THE PHYSICS OF LIGO

I. Lecture Notes & Exercises

Materials from a Course taught at Caltech
by members of the LIGO team and others
in Spring 1994

organized and edited by Kip S. Thorne

California Institute of Technology

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PREFACE

In the spring term of 1994, I organized a course at Caltech on *The Physics of LIGO* (i.e., the physics of the Laser Interferometer Gravitational Wave Observatory). The course consisted of eighteen 1.5-hour-long tutorial lectures, delivered by members of the LIGO team and others, and it was aimed at advanced undergraduates and graduate students in physics, in applied physics, and in engineering and applied sciences, and also at interested postdoctoral fellows, research staff, and faculty.

In my mind the course had several purposes: (i) It used LIGO as a vehicle for teaching students about the physics and technology of high-precision physical experiments. (ii) It served as a tutorial on the physics of LIGO for scientists and engineers, who had joined the LIGO team in the preceding year in preparation for the beginning of LIGO's construction. (iii) It served as an introduction to the science and technology of LIGO for other members of the Caltech community: In spring 1994, LIGO was just beginning to emerge from two years of controversy on the Caltech campus, and a number of faculty and staff wanted to learn in detail about the LIGO team's interferometer R&D, so they could form opinions of their own about whether the Project was well conceived and its interferometer development was being well executed. (It is my impression, in retrospect, that most and perhaps all of the faculty and staff who attended the course regularly emerged with a positive view LIGO.)

The lectures were delivered in Room 107 Downs on Wednesdays from 1:00 to 2:30 PM and Fridays from 10:30AM to noon. The audience typically consisted of about 5 undergraduates, 10 graduate students, 5 postdoctoral fellows, 8 professors, and 15 members of the LIGO team—and, for some lectures, rather more than this, especially more professors. The audience was mostly from Physics and Engineering, but a smattering of other disciplines was represented (including even an occasional social scientist). The undergraduates and some of the graduate students took the course for credit under the rubric of Physics 103.

These two Volumes contain the materials distributed at the lectures, augmented occasionally in Volume I by lecture notes that Malik Rakhmanov (the grader) or I have written, describing the lecture. More specifically:

Volume I contains (i) copies of the transparencies used in each lecture, or—in the case of lectures not based on transparencies—notes on the lecture prepared by Rakhmanov or me; and (ii) lists of references and sets of exercises prepared by me and/or the lecturers.

Volume II contains copies of the most important of the references that the lecturers chose to accompany their lectures. Some references are extracted from textbooks or technical monographs, others are from the original scientific literature, and a few are preprints of papers not yet published. Because we have not sought, from the publishers of these references, permission for widespread duplication and distribution, only a few copies of

Volume II are being made; and Volume II carries an admonition on its cover page that it should not be reproduced.

For these volumes I have given sequential capital-letter labels (A, B, C, ... Z, AA, BB, ... YY) to all the readings that appear in Volume II, and have revised the reference lists in Volumes I and II to reflect this labeling. References not included as readings are now labeled with lower-case letters (a, b, c, ... z).

These Volumes will be of value not only as a historical record, but also as a reference source for members of the LIGO team and others, and as an aid for people who did not attend the lectures and who want to begin learning about LIGO. For example, people who join the LIGO team during the next several years may find these volumes helpful in getting oriented. (To those who joined the team during the summer or early autumn of 1994, I apologize that I have been so slow in putting these volumes together.)

I thank the lecturers for the extensive time, energy, and enthusiasm that they put into this course. No single person could possibly have delivered this set of lectures, especially not I! I also thank Robbie Vogt and Stan Whitcomb who, as Director and Deputy Director of LIGO, encouraged me in 1993 to organize this course and encouraged the members of the LIGO team to help me make it a reality. Finally, for their enthusiastic backing of this effort, I thank the entire LIGO team, Barry Barish (LIGO PI), Tom Everhart (the Caltech President), Paul Jennings (the Provost), Charles Peck (the Chair of Physics, Mathematics, and Astronomy), and a number of Caltech faculty members.

