Guenakh Mitselmakher
University of Florida
LIGO PAC, January 6 - 97

RESEARCH in LIGO

(UF Proposal to NSF)

General, Simulations, Data Analysis, DAQ - G. Mitselmakher
IOO for Initial LIGO - D. Tanner

R@D for Advanced LIGO - D. Reitze

LIGO-G970017-00-R

Six faculty with broad background, coherent and well organized group:

- **High Energy physics (Avery, Mitselmakher) - instrumentation, computing, data analysis, management of large experiments,**
- **Lasers, optics, condensed matter experiments (Reitze, Tanner)**
- **Computational physics, noise analysis (Coldwell)**
- **Theoretical astrophysics, GW-signals (Whiting)**

Goals in LIGO:

participation in Initial LIGO including :

- **Input Optics - design and construction,**
- **contributions to DAQ, computing,**
- **contributions to operations (possibly Louisiana site)**
- **simulations**
  IO simulations, noise and signal simulations
- **contributions to data analysis**
  model independent noise (signal) characterisation

participation in Advanced LIGO R&D:

- **dual recycling and resonant sideband extraction**
- **optical materials and coatings**

IFO Modeling and Simulations

Initial LIGO - Input Optics/Core Optics Simulations

(Compatibility with LIGO: fully integratable in AVS environment)

Paraxial Ray and Modal Propagation Analysis:

– overall input optics design and layout; aberration analysis

– frequency response during locked operation from "twiddled components"

– mode cleaner cavity design; mode parameters; higher order mode suppression

– mode-matching telescope design; static core optics coupling efficiency; jitter contributions to in-band noise

Signal and Noise Simulation in LIGO

– validation of approach to signal/noise characterization

– modeling of locked response to "GW" signal and noise

Advanced R&D - Dual Recycling Tabletop IFO Simulations

Input Optics Modeling and Simulations

(Tanner, Reitze)

Performed as part of Input Optics Design Requirements Review, Nov. 7, 1996

- Gaussian modal modeling of mode-cleaner, 2 and 4 km IFO core optics including Fabry-Perot and recycling cavities
- Gaussian modal modeling of reflective IFO mode-matching telescope
  - telescope design
  - higher modal contamination
  - aberration analysis
- Gaussian modal modeling of mode-cleaner mode-matching telescope
- high order modal modeling of beam misalignment (ω dependence)
  - beam drift
  - beam jitter
  - initial alignment procedure

P. Avery

Data Handling and Computing in LIGO

- **Some familiar problems from HEP**
  - High data acquisition rate
    - *Storage medium*
    - *Filtering*
    - *Reliability*
  - Large data volume
    - *Compression*
    - *Distribution*
    - *Copying*
    - *Finding small signals in large noise*
  - Large computing capacity
    - *Omnidirectional searches*
    - *Need for parallel computing strategies*

P. Avery

UF Role in Data Handling and Computing

- **Develop LIGO "data model"**
  - Data Model ⇒ Everything connected with handling and management of data
  - Why?

    Provides documentation and common language
    Can design for consistent behavior
    Decouple higher functions from lower
    Manage change in the experiment!!!
    ⇒ *Avoid self-inflicted wounds.*

- **Parallel computing and databases**
  - Experience with current "Nile" project, NSF funded National Challenge computing project, plus previous projects.
  - Both problems are important for LIGO

- **Computing infrastructure**
  - Languages
  - Interfaces
  - Simulation and analysis environments

In association with MIT-Caltech computing people

G. Mitselmakher

LIGO Data Analysis:

Whiting, Coldwell - currently involved in a methodology development

Avery, Reitze, Tanner + postdocs + grad students - in the future

Immediate goal:

- **development of methodology of model independent noise (and possibly signal) characterization**
- **experience with similar problems (Coldwell) - Supernova gamma-rays, X-rays, nuclear gamma rays**
- **complementary to the templates approach**

B. Whiting & R.L. Coldwell

Data Analysis: Noise Characterization

1) All experimenters report non-gaussian "noise" in their output - signal which lies far from the mean with a frequency which greatly exceeds that to be expected on the basis of purely gaussian statistics.
2) Most long runs of data also seem to be composed of stretches which are "quieter", along with stretches which could be characterized as "less-quiet", i.e. more noisy.
3) We plan to obtain an intricate characterization of the data as composed of different types of noise, along with an estimation of the statistical properties of the various components.
4) In principle, this will allow a subsequent identification of non-noise components in real data. Through this approach, certain signals which cannot be easily modeled, such as, for example, bursts, could perhaps be recognized in a parameter-independent way.
5) Such an analysis, including cross-correlation of Gaussian and non-gaussian noises in the 2 km and 4 km interferometers, would appear to be a vital part of being able to identify components of a stochastic gravitational background, itself with very noise-like properties.
6) As members of the construction team, we are working towards looking at existing real data from the 40-meter interferometer as soon as possible, to initiate our program, and gain first hand experience at characterizing noise.

Data Analysis: Details of Proposal

A practical way to commence this analysis might go as follows:

i) Fourier transform small stretches of data,

ii) From sequences of such stretches, construct frequency vs time representations of longer data intervals, and express the results in terms of some convenient basis functions (e.g. splines),

iii) Attempt to identify quieter and nosier patches, and obtain independent characterization, including statistical properties (probably carried out utilizing non-linear optimization techniquess),

iv) Corroborate our identification and characterization by reference to operators of the 40-meter, and even to an operating interferometer,

v) Test our ability to identify foreign components, e.g. artificially introduced modification of data streams.

vi) Develop schemes to handle data from co-located instruments to give joint characterization of correlated and uncorrelated noise sources.

