New Folder Name Design Decision

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LIGO PROJECT

CALIFORNIA INSTITUTE OF TECHNOLOGY

TO LIGO Science Team DATE September 22, 1993
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SUBJECT Writeup for Interferometer Design Decision

To arrive at a recommendation for an initial LIGO interferometer design, experimental and analytic work has been performed on two trial schemes. A summary of the results to date of that research and a recommendation for the LIGO interferometer design is presented in the following writeup.

There will be a meeting on September 30 to give an overview of the work done and to discuss the recommendation. This writeup should provide you with a background for understanding the material presented at the meeting and the discussions that ensue.

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Comparison of 2 Fixed Mass Interferometer Testbeds and the Resulting Recommendation for the Initial LIGO Interferometer Design

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September 23, 1993

Objective and Overview

To arrive at a recommendation for an initial LIGO interferometer design, experimental and analytic/numerical work has been performed on two trial schemes. A summary of the results to date of that research is presented here, with the objective of moving toward a selection of a single scheme for further refinement (through experiment and modeling) and ultimately a design of the initial LIGO optical topology and modulation system.

The basic optical layout of a power recycled Michelson with Fabry-Perot cavities is shown in Figure 1. **The differences in the schemes discussed in this write up, lie in the means for sensing the distances between the optical components.** The most important is the differential cavity motion ($L_1 - L_2$ in Figure 1), which is the **readout system for the gravitational waves (GW)**. In addition, '**auxiliary lengths**' consisting of the near mirror Michelson path length difference ($l_1 - l_2$), the cavity common mode motion ($\frac{L_1+L_2}{2}$), and the recycling cavity length ($\frac{l_1+l_2}{2}$) must all be controlled.

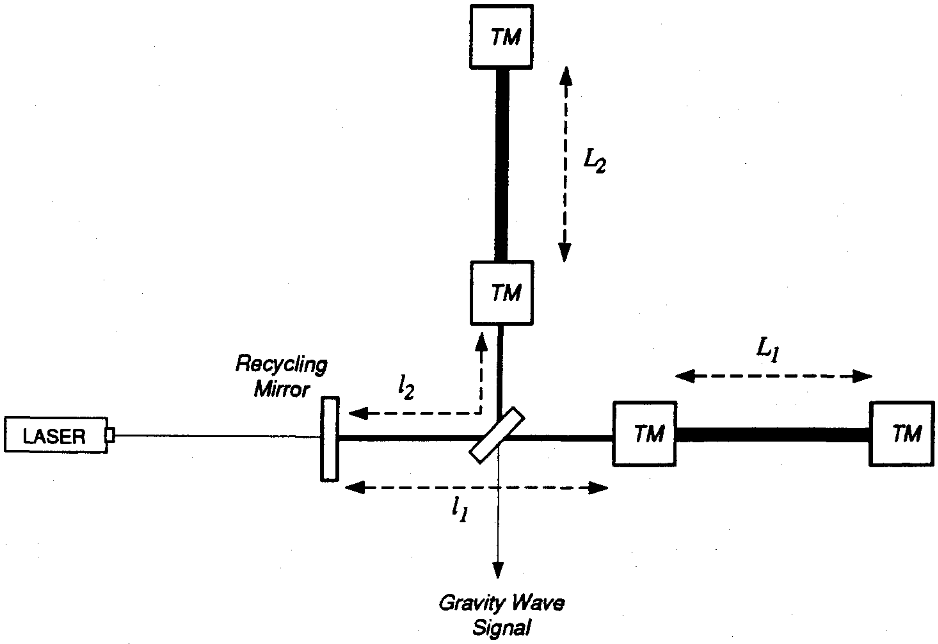

Figure 1 Optical layout of a power recycled Michelson with Fabry-Perot cavities.

Experiments have been performed on two Fixed Mass Interferometers (interferometer setups on optical tables) which have tested two complete schemes for the LIGO interferometer, the Asymmetry and the MZ/Subcarrier schemes. These are described on pages 3–6.

Tables describing the experiments and calculations performed to evaluate and compare the two schemes, and significant issues that have not yet been satisfactorily addressed, follow on pages 7 and 8.

