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Interferometers, from Michelson to LIGO

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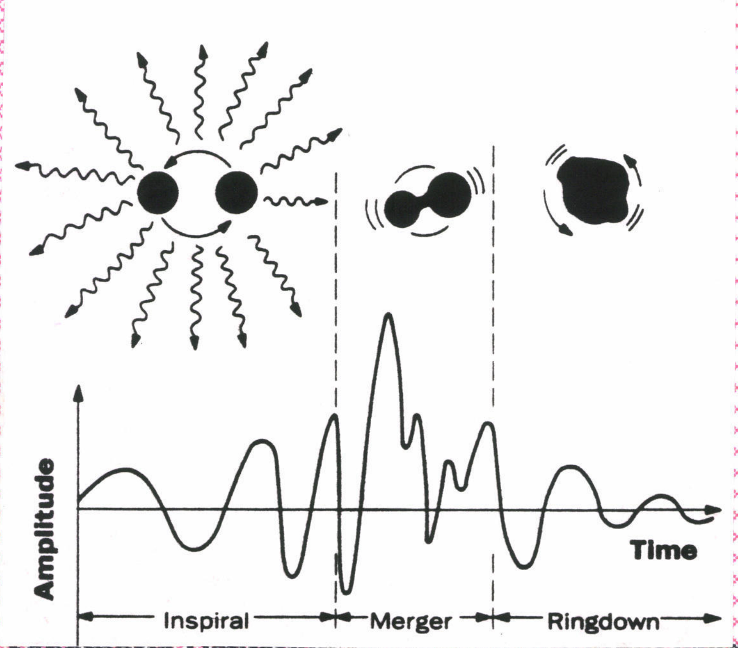

Figure 1. Schematic Depiction of the gravitational waves from the coalescence of two neutron stars

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Interferometers, from Michelson to LIGO
(Searching the Sound of Universe)

by

David T. Wei [ ]

Abstract

The Michelson L-shaped interferometer is adopted for direct detection of gravitational wave. Considered as the largest observatory on earth by year 2001, LIGO's principle and construction are described in layman's language and are accompanied by color photographs for poster. Comparison with classical interferometers is made. Brief discussions of gravitational wave and interferometry applications are also presented.

Introduction: Michelson and Einstein

Almost everyone knows A. Einstein, his unerring theory on relativity and unified field. That light

burn themselves into light, which accelerates and bends near the sun or a galaxy. Light may fall into a black hole and never re-emerge. Finally, when neutron stars collide and black holes swallow each other, they emit little light, but trains of energy called "gravitation waves." (See FIG. 1 above). So much from a single person? Who gave him the power to forecast and to discover? But zillions of experimental and supercomputer data have shown that he has been correct!

It all started by another scientific giant and his experiments. His name was A. Michelson and his weapons were "interferometers." Well known by opticists but obscured among the mass media, he was the one who declared that velocity of light is a constant. At the turn of 20th. century, the elegant experiments on his **L-shaped interferometer** threw away a stationary, universal medium call "ether" and also threw the classical physicists into disbelief. Michelson-Morley's reliable **"no ether drift"** experiment earned himself a Nobel price and ushered a young, unknown Einstein into the arena of physics, who has made history throughout this century. Now, spirit of Michelson is reappearing. By year 2001, his disciples will finish a monumental installation called LIGO and will begin to probe the universe by sound and by light.

What is LIGO? It is an acronym for "Laser Interferometer Gravitational-Wave Observatory." To fulfill Michelson's dream,[1] two large sites in U. S. are under construction and are technically supported by Caltech and MIT. It uses the most up-to-date technologies: ultrahigh vacuum in multiples of 4 km beam tubes, long distance network for coincidence electronics, supercomputer and online communication with sister observatories in Europe, Japan and Australia. Above all, the heart and soul of this new, gigantic L are sets and sets of gigantic ion beam-coated supermirror cavities,[2] linked by an ultralow noise laser and a mammoth size beam-splitter at each site. Without these optics the interferometers simply will not function.

We next present frequently asked questions (FAQ) on gravitational waves, facts of LIGO and other interferometers, and end with graphics.

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Sound of Universe

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[1] Michelson constructed a <u>mile long tube</u> in 1928 but did not see it finish in his lifetime.

[2] D. Wei, H. Kaufman, C. Lee,"Ion Beam Sputtering," Chap. 6 of "Thin Films for Optical Systems," ed. F. Flory, (publ. M. Dekker, 1995)

Question and Answer about Gravitational Wave

- Where do gravitational wave come from?