Epilogue:

We recognize that all attempts to use templates or other forms of optimally matched filtering require a detailed knowledge of the noise statistics in order to be able to achieve their designed performance criteria. Thus the work proposed will play an important part even when a high degree of modeling is being used in searches for known types of sources.

University of Florida

Item	1998-99			IOO			Sim			D.R.			Mat		
	no	o	amt	no	o	amt	no	o	amt	no	mo	amt	no	mo	amt
Faculty Salary															
1 Guenakh Mitselmakher	1	1		1	0.5		1	0.5		1			1		
2 Paul Avery	1	1		1			1	1.0		1			1		
3 Robert Coldwell	1	2		1	1.0		1	1.0		1			1		
4 David H. Reitze	1	1		1	0.3		1			1	0.5		1	0.2	
5 David B. Tanner	1	1		1	0.4		1			1	0.4		1	0.2	
6 Bernard Whiting	1	1		1			1	1.0		1			1		
Total Senior Personnel	6	7	*48,538*	6	2	*15,821*	6	4	*22,887*	6	0.9	*6,744*	6	0.4	*3,087*
Other Personnel															
Postdoc Associates	3	12	101,970	1.5	12	50,985	1.5	12	50,985		12			12	
Other Professionals	2.5	12	128,750	1.3	12	66,950		12		1.2	12	61,800		12	
Graduate Students	3	12	40,170		12		1	12	13,390	1	12	13,390	1	12	13,390
Undergraduate Students	2	12	5,150	1	12	2,575		12			12		1	12	2,575
Total Salaries and Wages			*324,578*			*136,331*			*87,262*			*81,934*			*19,052*
C Fringe Benefits			62,628			29,949			10,182			21,695			803
Total, Salaries, Wages and Fringes			**387,206**			**166,280**			**97,444**			**103,629**			**19,855**
D Equipment			20,000			8,000						10,000			2,000
Total, Equipment			*20,000*			*8,000*						*10,000*			*2,000*
E Travel															
Domestic			20,000			10,000			2,000			6,000			2,000
Foreign			10,000			2,500			2,500			2,500			2,500
Other Direct Costs															
Materials and supplies			50,000			20,000			2,000			20,000			8,000
Publication costs			5,000			1,250			1,250			1,250			1,250
(Tuition remission)			3,615						1,205			1,205			1,205
Total, Other direct costs			*58,615*			*21,250*			*4,455*			*22,455*			*10,455*
H **Total Direct Costs**			**495,821**			**208,030**			**106,399**			**144,584**			**36,810**
% of MTDC = TDC - equipment - tuitio			*472,206*			*200,030*			*105,194*			*133,379*			*33,605*
I Indirect costs	45	%	212,492	45	%	90,014	45	%	47,337	45	%	60,020	45	%	15,122
J **Total Request**			**708,313**			**298,044**			**153,736**			**204,604**			**51,932**

