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Gravitational Wave Searches Using the DSN

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The DSN doppler spacecraft link is currently the only method available for broadband gravitational wave searches in the 10^{-2}- to 10^{-4}-Hz frequency range. This report describes the DSN's role in the worldwide search for gravitational waves by first summarizing from the literature current theoretical estimates of gravitational wave strengths and time scales from various astrophysical sources. Current and future detection schemes for ground-based and space-based detectors are then discussed. Past, present, and future planned or proposed gravitational wave experiments using DSN doppler tracking are described. Lastly, some major technical challenges to improved gravitational wave sensitivities using the DSN are discussed.

I. Introduction

Gravitational waves are polarized gravitational fields that have escaped their sources and propagate independently [1]. These "ripples" in the curvature of space–time carry energy and momentum and move at finite speed. All relativistic theories of gravity agree on the existence of these waves, although the theories may differ in number of polarization states, propagation speed, efficiency of wave generation, etc. In General Relativity, gravitational waves are transverse, have two polarization states, and propagate at the speed of light. As a wave passes through space, it causes a strain—a dimensionless fractional change in the distances between massive objects and a similar fractional change in the rates at which separated clocks keep time. Figure 1 shows schematically the effect of a gravitational wave passing perpendicularly through a mass

(exaggerated by many powers of 10) according to General Relativity theory.

The search for gravitational waves has been going on since the 1960s using several detection approaches. In principle, gravitational waves can be detected through their effect on separated masses or clocks. All gravitational wave detectors attempt to sense some manifestation of these deviations in test mass separation (see Fig. 1 and Section III). However, gravitational waves are extremely weak, and they must be detected in a noisy environment; thus detection poses many experimental problems and provides profound challenges to instrument builders. Although gravitational waves are generated whenever there is time-varying, asymmetrical motion of any matter, they are generated at *appreciable* levels only by

extremely massive objects undergoing *extremely* violent dynamics. In other words, "strong" gravitational waves can be generated only by astrophysical sources. Because gravitational waves are so weak, Einstein—whose theory of General Relativity includes gravitational waves as a natural consequence—speculated that they could never be detected [2]. To date he is still right, although the search is gaining momentum worldwide, with ground- and space-based experiments being carried out or planned in Europe, Japan, China, the Soviet Union, Australia, and the United States.

There are many potential rewards of verified gravitational wave detection. Gravitational waves offer tests of fundamental physical law that may not be possible in any other way [3]. For example, comparison of arrival times of light and gravitational waves from, say, a supernova would test General Relativity's prediction that light and gravitational waves travel at the same speed. Polarization measurements could verify or refute the prediction of General Relativity that the waves are transverse and characterized by traceless tensor waves. Also, detailed waveform analysis might well be the first unequivocal proof of the existence of black holes and General Relativity's predictions of their dynamic behavior. Additional benefits of gravitational wave detection could include very accurate measurements of the Hubble constant and investigation of the dynamics of the Big Bang.

Another important consequence of a verified detection will be its implications for observational astronomy. Because gravitational waves interact very weakly with matter, they propagate unchanged from their sources. Thus detailed information about the time evolution of the source during violent events is preserved. This contrasts with electromagnetic waves, which can be absorbed or scattered by intervening matter. Even neutrinos produced in supernovae are scattered many times while leaving their sources. Relativistic motion of bulk matter and strong gravitational fields are central to most theoretical views about violent activity in supernovae, galactic nuclei, and quasars. When gravitational waves from these objects are detected, we will have the first observations of the interiors of strong-gravity, high-velocity regions. A new window will have opened for observational astronomy.

II. Gravitational Wave Sources and Anticipated Strengths and Frequencies

A. Gravitational Wave Sources

It is customary to classify gravitational waves and their sources based on their temporal waveforms [3].

Bursts (waves that are "on" for a few cycles) are expected to be produced by collisions of stars or black holes, the col-

lapse of a supernova to form a neutron star, the collapse of a star or star cluster to form a black hole, the coalescence of binary stars or black holes, and the fall of stars or small black holes into supermassive black holes.

Periodic waves, the prototypes of which are sinusoids, are expected to be produced by rotating neutron stars, binary stars, and binary black holes.

Stochastic waves (random fluctuations of long duration compared with observing times) are expected to be produced by ensembles of radiating binary stars, deaths of pregalactic massive stars, vibrations of cosmic strings, and the Big Bang.

Gravitational waves should be produced on a variety of time scales, depending on the masses of the objects involved. In general, stronger gravitational waves are expected to be produced on longer time scales. Figure 2 shows schematically some of the predicted waveforms from varying astrophysical events. Figure 3, adapted from [3], shows estimates of wave amplitudes at Earth as a function of the characteristic frequency of the waves.