Gravitational waves are created as huge masses of some other part of the universe collide, explode, or undergoing big change.

- What kind of wave is it.?

It is vibrational in nature like sound wave. But it has 2 transverse modes like electromagnetic wave.

- What is the transmitting medium?

It does not need a medium to transmit, (neither air nor ether, thanks to Michelson).

- How does LIGO distinguish gravitational wave from the earthborn vibrations?

It takes at lease three tests. (a) The signal should have a special signature, an impulse small and short. (b) this impulse should register at both stations 3 km apart, (c) Supported by other simultaneous evidences, such as from sister observatories all over the world, and also occurrence from telescopes, we can pinpoint where does the signal come from in the universe.

- Can you give more details about what happens when gravitational wave hits?

At LIGO, in resonance to a gravitational wave, the the cavity mirrors swing at a frequency from a few Hz to several 1000Hz. The 2 subcavities in the arms of LIGO are out of phase in the two transverse directions of the wave, one contracts while the other expands. They interfere at the detector, therefore modulate the laser light intensity.

- Does a fallen apple generate a gravitational wave? How can we detect it?

No. If LIGO picks up such a signal, it would have the wrong signature. What Newton observed was a static gravitation, not a wave. A gravitational wave is an impulse of energy created during rapid, huge loss of mass, or on the expense of some form of static gravitation, such as an exploding supernova, or the coalescence of two neutron stars as in Fig. 1. It would take much more than an H-bomb explosion to send a gravitation wave to outer space.

- Is there a way to explain what you said in layman's terms?

Yes! Because a vibration is detected, and its frequency overlaps with the range of human voice, the signal output can be amplified further and recorded or listened through an earphone. Combined with images through telescope, even color motion pictures are possible. Think of the excitement when you hear a song from a remote island in the universe for the first time.

Candidates for LIGO's Search

Some astronomical bodies that should emit gravitational Waves are:

I Spiraling Binary Neutron Stars[1*] -- See Figure 1
Black hole <--> neutron stars
Black hole <--> black hole
Supernova core activities
Big bang.

[1*] Binary neutron stars was discovered by R. Hulse and J. Taylor, University of Massachusetts, Nobel Price winners 1993 in Physics. The energy loss from the binary was interpreted as gravitation-wave emission by Taylor and Weisberg, 1989.

Major Advantages of LIGO

- High gain supermirror cavities to improve sensitivity by 11 orders;
- Mirrors as test-bobs to respond to the arriving wave;
- Long arms to increase their phase difference.

Interferometers, LIGO vs. Michelson-Morley

Now let us compare these two interferometers. Other types are presented on poster p.11. The main difference of LIGO from the Michelson-Morley interferometer (that threw out either theory) is its length of arms; and the supermirrors which play double role as resonance cavity in these arms, and as test-bobs to swing under gravitational waves. Similar to the anti-ether experiment of year 1901, arrival of a garvitational wave of year 2001 would induce a change of phase between the two arms, in this case caused by the asymmetrical swings of mirrors between x- and y-directions. Just as the sensitivity was improved by a high number of bounces between mirrors in the former; so, the mirror's high cavity gain will increase sensitivity by orders in .the latter. Yet the phase change in LIGO will be much smaller than that of Michelson-Morley's, only intensity change will be detected. Table 1 summarizes the comparison of the two experiments.

Table 1 Coparison of the two interferometers

	Michelson-Morley's [Disproved Stationary Ether]	**LIGO [To Detect Gravitational-Wave]**
Arm Length	1.375 m	4,000 m
Bounces	8	>>30 (estimated from cavity gain)
Δ-pathlength	2 x10^{-5} expected	3 x10^{-18} expected
Δ-detection mode	interference fringe shift	light intensity change
Mirrors/Arm	8	a pair per subcavity, upto 20.
Mirror Diameter	1 cm estimated	20 cm established
Light Source	C-Arc	Ar-Laser now Nd:YAG Laser in the future
Resonance Cavity	No	A super-cavity consist of 2 sub-cavities
Cavity gain (loss)	(<1)	100, in two stages
Redundancy	rotatable through 90^0	non-rotatable, but in different orientations at the two locations.

The Sister Laboratories.

