Searching for Gravitational Radiation

Richard Gustafson, Keith Riles

University of Michigan

The Seventh LIGO
Program Advisory Committee
(PAC7) Meeting

M.I.T., Cambridge, Massachusetts

November 18-19, 1999

LIGO-G990142-00-Z

Presentation Organization

- Introduction – Overview of Michigan Program
  Gustafson

- Results – What we've done; what we've learned
  - Research at the 40 Meter

  Gustafson

- Proposal – What we will do
  - LIGO Detector Characterization
  - Search for Periodic Sources

  Riles

- Summary
  Riles

Overview of Group and Goals

Michigan Gravitational Wave Group:*

Dick Gustafson	Senior Research Scientist	3 Years @ 40 Meter
Keith Riles	Associate Professor	1 Year @ 40 Meter (sabbatical
David Chin	Graduate Student	
Justin Dombrowski	Undergraduate	3 months @ 40 Meter
Joseph Marsano	Undergraduate	

Former member of group (now at M.I.T.):

Jamie Rollins	Undergraduate	7 months @ 40 Meter (senior thesis research)

Long Term Goals

- Apply expertise gained at 40 Meter to LIGO research
- Carry out systematic Detector Characterization
- Search for gravitational radiation: Periodic Sources

*Supported by NSF PHY9601197 (9/96)

The Search for Gravitational Radiation with Laser Interferometers and Improvements to the LIGO 40-meter Laboratory

Jameson Graef Rollins

In partial fulfillment
of the requirements
for the degree of
Bachelors of Science,
Physics

University Of Michigan
Ann Arbor, Michigan

Faculty advisors:
Prof. J. Keith Riles
Dr. Richard Gustafson

April 16, 1999

(co-awarded prize for outstanding Michigan undergraduate thesis in 1999)

Recycling Demonstration Experiment (RDE)

Major LIGO R&D milestone:

Demonstration of Recycled Michelson Fabry-Perot Interferometry with suspended test masses

First Lock: November 1997

40 Meter Crew of Last Several Years

Now working elsewhere:

F. Raab, M. Coles, L. Sievers, S. Kawamura,
R. Spero, B. Ware J. Logan (led RDE)

Active in last year of operation:

N. Mavalvala. W. Kells, S. Vass,
R. Gustafson. K. Riles, J. Rollins, J. Dombrowski

Research at the 40 Meter

Recycling Demonstration Experiment

I) First locks - 1997-98
Studies – Alignment
Mysteries

II) Michigan Summer 1999 (April-October)

- Implement & test new ℓ^+ carrier-independent Recycling Mirror (RM) servo
- Improve locking & running robustness, noise
- Data runs (recorded):

TAMA – Sept 17-19	Three 8-hour runs
MICH – Sept 30 - Oct 4	$\approx$100 hours

Research at the 40 Meter

Recycling Demonstration Experiment

- Gustafson, Riles & Rollins supported nearly every aspect of recycling demonstration
- Introduced many new diagnostics / monitors
- Designed & implemented beam shutters & selective attenuator
- Added auxilliary sideband capability
- Replaced / added amplifiers, RF equipment
- Resolved Pockels cell degradation
- Investigated servo instabilities
- Implemented new servos (see below)

