LIGO PART I & II

by

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Presented in
International Symposium on Laser and Optoelectronics
July 28-30, 1998
Lushan China

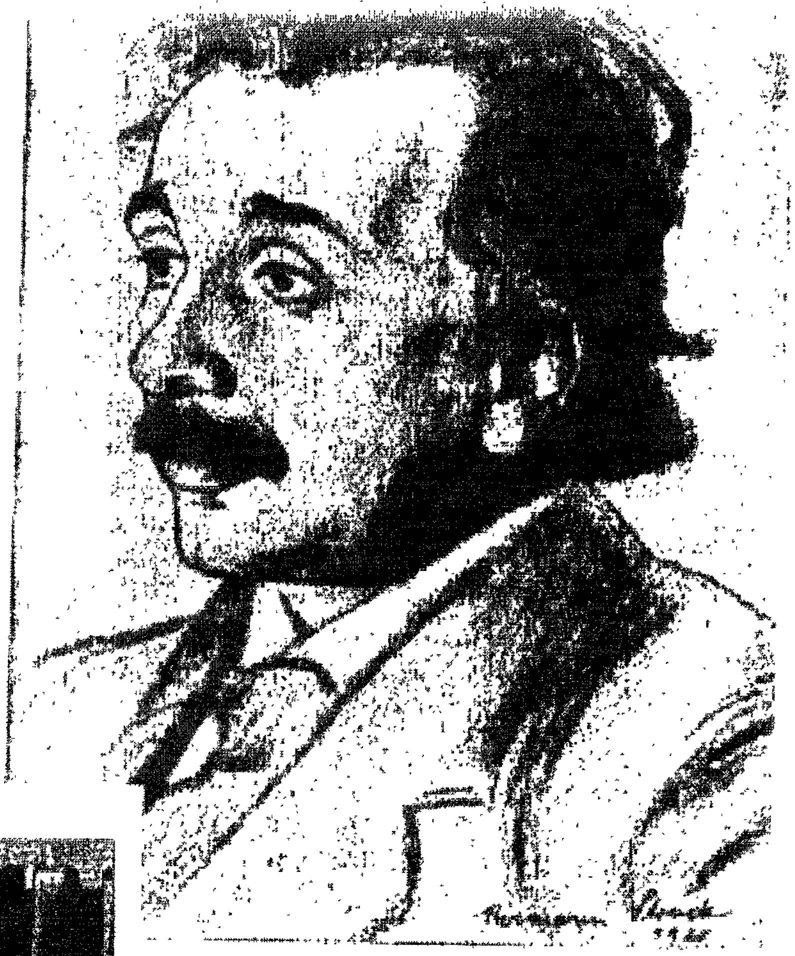
Part I: Exploring Gravitation Wave with Laser Interferometer
Part II: Interferometer under Construction

with Appreciation to
LIGO Project
Caltech/MIT

LIGO-G980147-00-D

The Story : A Nobel Prize
A New Leaf for Physics
1993

Theory : Einstein Equation
in General Relativity
At University of Berlin
1916



ALBERT EINSTEIN

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Laser Observatories
Around The World
2016

■ **JOSEPH TAYLOR** *(left)*, **Russell Hulse**

LIGO Part I
Exploring Gravitational Wave with Laser Interferometer

by

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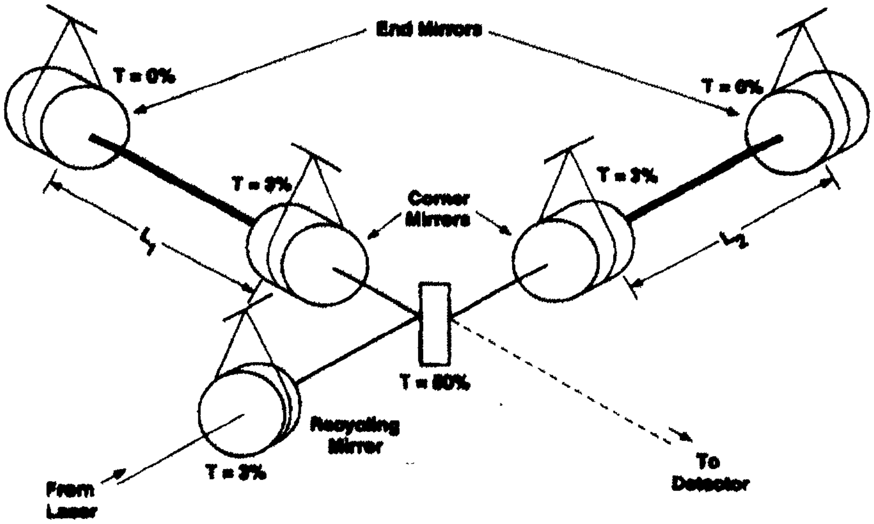

-- Acknowledgement --

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Presented in International Symposium on Advanced Laser and Optoelectronics (ISALO 98)
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LIGO Part I. Exploring The Gravitational-Wave with Laser Interferometer
(Invited Paper)

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1. Gravitation and Gravitational Waves

As we have learned from any standard physics text book, gravitation is the universal attraction between any two bodies. And legend tells, Newton was inspired by an apple falling from a tree and hitting his head on a holiday, when he was searching for an explanation why all planets obey the three laws of motion by Kepler: that planetary orbits are elliptical with sun at a focus, and their angular velocities and periods obey certain mathematical relations with their radii. As his result, all three Kepler's laws can be unified into one simple Gravitation Law, which states that the attraction between two heavenly bodies is proportional to the product of the two body's masses and inversely proportional to the square of their distance. The gravitation law has been good for all celestial motions observed in the last three hundred years and has lead to our space exploration today. However, this law has two major controversies as our knowledge of the universe expands. *First,* the Newtonian gravitational pull inside a dense star should be linear to distance from center, and be smaller than that immediate outside of its surface. *Second,* even from a distant galaxy where the light takes a million years to reach us, the gravitational force is instantaneous from this galaxy. *Are they true?*

According to Einstein's General Relativity, the Newton's gravitation law is not absolutely true. It is an approximation case that must be modified. To answer the first question, the coordinates of the universe should be mapped on a 4-dimensional fabric called SPACETIME. The spacetime is nearly flat only when the gravitational force is negligible. In the presence of a strong gravitational field, spacetime fabric is not flat, but warped (that is, having curvature in all directions like a rubber sheet). In a class of dense stars the gravitation is so much stronger inside than outside that the warpage becomes highly non-linear. Even light which enters cannot get out. Such a star is called a black hole.

To answer the second question, the gravitational force acting on earth from a distant galaxy a million light years away is actually from a field. A gravitational field is like an electrical field, which travels with the speed of light. We should be able to experiment with it on a body suspended by a wire called "test mass." The gravitational field of that distant galaxy acting on the test mass also takes a million of years to reach us. But how can we tell *one gravitation from the others?* (From now on, a gravitational field is called a "gravitation" or a "spacetime warp;" they are two views of the same thing). Aren't there *myriads of galaxies* in the sky? And they *move very slowly* related to us, *if at all?* It follows that if their is a sudden change of mass in that galaxy, such as two orbiting neutron stars called "binary" falling into each other to become one (an action called "coalescence"), a ripple (a train of waves) *may be created* in the the spacetime fabric and spreading out. Like an electromagnetic wave to an antenna, it will make the test mass oscillate. Now we can detect this gravitation by detecting a special of oscillation of the test mass.

2. The Candidates and their Detection.

Why did we say a gravitational wave only *"may" be created?* For not all the catastrophe in this universe would. There were two supernova events (explosion of an old star to create new but smaller ones) in the last decade. One of them was so bright that it was discovered with naked eyes in the southern Chili. And besides the bright light, it emitted large amount of neutrinos. Scores of neutrinos were detected from the observatories over the world, but no gravitational waves. So, supernovas are neutrino emitters but not gravitational wave emitters.

What are gravitational waves? They are like radio waves propagating through empty space, having two transverse modes of polarization, (as shown in Fig. 1(a) - (c)) and falling off inversely with the distance of travel ($\sim 1/r$, not $1/r^2$). *Who are the gravitational wave emitters?* Just as it takes an accelerating (time-derivative of second order) electric dipole moment to radiate electromagnetic wave; so, it takes a time-derivative of fourth order on a heavy but highly aspherical mass distribution called "reduced-mass quadrupole moment" to radiate gravitational wave. We shall show it as an example of embedded diagram later (Fig, 5(b)).

The neutron star binary discovered by Hulse and Taylor of University of Massachusetts[1] in 1974 fits this category. Fig. 2(a) is a computer generated model showing the binary and the gravitational wave emitted in spacetime fabric. Star catalog named it binary pulsar PSR 1913+16, and a Nobel Prize in Physics was awarded to them in 1993. Later at Princeton University, Taylor and Weisberg[2] analyze that object's delay in orbital pariastron, (i. e., the close-encounter period of those two bodies to each other, resembling the period of Mercury's perihelion to the Sun) firmly proved that the binary are losing energy by emitting gravitational waves (Fig. 2(b)). This is the still an indirect evidence of gravitational waves so far. Yet the binary will take about 4 hundred million years before the day of coalescence, (that will be the right place and time their direct evidence will reveal). *Can anyone wait that long?* Most astrophysicists say we shouldn't wait. Theorists say there is a long list of candidates to look for now. 'Because the stellar objects in the universe are more abundant than fish in the ocean,' reply the experimentalists, 'wouldn't it be better that we build a net that can catch big fishes first and *identify their species later?*' This marks the birth of LIGO, quite a NET-work.

So far, both gravitational wave emitters and black holes are elusive to direct detection. They not only exist, but should be abundant in the universe. The reason for their elusiveness is because we have not used the right detectors. Theorists have estimated that a train of gravitational waves could pass through earth more than once every month. All stars are burning themselves out and there are already more dark matter in the universe than visible stars. However, all our big astronomical instruments have been EM radiation (electromagnetic waves) detectors called telescopes: in the visible spectrum (Keck-twins, Hale and Hubble), in radio waves (Arecibo), in x-ray and gamma-ray-bursts (on satellites and balloons). But the the elusive duo are by nature no great emitters of EM radiation. They need a different breed of detectors to find them; the instruments that can tune in the gravitational waves selectively just as it takes a radio to tune in a broadcast station.

Wheeler said required sensitivity of detection is 10^{-18} (one part in 10^{18} in detector dimension) over a wiggle-waggle time of a millisecond (10^{-3} of a second).[3] In the past forty years, many research groups, including those in China, have used heavy metal bars as test mass to resonate to the passing gravitational waves. So far, they cannot get rid of quantum effects in deformation over the dimensions of a bar, which is limited in the length called "baseline." In the last decade, Laser interferometers are coming on strong because of its long baseline.

3. Laser Interferometer as Gravitational-wave Detector.

People would remember Michelson's interferometer as the instrument which proved that the velocity of light is a constant and ushered in Einstein's theory of relativity. In operation, it splits a light beam by a half-silvered "beam splitter" into two L-shaped arms of equal length, then bounce the beam back and forth by 8 mirrors (all silvered) in each arm, recombined by the same beam splitter and produced interference "fringes" on a screen. Though a delicate instrument in those days, it is a far cry from the Wheeler's requirement above, otherwise gravitational wave could have been detected many decades ago.