Because each of the two complete schemes which were tested experimentally contain separable elements which can be independently employed in the LIGO interferometer, the Synopsis and Discussion on pages 9–11 compares the GW readout methods, and auxiliary length sensing systems for lock acquisition and operation, separately.

The Recommendation of the team working on this task (pages 12–14) selects a GW readout system, and a lock acquisition auxiliary readout system. It leaves open two options for the choice of auxiliary readout system for the operational mode.

An outline of the additional work which is necessary to arrive at a LIGO interferometer design is shown on page 15.

An index of the working documents and contact people for more detailed technical information is in preparation as an appendix.

Description of the Asymmetry and MZ/Subcarrier Schemes

Asymmetry Scheme

1. Signal Extraction (see Figure 2)
    1. Gravity Wave Signal $(L_1 - L_2)$:
        - Sidebands at the antisymmetric output are produced by a common mode phase modulation before the interferometer and an asymmetry in the near mirror interferometer ($l_1 - l_2 \approx 60$cm). This asymmetry is chosen so that the loss in the modulation sidebands due to the asymmetry approximately equals the carrier loss on reflection from the cavities.
        - GW signal is extracted by demodulating antisymmetric port photocurrent
    2. Auxiliary Length Signals
        - extracted by demodulating photocurrent at two additional optical outputs:
            1. A signal from light reflected back towards laser
            2. Two signals are obtained from the pick-off inside recycling cavity (signal is demodulated both 'in phase' and also in 'quadrature phase').

               The pick-off quadrature phase output responds to $l_1 - l_2$, since changes in this degree of freedom enlarge one sideband and diminish the other.

               In phase output responds both to $L_1 + L_2$ (since carrier phase changes with this degree of freedom) and to $l_1 + l_2$ (since carrier and sideband phases change, but at different rates, with this degree of freedom).
        - 'Recycling cavity length', $l_1 + l_2$, signal (and, if demodulation phase not precisely set, 'Michelson near mirror difference' signal, $l_1 - l_2$) only available in linear combination with 'average arm cavity length' signal, $L_1 + L_2$.

2. Servo Systems:

- Signals are fed back to the laser frequency controller and the two arm cavity end mirrors, the beamsplitter, and the recycling mirror as shown in Figure 2.

3. Locking Techniques

- Fixed Mass Interferometer: beam splitter servo loop broken, beam splitter moved back and forth through at least one order until resonant condition established. At this point, beam splitter servo loop re-connected. Works very reliably in tabletop experiment (typical time to reacquire is less than one second). Mechanism not understood.
- LIGO Hanging Interferometer: it is not known whether this same procedure will work in LIGO.

