gustafson), September 2005.

[40] G.D. Meadors. E-bubble: seeing the sun's center. Columbia University technical report, web: http://www.nevis.columbia.edu/reu/2006/Meadors_Report.pdf (advisor: Jeremy Dodd), August 2006.

[41] G.D. Meadors. Searching for a gravitational wave stochastic background. LIGO technical report (advisors: Vuk Mandic, Stefan Ballmer), October 2007.

[42] G.D. Meadors. Re-searching galactic structure with Reed's radio telescope. Reed College bachelor's thesis (advisor: Robert Reynolds), May 2008.

[43] A.A. Michelson. *The velocity of light.* (U of Chicago P, Chicago, 1902).

[44] C.W. Misner, K.S. Thorne, and J.A. Wheeler. *Gravitation.* Freeman, New York, 1970.

[45] P.J. Mohr and B.N. Taylor. CODATA recommended values of the fundamental physical constants: 1998. *Rev. Mod. Phys.*, 72(2):351, 2000.

[46] P.F. Muciaccia, P. Natoli, and N. Vittorio. Fast spherical harmonic analysis: a quick algorithm for generating and/or inverting full-sky, high-resolution cosmic microwave background anisotropy maps. *Astrophys. J.*, 488:L63, 1997.

[47] R. Prix. *Neutron stars and pulsars*, page 651. Springer, Berlin, 2009.

[48] M. Rakhmanov and R. Savage. Measurement of dynamic responses of the 4-km ligo fabry-perot arm cavities. Technical Report G040045-00-Z, Laser Interferometer Gravitational Wave Observatory, February 2004.

[49] M. Rakhmanov, R.L. Jr. Savage, D.H. Reitze, and D.B. Tanner. Dynamic resonance of light in fabry-perot cavities. Technical Report P010013-00-D, Laser Interferometer Gravitational Wave Observatory, January 2001.

[50] P. Saulson. *Fundamentals of interferometric gravitational wave detectors.* World Scientific, Singapore, 1994.

[51] Nicolás de Mateo Smith-Lefebvre. *Techniques for improving the readout sensitivity of gravitational wave antennae.* PhD thesis, Massachusetts Institute of Technology, June 2012.

[52] The LIGO Scientific Collaboration. Enhancement of the astrophysical reach of a gravitational wave observatory using squeezed states of light. In preparation.

[53] The LIGO Scientific Collaboration. LALApps repository. Web: http://www.lsc-group.phys.uwm.edu/daswg/.

[54] The LIGO Scientific Collaboration. A gravitational-wave observatory operating beyond the quantum shot-noise limit. *Nature Physics*, 7(12):962–965, 2011.

[55] The LIGO Scientific Collaboration and The Virgo Collaboration. An upper limit on the stochastic gravitational-wave background of cosmological origin. *Nature*, 460:990–4, 2009.

[56] S. Waldman and S. Chua. eligo hanford output mode cleaner repair. Technical Report T1100562, LIGO, 2011.

[57] Joel M. Weisberg and Joseph H. Taylor. Relativistic binary pulsar B1913+16: Thirty years of observations and analysis. In *Aspen Winter Conference on Astrophysics: Binary Radio Pulsars*, Aspen, July 2004.

[58] R. Weiss. The LIGO interferometers: how they work and how well they work. Technical Report G030024-00-D, Laser Interferometer Gravitational Wave Observatory, February 2003.

ABSTRACT

Directed searches for continuous gravitational waves from spinning neutron stars in binary systems

by

Grant David Meadors

Chair: John Keith Riles

Gravitational wave (GW) detectors would reveal the universe in a way unlike any existing kind of telescope. These waves, predicted by general relativity, radiate from accelerating gravitational quadrupoles, such as black holes, neutron stars and the Big Bang. Indirect evidence for GW comes from the work of Hulse and Taylor; the Laser Interferometer Gravitational Wave Observatory (LIGO) and allies seek to observe gravitational waves directly. In this thesis, I discuss the goals and history of the LIGO project and the theory and practice of its operation, including my contributions to the scientific collaboration in feedforward signal filtering, directed binary pulsar star searches, and scientific outreach and education to the next generation of young scientists. (Probably conclude with a sentence describing numerical results of my projects, when known.)