The laser interferometer for gravitational wave detection is using Michelson's principle and his geometry (L-shape arms and beam splitter), but it is a far more sophisticated installation, a brainchild of two brilliant researchers, Weiss[4] and Drever,[5] (Fig. 3(a)). To improve detection sensitivity, Weiss proposed using high-quality laser to "split the fringe," while Drever configured a mirrored-cavity of $R= 0.997$ called "multiplereflection Michelson interferometer." Unknowing to these investigators, the R value above was already surpassed by this author in the mirrors used for laser gyroscope, thus R was more than a four-9 mirror at that time.[6] Once this fact was discovered, those "super-mirrors" were soon adopted for their use, while the suspended test masses became the mirrors themselves. A laser interferometer is now made of a supercavity, which includes the test-mass mirrors in each arm, the beam splitter, and a recycle mirror strategically placed to operate in passive mode. This cavity, when laser-lited, can resonate to a passing gravitational wave and store the wave information at its peak for much longer than a millisecond. All major reflecting surfaces in a super-cavity are made of material with negligible thermal expansion, super-polished, then coated with multilayers of ultralow loss dielectric by ion beam. The super mirrored-cavity permits up to a million of bounces of light with little decay. Such a cavity can amplify the laser input 100 times under a well-sealed vacuum. Figure 3(b) shows a prototype LIGO (the acronym for Laser Interferometer Gravitational-wave Observatories) at Caltech built to the above standard. This prototype is useful for studying the functional performance of the laser interferometer and the noise under artificially simulated signals. For example, by applying a shock to the test-mass mirrors in one arm and then the other, a phase detection of output is light intensity, (rather than fringes).

The full size LIGO is under construction and is expected to operate by year 2001.

4. Improvements.

a. Sensitivity. In every large experimental project there is a resident theorist who makes predictions. The name of the brain for LIGO is Kip Throne.[7] Some of his visions are summerized as follows: The observatories housing the full size LIGO have two giant detector stations separated 3000 km apart, each having L-shaped enclosure covering interferometers of arm lengths 4 km each. With such long base lines, the sensitivity should increase an estimated 2 orders of magnitude from the prototype. Table I compares LIGO with Michelson-Morley

A neutron star is a very dense star. Its mass is only comparable to the Sun, but its diameter is much smaller than Earth. The earth is made of atoms, but inside an atom there is a lot of empty space. It consists of a nucleus core and a shell of few electrons, each having a diameter less than 10^{-3} of the atom. A nucleus contains nearly equal numbers of protons and neutrons. Unlike a proton or an electron, a neutron has no charge but has a strong nuclear force to attract other neutrons or protons. Moreover, a proton can combine with an electron to form a neutron. Imagine the Sun would have a neutron core. The gravitation of the outer portion of solar atoms builds up a strong pressure to crush the inner atoms, electron shells disappear, all nuclei become neutrons only and the empty orbit space is squeezed out. A neutron star's size is so small and density so high compared to sun that all atoms are crushed by gravitation. Only neutrons are left.

A neutron star binary consists of two neutron stars closely orbiting each other, the centrifugal forces from orbiting balance the strong gravitation that pull them together. Their orbits are schematically shown in Fig. 7(a). However, the spacetime fabric around them are so warped (Fig. 2(a) and Fig. 5(b)), if they are losing energy to gravitation-wave emission such as the binary Hulse and Taylor discovered, the two neutron stars will coalesce into one. .

Finally, A black hole has much bigger mass than a neutron star but its diameter varies. Therefore its gravitation is so overwhelmed that anything (even light) near by is pulled in. Its spacetime warpage is like a funnel. Information of its structure is well-sealed toward outside except the three quantities as shown in Fig. 7(b). A blackhole binary should have similar orbit shape as Fig. 7(a) but have different sizes. Both black hole binary and neutron star binary that have strongly time-varying reduced mass quadrupole moments are strong GW emitters.

8. Conclusion: LIGO -- Opening a window vs. closing a book ?

(a) Scientists want to probe into the unknown, like x-ray a hundred years ago and transistor of 1949. Once we know it is possibly there, gravitational wave can give us a rich information of the other half of the universe, those belonging to dark matters, with vibration and sound. The technology developed from it, the super mirror-coating, the super low-noise laser and ultra-sensitive detector etc., can always benefit the mankind. The findings would be very rewarding.
(b) We have seen three levels of physical truth, one broader than the other. Newtonian mechanics still governs our daily life and guide us to the Moon and the Mars, but is limited to the motions not speedier than 10% of light. Einstein's special relativity generalize motion to all speeds (and also give us $E = \gamma Mc^2$, a bonus). Nevertheless this truth is still limited to our solar system (for most matters but 2), where gravitation is the weakest of all four forces known on earth. General relativity, the Einstein's legacy, is by far the most general. It has shows effects in gyroscoping laser on earth, in gravitational lensing in outer space, and leads us to the cosmological spacetime warp, black holes and big bang. Gravitational Wave, however, a useful missing link in General Relativity ever since inception but so far elusive, should also be true. Direct observation of GW would enhance Einstein's legacy. On the other extreme, if it turns out much weaker than Einstein's prediction, then another generalization of physical laws is needed and is imminent.

Acknowledgement. The author is indebted to the management of LIGO and faculty members of Caltech for their assistance and encouragement.

interferometer.

Table I Comparison of the two interferometers

	Michelson-Morley's [Disproved Stationary Ether]	LIGO [To Detect Gravitational-Wave]
Arm Length	1.375 m	4 km, 2 locations 3000 km apart
Bounces	8	thousands (in cavity gain)
Δ-pathlength	2×10^{-5} expected	3×10^{-18} expected
Δ-detection mode	interference fringe shift	light intensity change
Mirrors per arm	8	a pair per subcavity, upto 20.
Mirror Diameter	1 cm estimated	20 cm established
Light Source	C-Arc	Ar-Laser for 40 m prototype Nd:YAG Laser for 1st-gen. LIGO
Resonance Cavity	No	A super mirror-cavity consist of 2 sub-cavities
Cavity gain (loss)	(<1)	100
Redundancy	rotatable through 90^{o}	non-rotatable, but in different orientations at the two locations.

Figure 4 (a) shows a theoretical chart of wave amplitude h_c vs. frequency with 3 bands of h_{sb} (noise sensitivity to bursts) with improvement effort as parameter.[7] The band marked First h_{sb}, corresponding to the completion of detector system, shows the search confidence to sense the coalescence of neutron star binary (NS/NS) to 30 Mpc (90 million light years), and the black hole binary (BH/BH) distance another order farther. In the bands of Enhanced h_{sb} and Advanced h_{sb}, increasingly sophisticated detection schemes should be devised.

b. Coincidence. Simultaneity detection of two LIGO systems, one in the North-West United States and the other in the South-East, by coincidence circuits are planned to reject false signals if gravitational wave (GW) does not strike. They can also locate a GW source within 1 degree

c. Networks. Sister Laboratories outside U. S. will provide instantaneous confirmation on GW. List of sister laboratories are listed in Table 2.

Table II. The Sister Laboratories.

Name	Arm length	Sponsoring Country	Location	Year expected
LIGO	4 km	U. S. A.	NW & SE	1st. in 2000
VIRGO	3 km	Italy-France	Pisa	2001
GEO600	600 m	Germany-Britain	Hannover	1999
TAMA	300 m	Japan	Tokyo	--
Consortium	---	Australia (works with LIGO)	Sydney	--

5. What signatures should gravitational waves show?

The following information are taken from reference 6):

a. Candidates for LIGO's search.

Some astronomical bodies that should emit gravitational Waves are:

- Neutron stars -- Neutron star
- Black hole <--> black hole
- Big bang remnants
- Black hole <--> neutron star
- Supernova's remnants, Pulsars
- Sources of gamma ray bursts

The two most hopeful candidates are neutron stars (NS) and black holes (BH). Their coalescence, such as NS/NS or BH/BH have been theoretically predicted.

b. The waveform. Waveforms of theoretical coalescence are quantitatively divided into 3 epochs (Fig. 4(b)), the inspiral, the merger, and the ringdown.. Their names speak for themselves.

c. The frequency bandwidth. The calculated frequency range of a typical laser interferometer detector is shown in Fig. 4(a). The least noisy frequency is at the minimum of First h_{sb} band. approximately 200 Hz, near the center-C note of any audio instrument. Adding the fact that the test masses are set to vibrate when GW arrives, the signal during inspiral epoch can be best listened than watched. (Just add broad band amplifier, no need to use modulator or filter.) However, frequency of the source is between 600 to 2500 Hz during merger epoch, where photon noise increases and the Enhanced-h_{sb} will need narrow band frequency detector.

6. General relativity effects in 3-d graphics.

The spacetime is flat in special relativity where gravitation is neglected and acceleration is small. Cartesian coordinates make good reference frame. But in case of strong gravitation or acceleration how would spacetime fabric be affected?

Einstein's answer in 1912 was: acceleration and gravitation cannot be distinguished when an absolute reference frame is does not exist. When we ride in an airplane or an elevator, the gravitation under us is increasing if the vehicle rises, and decreasing if it falls. Since there is no reference frame that is absolutely at rest (not our earth), we cannot tell how much pressure from under our seat on us is due to gravitation and how much is due to acceleration of our chair. Without an absolute rest frame they are completely equivalent.

After much study about spacetime, Einstein concluded in 1916 that spacetime in the universe is not infinite but closes on itself just like the world we live in. But in the "4-dimensional world" we live, we can only experience a 3-d space and a separate dimension of time. Or we can watch only a 2-d picture in 6o minutes. As to the gravitation (of a heavy star), it corresponds to a warpage in spacetime. When we examine it from afar, we say it is gravitation. But when we are in that star, we say that the spacetime is warped. For example, if you were born and raised on that star, the ratio circumference/diameter of a circle could be 2.5 and the sum of 3 angles of a triangle $> \pi$ by your best measurements. Thus, a warped spacetime and a gravitation are also equivalent. And to to gain insights, you can play with a toy balloon with a finger poking at its surface. You can also make some ripples to simulate a gravitational wave.

Fortunately, there are several ways to express spacetime in 3-d pictures. Figure 5(a) shows a warpage in the 2-d universe to demonstrate differences of Euclidian and Riemannian geometry. Figure 5(b) shows a spacetime warp of an object rich in "reduced-mass quadrupole moment." Figure (6) is a tidal gravitation expressed in Newton's view and in Einstein's view (plotted with tide vs. time). I shall post these figures in the poster session for you to scrutinize.

7. What is a neutron star binary? What is a black hole?

Gravitation and LIGO References.