Kip S. Thorne
Caltech
20 October 1994

CONTENTS OF VOLUME I

Note: The contents of each lecture are described below in outline form (though the lecture typically does not follow the outline sequentially). For each lecture, this volume contains: (i) a list of references prepared by the lecturer and broken down into "Assigned Reading" and "Supplementary Reading," with comments about the relevance of each reference;* (ii) a set of exercises that the reader is invited to try, as a tool to better understanding;† and (iii) the transparencies from which the lecture was delivered and/or notes on the lecture prepared by Kip, or by Malik Rakhmanov.

* Those references labeled by capital letters (A, B, C, ... Z, AA, BB, ... YY) are reproduced in Volume II; those labeled by lower-case letters are not

† The students who took this course for credit were required to work many of these exercises or do supplementary reading and write essays about it.

4. **Idealized theory of interferometers—I** *by Kip S. Thorne* [8 April]
   a. Gaussian beams and their manipulation
   b. beam splitters and mirrors
   c. simple delay-line interferometers
   d. Fabry-Perot cavities
   e. simple Fabry-Perot interferometers

5. **Idealized theory of interferometers—II** *by Ronald W. P. Drever* [13 April]
   a. Power recycled interferometers
   b. Resonantly recycled interferometers
   c. Dual (or signal) recycled interferometers
   d. Doubly resonant signal recycled interferometer
   e. Resonant sideband extraction

6. **Overview of a real interferometer** *by Stanley E. Whitcomb* [15 April]
   a. what is in a real interferometer
   b. survey of potential noise sources
   c. scaling of noise sources
   d. introduction to control systems
   e. diagnostic techniques for real interferometers

7. **Lasers and input optics—I** *by Robert E. Spero* [20 April]
   a. Fabry-Perot cavities as displacement sensors
   b. shot noise in photodetection, signal-to-noise ratio
   c. effect of mirror losses; equivalence of active and passive cavities
   d. phase modulation to sense optical phase and eliminate sensitivity to laser intensity fluctuations; sideband analysis; reflection ("Pound-Drever") locking
   e. experimental demonstration of shot noise limited sensitivity.
   f. non-recombined and recombined optical configurations; sensitivity vs. storage time, visibility, modulation waveform
   g. optimization of optical and modulation parameters

8. **Lasers and input optics—II** *by Alex Abramovici* [22 April]
   a. general requirements on light for LIGO interferometers
   b. configuration of the light source (laser, mode cleaner, other components and subsystems)
   c. Argon ion laser; its single-frequency operation and frequency prestabilization
   d. beam jitter in terms of mode superposition
   e. mode cleaner and mode matching
   f. Nd:YAG laser and frequency doubling

9. **Optical elements** *by Rick L. Savage* [27 April]
   a. overview of LIGO's requirements for mirrors, beam splitters, phase modulators, photodiodes, pick offs, etc.
   b. detailed requirements for test-mass optics:
      general requirements—total losses, reflectivity, radius of curvature, etc.
      mirror surface imperfections and how they influence the interferometer;
      contamination-induced mirror heating.
   c. the LIGO core optics pathfinder program:
      mirror substrates (mechanical quality factors, polishing, Zernike polynomials, measurement of polished surfaces);
      mirror coatings.

10. **Control systems for test-mass position and orientation** *by Seiji Kawamura* [29 April]
   a. test-mass suspension systems
   b. test-mass position and orientation damping
   c. transfer function of a pendulum
   d. sensors and actuators
   e. test mass orientation noise in a Fabry-Perot interferometer
   f. noise from the control system

11. **Optical topology for the locking and control of an interferometer, and signal extraction** *by Martin W. Regehr* [4 May]
   a. overview and explanation of the modulation methods used to extract the gravitational wave signal
   b. methods of extracting the auxiliary signals necessary for locking an interferometer
   c. analysis of multivariable control systems, with examples

12. **Seismic isolation** *by Lisa A. Sievers* [6 May]
   a. seismic background: its origin and spectrum
   b. isolation stacks: basic theory, design issues, chosen design and performance
   c. isolation via pendulum suspension; compound pendulum
   d. active isolation systems