There are other gravitational-wave projects using similar technology as follows:

Table 2. Sister Laboratories of LIGO

Name	**Arm length**	**Sponsoring Country**	**Location**	**Year expected**
GEO600	600 m	Germany-Britain	Hannover	1999
VIRGO	3 km	Italy-France	Pisa	2002
TAMA	300 m	Japan	Tokyo	--
Consortium	---	Australia (coop. with LIGO)	Sydney	--

Appendix

Various Interferometers and Their Applications.

A. Michelson Interferometer--the **original "L"**. It uses 1 semi-transmitting and 2 reflecting mirrors. The former plays a double role: (i) splits input light into two beams and (ii) recombines the 2 beams into one that contains an interference pattern. Bounced by a reflecting mirror each, the split beams take a round trip in mutually perpendicular directions. The difference of media encountered on their ways (e. g., a plate insertion or a flowing fluid) correspond to a shift in the interference pattern. A broad beam source was used for early day pattern fringes.

B. Michelson-Morley Interferometer. This is the instrument by which the experiment denying **a stationary ether** is carried out. Such phenomenon was consistently explained by Einstein's **relativity** later. It has eight bouncing mirrors in each arm to fold a path length of 11 m. It is able to rotate through 90 degrees on a floating base. Minimized mirror loss and maximized path length are the two major factors for its improved sensitivity.

C. Mach-Zehnder Interferometer. It requires 2 semi-transmitting mirrors (one to split the light path into two and the other to re-combine them into one), and is getting popular in integrated optics as shown. Using 2 or more fibers fused together to replace mirrors, they can control the branching ratio vs. wavelength of light, thus useful in **DWDM** and **fiber gyroscope**.

D. Two Beam Interferometry. Evolving around Michelson interferometer, newer concepts were to split light into a probe beam and a reference beam and which modify the fringes with spatial frequency. First used to find lens defects by **Twynman-Green**, coherent laser beam was adopted in 1960's and has led to new fields like **holography** and **Fourier optics**.

E. Sagnac Interferometer. A beam splitting instrument guides two counter-rotating light beams in the same loop: one clockwise and the other counterclockwise. Combined to produce interference, their fringes have a movement in proportion to the rotation speed of the interferometer if and only if the circulating instrument of light would not mix the two opposing beams in their path. Two such instruments are found, (i) an endless supermirror cavity, and (ii) a long single mode fiber loop. They find applications in **ring laser gyroscope** and **fiber gyroscope**.

F. LIGO. This interferometer has all the cutting edge technology, but major improvement is still from the mirror quality and path length.. Its sensitivity is valuable for earthquake prevention and for remote sensing. Most optical sensors are extensions for eyes. This is an **extension for ears**.

Conclusion. A standard question about scientific accomplishments is their benefit to the society. Questioning what earthbound application can LIGO have today is like questioning what is the use of $\mathbf{E = mc^2}$ in 1905 or that of a **satellite** in 1955. Today's **energy** and **communication** depend on them both. We have demonstrated a clan of Michelson Interferometers and offsprings, and have shown his rich inheritance. We end it with a forecast that LIGO has practical values. In a Chinese proverb: a man of good business sense not only needs a far-sighted visibility, but also a wind-gifted hearing (千里眼, 順風耳). Huge resources from LIGO's technology should provide us excellent commercial values.