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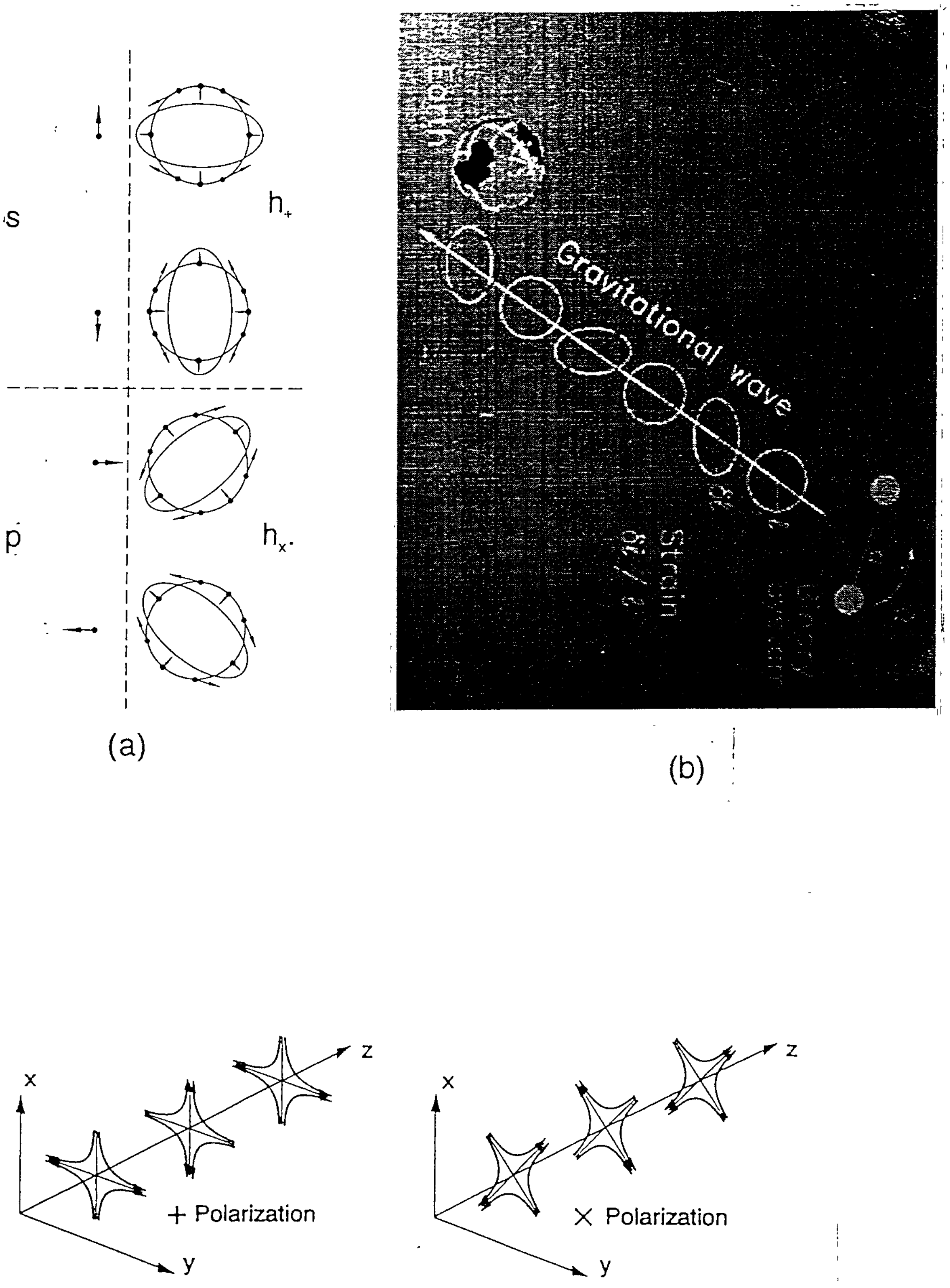
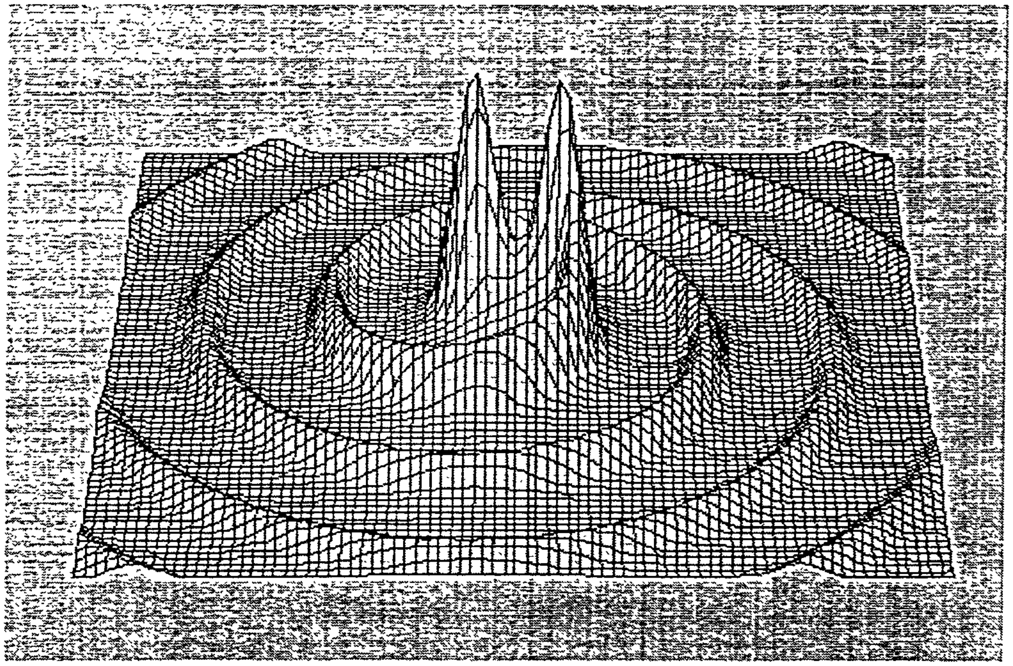


(a)

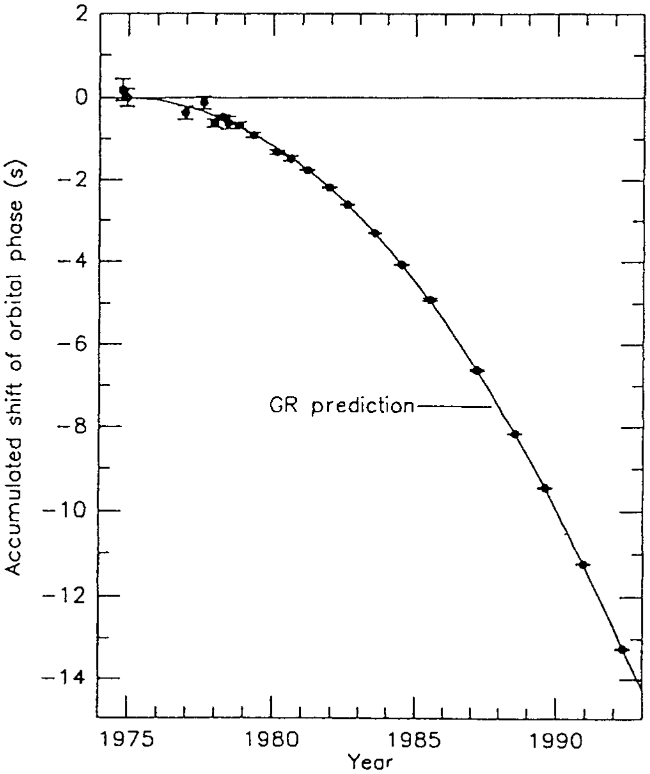
(b)

(c)

Figure 1. (a) Polarizations of electromagnetic wave [s,p] and gravitational wave [h_+, h_x] are compared. (b) Gravitational wave propagating in space as tidal wave. (c) The lines of force associated with the two polarizations, h_+ and h_x.



(a)



(b)

Figure 2. (a) a spacetime model of the neutron star binary (high warp) and the gravitational wave they emit (ripples)
(b) Accumulated shift of periastron phase vs. time of the neutron star binary psr 1913+16. The solid curve is the theoretical curve if the delay is due to energy loss due to gravitational wave emission. The dots are observational points. The parabola has been adjusted for best fit of data. (After J. Taylor)

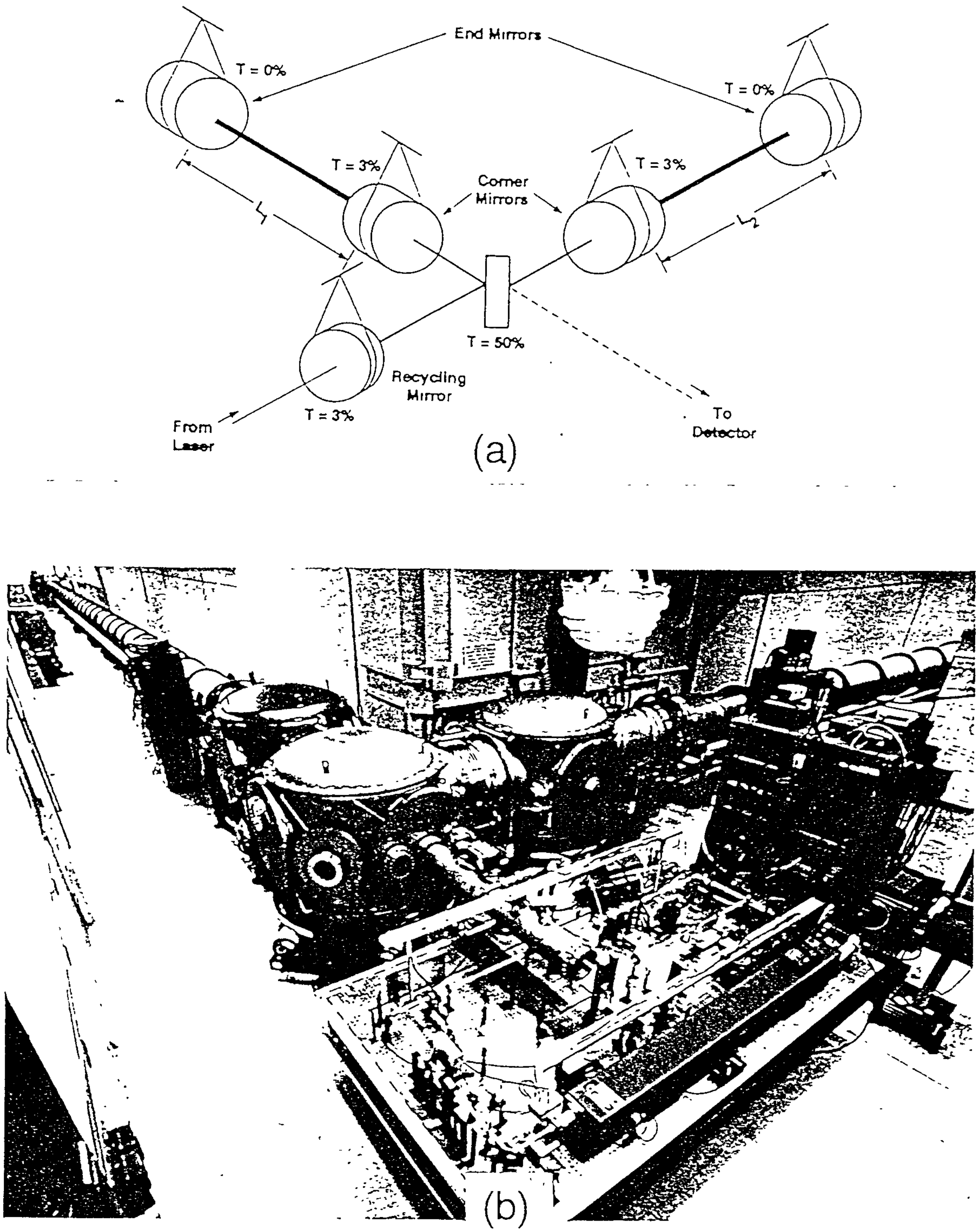


Fig. 3. (a) Schematics of a simplified cavity arrangement: L1 & L2 are 4 km each. The rectangle in the middle is the beam splitter. Round objects are supermirrors suspended by wires. T = transmittance. Each arm forms a sub-cavity and recycling mirror ends the supercavity.
(b) Prototype LIGO at Caltech 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.