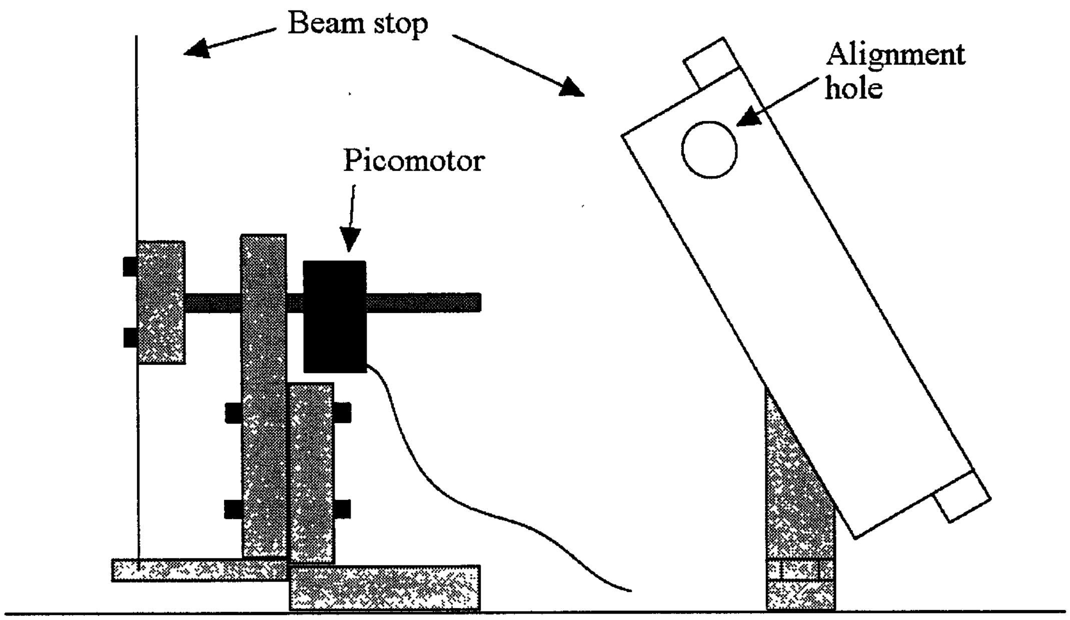
Research at the 40 Meter

Recycling Demonstration Experiment

- Supported Wave Front Sensing (WFS) control of test mass orientation
- Implemented digital WFS control
- Shook down data acquisition system
- Shook down & augmented data viewer with
  - 2-channel correlation analysis
  - Real-time graphics manipulation
  - Time-frequency analysis (*e.g.*, waterfall plots)

Overview of Group and Goals

Beam stop / selective attenuator:



- J. Rollins: Fabricated 9/98
- Four built and vacuum-prepped
- Installed 2/99
- Extremely useful

Research at the 40 Meter

Michigan Summer at 40 Meter (May-Oct 1999)

- New ℓ^+ carrier-independent RM servo scheme
  $\Longrightarrow$ Tested, proven, commissioned
- Improved operational performance of 40 Meter
- Recorded data in LIGO-like configuration:
  - >100 channels (16 kHZ, 16 Hz)
  - Coincidence run with TAMA – Sept 17-19
  - Second run – Sept 30 - Oct 4

Research at the 40 Meter

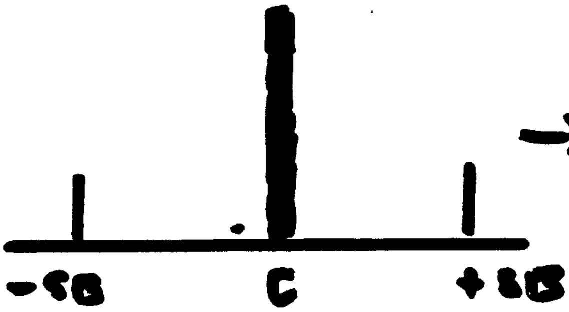
Development of Alternative Michelson Cavity Servos
("ℓ^+", "ℓ^-" error signals)