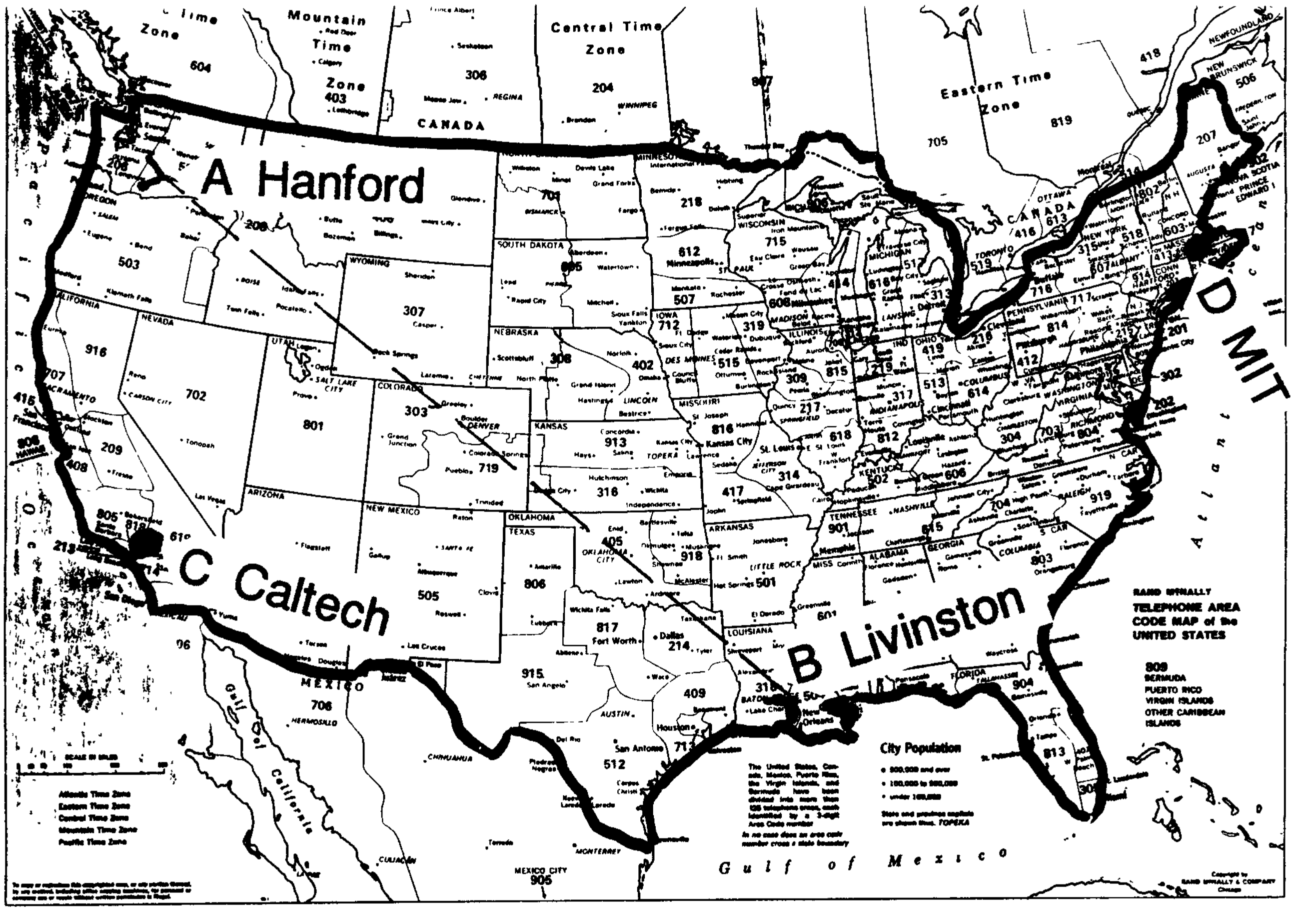


Figure 2. The four components of LIGO
A. Observatory at Hanford, Washington
Under construction; finishing date 1999.
B. Observatory at Livingston, Louisiana
Under construction; finishing date 2001.
Linear distance between the two sites is 3000 km.
C. Supporting Laboratory at Caltech, Pasadena, CA
Office of Director, Optics Prototyping.
D. Supporting Laboratory at MIT, Cambridge, MA
Electronics Design and Development.
E. Principal Investigator: B. Barish.
Chief Scientist: R. Vogt.

