Gravity Wave Detection and Astrophysics

Richard Gustafson, Keith Riles & Jamie Rollins

University of Michigan

The Fifth LIGO
Program Advisory Committee
(PAC5) Meeting

Caltech - Pasadena, California

November 16-17, 1998

LIGO-G980139-00-M

Presentation Organization

- Introduction and overview of Michigan program
  H.R. Gustafson

- 40 Meter research status, accomplishments & plans; Search for periodic gravitational radiation sources
  – K. Riles

- Noise Studies and Advanced Diagnostics & Controls; Summary
  – H.R. Gustafson

Overview of Group and Goals

Michigan Gravity Wave Group*

Dick Gustafson	Senior Research Scientist	2 Years @ 40 Meter
Keith Riles	Associate Professor	1 Year @ 40 Meter (sabbatical)
Jamie Rollins	Undergraduate	7 months @ 40 Meter (thesis work)

Goals

- Analyze 40-Meter Data for Periodic Sources
- Analyze Early LIGO Data for Periodic Sources
- Develop Search Algorithms/Engines for the All Sky Survey Problem
- Study Systemic Noise in LIGO I for Advanced LIGO
- Develop New Diagnostics, Controls, and Control Algorithms for LIGO

*Supported by NSF PHY9601197 (9/96)

Michigan Research at the 40 Meter

Summary of research:

- We have supported the 40 Meter Recycling Demonstration Experiment
- We have supported and now lead the demonstration of wave front sensing (WFS)
- We will take responsibility for data taking in the full recycling configuration

Recent status of the 40 Meter

The good news:

- Achieved recycled, fully locked state
- Prototypical DAQ and data display system in place
- Wave front sensing control demonstrated on several suspended test masses (old & new suspensions)

Michigan Research at the 40 Meter

The bad news:

- Noise performance worse than previous best (non-recycled with higher arm finesse)
- Noise varies from stationary to transient to glitches
- Large intensity fluctuations observed in full, double-arm lock
- Unexpected servo signs in full lock (IFO coupling issue)
- Stable lock requires deliberate misalignment of one test mass orientation
- Chronic *in-vacua* Pockel cell failures (Cell needed for RF phase modulation)

We have helped to understand and fix many of these problems / puzzles

Michigan Research at the 40 Meter

The 40 Meter Crew in 1998:

Caltech

Mark Coles[1], Bill Kells, Jenny Logan[2],
Nergis Mavalvala[3], Steve Vass

U. Michigan

Dick Gustafson, Keith Riles, Jamie Rollins[4]

Short-term Visitors

Raffaele Flaminio (Virgo), Koji Arai (Tama)

[1]Departed in June for Livingston

[2]Departed in September for JPL

[3]Began 40M work in September

[4]Began 40M work in May

Michigan Research at the 40 Meter

Immediate 40 Meter goals:

- Complete demonstration of recycling
- Implement simultaneous wave front sensing control of end masses and recycling mirror
- Identify and fix worst noise sources
- Take data

Michigan Research at the 40 Meter

Summary of Michigan contributions to 40 Meter:

- Diagnosis / elimination of various electronic noise sources*
- Modification of analog electronics modules for improved performance / sensitivity
- Shakedown of data acquisition system
- Enhancement of data display program
- Commissioning of digital control system for wave front sensing
- Implementation of wave front sensing of end masses (in progress)
- Investigation of Pockel cell failure
- Design / fabrication of beam shutter / locator devices*
- General support of recycling demonstration experiment (day-to-day operation / maintenance, measurements)

* To be discussed below by Gustafson

Michigan Research at the 40 Meter

Enhancements to data display program
(now running at Hanford)

- Trigger
- Two-channel correlation displays
- Real-time graphics manipulation
- Time frequency analysis (waterfall, carpet plots)

Commissioning of digital WFS control

- Rewrote MIT control software for 40 Meter configuration
- Investigated maximum sampling rate
- Implemented pole/zero, double pole/zero, resonant gain filters
- Created EPICS-based control panel for setting pedestals, gains, offsets, filter parameters, etc. and for obtaining status, numerical readings, etc.