Input Optics conceptual layout

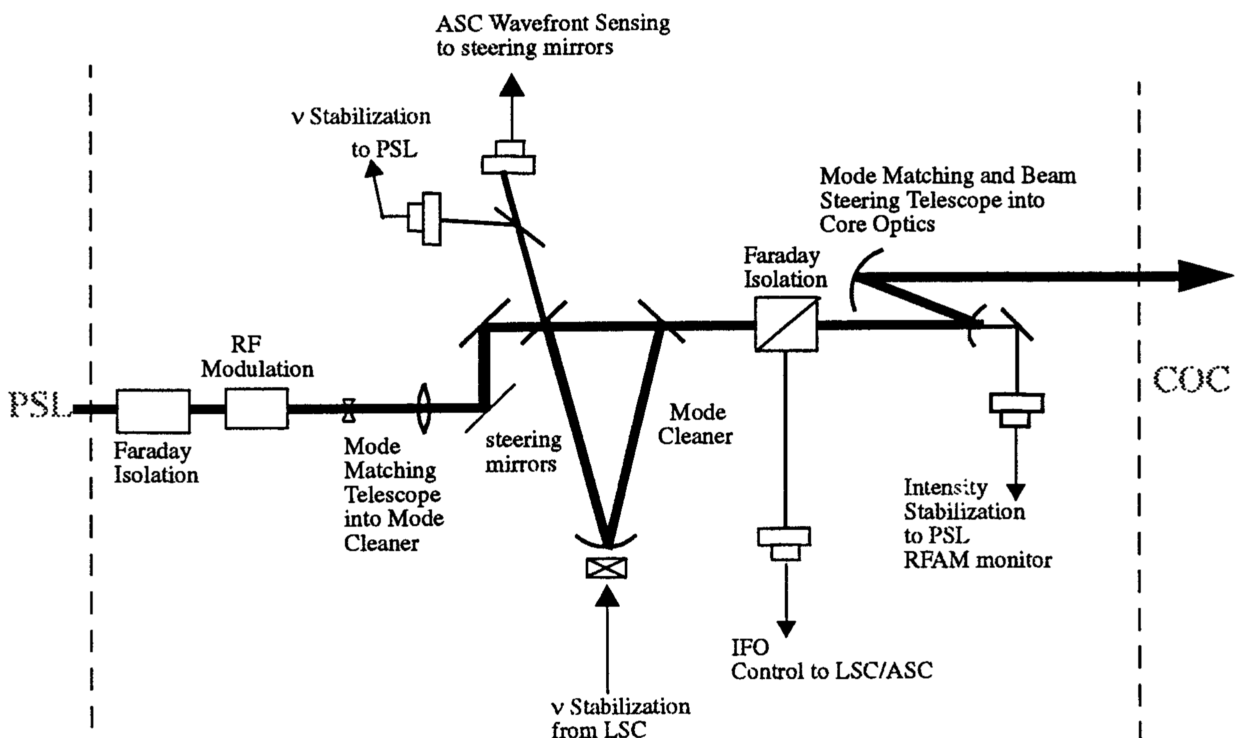


Figure 2: Conceptual layout of IOO optical components

*UF*LIGO

IOO R&D

- RF Modulation
  - ››Avoid cross products of 2 modulation frequencies
  - ››Non-sinusoidal modulation
- Mode cleaner
  - ››PM of side bands as λ laser changes
- Mode matching to IFO
  - ››2 or 3 optics
  - ››use of spheres off-axis
  - ››cancellation of aberrations (Czerny-Turner trick)
- Steering with telescope
- Unsuspended Faraday isolator
- Efficiency

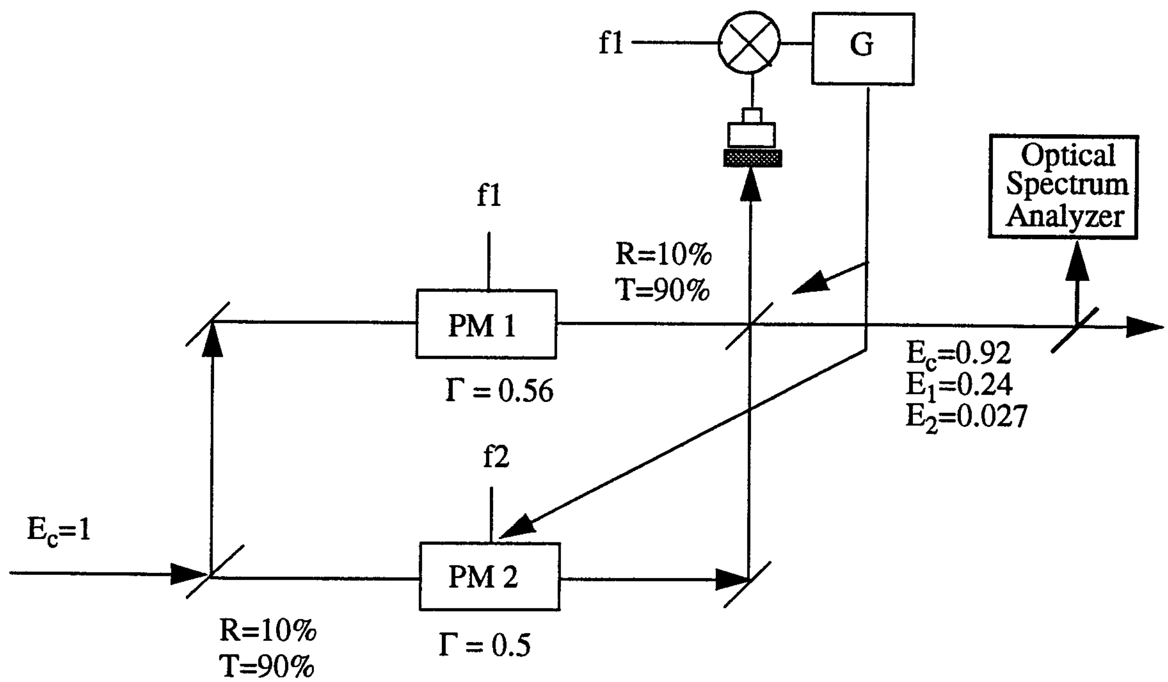
RF modulation

- Modulation frequencies
  - Frequency sideband resonant in the recycling cavity.
  - Additional frequency which is not resonant in the IFO.
  - Both frequencies must pass through mode cleaner.
- Modulation depths
  - Resonant (set by GW shot noise considerations): $\Gamma \sim 0.5$
  - Non-resonant (reflected light shot noise / ASC sensitivity): $\Gamma \sim 0.05$
- Modulation cross products
  - Modulation cross products, far from IFO resonance and anti-resonance, can mix to give in-band signals. To ensure the cleanest possible frequency reference, we require a modulation spectrum with no cross-products.
- Nominal frequencies

	Units	4k	2k
Resonant frequency, f_m	MHz	25	30
Non-resonant frequency, f_n	MHz	37	20

RF modulation scheme

- Produces both resonant and non-resonant sidebands.
- Modulation is applied so cross products of the two frequencies do not occur.
- Length control either of beam combiner or PM2.