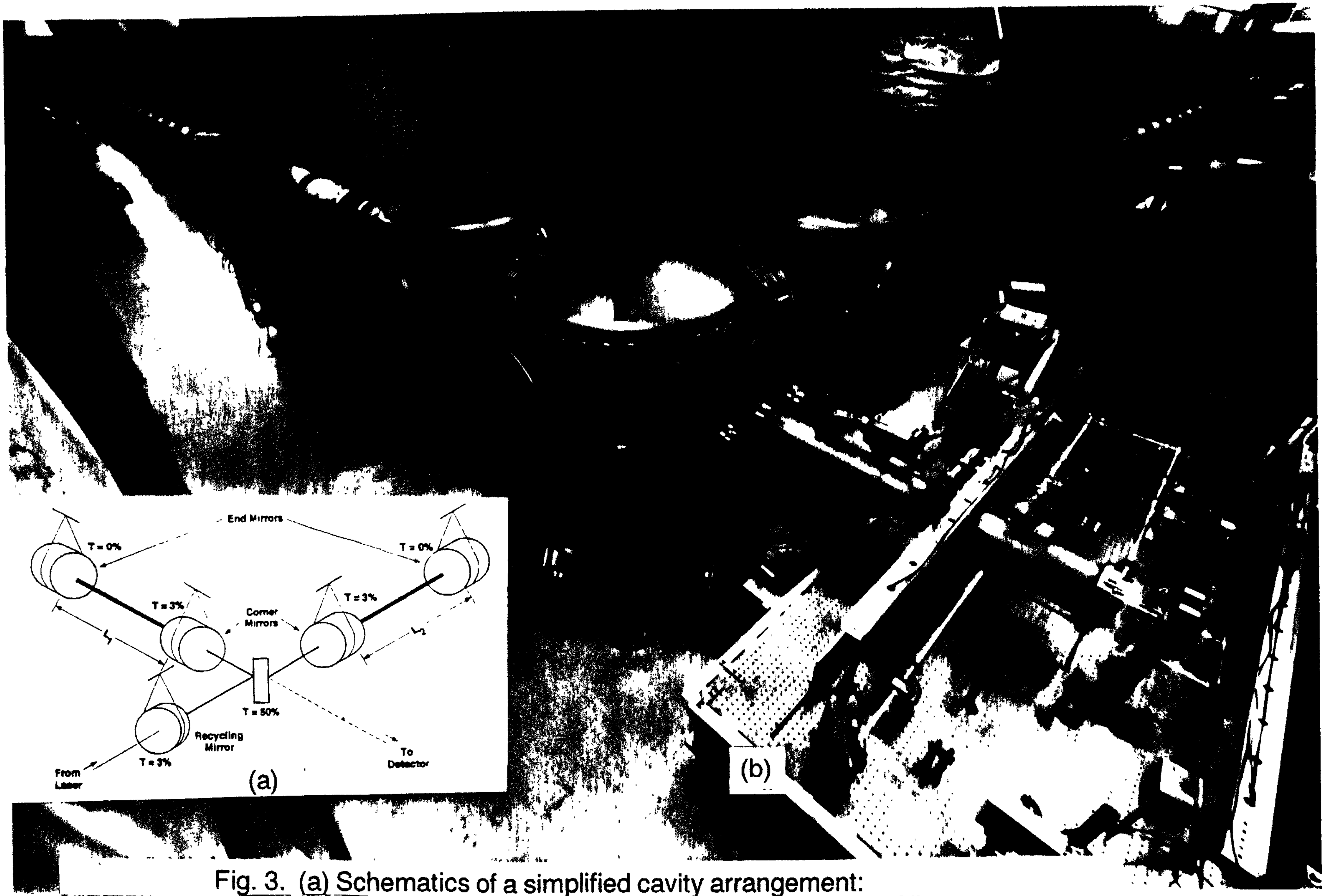


Fig. 3. (a) Schematics of a simplified cavity arrangement:
(b) Prototype LIGO at Caltech with 40 m long arms. All mirror cavities are under high vacuum in stainless steel enclosure. In the foreground is an Ar injection laser (blue) performing an experiment.

Fig. 4. An aerial view of the construction work at Hanford. It shows the extensive Michelson interferometer in full view. Two arms, each 4 km long, will house more than one set of supermirror cavity under vacuum. In the foreground, a building at the corner of the "L" will house injection laser, beam splitter and control electronics.

Fig. 5. (a) Two supermirrors. The one on the left is 5 cm dia., the one on the right is 20 cm dia. Note that the are transparent in the visible but have superhigh reflectance at 1024 nm (b) A test stand showing a supermirror as test mass (wide arrows) and its suspension wires (fine arrows).