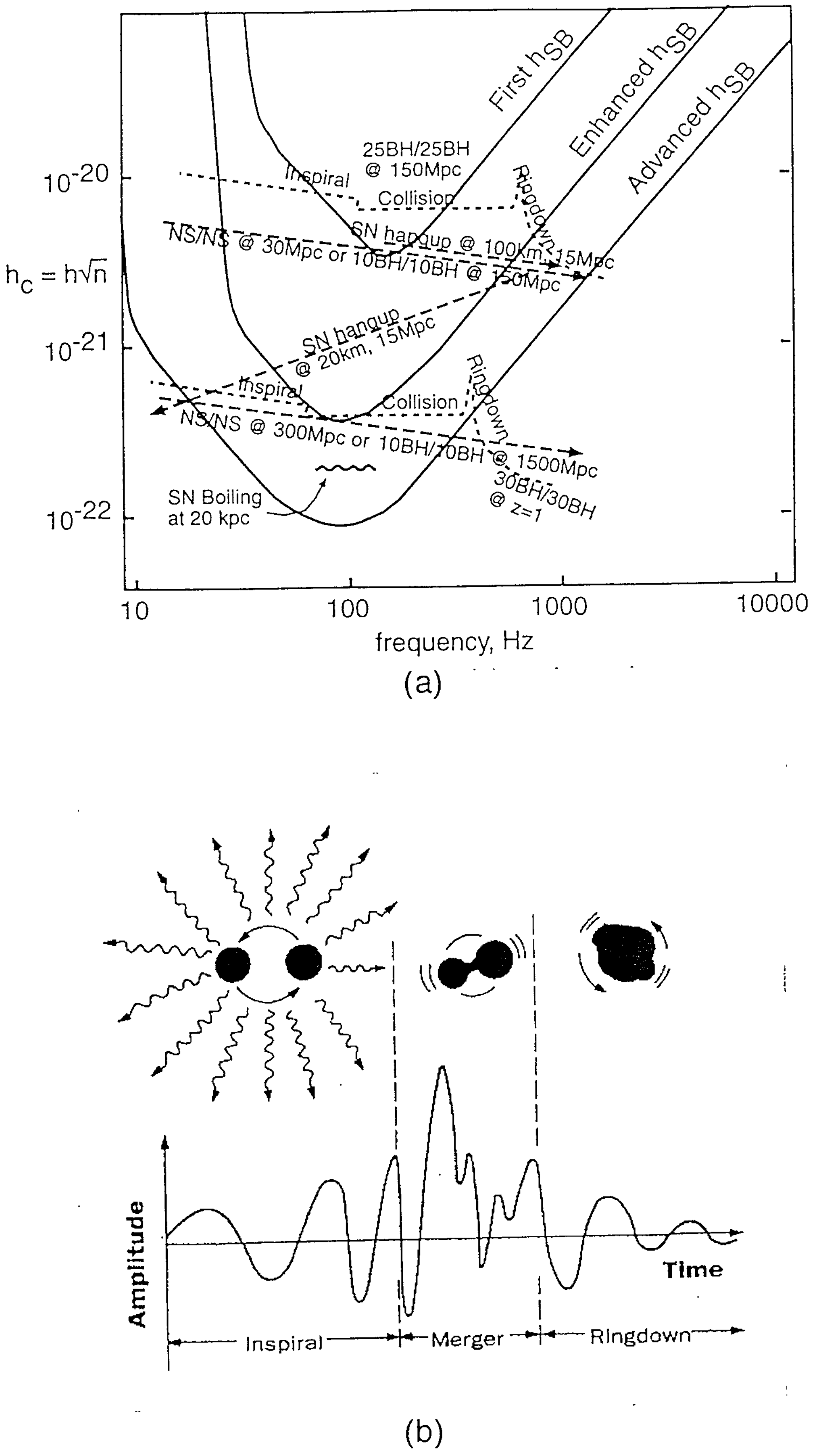


Figure 4. (a) A projected broadband noise sensitivity to bursts h_{sb} compared with characteristic amplitdes, h_c.
(b) Schemaitc gravitational waveforms for coalescence of two neutron stars. Waveform of a black hole is similar.

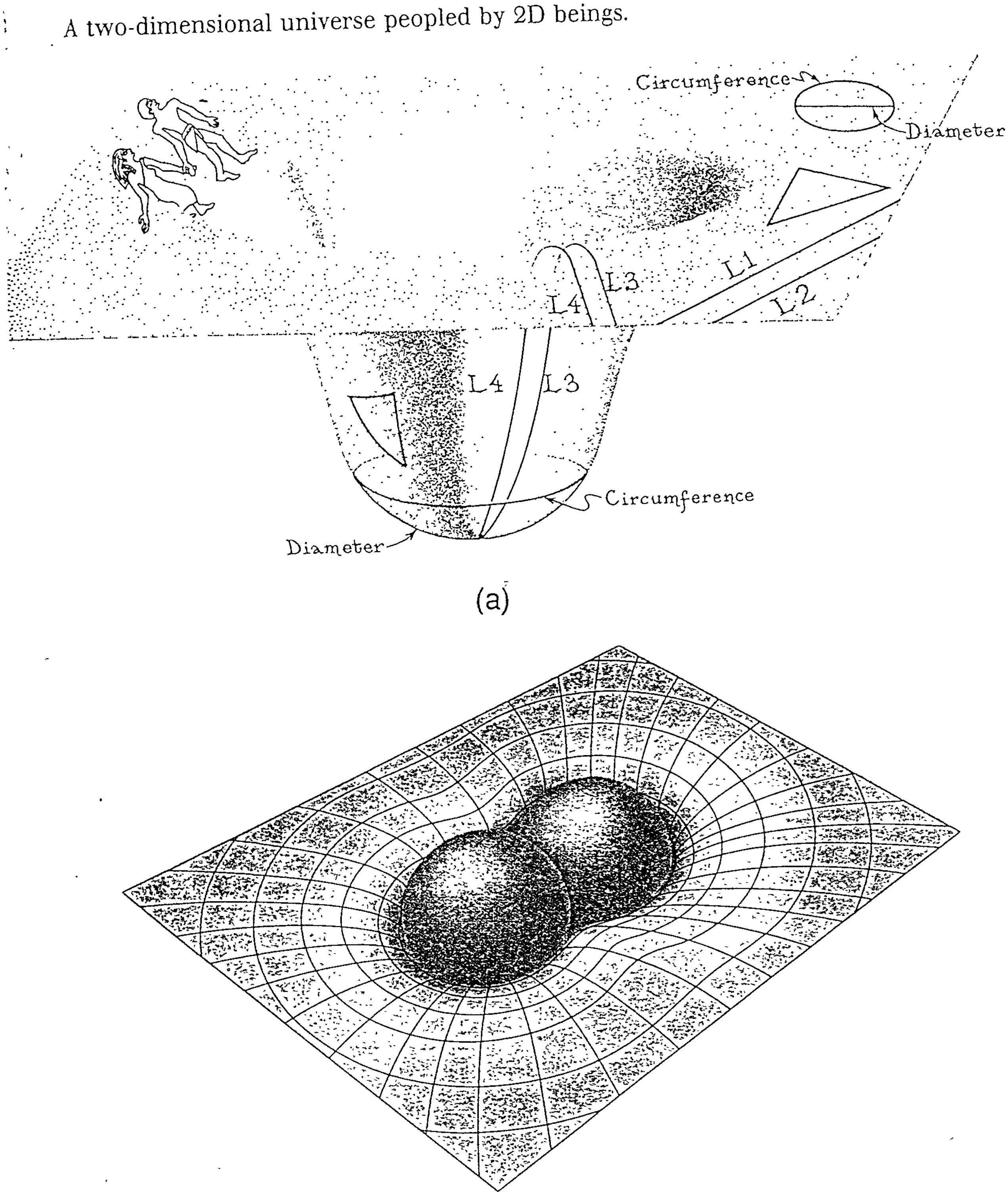
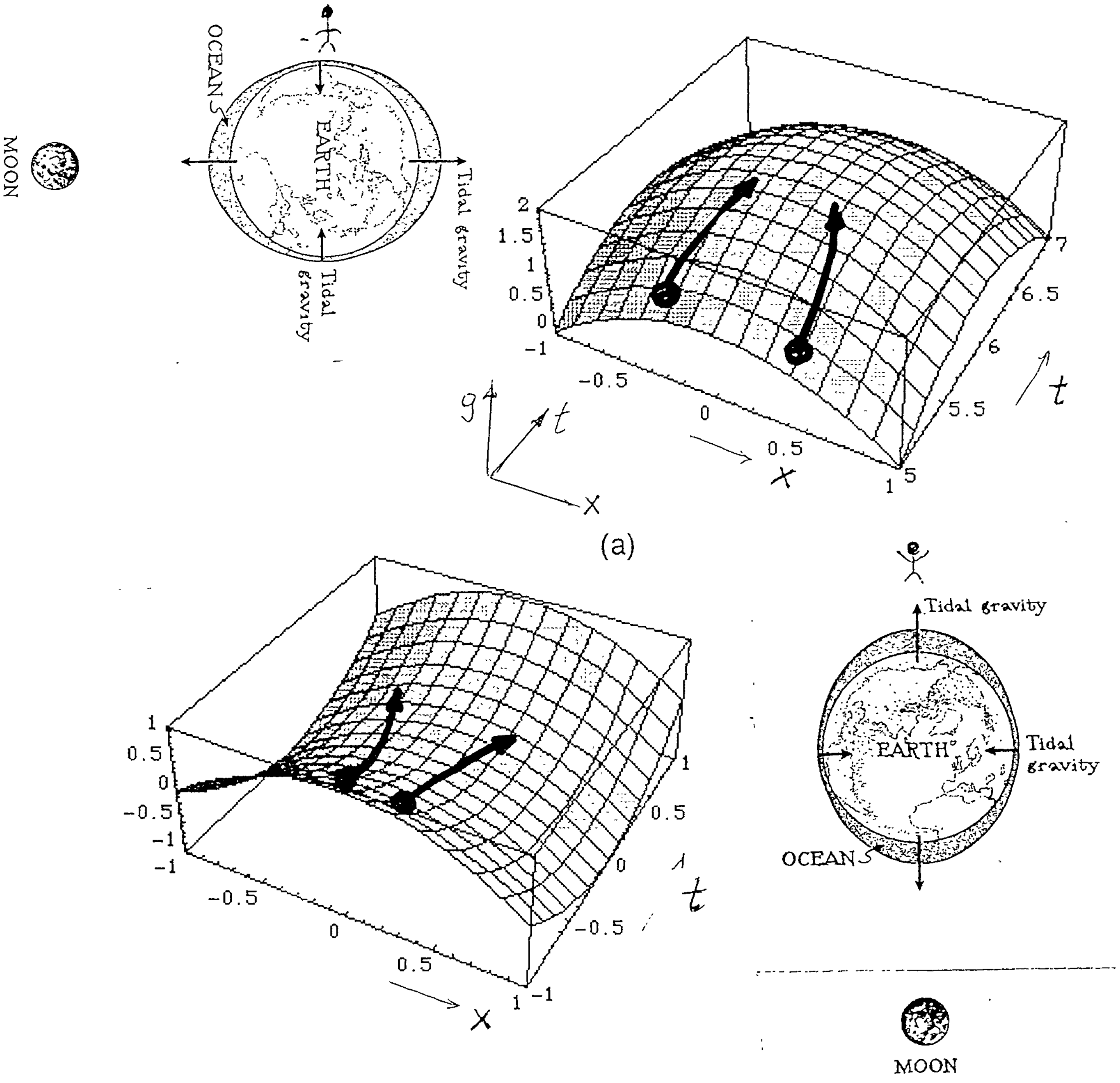