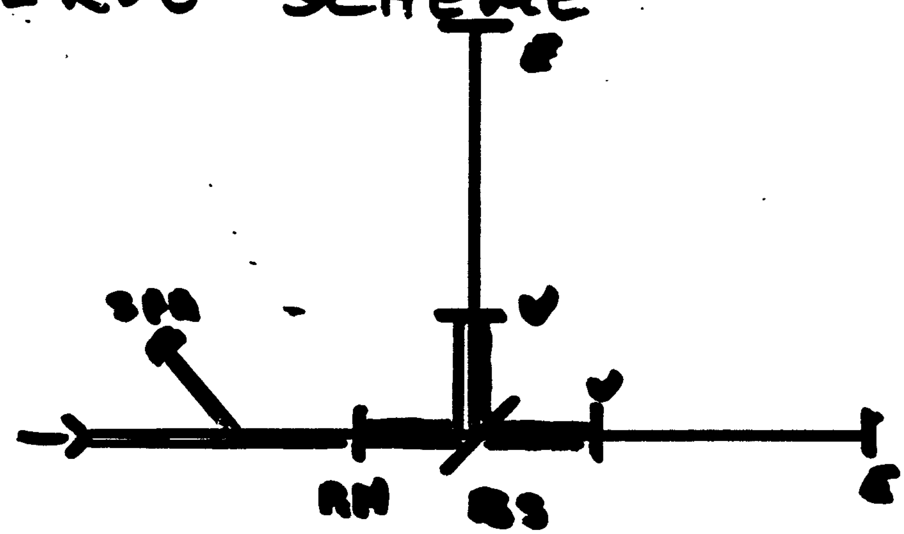
- Default (LIGO) recycling mirror and beam splitter servo error signals exploit same phase modulation used for arm length servos
- Two major potential drawbacks:
  - Relies on heirarchical servo scheme to separate arm cavity error signal from Michelson cavity
  - Relies on sign-changing error signal during lock acquisition
- Alternative scheme: Amplitude Modulation
  $\Longrightarrow$ "Carrier-independent"
  $\Longrightarrow$ Decouples arms / Michelson cavity
- Developed & tested at 40 Meter as both diagnostic and run-time option
- ℓ^+ found especially useful & robust in data runs

Applicable to LIGO I (see below)

NEW ℓ_+ Recycling MIRROR SERVO SCHEME

STANDARD SCHEME:





- ℓ_+ RESONANT 32 MHz SIDEBANDS HAVE RECYCLING OPTICAL CAVITY ERROR ℓ_+
- THESE BEAT w CARRIER TO GIVE RF SIGNAL WITH ℓ_+ PHASE ERROR @ 32 MHz
- BUT THE CARRIER LIGHT CAN BE GARBAGED UP WITH ARM L_+ PHASE ERROR:

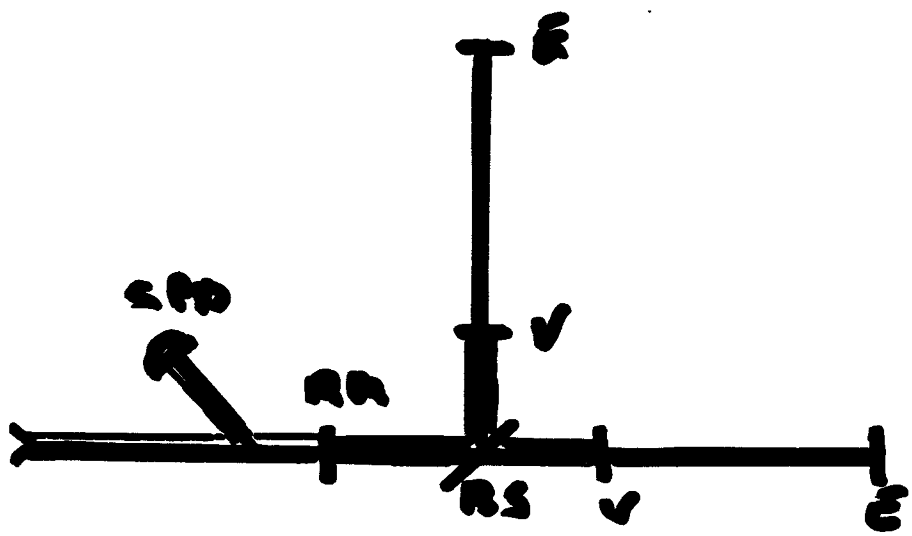
$$S_{OPD} \sim 1\,\ell_+ + 100\,L_+$$

HOW CAN WE GET A CARRIER INDEPENDENT ℓ_+ RM SIGNAL?