Michigan Research at the 40 Meter

Implementation of wave front sensing

- Demonstrated simultaneous digital WFS control of pitch & yaw for beam splitter and recycling mirror
- Demonstrated digital WFS control of east end yaw
  - Complicated by old suspensions, 2nd yaw resonance
  - Can run WFS in place of optical lever control or in parallel
- Now implementing for pitch and for south end mass (at lower priority)
- Hope to substantially kill large intensity variations in arm light due to differential yaw / pitch fluctuations

Investigation of Pockel cell failures

- Strong suspicion: chronic failure due to heating in vacuum
- Heating caused by RF modulation
- Short-term solution:
  - Reduce modulation index when running
  - Turn off modulation at night
    $\Rightarrow$ degradation rate much reduced
- Long-term solution: heat-conducting substrates (prototype ready for testing at next venting)

Michigan Research at the 40 Meter

Remarks

- We have attained hands-on familiarity with the 40 Meter
- We understand the interferometer and its control
- Improving interferometer performance is essential and is an appealing challenge we welcome
- But we are not primarily interferometer scientists

- We are driven by the astrophysics
- Our goal is discovery & investigation of gravity waves
- Our approach is flavored by our high energy experience:
  - Major contributions to instrumentation
  - Data analysis taking into account detailed instrumental idiosynchrasies

Michigan Research at the 40 Meter

Analysis Hopes / Plans

- Record ~1-2 weeks recycling-configuration data by end of 1998 with all (≈130) DAQ channels active
- Characterize data – Identify:
  - Pathologies
  - Noise sources
  - Correlated channels
- Search in data for periodic gravity wave sources
  - Exercise in analyzing real data
  - Exercise in developing algorithms
  - No signal expected
  - But interesting broadband limits possible

LIGO Research at Michigan

Plans for Long Term LIGO Research in Ann Arbor

- Wrap up 40 Meter analysis
- Search LIGO I data for periodic sources
- Develop advanced wave front sensing for advanced LIGO

Addition of postdoc to group essential to these efforts

Search for Periodic Sources

Most promising periodic source:

Rotating Neutron Stars

But axisymmetric object rotating about symmetry axis generates NO radiation

Radiation requires an asymmmetry or perturbation

- Equatorial ellipticity ("hill"):

$$h \quad \propto \quad \epsilon_e$$

- Poloidal ellipticity (natural) + wobble angle:

$$h \quad \propto \quad \epsilon_p \times \theta_W$$

(precession due to different $\vec{L}$ and $\vec{\Omega}$ axes)

Notation: henceforth $\epsilon \quad \equiv \quad \{\epsilon_e \text{ or } \epsilon_p \times \theta_W\}$

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

Possible contributions to ϵ:

- Pressure from trapped B fields $\Rightarrow$ density perturbations
- History of cooling crust (but "starquakes" force $\epsilon_e < 10^{-5}$)
- Gravitational radiation reaction
  - f modes (CFS instability, high frequency)
  - r modes (low frequency)
  - (but only in limited temperature range – short lived)
- Accretion of matter from binary companion
  - Perhaps best mechanism for sustained large ϵ
  - Can drive both ϵ_e and θ_W
  - But orbital motion complicates analysis

Search for Periodic Sources

What about millisecond pulsars?