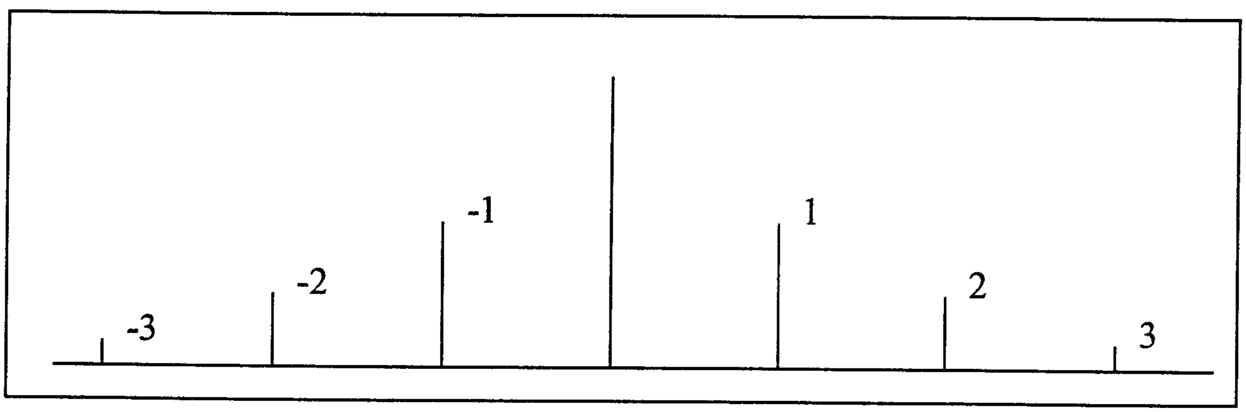
RF modulation scheme (2)

- Phase modulation with Pockel's cell

  ›› $E = Eoe^{i(\omega t + \phi)}$

  ›› with $\phi = \Gamma \sin \omega_m t$, where Γ is related to the strength of the rf field providing the modulation.

  ›› Sidebands at $\omega \pm \omega_m$, $\omega \pm 2\omega_m$, $\omega \pm 3\omega_m$, etc.



  ››The amplitude of the *m*th sideband given by the *m*th Bessel function of Γ

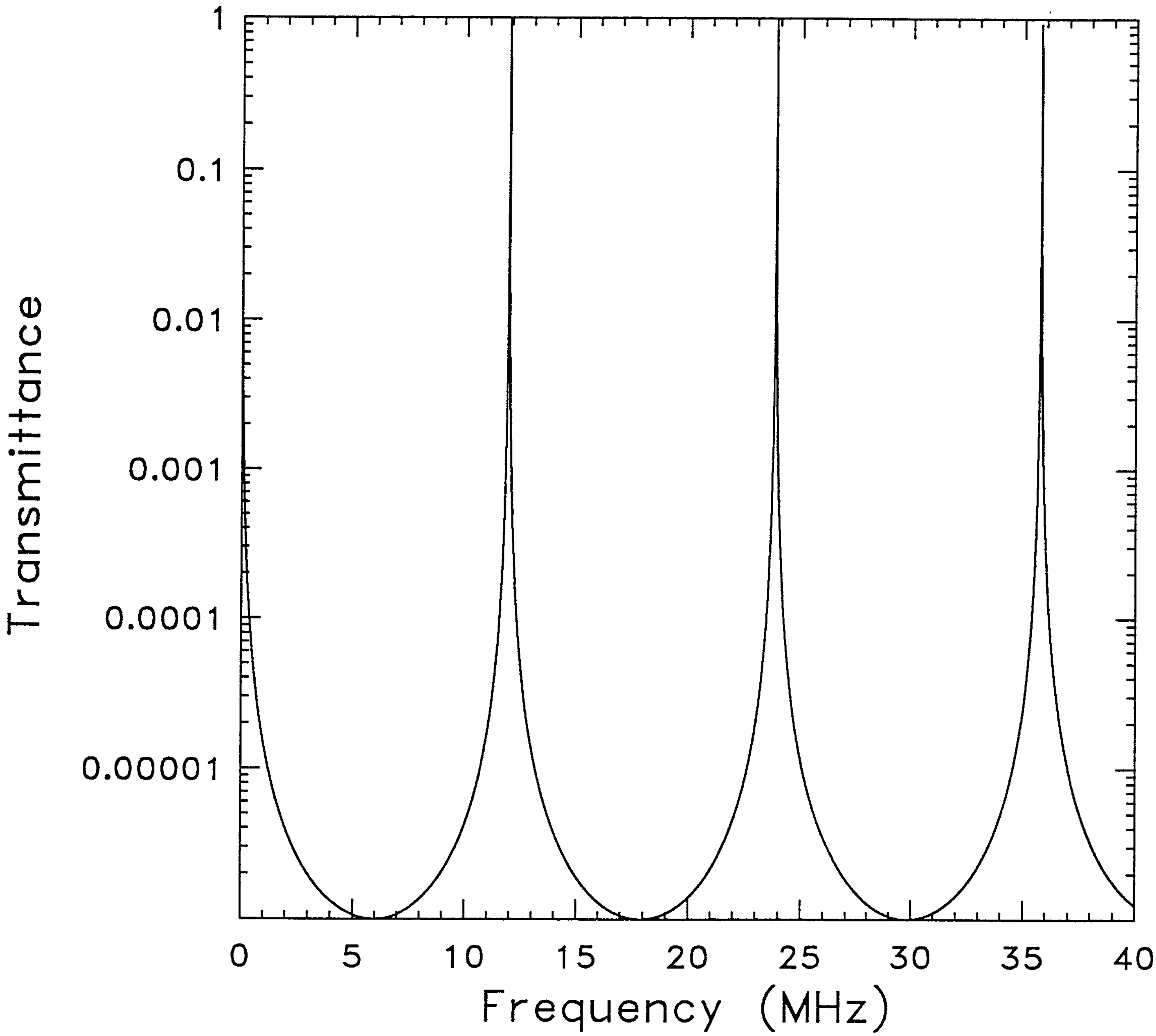
- Can the amplitude be reduced if a different function for $\phi(t)$ is chosen?
- Our simulations suggest: Yes.