13&14. **Test masses and suspensions and their thermal noise** *by Aaron Gillespie* [11 May and 13 May]
   a. key issues in elasticity theory
   b. fluctuation-dissipation theorm
   c. causes of losses in materials
   d. frequency dependence of noise
   e. suspension noise
   f. violin-mode noise
   g. internal-mode noise
   h. "excess" (non-Gaussian) noise
   i. choices of materials

15. **Light scattering and its control** *by Kip S. Thorne* [18 May, 1st half]
    a. how scattered light can imitate a gravitational wave; the magnitude of the danger
    b. control of scattered light by baffles and by choice of materials
    c. the chosen LIGO baffle design
16. **Squeezed light and its potential use in LIGO** *by H. Jeff Kimble* [18 May 2nd half, and 20 May]
    a. theory of squeezing
    b. practical methods of squeezing
    c. present state of the art
    d. use of squeezed vacuum state in interferometers
    e. methods to beat the standard quantum limit
17. **The physics of vacuum systems, and the LIGO vacuum system** *by Jordan Camp* [25 May]
    a. basic physics and engineering of vacuum systems
    b. noise in an interferometer due to residual gas
    c. LIGO vacuum specifications
    d. LIGO's special low-hydrogen steel
    e. outgasing and pumping strategy
    f. construction of the vacuum system
18. **The 40 meter prototype interferometer as an example of many of the issues studied in this course** *by Robert E. Spero* [27 May]
    The following abstract gives the flavor of how Spero approached this topic:
    Building gravity wave detectors like the 40 m interferometer or LIGO proceeds in two steps: constructing an array of test masses that is free from external disturbances and other sources of displacement noise, and devising a sensitive readout of the relative positions of these masses. The noise sources that constrain sensitivity can be classified as *fundamental*, meaning they were expected, ultimately, to limit the detector's sensitivity and their limits were estimated (around 1971) before the first detectors were built, and *technical*, meaning that, whether they initially were thought of or not, they are unlikely to place ultimate limits on sensitivity. Since the required sensitivity is many orders of magnitude greater than anything previously achieved, one might worry about a third class of noise sources: unanticipated fundamental phenomena revealed in the course of the R&D, which will limit the ultimate sensitivities. Luckily, no such phenomena have been discovered. The 40 m interferometer has been invaluable at sorting out which sources of noise (both fundamental and technical) are the most important in the short run and the long, and in guiding the design of LIGO. Our current understanding of the effects of imperfections in phenomena such as phase modulation, intensity stabilization, mechanical servos, and lock acquisition is due largely to investigations conducted on the 40 m and similar experimental interferometers.

Note: A tour of the 40 meter prototype interferometer was taken twice outside lecture hours: once early in the term, largely for impressionistic purposes; once at the end of the course, following up on the last lecture. A tour of the LIGO Optics laboratory in the basement of West Bridge was also taken twice: once in the middle of the term focusing

on issues discussed in the term's first half; once at the end of the term, focusing on issues from the term's second half.

CONTENTS OF VOLUME II

Note: For each lecture, this volume contains the list of references prepared by the lecturer with comments about the relevance of each reference, followed by a copy of each of the most important references. In the contents below, we list the copied references for each lecture. The copied references are labeled sequentially by capital letters (A, B, C, ... , Z, AA, BB, ... YY). The other references are labeled sequentially by lower-case letters.

J. B. J. Meers, "Recycling in laser-interferometric gravitational-wave detectors," *Phys. Rev. D*, **38**, 2317–2326.

K. B. J. Meers, *Physics Letters A*, "The frequency response of interferometric gravitational wave detectors," *Physics Letters A*, **142**, 465 (1989).

L. B. J. Meers and R. W. P. Drever, "Doubly-resonant signal recycling for interferometric gravitational-wave detectors." (preprint)

M. J. Mizuno, K. A. Strain, P. G. Nelson, J. M. Chen, R. Schilling, A. Rudiger, W. Winkler and K. Danzman, "Resonant sideband extraction: a new configuration for interferometric gravitational wave detectors," *Phys. Lett. A*, **175**, 273–276 (1993).