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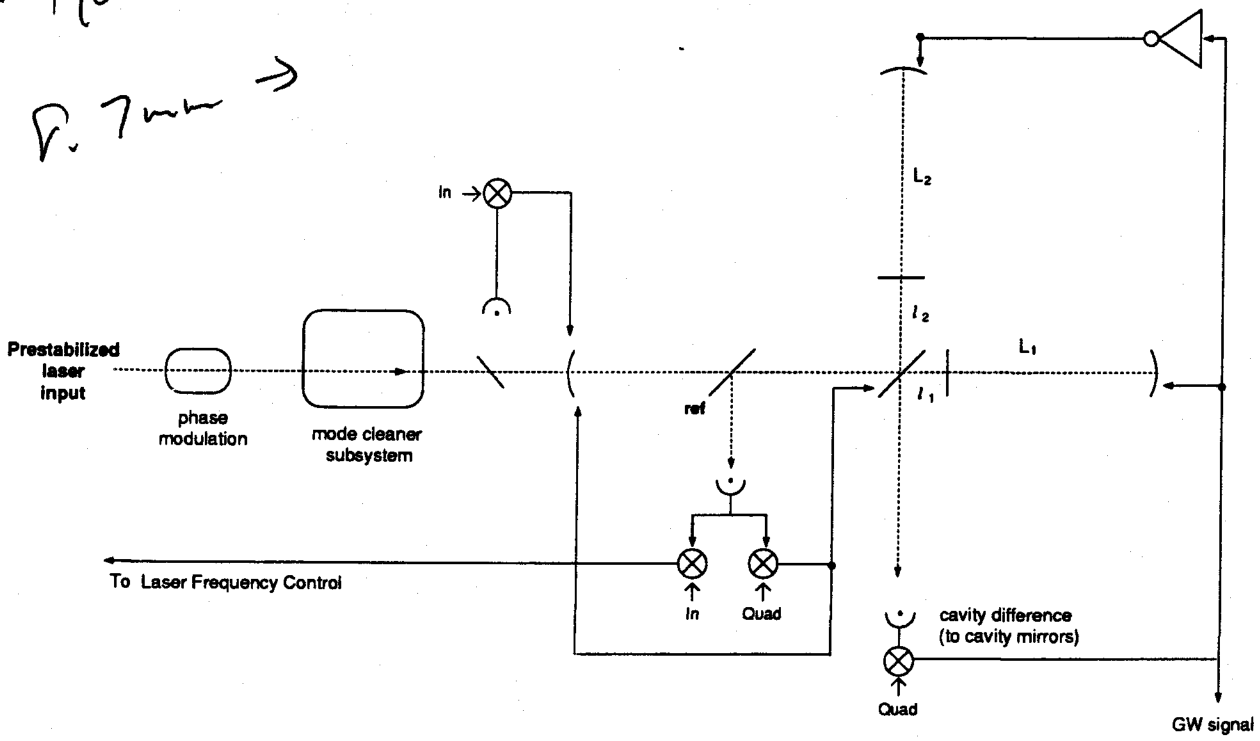


Figure 2 Schematic of a LIGO Asymmetry Scheme Showing Optical Layout, Modulation, and Control Signal Paths.

MZ/Subcarrier Scheme: Mach-Zehnder Gravity Wave Readout and Subcarrier Auxiliary Readout

1. Signal Extraction (see Figure 3)
    1. Gravity Wave Signal
        - The GW signal is detected by comparing the antisymmetric port phase with an RF phase modulated reference beam (at f_3) in a Mach-Zehnder interferometer.
    2. Auxiliary Length Signals: There are four auxiliary lengths to be detected, two which use the carrier light, and two which use a frequency-shifted subcarrier (FSS). The FSS is at a frequency which is not resonant in the arm cavities and so only senses motion of the near mirrors.
        - The common-mode cavity error, $L_1 + L_2$, appears as the phase of the cavity light emerging from the symmetric port of the main BS, and circulating in the RC. This phase is detected by comparison with phase-modulation sidebands at f_1, on PD5.
        - The error signal used to hold the MZ at mid-fringe is derived from the carrier f_1 sideband light emerging from both ports of the main BS. A $2f_1 + f_3$ term on the PD2 and PD3 contains the signal.
        - The length of the RC is obtained with a phase modulation at f_4 which is imposed on the FSS; f_4 is chosen so these sidebands reflect from the RC. This is sensed at PD1.
        - To measure $l_1 - l_2$, a modulation of the FSS at f_2 and a small asymmetry ($l_1 - l_2 \approx 1\text{cm}$) is used (as for the GW signal recovery in the asymmetry scheme). This is sensed at PD4.
2. Servo Systems: Signals are sent to the two arm cavity end mirrors, the Michelson beamsplitter, the recycling mirror, the Mach-Zehnder beamsplitter, and the laser frequency controller as shown in Figure 3. (Although the laser frequency feedback loop is not needed for the operation of this servo design it is required for meeting the specs on stability of the light at the input of the interferometer).
3. Locking Techniques:
    - Fixed Mass Interferometer:

      The Michelson interferometer is brought near the dark fringe. The recycling cavity loop is brought to within $\lambda/2$ of resonance and the loop is closed. The arm cavities are adjusted to be out of resonance for the FSS (the natural mirror motions are such that in the FMI they remain so for ≈ 1 minute; in LIGO ≈ 10 seconds). The Michelson and MZ loops are closed. The arm cavities are brought within a linewidth of resonance and the arm common-mode loop closed. The arm differential-mode loop is closed.