Mode Cleaner

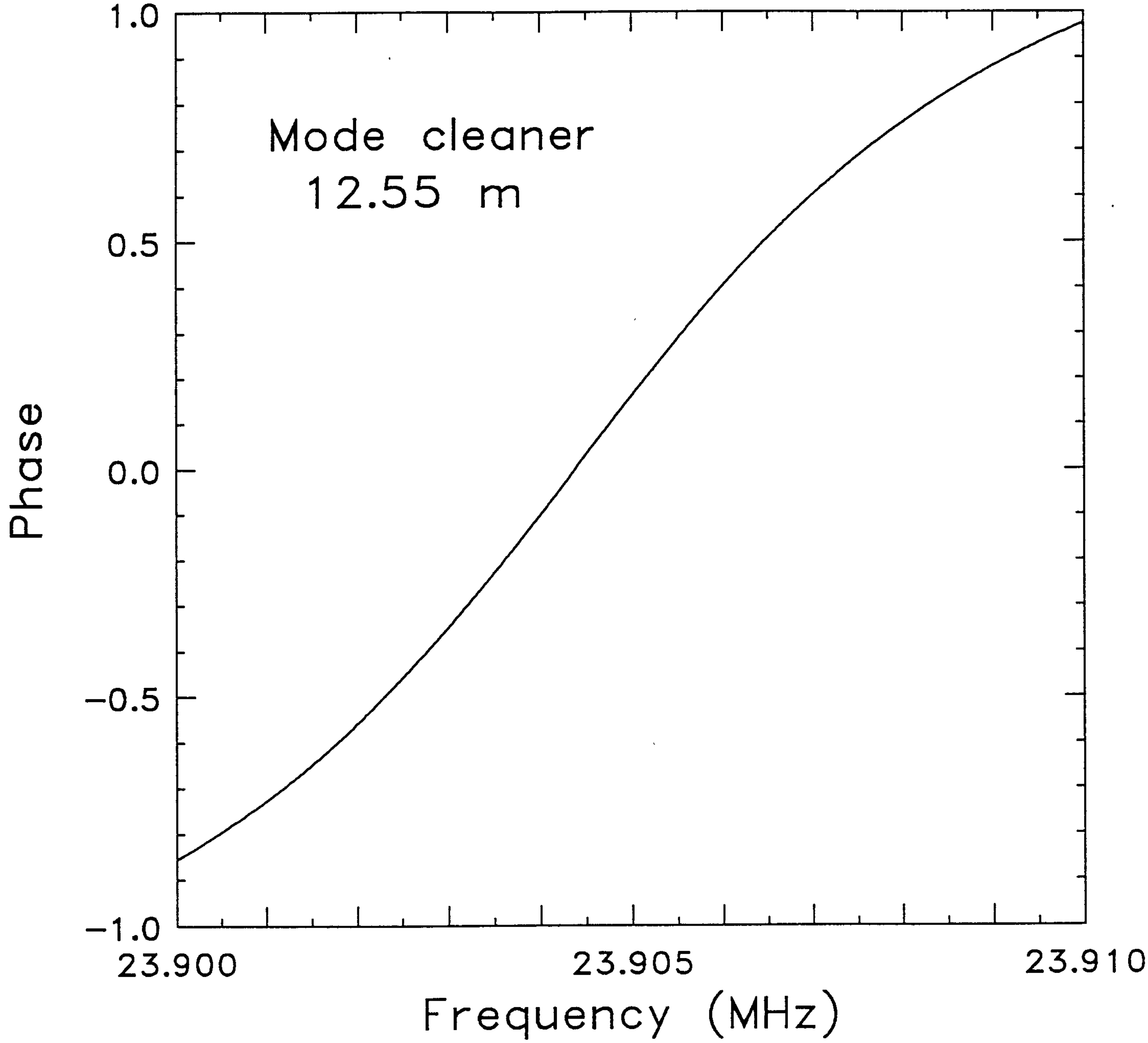
- The mode cleaner provides active frequency suppression through feedback to the PSL, passive frequency noise suppression above its cavity pole frequency, and passive spatial stabilization at all frequencies.

	4k IFO	*2k IFO*
Cavity length, *L* (m)	12.23	15.29
Free spectral range (MHz)	12.3	9.8
Radius of curvature of converging mirror, *R* (m)	17.7	22.1
Waist size (mm)	1.66	1.86
Cavity stability product $g = 1 - L/R$	0.309	0.309
Beam radius at curved mirror (mm)	3.0	3.2
Beam radius at flat mirrors (mm)	1.7	1.9
Flat mirror transmittance (%)	0.2	0.2
Mirror absorption/scattering loss (ppm)	30	30
Intensity at curved mirror (kW/cm^2)	14	11
Intensity at flat mirror (kW/cm^2)	46	37
Circulating power (kW)	4.0	4.0