- Old stars spun up by accretion from long-ago companion
- Now slowly spinning down
- Spin down rates constrain ϵ to be small ($<\approx 10^{-8}$)
- Long-term annealing drives ϵ downward
- Younger, longer-period stars should be less annealed
- But $\quad h \propto \Omega^2 \quad \Longrightarrow \quad$ Intrisically weaker for given ϵ

Search for Periodic Sources

Data analysis is major challenge

- Investigations by Brady *et al.*, Schutz group find that brute-force techniques severely limit integrated observing time for an all-sky search
- With forseeable computers, must invent clever algorithms
- "Heirarchical searches" (coarse scanning followed by fine scanning if signal indicated) seems reasonably promising
- Technique used so far: "pre-stretching" of data (Doppler corrections) followed by Fourier transform
- Other ideas: direct time averaging, algorithms exploiting fast DSP modules
- We believe that intimate understanding of the instrument will be essential in extracting credible signal
- We look forward to the challenge

Search for Periodic Sources

Remarks

- Have emphasized the difficulties in detecting neutron stars

- But the search is nonetheless attractive and intriguing
  - Potentially many electromagnetically quiet, undiscovered neutron stars in our galactic neighborhood
  - We simply don't know realistic values for ϵ
  - A nearby source could lie buried in the data, waiting for just the right algorithm to tease it into view

- Another potentially "periodic" source is repetitive "clicks" from kissing passes of compact stars in highly eccentric orbits about massive black holes
  - Broadband transients at rep. rates of 1-100 mHz
  - We plan to develop algorithms to undertake a search

Advanced Wave Front Sensing (WFS)

LIGO I WFS Plans

- WFS exploits interference pattern between lowest order (Gaussian) cavity mode and first-order transverse modes (*e.g.*, TEM_{10})
- LIGO I WFS based on "quadrant bullseye" segmented photodiodes
- Each DOF (pitch, yaw, curvature) effectively sensed by pair of photodiode segments
- Decoupling of effects from different mirrors accomplished via different modulation frequencies & Guoy telescopes
- Present scheme designed for 1st-order servo control of each DOF and should work fine

Advanced Wave Front Sensing (WFS)

We want to extend this technique

Why?

- Better control / diagnosis of 1st-order transverse modes
- Attack higher order modes (diagnostic, perhaps control)

How?

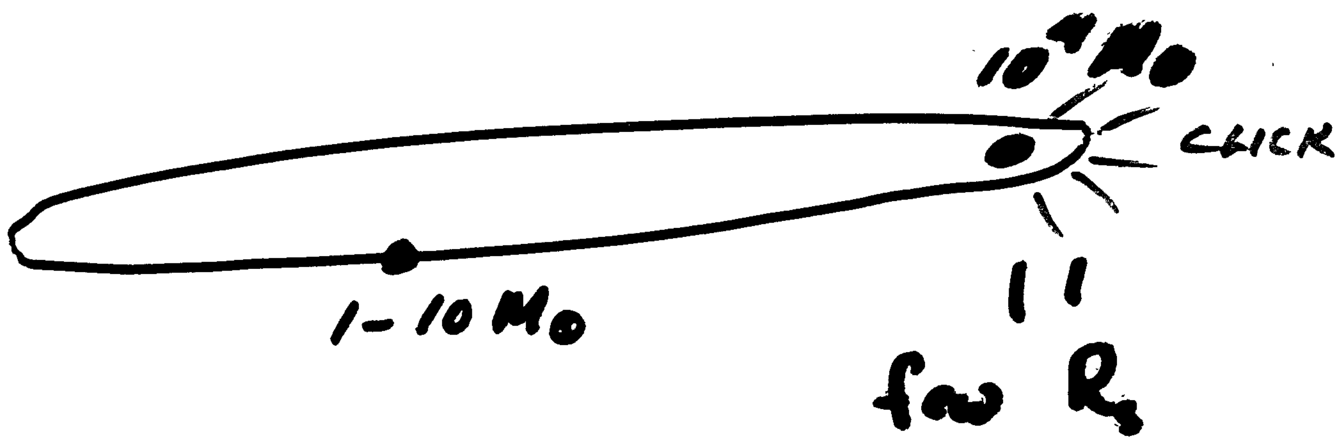
- Brute force: Increase photodiode segmentation
  (need more RF amplifiers & demodulators)
- More ambitious: True imaging system
  - Pre-sensor demodulation
  - Use CCD or active pixel sensor (APS) array for detector
- Work so far at the idea level – development needed
- But experience at the 40 Meter indicates the immense value of image information

Periodic Sources (continued)

Putative Gravity Wave Sources

HUMS	Studied, planned for
CHIRPS	Studied, planned for
CLICKS	???