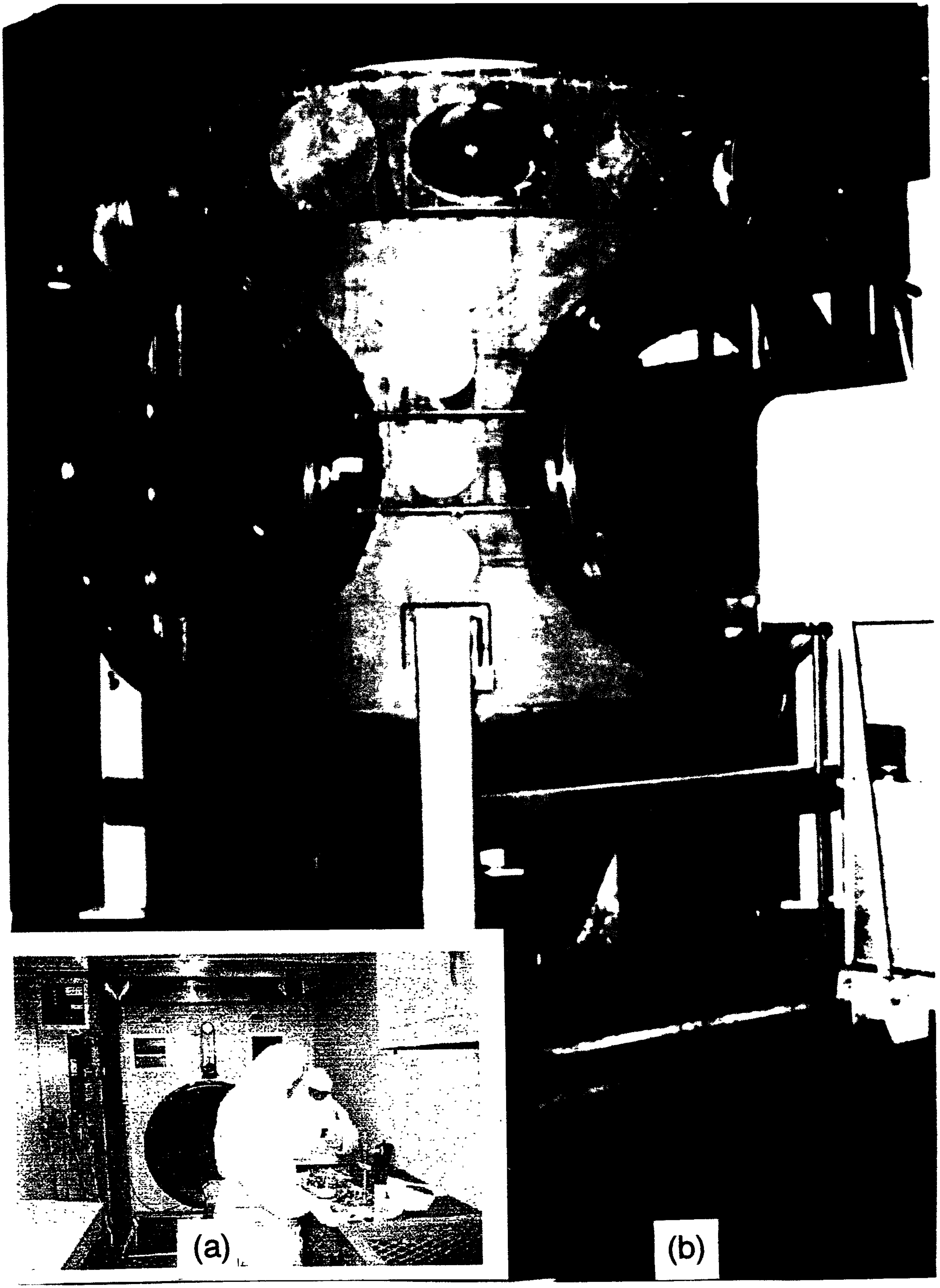
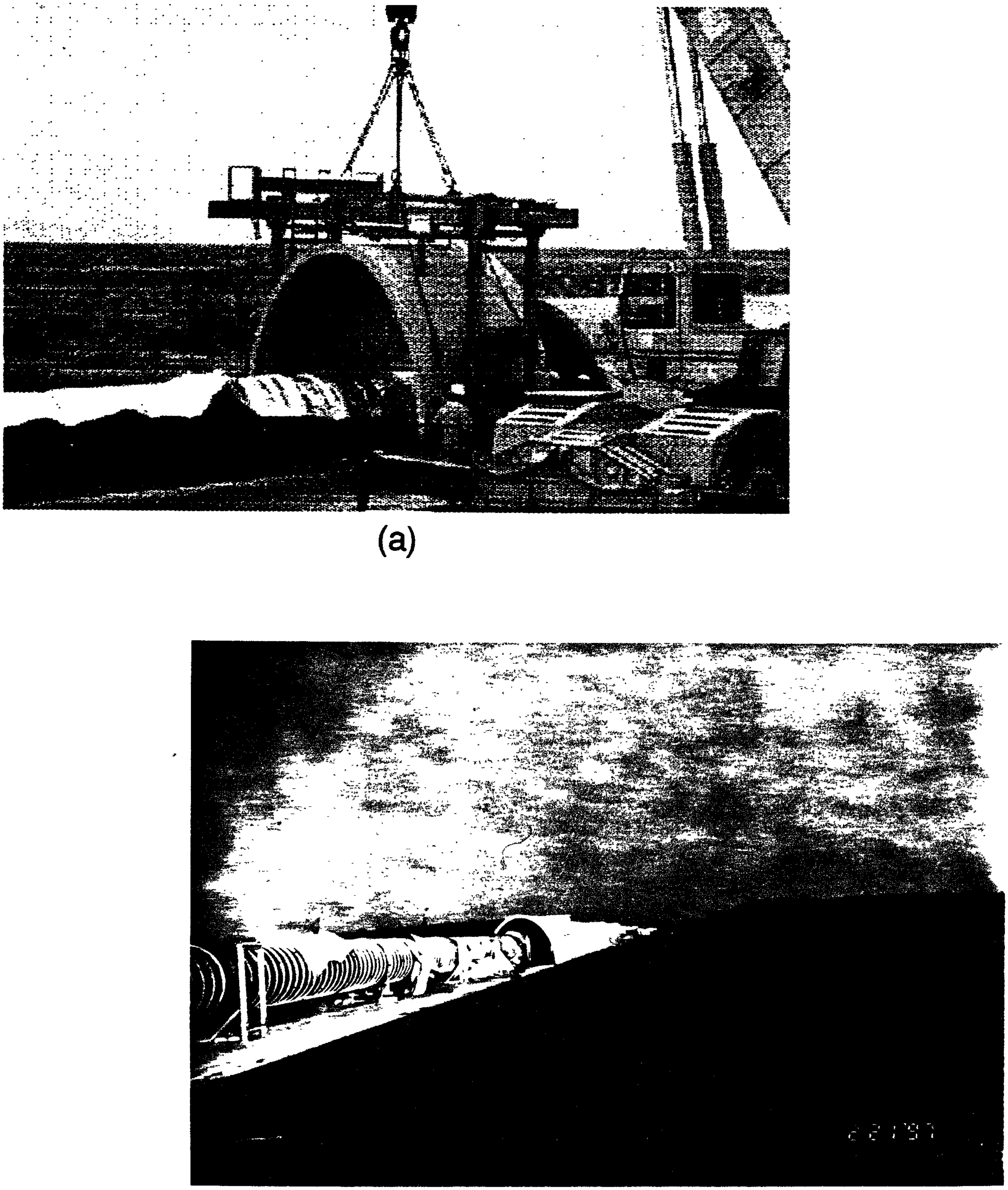