GUSTAFSON

OUR SCHEME

2ND NON RESONANT SB



$$S \propto SB_{32} \times SB_{.1}$$

CATCH! $PM^-_{32} \times PM^-_{.1}$ CANCELS

$PM^+_{32} \times PM^+_{.1}$

USE AM 2nd SB : WORKS

TESTED ON 40M

COMMISSIONED

USED IN RUNNING

- OPTICS LETTER

Research at the 40 Meter

Preparing for and Taking Data

August – September 15

Reestablish locking
Work toward robustness
Get DAQ and data viewer operational (again)
First calibrated power spectrum

TAMA Coincidence Runs: Three × 8 hours

Sept 17, 18, 19: 0600-14:00 PDT
Start: $\sigma_L \approx 2 \times 10^{-17}$ m/$\sqrt{\text{Hz}}$
End: $\sigma_L \approx 1 \times 10^{-17}$ m/$\sqrt{\text{Hz}}$
Lock periods: 10-30 min at night; 1-20 min in day
Lock duty factor: >0.9 at night; 0.6-0.8 in day

Research at the 40 Meter

More Data Running

September 20–30:

Retune servos
Balance actuator drives
Automate acquire / run control

September 30 – October 4 ($\approx$100 hours running):

Unattended Running
Readjusted laser power / pointing on 12-hour basis
$\sigma_L \approx 4 \times 10^{-18}$ m/$\sqrt{\text{Hz}}$
Lock periods: $\approx$hours at night; 0.2-1.0 hour in day
Lock duty factor: >0.95
Lock breaks: $\approx$ seconds

Summary:

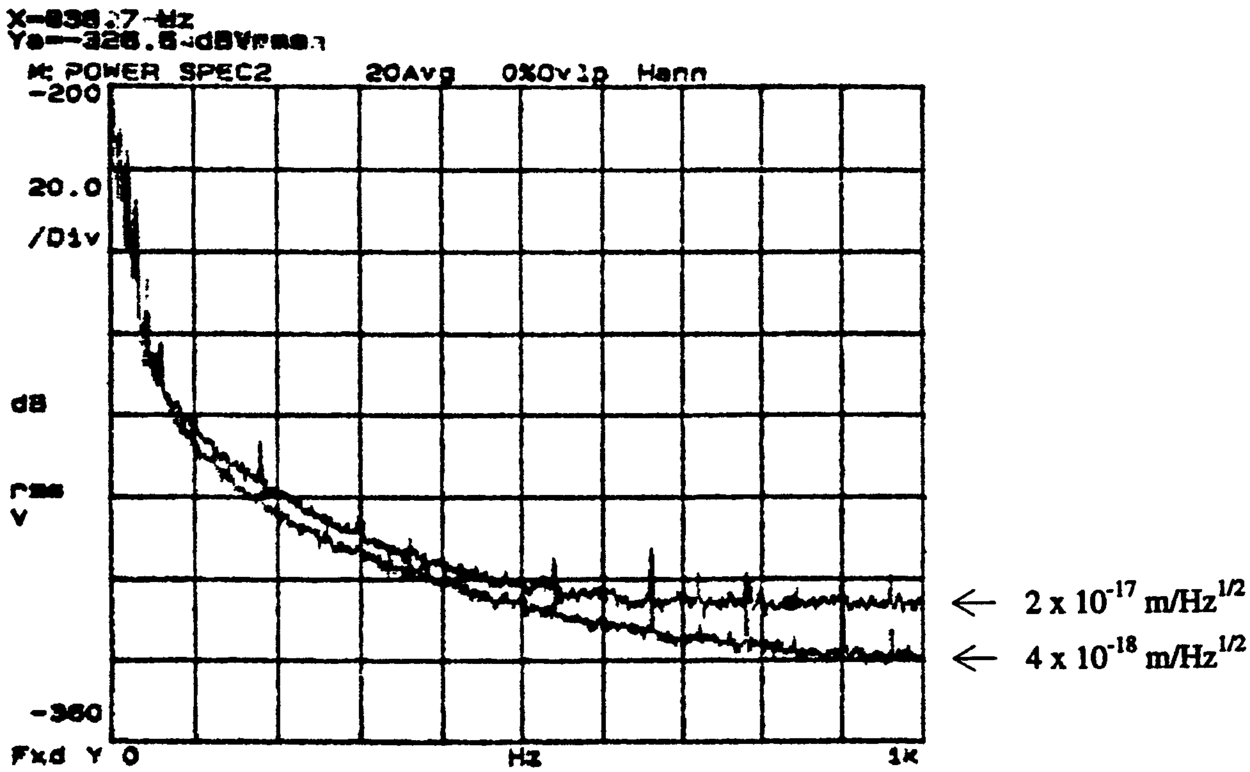
- Two successful running periods
- >100 channels recorded in LIGO-like configuration (Recycled Fabry-Perot Michelson Interferometer)