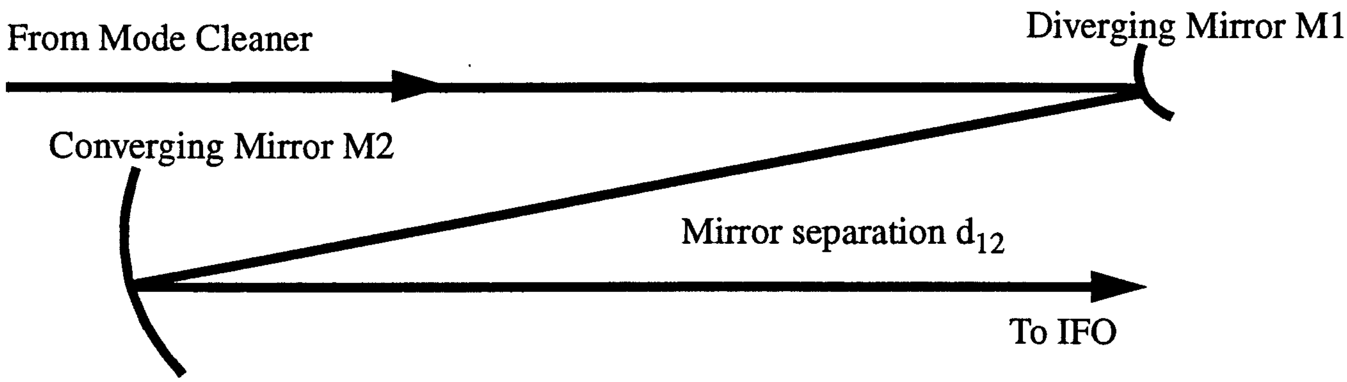
Mode cleaner transmission



Phase shift near resonance

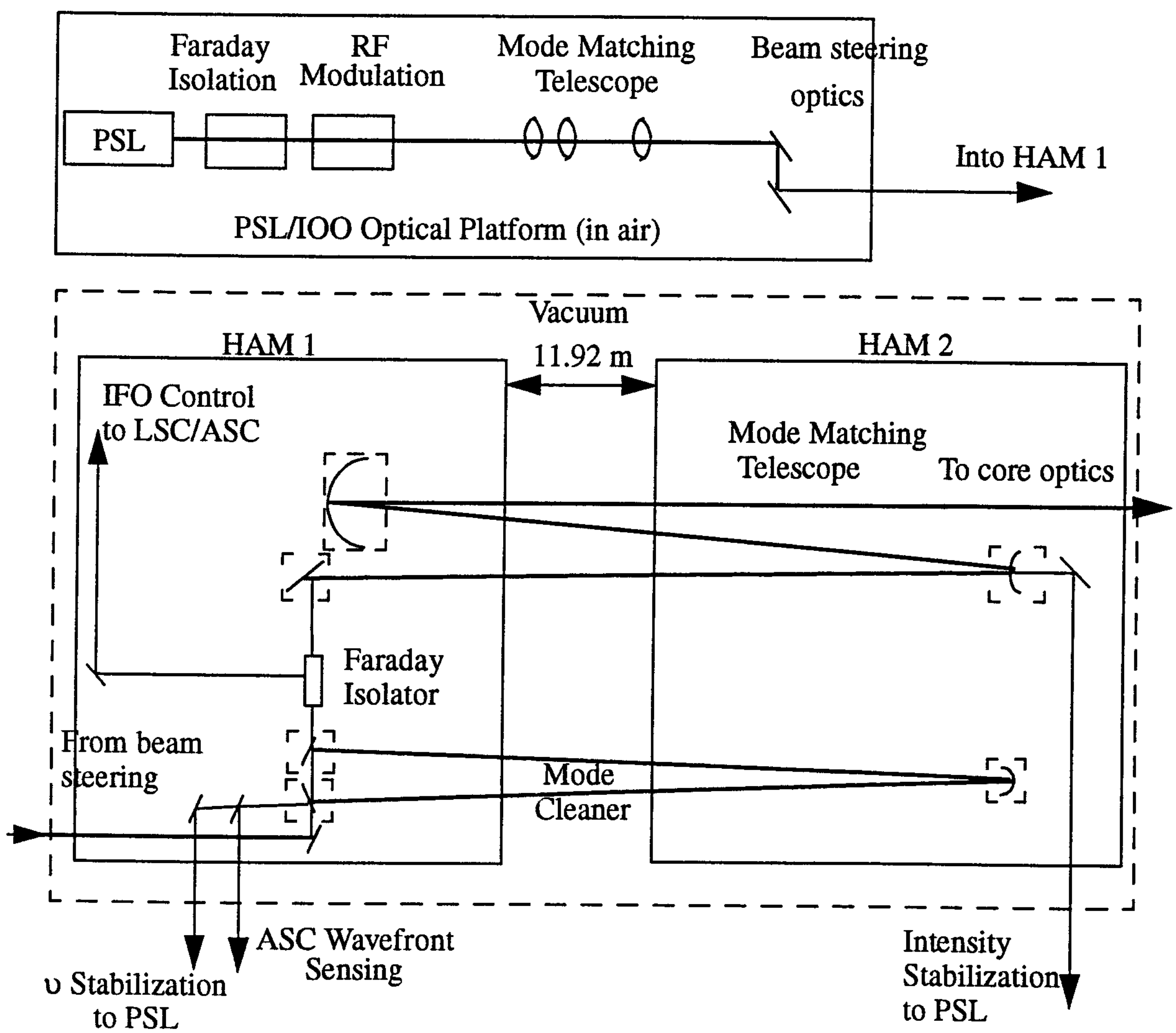


IFO Mode-Matching Telescope



- Reflective Galilean design advantages
  - ›› Optical isolation / parasitic interferometers
  - ››Beam steering with reflective optics
- Radii of Curvature Selection
  - ›› waist magnification: $w_{o,IFO} / w_{o,MC}$ = 20.9 (4 km)
    = 17.1 (2 km)
  - ›› $d_{12} \sim f_2 - f_1$, constrained by HAM dimensions and separation