- LIGO Hanging Interferometer: it is not known whether this same procedure will work in LIGO.

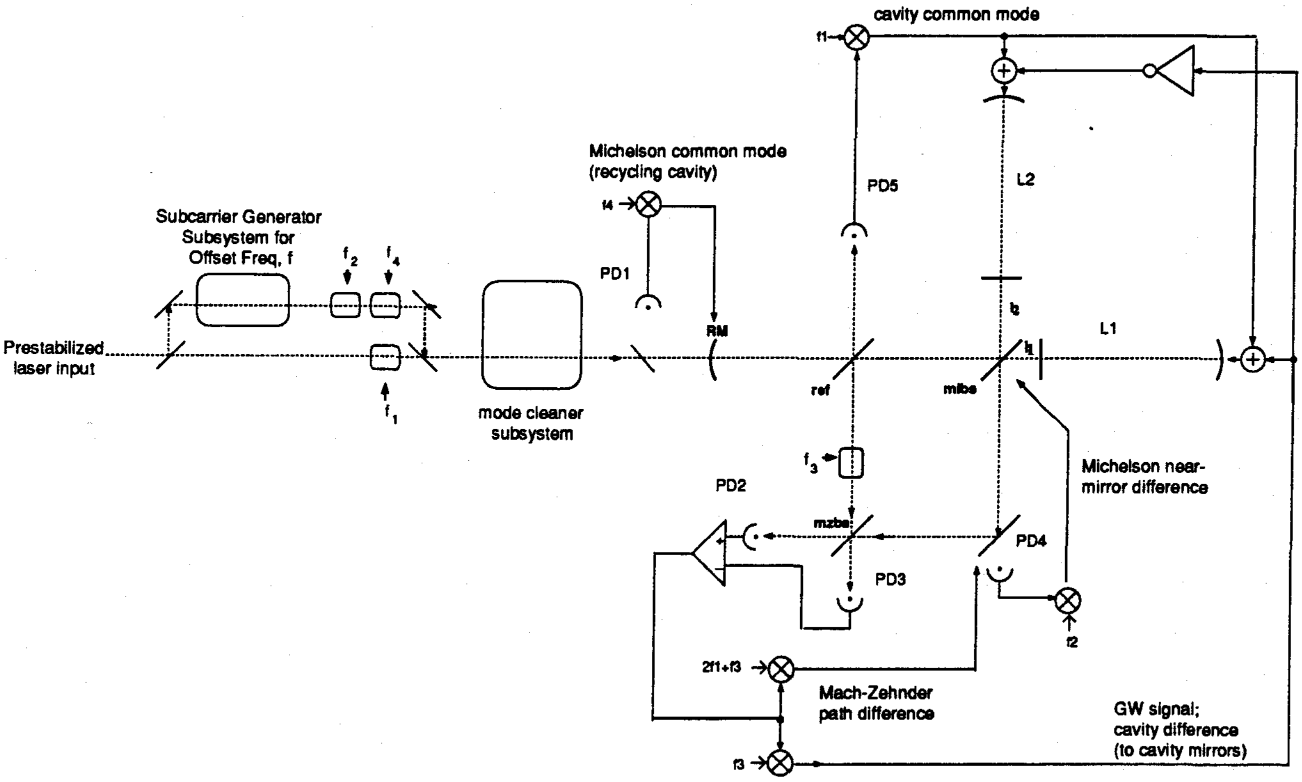


Figure 3 Schematic of a LIGO MZ/Subcarrier Scheme Showing Optical Layout, Modulation, and Control Signal Paths.