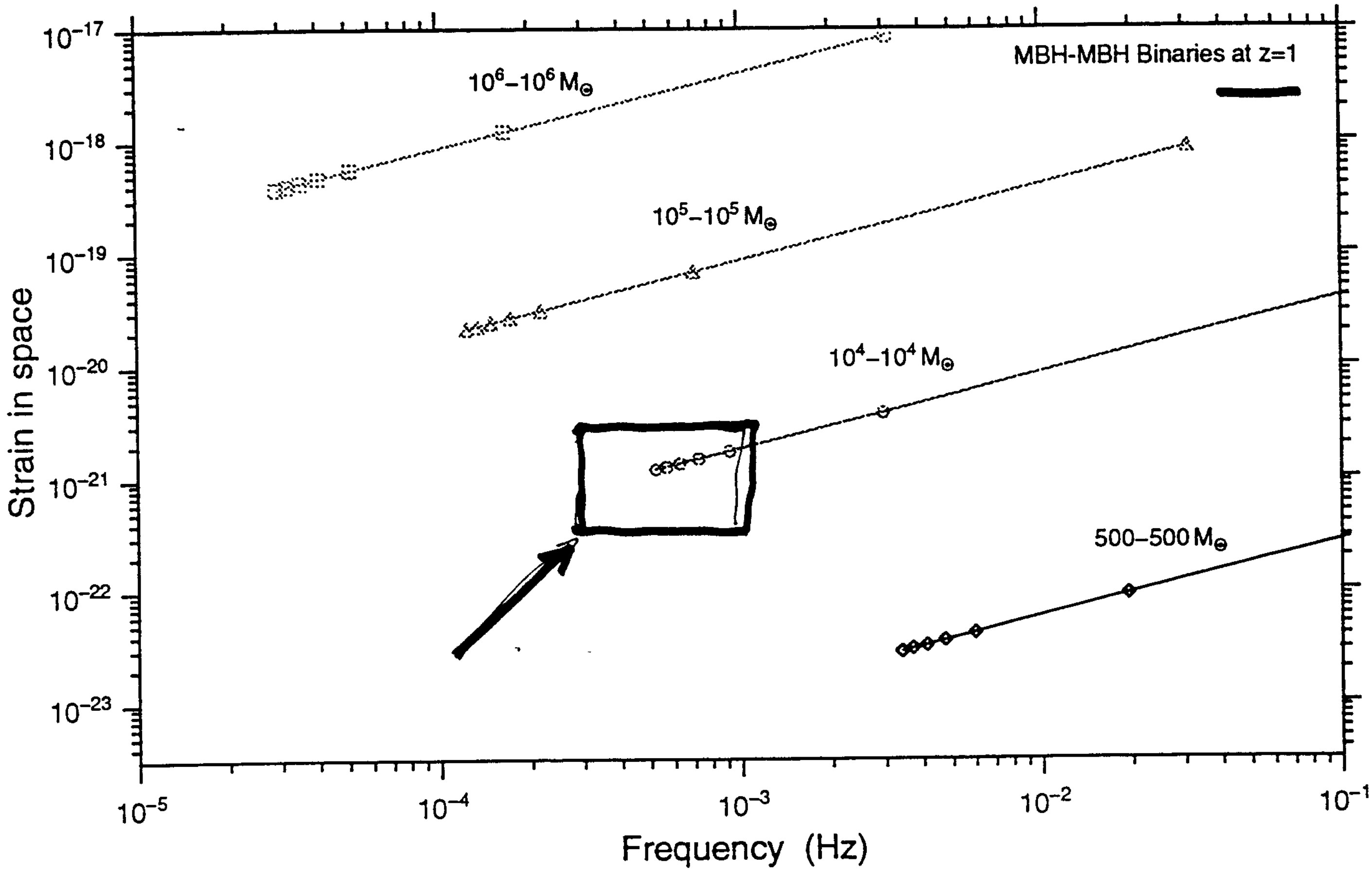
We have in mind gravity wave emission of BH-BH or BH-NS pairs in non circular kissing orbits



LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

Pre-Phase A Report
Second edition, July 1998



Strain amplitude during the last year before MBH-MBH coalescence.