Overall IOO Layout



Advanced R&D I: Interferometer R&D

Initial LIGO - power recycled Michelson IFO

›› h ~ 10^{-21} / rHz in broadband operation

Enhanced LIGO - increase strain sensitivity by 10X using alternative IFO topologies

Constraint on enhanced LIGO detector: easily upgradable from current LIGO

›› dual recycling (DR) and resonant sideband extraction (RSE)

Collaborative research program between UF and Caltech/MIT to compare RSE and DR as candidates for enhanced LIGO

Tabletop Dual Recycling

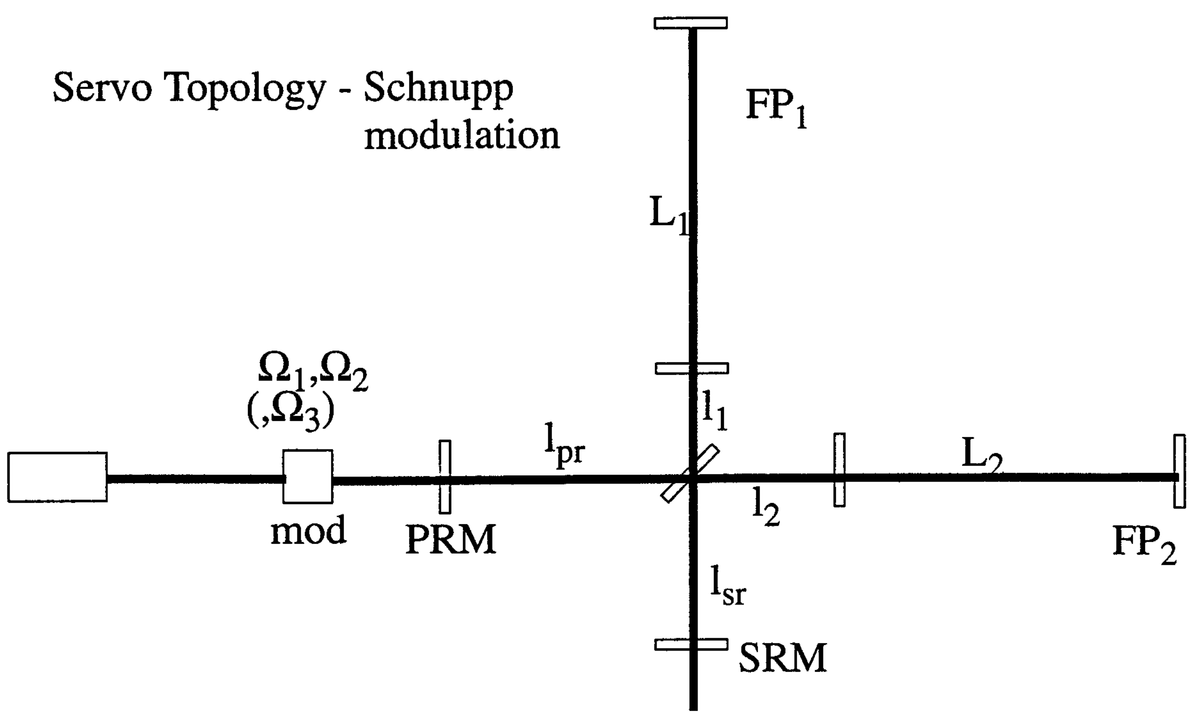
Signal Recycled IFO - proposed by Meers to enhance GW sensitivity at a specific GW frequency by resonant enhancement of GW sidebands.

Dual Recycled IFO - combines SR and PR. Prior demonstration using simple Michelson IFO.

Advantages: enhancement of specific frequency GW signal by SR cavity finesse, narrowband tunability.

But: hasn't been implemented with FP arms

Servo Topology - Schnupp modulation



Advanced IFO R&D Workplan

Phase I : Tabletop Experiments (1997, 1998)

- Construction of Tabletop DR IFO
- Evaluation of DR
  - ›› alternative locking topologies
  - ›› lock acquisition and stability
  - ›› GW band tunability

Done in parallel with Caltech/MIT assessments of RSE

Phase II : Suspended IFO testing (1999,2000)

- Selection of either DR or RSE based on Phase I
- Low frequency performance on suspended IFO

Work done at Caltech/MIT by UF/LIGO scientists

UF Personnel:

Reitze, Tanner, Research Scientist, Graduate Student

NSF requested equipment funds:

$150K for laser/optics/measurement apparatus

Advanced R&D II: Optical Materials Research for Future LIGO

Next generation LIGO: 100 W lasers + novel IFOs

- optical materials subjected to increase in peak power, intensity by 10 - 100 X or more
- deviation in optic surface figure caused by high peak powers
  - ››"Linear" effects
    - – thermal expansion of coatings, substrates
    - – hydrocarbon mirror contamination in vacuum
  - ››"Nonlinear" effects
    - – field-induced memory effects (birefringence)
    - – nonlinear phase shift
- spatial wavefront distortion of beam
  - – *cumulative optical "damage"*
  - – *change in cavity storage times/control loops*