Experimental Tests and Calculations/Modeling Done for Verifying Feasibility of the Two Schemes

<table>
<tr><th colspan="2">TESTS</th><th>ASYMMETRY SCHEME</th><th>MZ/SUBCARRIER SCHEME</th></tr>
<tr><td>Shot Noise Sensitivity</td><td>Calc.</td><td colspan="2">The two schemes were identical over a set of parameters corresponding to probable scenarios for LIGO.</td></tr>
<tr><td rowspan="2">Low Frequency Optical Response</td><td>Exper.</td><td>Agreement between model and experiment within a factor of ≈ 2 (likely experimental error) of optical response between end cavity mirror and GW signal. Other signals not yet verified.</td><td>Most (i.e. 23 of 25) matrix elements relating motions and signals measured. The diagonal elements (including GW signal) agree to factor of ≈ 3 to 4 (likely experimental error). Unexpected sensitivity of subcarrier (FSS) signals to near cavity mirror motion.</td></tr>
<tr><td>Calc.</td><td colspan="2">Calculations for both schemes have been completed and models showed no surprises</td></tr>
<tr><td rowspan="2">High Frequency Optical Response</td><td>Exper.</td><td colspan="2">It is very difficult to conduct experiments on short cavities to verify high frequency response. No experiments have been succesfully done to test model.</td></tr>
<tr><td>Calc.</td><td>Numerical model complete; no surprises.
Analytical derivation supports numerical model qualitatively (not yet compared in detail)</td><td>GW frequency response expected to be the same as for Asymmetry Scheme.</td></tr>
<tr><td>Mechanisms for Noise Coupling Due to Asymmetry</td><td>Calc.</td><td>Analyzed in some detail: frequency noise coupling, mode matching loss, intensity noise coupling, beam wiggle. No problems found.</td><td>NA</td></tr>
<tr><td>Table Top Locking Capability</td><td>Exper.</td><td colspan="2">Both lock onto the TM00 mode consistently and remain locked for stretches of minutes</td></tr>
<tr><td>Sensitivity to Misalignment</td><td>Exper.</td><td colspan="2">No systematic studies performed</td></tr>
<tr><td>Sensitivity to RF Phases, Gains, DC Offsets</td><td>Exper.</td><td colspan="2">No unexpected sensitivities in the fixed mass interferometer tests</td></tr>
</table>

Issues Not Addressed By or Not Resolved in Experiments or Calculations

ISSUES NOT ADDRESSED	POSSIBLE CONSEQUENCES	EFFORT/APPROACH TO RESOLVE	RISK
Servo Loop Design for Common Mode Degrees of Freedom (Asymmetry Scheme only)	Each common mode feedback loop could be complicated (e.g. Bandwidth requirements might necessitate several notch filters in servo loop so test mass modes aren't excited)	Detailed servo modeling and analysis required. Preliminary results suggest this is not a problem.	low
Signal to noise issues in servo loop design for beamsplitter controller (both schemes)	Requirements for greater low frequency seismic isolation of beam splitter and/or better frequency or intensity control	Detailed servo modeling and analysis required. Preliminary results expected in a few weeks	unknown but modeling can predict
Experimentally Observed Sensitivity of Subcarrier Signal to Arm Cavity Lengths (MZ/Subcarrier Scheme only)	Mixing of cavity and near mirror readout and/or reduced acquisition range.	Change in experimental measurement technique to avoid possible PZT tilting effects; numerical analysis underway	moderate to low
Mirror Figure Imperfections Leading to Excitation of Recycling Cavity Higher Order Spatial Modes by Carrier Sidebands (Asymmetry GW Readout only; will not affect choice of auxiliary sensing scheme)	In Gravity Wave signal, excess shot noise, excess sensitivity to beam motion, photodiode non-uniformity, and/or mirror misalignments	Numerical analysis underway. Preliminary results due in next few weeks.	unknown but modeling can predict
Mirror Figure Imperfections Leading to Excitation of 4 Km cavities by subcarrier and (carrier and/or subcarrier) sidebands. (both schemes)	Unexpected coupling of auxiliary signals to arm cavity lengths; dependence of auxiliary signals on alignment and beam position.	Numerical analysis underway. Preliminary results due in next few weeks.	unknown but modeling can predict
Effects of Higher Harmonics of Modulation Frequencies (MZ/Subcarrier Scheme only)	May put constraints on mode cleaner design (i.e. lower finesse of mode cleaner cavity)	Calculation needs to be done with all of the frequencies present to check for interference in a LIGO design	low
Acquisition of Locked State of LIGO Interferometer (both schemes)	Need for additional sensing scheme (such as dithering of test masses) or for mechanisms reducing the background seismic motion	Small modeling effort underway. Hanging interferometer test will probably provide helpful insight	low