N. R. W. P. Drever, "Interferometric Detectors of Gravitational Radiation," in *Gravitational Radiation*, N. Deruelle and T. Piran, eds. (North Holland, 1983).

6. Overview of a real interferometer *by Stanley E. Whitcomb* [15 April]

O. D. Shoemaker, R. Schilling, L. Schnupp, W. Winkler, K. Maischberger, A. Rudiger, "Noise behavior of the Garching 30-meter prototype gravitational-wave interferometer," *Physical Review D,* **38**, 423-432 (1988).

P. Benjamin C. Kuo, *Automatic Control Systems* (Prentice-Hall), "Chapter 1. Introduction."

7. Lasers and input optics—I *by Robert E. Spero* [20 April]

Q. A. Rüdiger, R. Schilling, L. Schnupp, W. Winkler, H. Billing and K. Maischberger, "A mode selector to suppress fluctuations in laser beam geometry," *Optica Acta,* **28**, 641–658 (1981).

R. A. Yariv, *Optical Electronics* (Saunders College Publishing, 1991), "Chapter 10. Noise in Optical Detection and Generation."

S. A. Abramovici and Z. Vager, "Comparison between active- and passive-cavity interferometers," *Phys. Rev. A*, **33**, 3181 (1986).

T. J. Gea-Banacloche, "Passive versus active interferometers: Why cavity losses make them equivalent," *Phys. Rev. A*, **35**, 2518 (1987).

U. T.M. Niebauer, R. Schilling, K. Danzmann, A. Rudiger, W. Winkler, "Nonstationary Shot Noise and its Effect on the Sensitivity of Interferometers *Phys. Rev A* **43**, 5022–5029 (1991).

V. P.H. Roll, R. Krotkov, and R.H. Dicke, "The equivalence of inertial and passive gravitational mass," *Ann. Phys* **26**, 442 (1964); pages 466–470.

8. Lasers and input optics—II *by Alex Abramovici* [22 April]

W. A. Rüdiger, R. Schilling, L. Schnupp, W. Winkler, H. Billing and K. Maischberger, "A mode selector to suppress fluctuations in laser beam geometry," *Optica Acta,* **28**, 641–658 (1981).

X. W. Koechner, *Solid-State Laser Engineering* (Springer Verlag, Berlin, 1988), "Chapter 1. Introduction."

9. Optical elements *by Rick L. Savage* [27 April]

Y. W. Winkler, K. Danzmann, A. Rüdiger and R. Schilling, "Optical Problems in Interfereometric Gravitational Wave Antennas," in *The Sixth Marcel Grossmann*

Meeting, eds. H. Sato and T. Nakamura (World Scientific, Singapore, 1991), pp. 176–191.

Z. D. Malacara, *Optical Shop Testing* (John Wiley and Sons, New York, 1978), section 1.2, "Fizeau Interferometer," pp. 19–37.

AA. H. A. Macleod, *Thin-Film Optical Filters,* 2nd edition (Adam Hilger Ltd., Bristol, 1986), "Introduction," pp. 1–10.

10. Control systems for test-mass position and orientation *by Seiji Kawamura* [29 April]

BB. S. Kawamura and M. E. Zucker, "Mirror orientation noise in a Fabray-Perot interferometer gravitational wave detector," *Applied Optics*, in press.

CC. M. Stephens, P. Saulson, and J. Kovalik, "A double pendulum vibration isolation system for a laser interferometric gravitational wave antenna," *Rev. Sci. Instrum.*, **62**, 924–932 (1991).

DD. R. C. Dorf, *Modern Control Systems* 5th editon (Addison-Wesley, 1989): §§7.1 and 7.2 of Chapter 7, "Frequency Response Methods;" and §§8.1–8.4 of Chapter 8, "Stability in the Frequency Domain."

11. Optical topology for the locking and control of an interferometer, and signal extraction *by Martin W. Regehr* [4 May]

EE. P. W. Milonni and J. H. Eberly, *Lasers* (Wiley, New York, 1988): §§12.9 "AM Locking" and 12.10 "FM Locking," pp. 385–390.