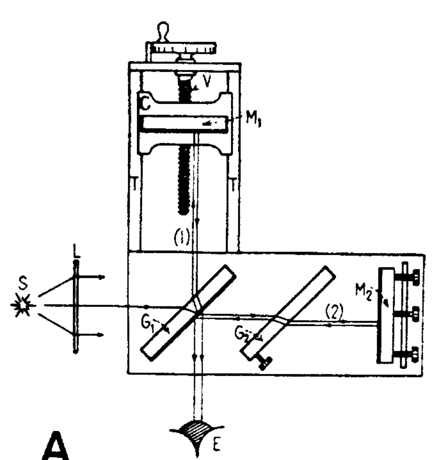
Fig. 6. (a) A weld-on beam tube section in a portable clean room. (b) A beam splitter chamber at Hanford (2 m high)



(a)

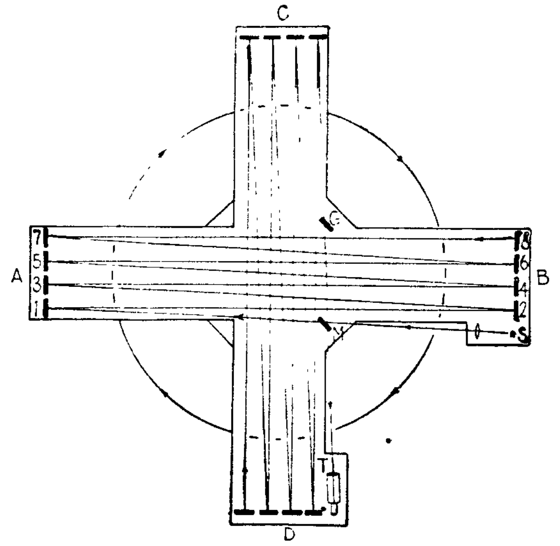
(b)

Fig. 7. (a) The assembly of beam tube and tunnel enclosure at Hanford. (b) Crane operator and beam tube enclosure.



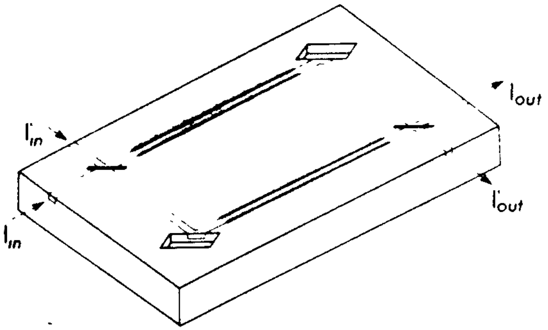
A

Diagram of the Michelson interferometer.