Synopsis and Discussion of Differences of the Two Schemes

The experimental and theoretical work have convinced us that the schemes outlined above are workable. Both 'lock', both should deliver an acceptable LIGO GW sensitivity, and both can control all of the needed motions. It would be possible to test most aspects of either scheme in either the 5M or 40M suspended interferometer prototypes (however vacuum modifications/ additions would be necessary to test the MZ scheme in the 40M, and the size of the asymmetry available in the 5M is limited but probably sufficient). Thus, to choose a single scheme, some more detailed considerations are needed. We highlight the advantages and disadvantages of the schemes below.

The fixed mass interferometers described on the preceding pages use a mixture of techniques for the GW readout and the auxiliary length control for both 'lock acquisition' and 'operation mode' ('operation mode' is the time while the interferometer is locked and data is being taken). These can be independently chosen for LIGO, so we discuss them separately. We believe a synthesis of the two schemes may be the best choice for the initial LIGO.

1. **Gravity Wave Readout**: Asymmetry or MZ (MZ/Subcarrier Scheme) readout.

   - Calculations and limited experimental results indicate that the shot-noise limited sensitivity of the two means of GW readout is effectively the same for the quality of optical components we expect to have in the initial LIGO. Thus, this very important measure is not a way to differentiate between the schemes.
   - The clearest **advantage of the Asymmetry Scheme** is its optical simplicity. By contrast, the MZ system requires roughly 6 more suspended masses (one additional telescope, two Pockels cells, a folding mirror, and the second beamsplitter). With these extra components comes another length control and alignment control system, although with relatively relaxed performance requirements.
   - The most important potential **disadvantage of the Asymmetry system** is the asymmetry itself: it might introduce sensitivity to various defects in the input laser beam. Straightforward calculations have not shown any significant problem due to the length asymmetry (asymmetries due to optical imperfections are typically more important). Numerical modeling to study this is now underway.

2. **Auxiliary Length Readout for *Lock Acquisition***: Asymmetry or Subcarrier readout of the near mirror positions.

   - Both schemes have been used successfully to lock a recycled table top interferometer. However, lock acquisition has not been modeled for either scheme and conditions affecting lock acquisition will be very different in suspended mass interferometers than in fixed mass prototypes.
   - The principal **advantage of the subcarrier approach** is the independence of the recycling cavity resonance condition from the arm cavity resonance condition. This allows a step-wise locking procedure to be followed, where the recycling cavity and near-mirror Michelson are locked sequentially, and then the 4 km arm cavities are locked afterwards. Moreover, it does not require feedback to the laser frequency during lock acquisition. Both schemes will use a feedback path to the laser during interferometer operation, but in the Asymmetry Scheme this path is necessary for acquisition. Because we have not modeled the acquisition for a LIGO interferometer (where significantly different time constants may qualitatively change the acquisition problem) this added flexibility is welcome; the step-wise locking procedure may prove to be a significant aid in experimentally troubleshooting any observed lock acquisition problems.
   - A **disadvantage of the subcarrier approach (MZ/Subcarrier scheme)** is that there are more optical components at the input to the interferometer (before the mode cleaner).
   - The main **advantage of the asymmetry approach** is that the optics and hardware are simpler, and that there are fewer optical frequencies for which we must understand the behavior of the optical system (including the mode cleaner).

3. **Auxiliary Length Readout for *'Operation Mode'***: Asymmetry or Subcarrier readout of the near mirror positions.

   - The principal **advantage of the Subcarrier approach** is that the GW readout and each of the auxiliary readouts are, to a high degree, orthogonal to each other; the independence of the signals would make the servo control easier to design and analyze. An unexpected sensitivity of the subcarrier to the cavity lengths has been observed in the fixed mass interferometer. Experiments are underway to understand this observation. The possibility of coupling to higher order spatial modes in the arm cavities via mirror imperfections is being addressed with numerical modeling, and may provide an explanation for the observed coupling.