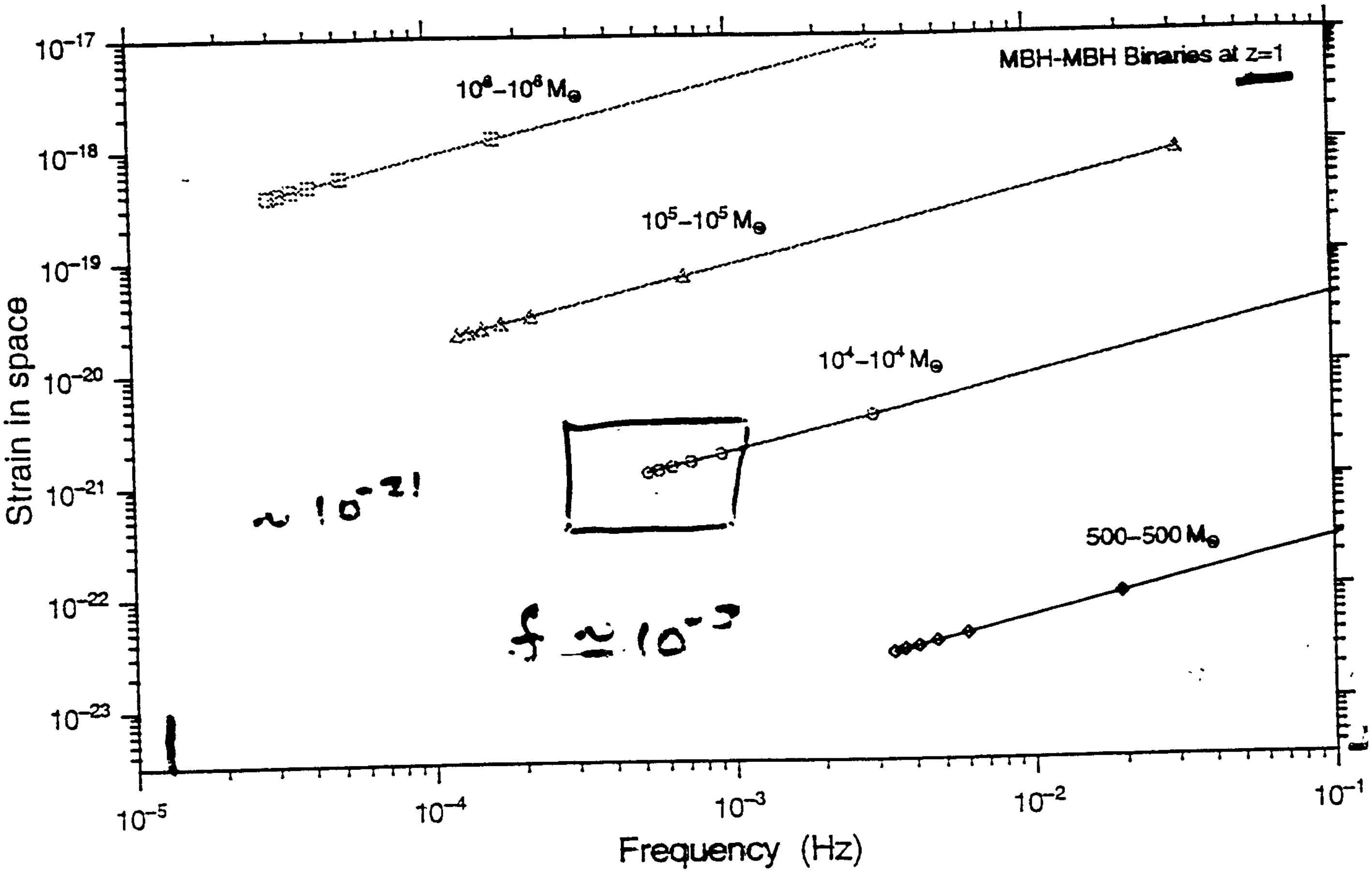
Notice huge 10^{-21} signals at $z=1$ for 10^{+4}–$10^4\,M_\odot$

BINARY SYSTEMS.

LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

Pre-Phase A Report
Second edition, July [illegible]



Strain amplitude during the last year before MBH-MBH coalescence.

$10^9 - 10^9$ BH BIN PAIR $h \sim 10^{-21}$
$z = 1$

SCALE TO BIN PAIR

$10^9 - 10$ $h \sim 10^{-24}$
$10^9 - 1$ 10^{-25}

SCALE TO $z = 10^{-4}$ OUR GALAXY

$10^9 - 10$
$10^9 - 1$

$h \sim 10^{-20}$
10^{-21}

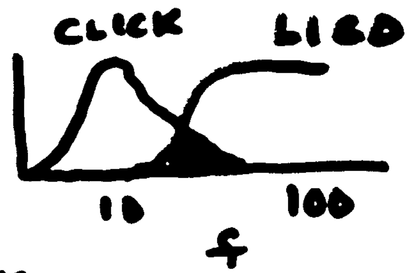
Periodic Sources (continued)

10%, ? 1%

11

~ 1 sec

1000 sec



"Click" ≈ 10 Hz peak (could be higher)

S/N ≈ 1/1 .1/1 .01/1 / Per Click

10 Days ⇒ 100/1 10/1 1/1

Clearly speculative

Issues to address:

- # Viable black hole candidates
- Spectral overlap (Click *vs* LIGO)
- Observation window time
- Chirp pattern
- Human background
- Hanford-Livingston ~~coincidence~~ COHERENT search
  $\Longrightarrow \geq 30$ S/N improvement

⇒ MORE INTERESTING SEARCH VOLUME.

Systemic Noise Studies

We plan to trace and analyze the NOISE of LIGO I (as implemented) for

Data Analysis, LIGO I Science, and LIGO II

We will work backwards from the Gravity Wave Signal to isolate:

- 60 Hz and its Harmonics
- RF Leakage: out and in
- Accidental Couplings to High-Q Degrees of Freedom
- Non Stationary Processes, *e.g.*,
  - Out-of-Band Alignment or Servo Perturbations and Fluctuations leading to or driving upconversion of low Frequency noise

60 Hz and Harmonics

Historic Spectra:

Populated with 60 Hz and harmonic lines

Why?

If	1 micron	$\Longleftrightarrow$	1 Volt	in Servo for Acquisition
	10^{-18} m	$\Longleftrightarrow$	1 pico Volt	in a data stream

This is challenging!!

Obvious remedies:

- Regulated Power Supply
- Power Regulation on Boards
- Power Insensitive Chips, *e.g.*, opamps
- Clever Design

$\Longrightarrow$ Roughly good enough: Rejects AC at 10^{12} level

60 Hz and Harmonics

But it's still there

Ground loops and induced signals from simple Lenz Law induction from AC Transformers flux leakage is endemic at this level

Strategies

- Remove in Software
- Brute Force   Remove all local AC
- Search out Offenders. Critical Systems and Resolve
  One approach: Swap in 55-Hz power supply
  Identify / eliminate suspects, system by system, module by module

New Diagnostics and Controls for LIGO

Light Shutter - Beam Locator

We need to isolate one or both arms for tuning, testing, or aligning:

- Power Recycled Michelson Configuration
- Individual Arms

Usually done by misaligning mirrors, but problems arise:

- Hysteresis; you never get exactly back
- Insufficient range
- Incomplete light blockage