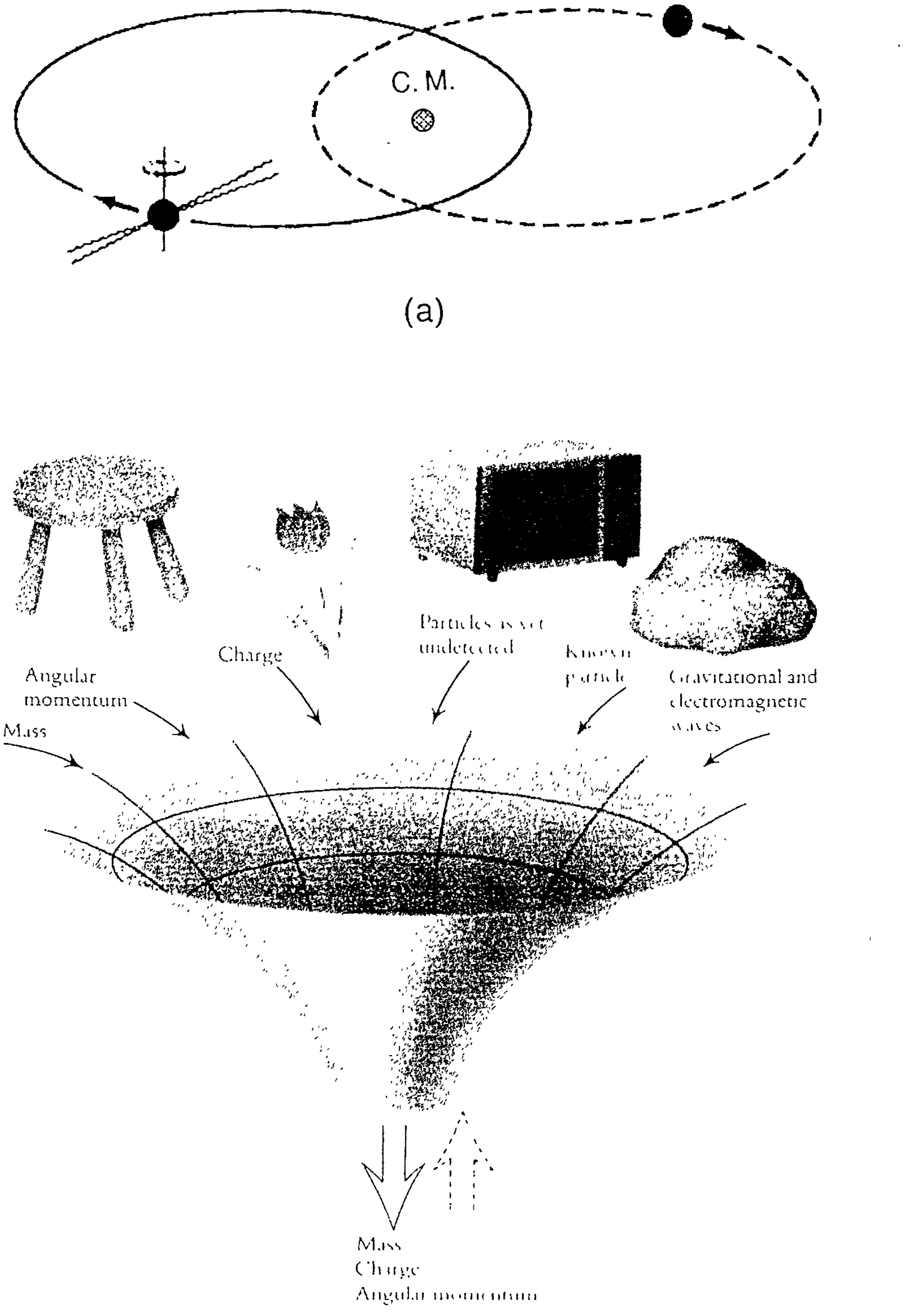
Figure 5. (a) A 2-d embedding diagram demonstrating warpage. The world is flat (no gravitation) except a spherically warped (gravitational) hyperspace. The 2-d people, who is familiar with Euclidian geometry in the flat region, will discover Riemannian Geometry in the warped region, where straight parallel lines become geodesics and cross each other, and π loses its original meaning.
(b) A 2-d embedded diagram showing the mass possessing "reduced-mass quadrupole moment" is highly aspherical, such as this star binary.



(a)

(b)

Figure 6. The tidal gravity from the moon is shown in Newton's view (shaded 2-d area with vectors) and in Einstein's view (warped 2-d spacetime pieces) (a) low tides (compression) and (b) high tides (tension)



(a)

(b)

Figure 7. (a) Depiction of the orbits of neutron star binary (psr 1913+16), each rotating about a common center of mass. The one on the left is pulsed at regular time intervals (pulsar), the other one is a dark star. (After R. Hulse)
(b) Conceptual representation of a black hole. Any object that falls in loses its information. The only information known to an outside observer are: their total mass, charge, and angular momentum. (After J. Wheeler)

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Part II: Interferometer under Construction

by

David T. Wei

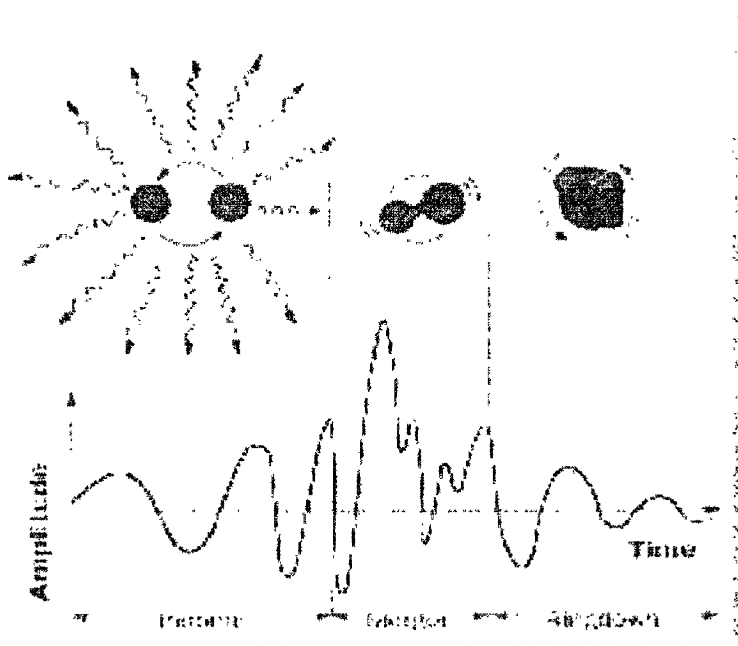


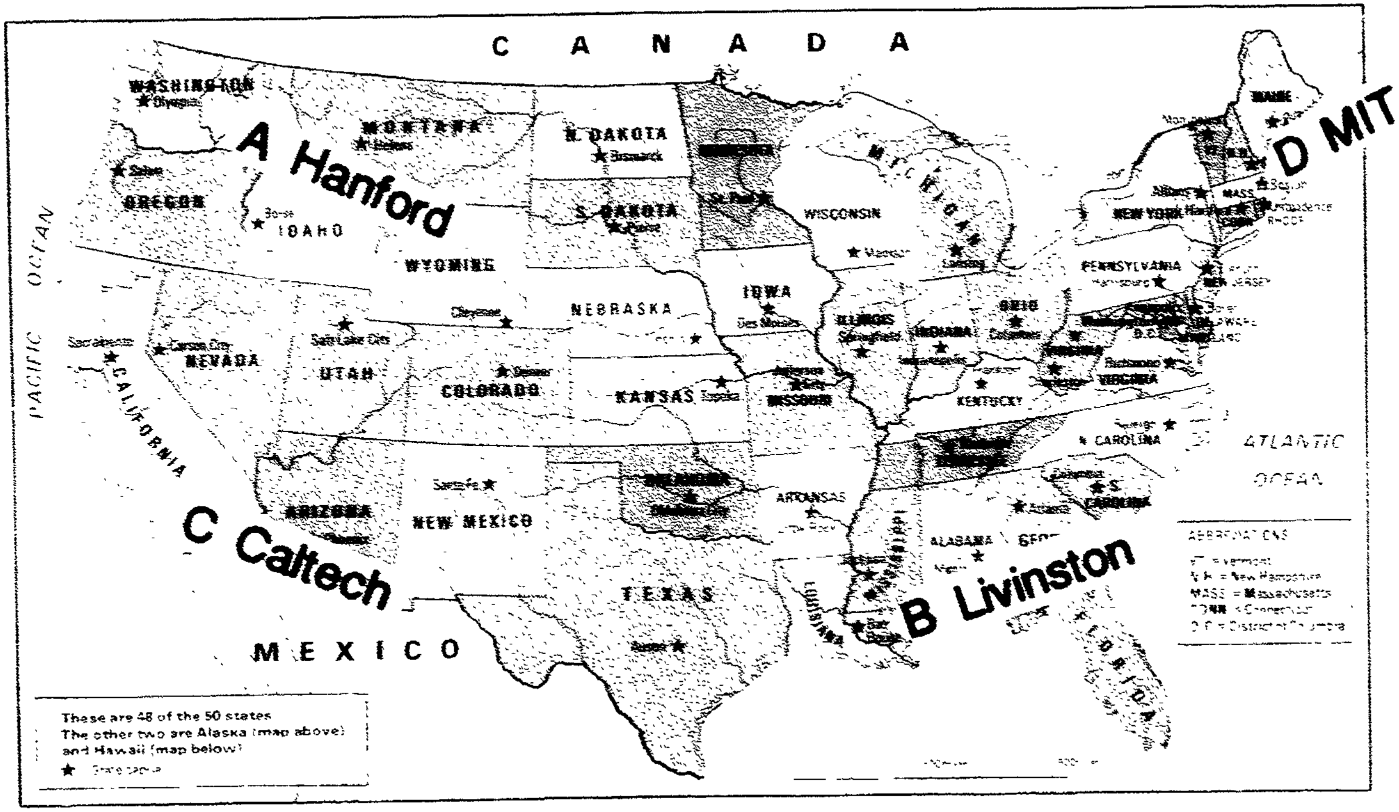
Figure 1. Schematic Depiction of the gravitational waves from the coalescence of two neutron stars

双星凝珠

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.

Figure 2

All Original Photographs
are in Color

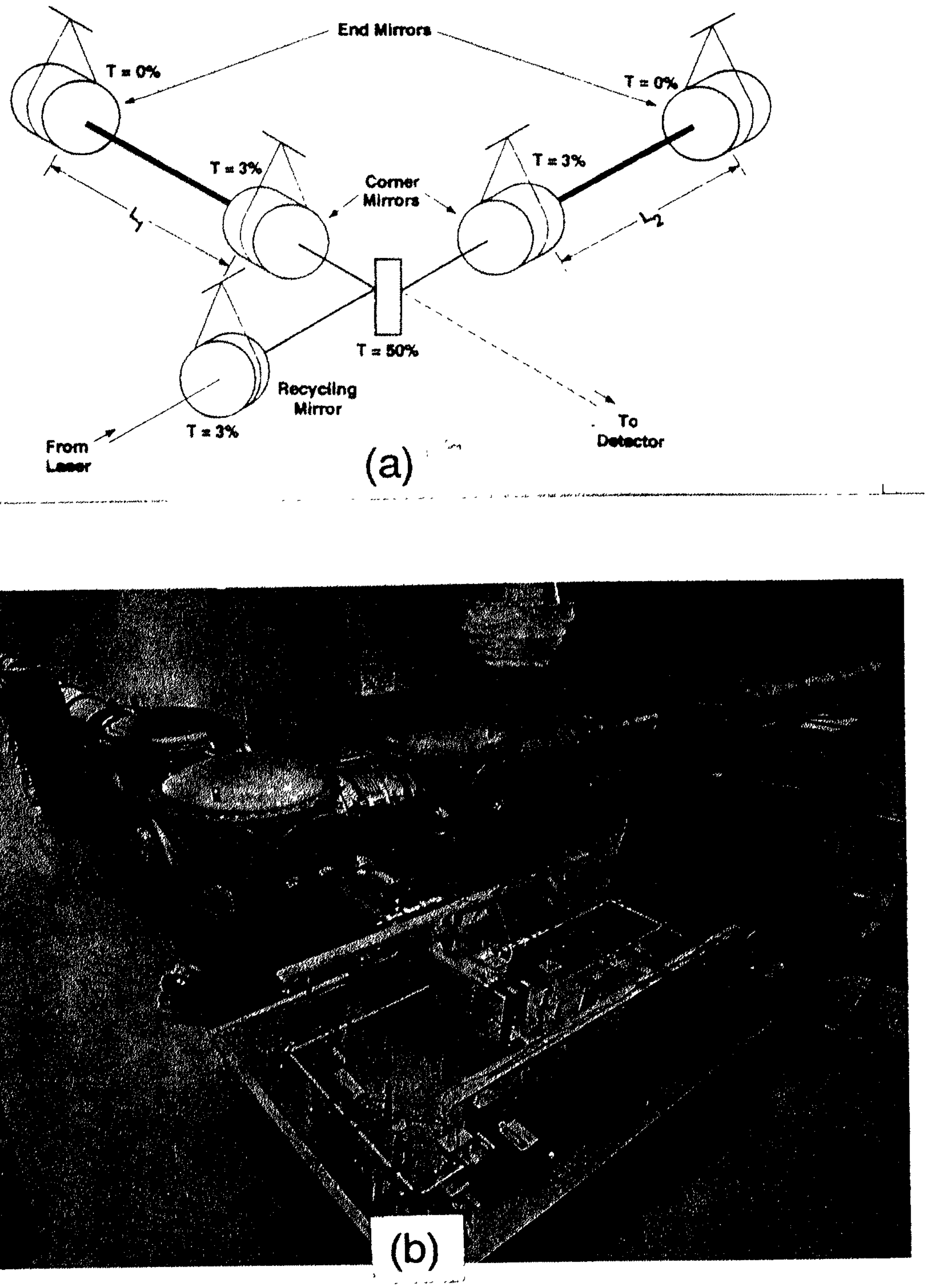


Fig. 3. (a) Schematics of a simplified cavity arrangement: L1 & L2 are 4 km each. The rectangle in the middle is the beam splitter. Round objects are supermirrors suspended by wires. T = transmittance. Each arm forms a sub-cavity and recycling mirror ends the supercavity.
(b) Prototype LIGO at Caltech 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.