- A potential **disadvantage of the Subcarrier approach** is that all of the modulation frequencies must fit through the mode cleaner while being sufficiently spaced apart (modulo the mode cleaner free spectral range) to prevent interference between the various signals. This problem is being analysed; at present it appears that an 8 kHz mode cleaner bandwidth would be wide enough.
- The main **advantage of the asymmetry approach** is that the optics and hardware are simpler, and that there are fewer optical frequencies for which we must understand the behavior of the optical system.
- A potential **disadvantage of the asymmetry approach** is that the coupled 'average recycling cavity' length signals may make servo design for these degrees of freedom more difficult. Modeling is underway to test this but preliminary results suggest that this will not be a problem.

Recommendation for Scheme to be Used in LIGO

1. Recommendation for the **GW readout**: Asymmetry GW readout

   - Asymmetry scheme has important advantages in its simplicity and the Mach-Zehnder scheme has no established compensatory advantage over the asymmetry scheme.
   - The only remaining uncertainty for the Asymmetry readout is the influence of higher order spatial modes of the modulation sidebands brought about by mirror and substrate imperfections, and we expect an answer soon from numerical modeling.

2. Recommendation for ***Lock Acquisition*** **Auxiliary Length Readout**: Subcarrier length readout is included in the lock acquisition design, independent of which scheme is chosen for 'operational mode'

   - If the Subcarrier scheme is chosen for 'operation mode', the subcarrier scheme will also be used as the means for lock acquisition.
   - If the Asymmetry scheme is chosen for 'operation mode', ideally the Asymmetry locking scheme would be used for locking the interferometer under normal conditions. The reason for including the Subcarrier capability is for handling situations where difficulties exist in acquiring lock, such as during initial installation or when changes are made to the interferometer. The added flexibility of being able to lock 2 degrees of freedom at a time should provide valuable troubleshooting capabilities.

3. Recommendation for ***Operation Mode*** **Auxiliary Length Readout**: The above choices permit two options for Operation Mode. The advantages of each option are listed below.

   - Because of the independence of the GW and auxiliary signals, the Subcarrier auxiliary sensing system has advantages over the Asymmetry; the independence of the signals makes the servo control easier to design and analyze, and may aid in troubleshooting the interferometer. While there is some increased technical complexity in this approach, the needed elements will be in place for the acquisition scheme recommended above.
   - The Asymmetry method of auxiliary sensing has an advantage over the Subcarrier auxiliary sensing since it has the smallest number of frequencies and therefore the fewest active optical components. Potential difficulties associated with overlapping (or

nearly overlapping) modulation sidebands will be avoided with this scheme. The subcarrier used for acquisition could be designed to noise specifications adequate for lock acquisition only since the subcarrier would be shut off after acquisition.

A summary of the recommendation is as follows:

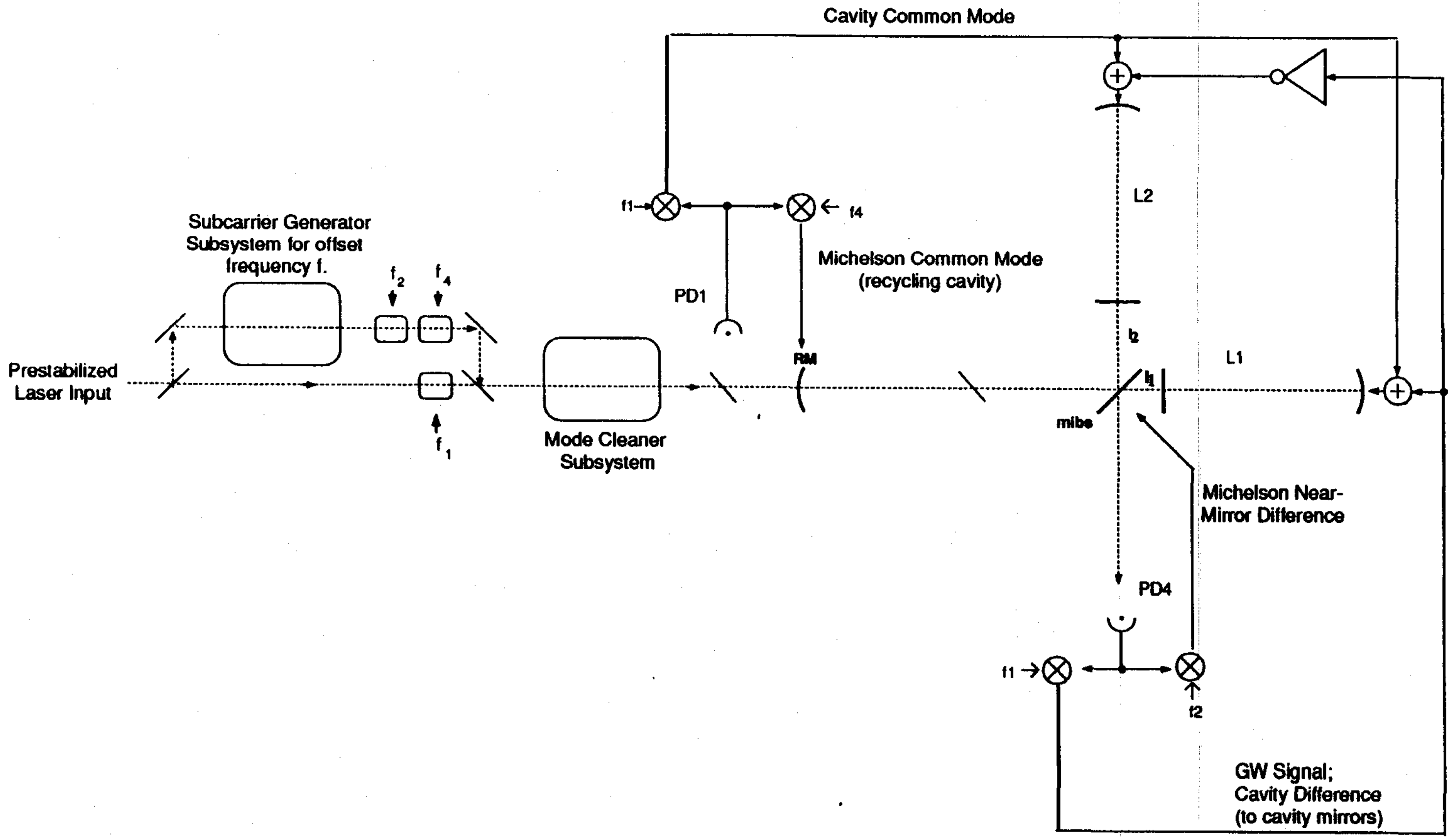
GW Readout: Asymmetry GW readout

Auxiliary Length Readout for Lock Acquisition:
Subcarrier readout included as means for Lock Acquisition

Auxiliary Length Readout for Operation Mode:
2 options have been discussed, we have not been able to find a convincing argument for choosing one over the other

1. Subcarrier readout (layout shown in Figure 4)
2. Asymmetry readout (layout for normal operations shown in Figure 2, layout for diagnosing lock acquisition problems shown in Figure 4)

Figure 4 Layout for Scheme1 (hybrid scheme where gravity wave signal detection is done using Asymmetry scheme, and servo control and lock acquisition are done using the Subcarrier method). This figure also depicts the lock acquisition layout used for toubleshooting acquisition problems in Scheme 2. The method for subcarrier generation has not been decided for the two different schemes.



Next Step in R&D Program for LIGO

1. Further fixed mass interferometer experiments and breadboarding
    - finish low frequency measurements, comparison with models
    - finish (if feasible) frequency-response measurements on MIT FMI
    - if a hybrid is chosen, we may need an FMI of that hybrid
    - if chosen, more complete tests of a frequency shifting prototype
    - if suggested by modeling, tests of lock acquisition
    - if suggested by modeling, consequences of high-order spatial modes
2. Modeling
    - finish low and high frequency response model of signal paths
    - incorporation of shot and seismic noise into models
    - incorporation of controller mechanical dynamics into models
    - acquisition modeling
3. Suspended interferometer tests
    - test of shot noise sensitivity on 5m instrument (simple recycled MI)
    - test of system on 40m instrument (complete topology)