Research at the 40 Meter

Recording of Data in Fall 1999

- Summer 1999 devoted to shaking down 40 Meter (and servo development)
- Fragile instrument evolved into high-duty-cycle machine
- Permitted useful data collection in fall 1999:
  - 1st run: Sept. 17-21 (in coincidence with TAMA 300)
    $\sigma_L \approx 2 \times 10^{-17}$ m/$\sqrt{\text{Hz}}$ @ 1 kHz
  - More tweaking & tuning
  - 2nd run: Sept. 30 - Oct 4
    $\sigma_L \approx 4 \times 10^{-18}$ m/$\sqrt{\text{Hz}}$ @ 1 kHz
    $\Longrightarrow \sigma_h \approx 1 \times 10^{-19}$ (see power spectra)
- Further improvements possible – but Hanford beckons!
- TAMA coincidence run coordinated by LIGO / TAMA management to pioneer international collaboration in analysis of gravitational wave interferometer data
  $\Longrightarrow$ Provides first test of coincidence analysis algorithms
- Analysis by subset of LIGO / TAMA scientists

Calibrated power spectra from Fall 1999 data runs:



$$\Longrightarrow \quad \sigma_h \quad \approx \quad 1 \times 10^{-19} \quad @\, 1\text{kHz}$$

Research at the 40 Meter

Analysis Plans for 40 Meter Data

Recent data provides algorithm testbench for

- Detector characterization
- Gravitational radiation search

Detector characterization:

- Data taken in fully recycled LIGO-like configuration
- More than 100 daq channels recorded
- Of general interest to LSC physicists (see below)
- Allows correlation studies that were impractical online:
  - Between common mode arm & Michelson servos
  - Between longitudinal and orientational servos

Astrophysics search

- Michigan group active in LIGO search for periodic sources (see below)
- Recent 40 Meter data has limited sensitivity, but provides real-world test of algorithms (search and discrimination)
- Plan to carry out formal search through to published limits on CW sources

Research at the 40 Meter

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Detector Characterization

Data analysis requires systematic understanding and characterization of the detector:

- Response function
- Noise behavior
- Sensitivity to environment

Performance characteristics include:

- Power spectra
- Probability distributions
- Stationarity
- Transient statistics

Characterization carried out at several levels

- Online diagnostics - passive or invasive (stimulus-response)
- Offline, on-site monitoring - Data Monitor Tool
- Off-site monitoring and instrument modelling

Detector Characterization

- Riles chairs LSC working group dedicated to LIGO Detector Characterization
  - LIGO Liaison – Daniel Sigg (LIGO-LHO)
  - Subgroup leaders:
    * Transient Analysis – Fred Raab (LIGO-LHO)
    * Data Set Reduction – Jim Brau (U. Oregon)
    * Data Set Simulation – Sam Finn (Penn. State U.)

- Main responsibilities of chair (so far):
  - Task compilation, prioritization, coordination & volunteer recruiting
    ⇒ See summary task table
  - Meeting / teleconference organization
    ⇒ See agendas
  - Co-writing of Data Analysis White Paper
  - Web site creation & maintenance:

    `http://www-mhp.physics.lsa.umich.edu/~keithr/lscdc/home.html`

Detector Characterization

LSC Detector Characterization Tasks

Summary of task categories, priorities & active institutions†

Task Category	Priority	Institutions
Online Diagnostics & Measurements	1, 3	CIT LSU MIT Mich
Offline Monitoring Infrastr.	1	CIT
Environ. Monitoring (hardware)	1, 2, R	CIT LSU MIT LaTech Oreg PSU
Line Noise Identification	1	AEI ANU Dublin Flor LSU Mich PSU Wisc
Instrumental Correlations	1	Dublin PSU Wisc
Enviromental Correlations	1, R	LSU LaTech Oreg PSU Syr
IFO State Summaries	1, 2, 3	ANU CIT LSU Flor Mich PSU Wisc
IFO–IFO Correlations	3	PSU
Transient ID / Analysis (instr.)	1, 2, 3	AEI IUCAA MIT Mich PSU
Transient ID / Analysis (instr.)	2, 3	CIT Oreg
Time / Frequency Analysis	2, 3	CIT Flor
Data Set Reduction	1, 2	Flor Oreg
Phenomenological Modelling	2	MIT PSU
End-To-End Modelling	1, 2	CIT Flor PSU Pisa