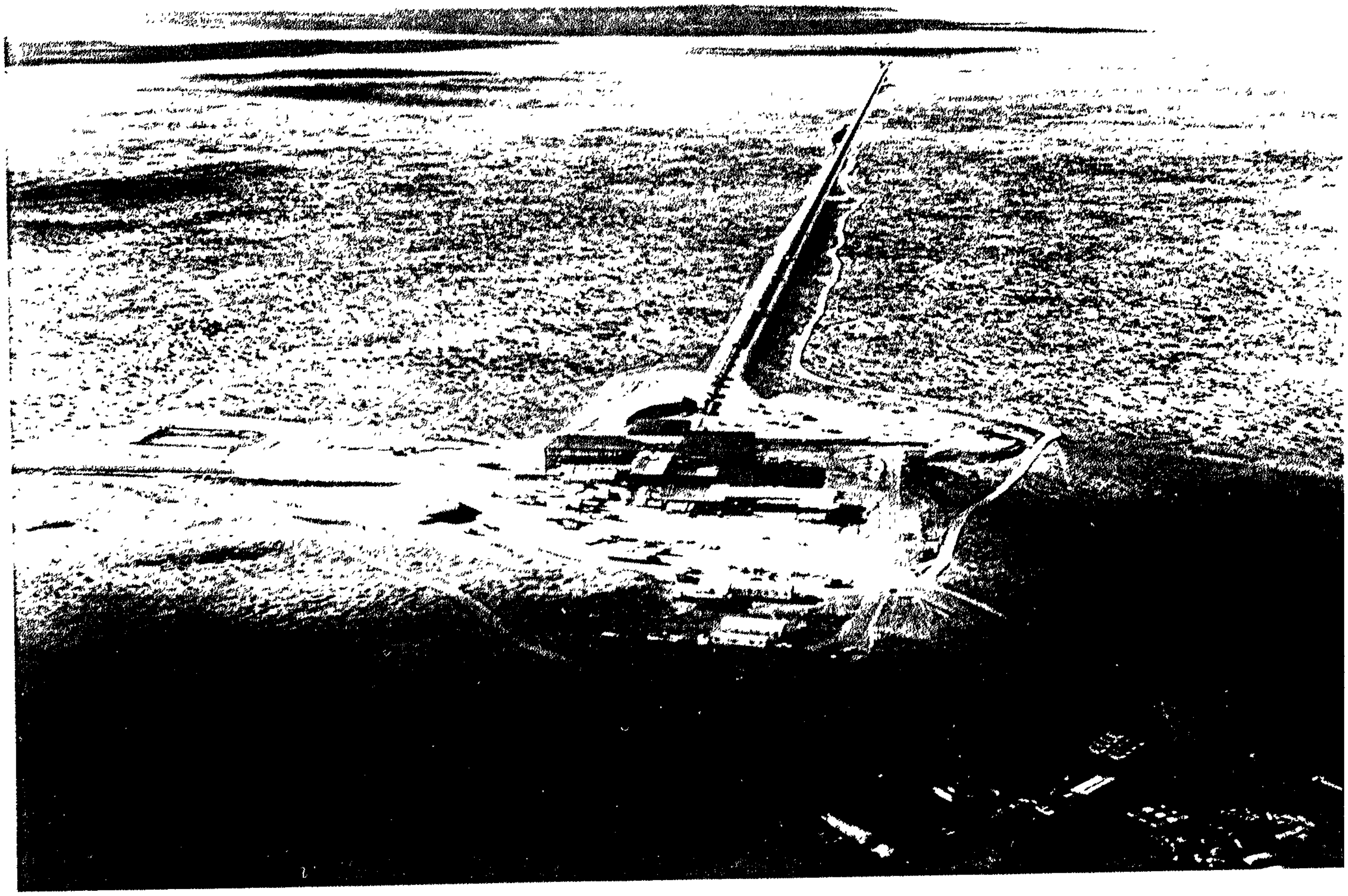
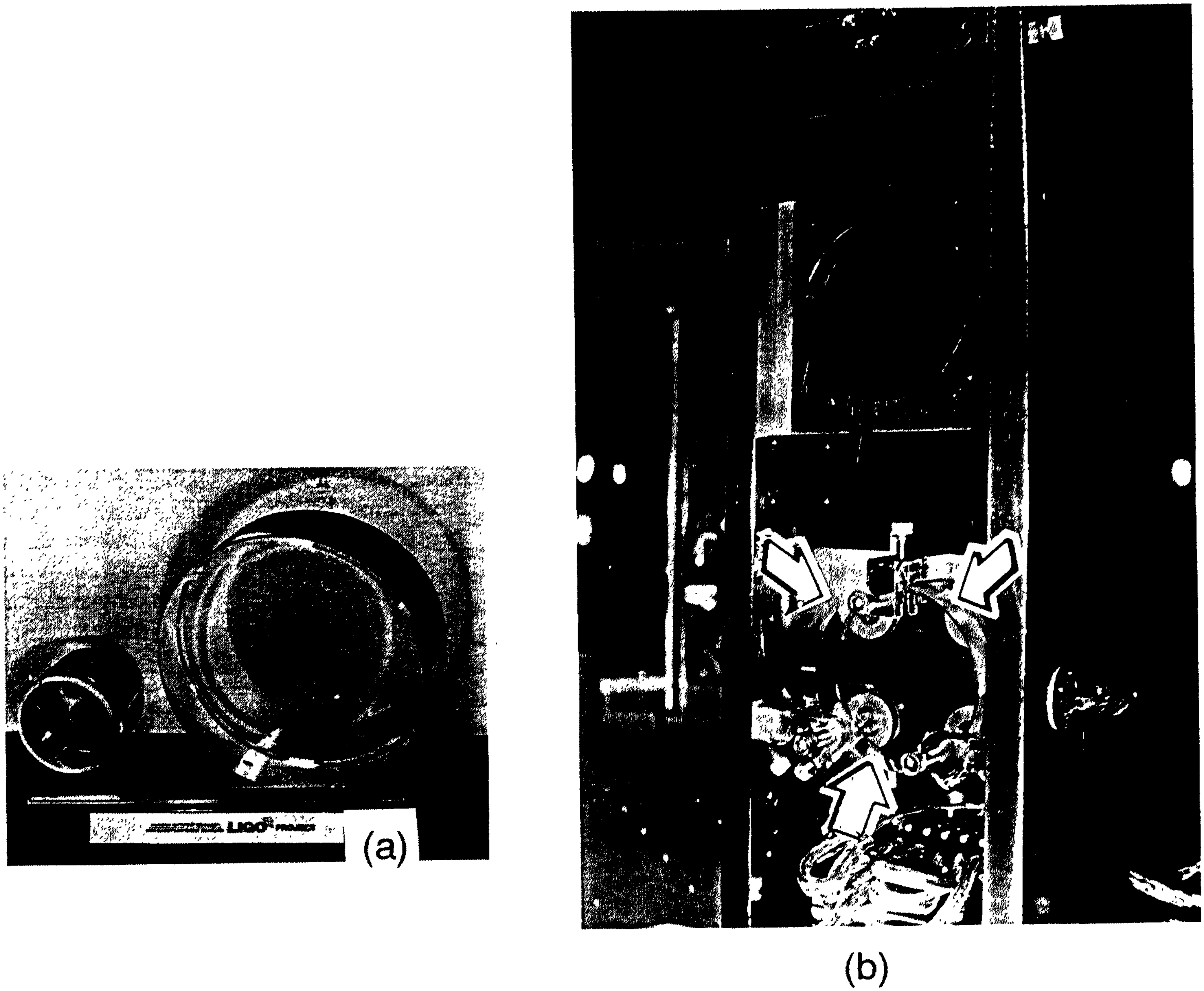


Fig. 4. An aerial view of the construction work at Hanfc shows the extensive Michelson interferometer in full vi Two arms, each 4 km long, will house more than one s supermirror cavity under vacuum. In the foreground, a building at the corner of the “L” will house injection lase beam splitter and control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



(a)

(b)

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).