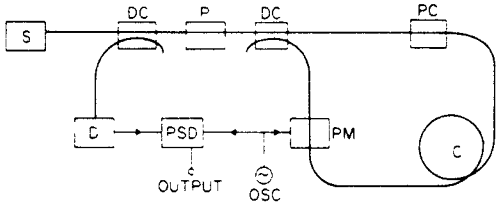
B

Miller's arrangement of the Michelson-Morley experiment to detect ether drift



C

Schematic view of the guided wave Mach-Zehnder interferometer with semitransparent mirrors and totally reflecting mirrors



(c)

Schematics of fiber gyroscopes with source *S*, polarizer *P*, filter *F*, polarization controller *PC*, phase modulator *PM*, oscillator *OSC*, phase sensitive detector (lock-in amplifier) *PSD*, detector *D*, and directional coupler *DC*.

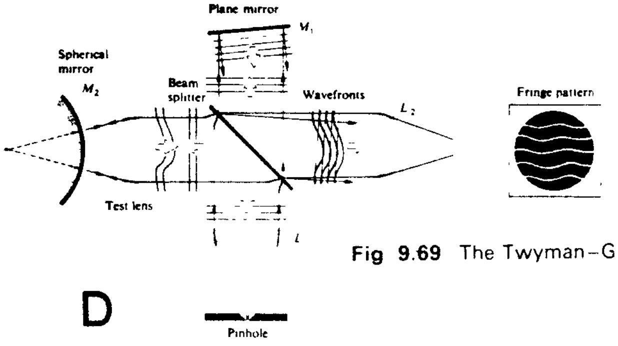
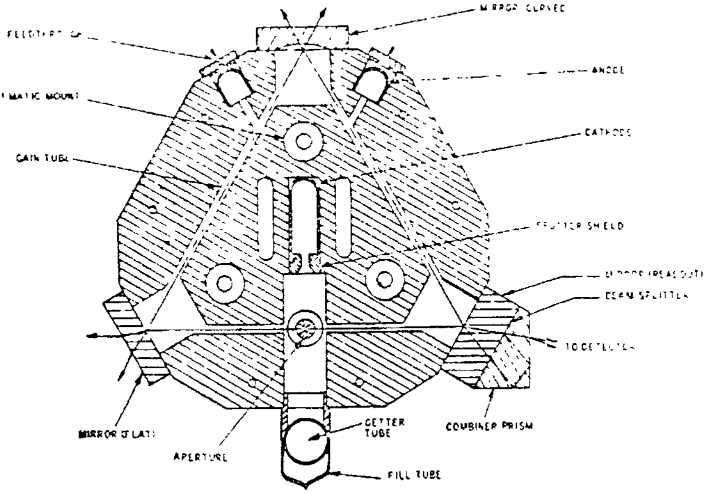
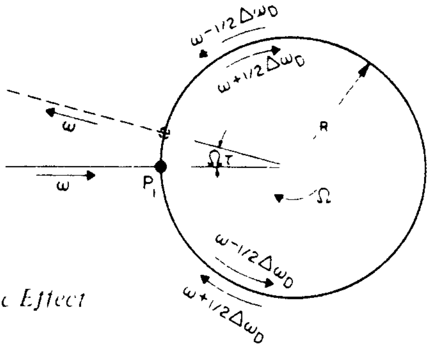


Fig 9.69 The Twyman–Green interferometer

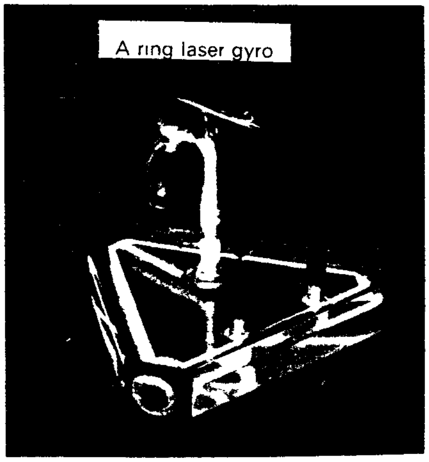
D





E.

Sagnac Effect



A ring laser gyro

Fig. 8 Various Interferometers