The UF materials research program will investigate/ characterize/identify optical materials for next generation LIGO

Optical Materials Research for Enhanced/Advanced LIGO

Absorption in optical coatings and substrates:

thermal expansion:

$$\Delta L = \frac{\alpha}{\kappa} L^2 A I_{peak}$$

Coating:
L = 10 - 20 μm, A = 1 - 5 ppm absorption
thermal expansivity: $\alpha \sim 10^{-5}$ / K
thermal conductivity (barrier): ~ $\kappa \sim 10^{-3}$ W/cm K

Substrate:
L = 10 cm, A < 0.1 ppm absorption
thermal expansivity: $\alpha \sim 10^{-5}$ / K
thermal conductivity: ~ $\kappa \sim 5 \times 10^{-2}$ W/cm K

	I_{coat} (W/cm^2)	I_{sub} (W/cm^2)	ΔL_{coat} (A)	ΔL_{sub} (A)
Current LIGO	10^3	10	0.1	2
Advanced LIGO	10^6	100	10	20

Optical Materials Research for Enhanced/Advanced LIGO

In Situ Mirror Contamination

Hydrocarbon deposits ‘baked’ on FP cavity mirrors by cumulative exposure to laser

›› change in mirror surface figure, mirror reflectivity

---> change in FP finesse and cavity ring down time

--> change in stability of control loop

Nonlinear Effects in Optical Materials

Field-induced birefringence: light fields induce field-dependent polarization which substrates remember (magnitude depends on material, wavelength, power)

›› substrate acts like a field-dependent waveplate; reduction in fringe contrast

Nonlinear Phase Shift:

$$\Delta\phi(r) = \frac{2\pi n_2}{\lambda}\int_0^L I(r, z)\, dz$$

›› Spatial beam distortion & spatial dependent phase

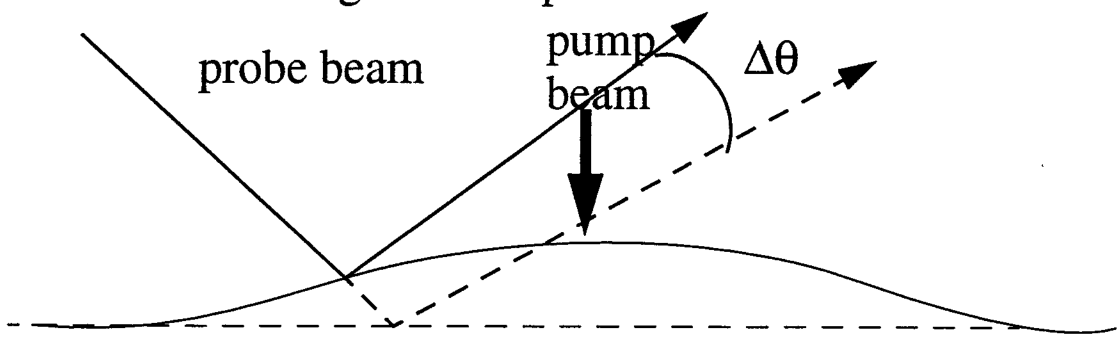
››

*UF*LIGO

Optical Materials Research Workplan

Linear/thermal characterization:

- Photothermal displacement spectroscopy (PDS) - high precision measurement of sub-angstrom displacements



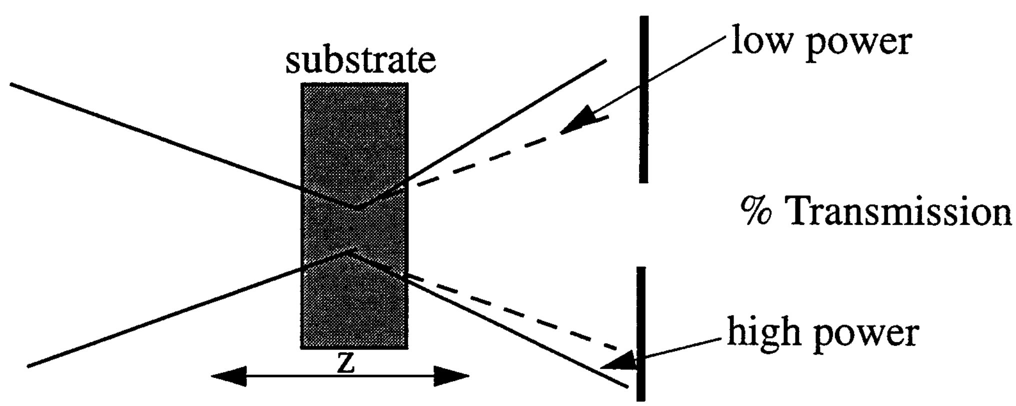
Contamination measurements:

- Controlled cavity ringdown measurements
- post-mortem analysis: identify specific nature of contamination
  - ›› surface analysis: alpha-step, surface x-ray, composition analysis
- Formulate in situ cleaning strategy (laser desorption)

Optical Materials Research Workplan

<u>*Nonlinear characterization:*</u>

- Z-scan: high precision (λ/10000) measurement of nonlinear phase shift



<u>UF Personnel:</u>

Reitze, Tanner, Postdoc, Graduate Student

<u>NSF requested equipment funds:</u>

None; available through UF seed money