FF. C. N. Man, D. Shoemaker, M. Pham Tu and D. Dewey, "External modulation technique for sensitive interferometric detection of displacements," *Physics Letters A*, **148**, 8–16.

GG. John H. Moore, Christopher C. Davis, and Michael A. Coplan, *Building Scientific Apparatus: A Practical Guide to Design and Construction* (Addison-Wesley, 1983), Sec. 6.8.3 "The lock-in amplifier and gated integrator or boxcar," (pp. 435–437).

HH. Paul Horowitz and Winfield Hill, *The Art of Electronics* (Cambridge University Press, Cambridge, 1980), Sec. 14.15 "Lock-in detection" (pp. 628–631) and an earlier section to which it refers, Sec. 9.29 "PLL components, Phase detector" (pp. 429–430).

12. Seismic isolation *by Lisa A. Sievers* [6 May]

II. Leonard Meirovitch, *Elements of Vibration Analysis* (McGraw-Hill, 1986), pp. 39–57.

JJ. R. del Fabbro, A. di Virgilio, A. Giazotto, H. Kautzky, V. Montelatici, and D. Passuello, "Three-dimensional seismic super-attenuator for low frequency gravitational wave detection," *Physics Letters A*, **124**, 253–257 (1987).

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MM. L. Ju, D. G. Blair, H. Peng, and F. van Kann, "High dynamic range measurements of an all metal isolator using a sapphire transducer," *Mass. Sci. Technol.*, **3**, 463–470 (1992).

13&14. Test masses and suspensions and their thermal noise *by Aaron Gillespie* [11 May and 13 May]

NN. H. B. Callen and T. A. Welton, "Irreversibility and generalized noise," *Phys. Rev.*, **83**, 34–40 (1951).

OO. Peter R. Saulson, "Thermal noise in mechanical experiments," *Phys. Rev. D*, **42**, 2437–2445 (1990).

PP. Aaron Gillespie and Frederick Raab, "Thermal noise in mechanical experiments," *Phys. Rev. D*, **42**, 2437–2445 (1990).

QQ. Aaron Gillespie and Frederick Raab, "Thermally excited vibrations of the mirrors of a laser interferometer gravitational wave detector," unpublished (1994).

RR. Aaron Gillespie and Frederick Raab, "Suspension losses in the pendula of laser interferometer gravitational wave detectors," *Phys. Lett. A*, in press (1994).

15. Light scattering and its control *by Kip S. Thorne* [18 May, 1st half]

SS. J. M. Elson, H. E. Bennett, and J. M. Bennett, "Scattering from Optical Surfaces," in *Applied Optical Engineering*, Vol. VII (Academic Press 1979), Chapter 7, pp. 191–243.

16. Squeezed light and its potential use in LIGO *by H. Jeff Kimble* [18 May 2nd half, and 20 May]

TT. C. M. Caves, "Quantum mechanical noise in an interferometer," *Phys. Rev. D*, **23**, 1693–1708 (1981).

UU. D. F. Walls, "Squeezed states of light," *Nature*, **306**, 141–146 (1983).

VV. M. Xiao, L. A. Wu, and H. J. Kimble, "Precision measurement beyond the shot-noise limit," *Phys. Rev. Lett.*, **59**, 278–281 (1987).

17. The physics of vacuum systems, and the LIGO vacuum system *by Jordan Camp* [25 May]

WW. J. Moore, C. Davis, M. Coplan, *Building Scientific Apparatus* (Addison-Wesley, 1983), Chapter 3. "Vacuum technology."

18. The 40 meter prototype interferometer as an example of many of the issues studied in this course *by Robert E. Spero* [27 May]

XX. Rainer Weiss, "Electromagnetically coupled broadband gravitational antenna," *Quart. Prog. Rep. Res. Lab. Electron. M.I.T.* **105**, 54 (1972).

YY. Robert L. Forward, "Wideband laser-interferometer gravitational-radiation experiment," *Phys. Rev. D* **17**(2), 379–390 (1977).