New Diagnostics and Controls for LIGO

Light Shutter - Beam Locator

Our student, J. Rollins, has fabricated and vacuum prepped four shutters for the 40 Meter

To be located:

- Just in front of the vertex test masses
- Just in front of the end masses (for beam location)

Consists of a vacuum-optics-compatible "Pico Motor" with a rotating vane

Vane has two stopped positions:

- Shutter
- Alignment hole

We propose to design and fabricate a similar system for LIGO

New Controls and Diagnostics for LIGO

Selective Attenuator

We extend the Light Shutter to Selective Attenuator

Add another vane setting - highly transmitting optic

Purpose: Calibrated pertubation of recycling cavity

- Increase cavity loss
- Change contrast defect

Perhaps extend to arm cavities (higher quality optics)

Thermal lensing needs study

New Diagnostics and Controls for LIGO

Coupling Diagnostic

Overall coupling of the input to the IFO is important and hard to measure

At the 40 Meter we step the input light and observe the transient response of the light and probe signals

The family of responses as a function of amplitude chaaracterizes the coupling

This needs analysis and development

We will develop and test this diagnostic

New Diagnostics and Controls for LIGO

Independent Arm Lock Scheme

Lock via arm Servo on transmitted light at End

Each arm is then semi independent

Study the "open loop" arm servo

Debug, measure stuff

We have locked one arm of the 40 Meter this way

Two Schemes:

- Length Modulation
- Laser modulation

Requires modestly good laser frequency stabilization

Locking 40M laser to the mode cleaner is marginally adequate

Possible further uses:

- Establish beam for WFS startup
- Possible simple brute force path to lock
- Diagnostic replacement of CM Servo.

New Diagnostics and Controls for LIGO

Auxillary Laser Lock Cavity A Third Arm

We propose a third Fabry-Perot arm-like Cavity

Purpose

Stabilize laser so well that either or both arms could be cleanly locked to it and studied with only a length servo

The recycled / recombined arms are inextricably coupled in the 40 Meter and LIGO

Decoupling was a convenient feature of the unrecombined 40 Meter IFO

Stability goal:

Intermediate between a full arm and mode cleaner lock

New Diagnostics and Controls for LIGO

Auxillary Laser Lock Cavity   A Third Arm

Possible implementation schemes:

- Mode cleaner derived – but you want test this too.
- Second FP cavity in 2K or 4k arm
- External system in vertex area *e.g.*, based on extension of the unused 40M 12-meter Mode Cleaner hardware

This system would stablilize the laser such that the arms could be independently locked with only length servo

Would enable stringent diagnostics of the main IFO-laser frequency control system

Research Plan

Gustafson

At 40M and Hanford: (> 50%)

- Data Runs and Analysis
- Diagnostics, Controls
- Systemic Noise Study

At Michigan:

- Data Analysis
- Hardware Fabrication
- WFS Development
- Periodic Source Astrophysics and All Sky Problem

Riles

At Michigan:

- Data Analysis
- WFS Development
- Periodic Source Astrophysics and All Sky Problem

At 40M and Hanford (periodic visits):

- DAQ Tests and Improvements
- Advanced Alignment Issues

Research Plan

Postdoctoral Associate

At Michigan ($> 50\%$)

- Data Analysis
- WFS Development
- Periodic Source Astrophysics

At 40M and Hanford

- Data Runs
- Diagnostics, Noise Study

SUMMARY

We are relative newcomers to Gravity Wave Physics

We've jumped in and made a strong contribution to 40 Meter R&D

We are now preparing to record and analyze LIGO-like data with the 40 Meter

We have substantially learned the LIGO/IFO trade

In the coming period we will:

- Carry out 40 Meter Gravity Wave Analysis
- Extend this to LIGO data
- Advance LIGO:
  - Contribute to Noise Study and Diagnostics
  - Develop Advanced Wavefront Sensing
  - Search for and Study Periodic Sources

$\boxed{\text{Our Goals}}$

Detect Gravity Waves

Study their Sources