†Details can be found at:
`http://www-mhp.physics.lsa.umich.edu/~keithr/lscdc/tasktables.html`

Detector Characterization

Agenda of March 1999 Detector Characterization Meeting (Gainesville, Florida)

9:00-10:30 - Session 1

10'	K. Riles / D. Sigg	Introduction
20'	B. Allen	Existing data monitoring tools (GRASP)
10'	W. Hua	Violin Modes of the 40 Meter
10'	All	Discussion
30'	D. Sigg	LIGO Global Diagnostics System
10'	All	Discussion

10:30-10:45 - Coffee Break

10:45-12:00 - Session 2

15'	M. Coles	Environmental monitoring at Livingston
15'	W. Johnson	Electromagnetic field monitoring
5'	All	Discussion
15'	W. Majid	LIGO algorithm library
15'	J. Zweizig	LIGO Data Monitor Tool
10'	All	Discussion

12:00-1:00 - Lunch

1:00-2:30 - Session 3

20'	S. Finn	Existing data monitoring tools (MATLAB)
15'	F. Raab	Transient analysis subgroup plans
15'	J. Brau	Data set reduction subgroup plans
15'	S. Finn	Data set simulation subgroup plans
15'	K. Riles / D. Sigg	Performance characterization plans
10'	All	Discussion

2:30-2:45 - Coffee Break

2:45-3:45 - Session 4

15'	H. Yamamoto	Overview of End-to-End Model
15'	B. Bhawal	End-to-End optics implementation
15'	S. Klimenko	End-to-End input optics modelling
15'	All	Discussion

Detector Characterization

Agenda of June 1999 Detector Characterization Teleconference

1) Data monitor tool status (Zweizig)

2) Algorithm library status (Majid)

3) Performance characterization status (Riles)

4) Transient analysis status (Raab)

5) Data reduction status (Brau)

6) Data simulation status (Finn)

7) Data tape technology (Sigg)

8) Brief discussion of just-released detchar contribution to
   analysis white paper (click here for latest draft)

Detector Characterization

Agenda(1) of July 1999 Detector Characterization Meeting (Stanford, California)

Monday afternoon 5:00-6:00

10'	K. Riles & D. Sigg	Introduction
15'	J. Zweizig	Data Monitor Tool (DMT) update
30'	All	Discussion on DMT and algorithms

Tuesday afternoon 1:00-3:00

10'	K. Riles	Performance characterization update
10'	F. Raab	Transient analysis subgroup update
10'	D. Strom	Data set reduction subgroup update
15'	S. Finn	Data set simulation subgroup update (5' on Thermal Noise of Violin Modes)
15'	All	Discussion
15'	H. Yamamoto	End-to-End Model update
20'	R. Schofield	Ambient and diagnostic magnetic Fields measured inside of a BSC vacuum chamber at Hanford
10'	D. Sigg & E. Daw	On-site seismic correlations
15'	All	Discussion

Detector Characterization

Agenda(2) of July 1999 Detector Characterization Meeting (Stanford, California)

Wednesday morning 9:00-11:00

15'	G. Gonzalez & S. Finn	Statistical properties of the detector's power spectrum
15'	S. Mohanty	A non-parametric method for detecting non-stationarity
10'	S. Mukherjee	Simultaneous dynamical tracking and removal of multiple violin modes
15'	B. Whiting	Progress in noise characterization
10'	S. Klimenko	Input optics simulation status
10'	N. Simicevic	Seismic measurements at Livingston
15'	All	Discussion of favored data tape technology
30'	All	Discussion of working group contribution to LSC Data Analysis White Paper