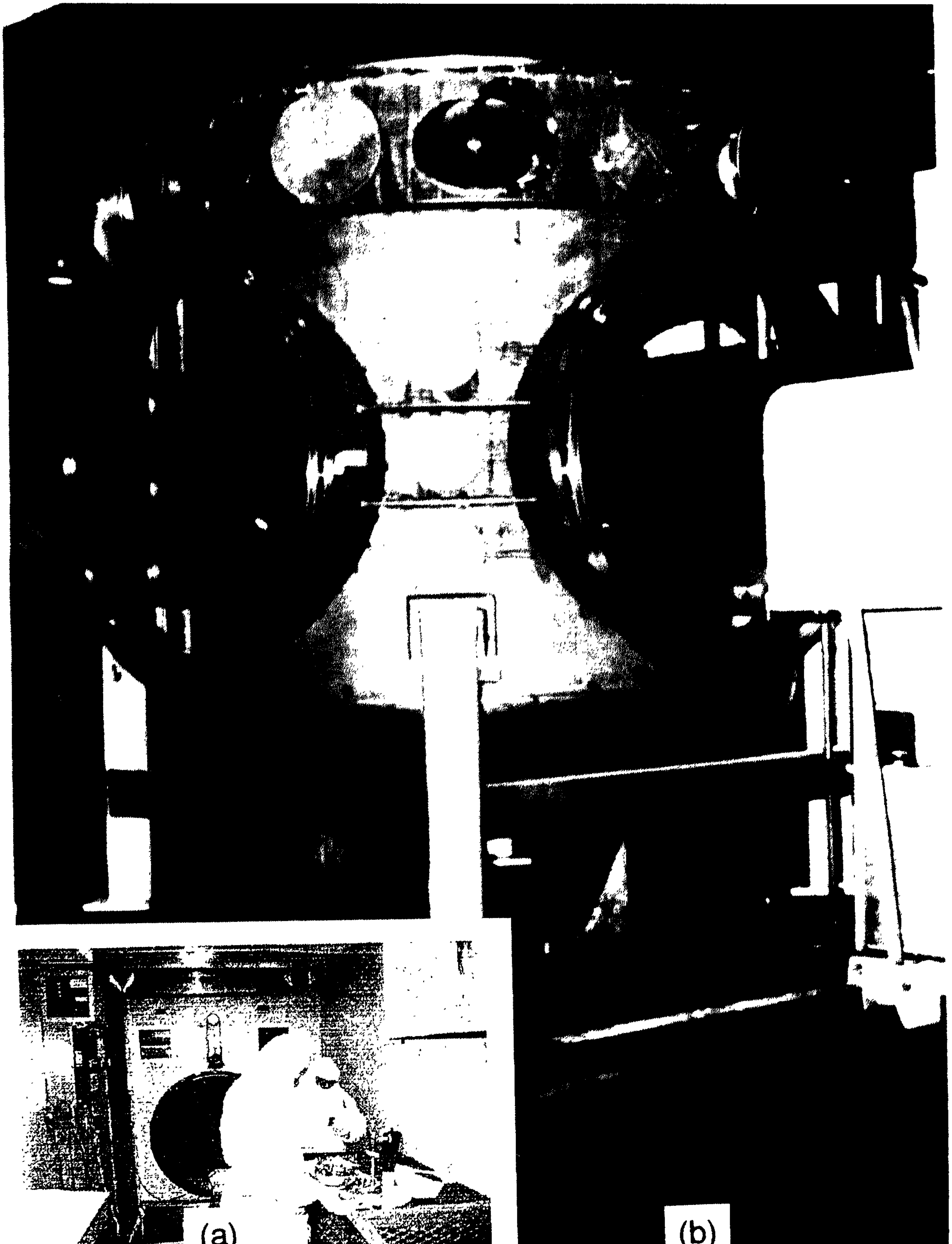
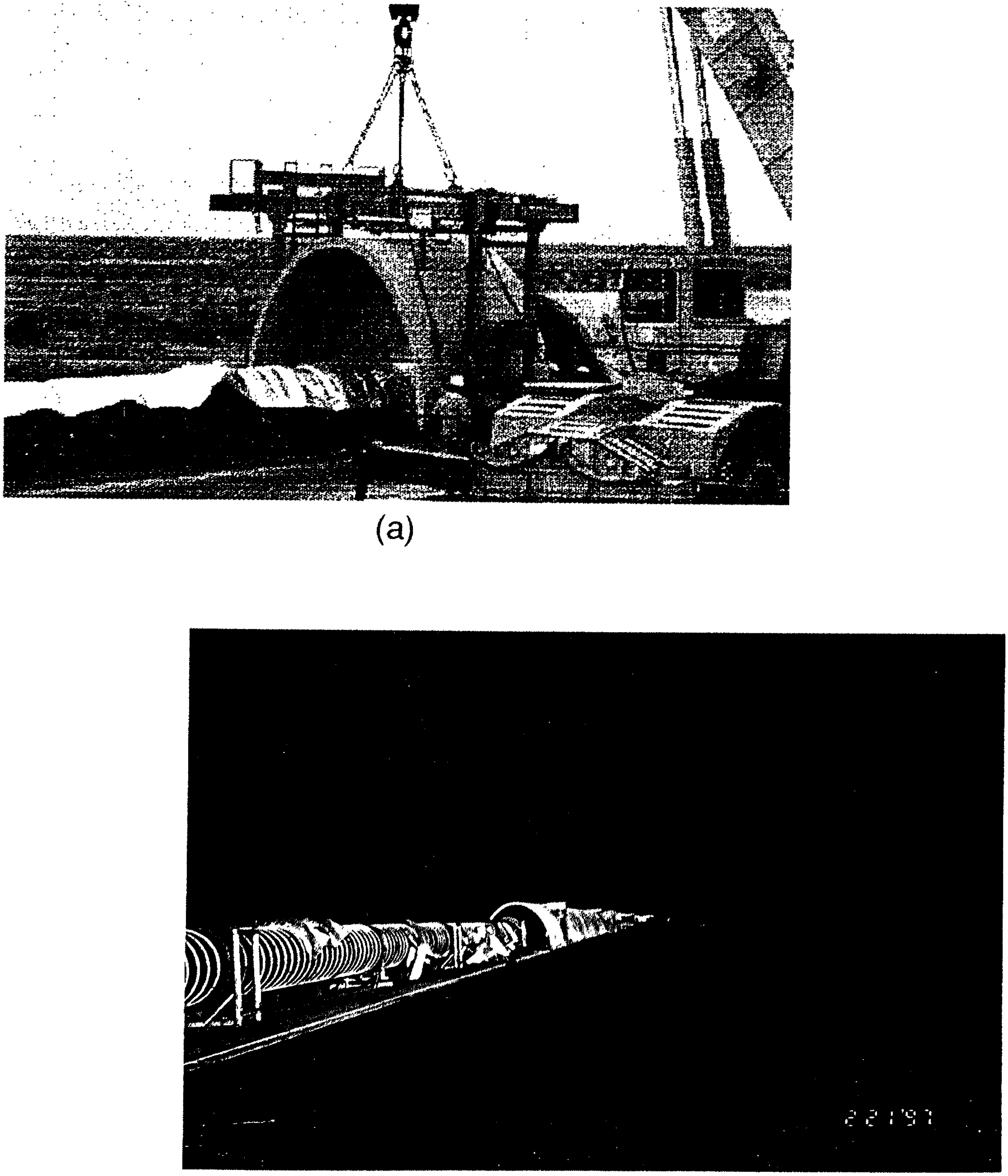


Fig. 6. (a) A weld-on beam tube section in a portable clean room. (b) A beam splitter chamber at Hanford (2 m high)



(a)

(b)

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

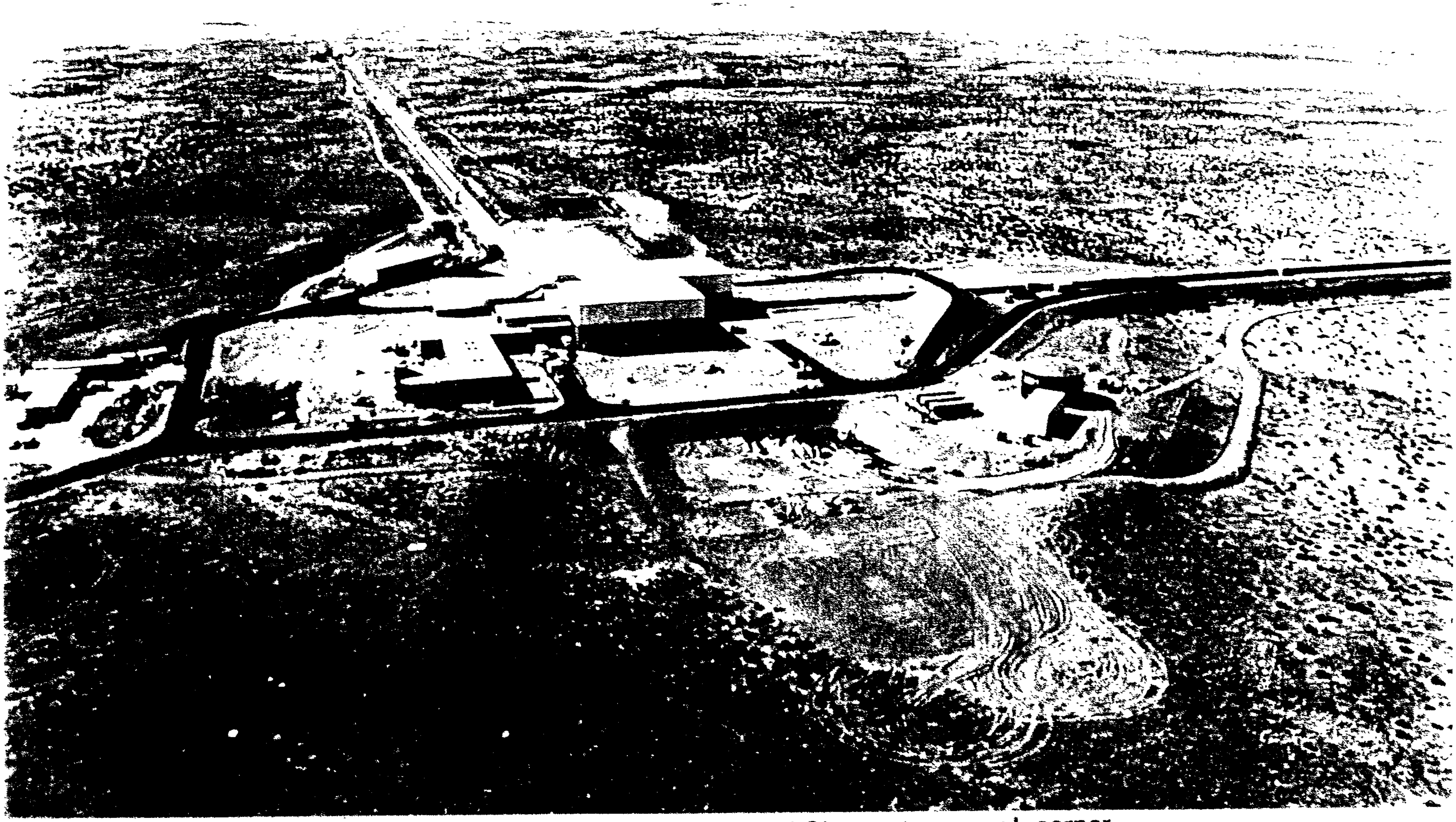


Figure 8. Recent ariel view of Hanford Observatory near L-corner

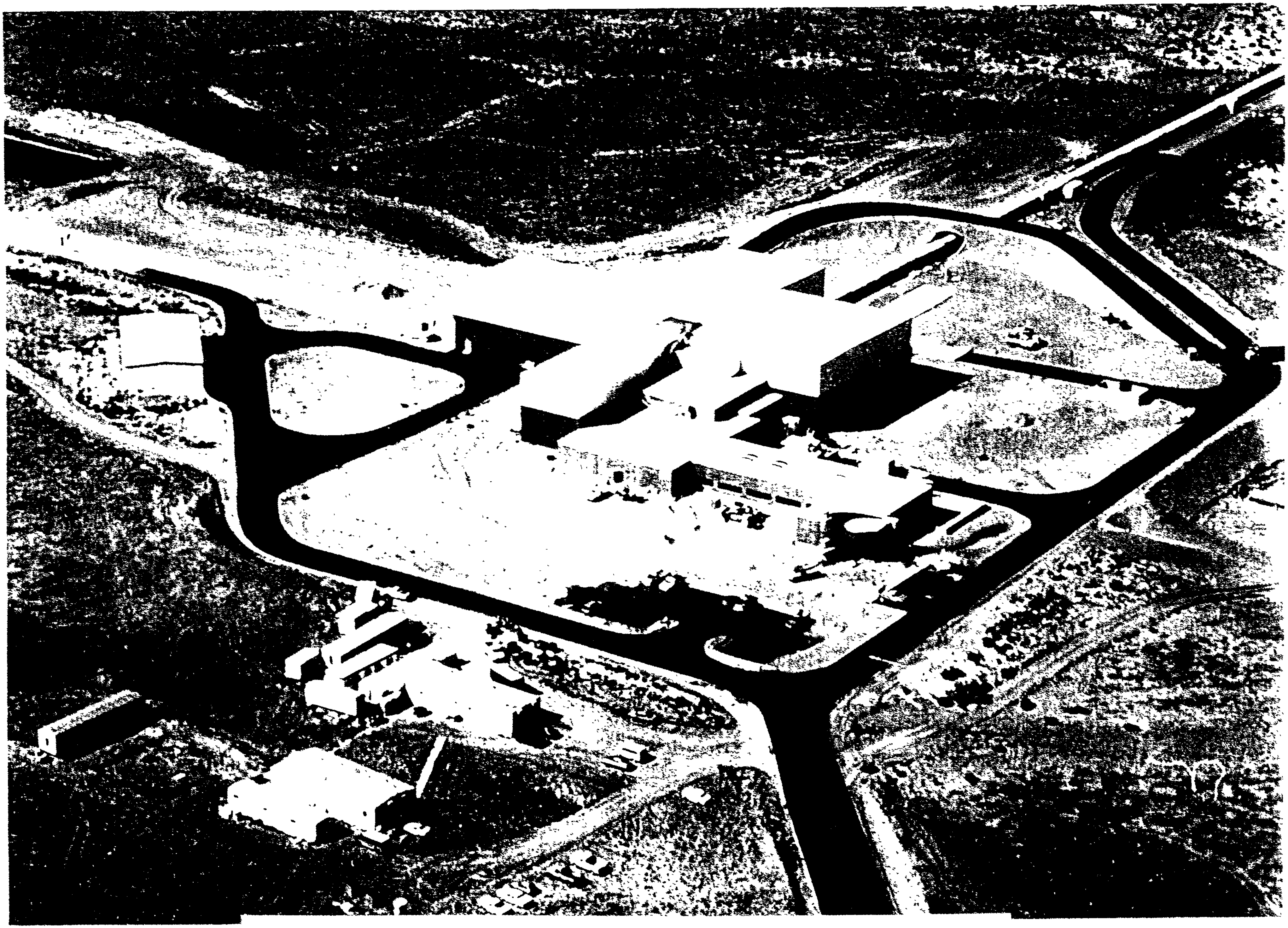


Figure 9. Operation Support Building of Hanford Observatory

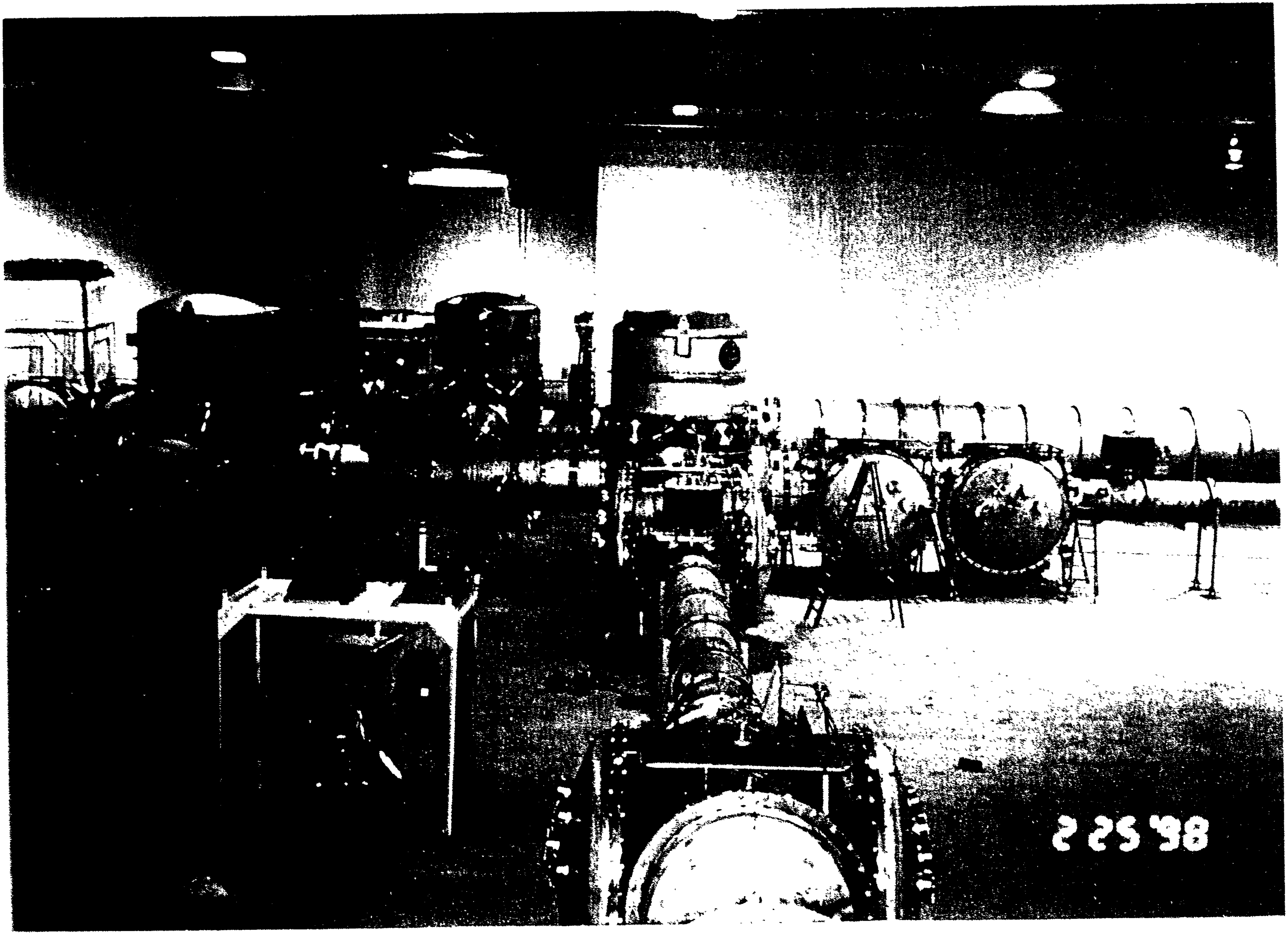


Figure 10. Vacuum facility in Hanford Observatory

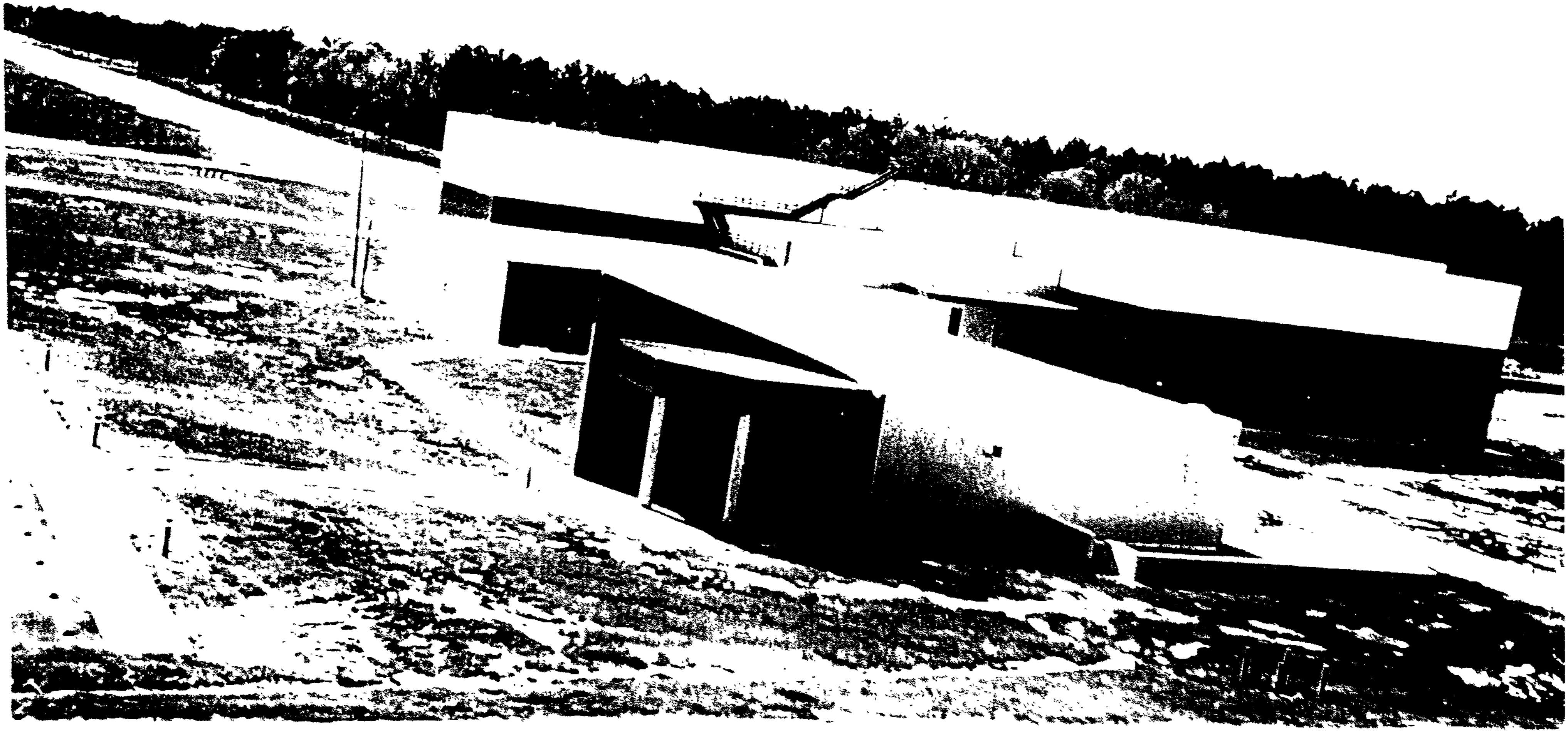


Figure 11. L-corner Building of Livinston Observatory

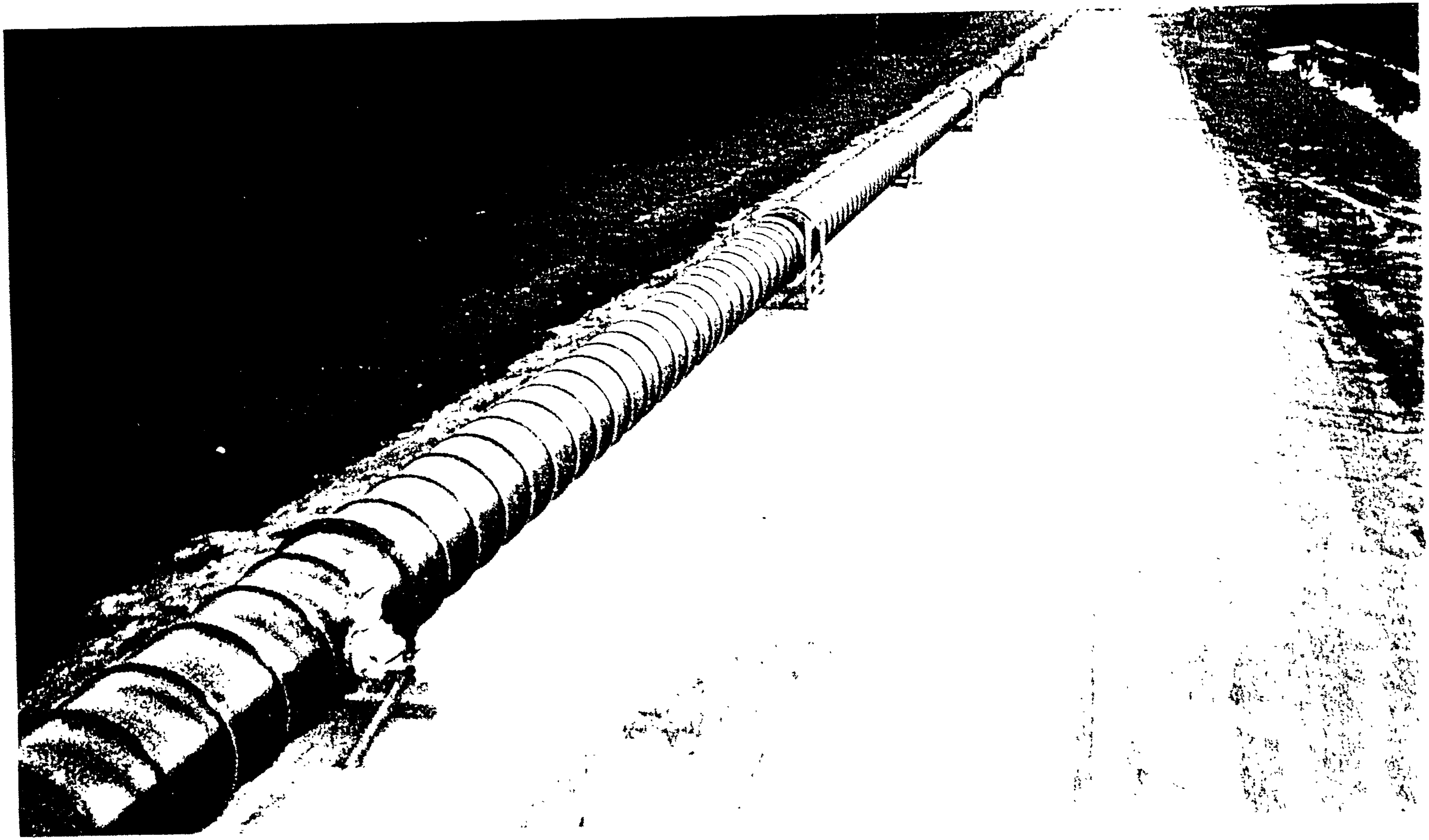


Figure 12. Beam tube laying at Livinston Observatory