Detector Characterization

Specific responsibilities of the Michigan group

- Performance characterization, transient analysis software
  - Operational state
  - Stationarity / non-Gaussian behavior
  - Onset of servo instabilities

- On-site diagnostics interpretation & enhancement
  - Liaisons to LSC working group (Gustafson & students)
  - Direct feedback on diagnostic software utility & veracity

- Systemic noise characterization, investigation & reduction
  - Track down residual 60 Hz & harmonics in electronics (pin down elusive sources with portable 65 Hz power)
  - Attack RF leakage
  - Attack up- and down-conversion of out-of-band noise into LIGO GW band
  - Attack GW channel noise coupled from other channels (many software tools available soon for detection)

Detector Characterization

- Diagnostic / Alternative servos for LIGO I
  - Investigate analytically benefits / drawbacks of AM-based ℓ^+ (and ℓ^-) servos developed at 40 Meter
  - Investigate nuts 'n bolts feasibility of implementation
  - Implement new servos as diagnostics
  - Perhaps migrate diagnostic to default

- Additional LIGO control innovations
  - "Lock stepper" – Allows graceful movement from extreme fringe (preferred by lock acquisition) to central (relaxed) fringe
    (LIGO I)
  - "True ℓ^- Beam Splitter" – Modified beam splitter design to cleanly orthogonalize differential and common mode servo actuation in Michelson cavity
    (Advanced LIGO)

Search for Periodic Sources

Most promising periodic source:

Rotating Neutron Stars

Requires non-axisymmetric star or wobbling spin axis:

- Density perturbation (*e.g.*, trapped magnetic fields)
- Crustal cooling history
- Accretion from binary companion
- Driven excitation of normal modes

Search for Periodic Sources

Serious technical difficulty: Doppler motion

- Frequency modulation from earth's rotation ($\frac{v}{c} \approx 10^{-6}$)
- Frequency modulation from earth's orbit ($\frac{v}{c} \approx 10^{-4}$)

Additional, related complications:

- Daily amplitude modulation of antenna pattern
- Spin-down of source
- Orbital motion of sources in binary systems

Modulations / drifts complicate analysis enormously:

- Simple Fourier transform inadequate
- Every sky direction requires different demodulation
  $\Rightarrow$ All-sky survey = Formidable / intriguing challenge

But two substantial benefits come from these complications:

- Reality of signal confirmed by need for corrections
- Corrections give precise direction of source

Search for Periodic Sources

Michigan Role in LIGO Astrophysics

Longer term plans:

- Collaborate with other LSC physicists in search for CW sources:
  - Known pulsars
  - Promising sky patches (*e.g.*, galactic center)
  - All-sky survey

- Lead search for periodic transients (*e.g.*, "kissing" high-ellipticity binaries)

Summary

Major goals at 40 Meter accomplished:

- Acquired interferometer expertise in assisting Recycling Demonstration Experiment
- Improved 40 Meter instrumentation and noise
- Collected data in LIGO-like configuration (Bonus: TAMA coincidence running)

Research in progress and planned:

- Analysis of 40 Meter data as exercise in detector characterization and astrophysical source search
- Continue leading role in LSC detector characterization, including software, on-site noise studies, diagnostics, and servo control investigations & development
- Collaborate in LSC effort to find and study periodic sources of gravitational radiation

Concluding Remarks

- LIGO Laboratory thinly stretched in coming years:
  - LIGO I operation
  - LIGO I data analysis
  - LIGO II R&D, engineering & construction
- Experienced LSC physicists will be needed
- We have attained hands-on familiarity with the 40 Meter and have made it better
- We expect to gain same familiarity with LIGO and to make it better
- Improving interferometer performance is essential and an appealing challenge we welcome

Concluding Remarks

- However, we are not primarily interferometer scientists
- We are driven by the astrophysics
- Our goal is discovery & investigation of gravitational waves
- Our approach is flavored by our high energy experience:
  - Major contributions to instrumentation
  - Data analysis taking into account detailed instrumental idiosynchrasies

We look forward to gravitational wave physics