B. Frequency Ranges

To detect gravitational waves in the full frequency range over which they are expected to occur, both ground-based and space-based technologies must be employed. Detector sensitivity depends on a number of factors, including test-mass separation and competing noise strengths. At present, doppler tracking of interplanetary spacecraft offers the only method for a broadband search in the 10^{-2}- to 10^{-4}-Hz frequency range. Ground-based detectors achieve good sensitivity at frequencies above about 10 Hz. (Below about 10 Hz, it becomes prohibitively difficult to isolate ground-based detectors from seismic and other noise.)

III. Gravitational Wave Detectors

A. Ground-Based Detectors

For very short period waves—on the order of 1/1000 second (e.g., from a supernova)—two ground-based technologies are currently employed: resonant bars and laser interferometers. Figure 4 shows schematically the two types of ground-based detectors.

Bar technology was pioneered in the 1960s by Joseph Weber of the University of Maryland. Gravitational waves excite mechanical oscillations in a cryogenically cooled bar which are read out by a transducer/amplifier system. Current-generation bars, like the one at Stanford University, now achieve sensitivities of better than 10^{-17} in strain amplitude.

This excellent sensitivity is comparable to the expected strain from a 1 percent efficient supernova collapse in our galaxy [3] and represents the best sensitivity achieved by any detector technology to date.

Laser interferometer detectors consist of three freely suspended test masses arranged at the corners of a right-angled "L." A gravitational wave incident on this system will "push" the test masses in one arm and "pull" the test masses in the other arm. This displacement will be reversed on the next half cycle of the wave (see Fig. 4). A laser light beam is split with a beam splitter, sent down both arms, bounced off mirrors on the test masses, and then recombined. The relative motions caused by a gravitational wave are detected as a fringe shift in the recombined light. This system is inherently broadband; many Fourier components are measured, and thus the gravitational waveform can be reconstructed. The prototype laser interferometers, such as Caltech's 40-meter system [4], currently have sensitivities comparable to those of the cryogenically cooled bars. A joint Caltech/MIT collaboration has been proposed to the National Science Foundation for construction of twin 4-km arm detectors that would yield more than three orders of magnitude better sensitivity [5]. The proposed joint facility has been named the Laser Interferometer Gravitational Wave Observatory (LIGO).

B. Space-Based Detectors

The current generation of space-based detectors uses the Earth and a distant spacecraft as free test masses. The DSN doppler tracking system, driven by an ultrastable time base on the ground, monitors a two-way coherent transponded microwave link with a distant spacecraft. In doing so, it continuously measures the relative dimensionless velocity ($\Delta v/c$) between the Earth and the spacecraft. A gravitational wave passing through the solar system produces strain ($\Delta l/l$) on the Earth–spacecraft system and similarly shifts the frequency of the clock driving the system. The result is that the gravitational waveform is replicated three times in the doppler tracking time series: once when the wave "buffets" the Earth, causing a small change in the difference between the transmitted and received doppler frequencies; once when the spacecraft is buffeted by the wave, causing the transponded signal to be different from the transmitted signal; and once when the initial Earth perturbation is transponded back to the Earth at "two-way light time" after the initial pulse (see Fig. 5). This three-pulse signal is an important signature of a gravitational wave and allows discrimination against noise sources in the doppler measurement system [6].

The sensitivity of a spacecraft-tracking gravitational wave search is limited by a variety of noise sources. The leading noise source for the current-generation (S-band radio link) experiments is plasma scintillation noise. In the next generation of experiments (X-band radio link), the plasma noise will be reduced by more than an order of magnitude. At that point, very careful attention to other noise sources will be required. Instrumental contributions to the noise include, for example, station timekeeping, frequency–time distribution within the station, antenna mechanical changes with time, and spacecraft transponder instability. Tropospheric phase scintillations are also expected to be an important noise source for X-band experiments.

Other space-based detectors have been suggested that do not involve doppler tracking. These include orbiting optical interferometers that are conceptually similar to ground-based interferometers. See [3] for details of gravitational wave space-based experiments that are currently under consideration.

IV. Past, Current, and Future Low-Frequency Gravitational Wave Experiments

The first attempt to use spacecraft doppler data to search for gravitational waves was conducted at JPL by A. J. Anderson in 1971. Since that time, the DSN has obtained data from the Pioneer, Viking, and Voyager spacecraft that have been used to characterize noise sources, gain insight into experimental problems, and put upper limits on the strengths of the waves in the "low-frequency" band [7]–[11]. Both the Ulysses and Galileo missions have approved gravitational wave experiments and will be able to do experiments with better sensitivity than the current-generation prototype searches. Pulsar timing and precision celestial mechanics data allow searches for waves in the "very-low-frequency" band [11]–[13]. Finally, observation of excitations of the Earth, Moon, and Sun can also be used in principle [14]. Table 1 lists the published sensitivities of searches in the low-frequency and very-low-frequency bands.

V. Technology Needed for Future Experiments

As described previously, the current leading noise source in low-frequency experiments is plasma scintillation noise, i.e., random phase variations of the radio wave imposed as the signal propagates through the ionosphere and the solar wind plasma. Because of these variations, the apparent electrical distance to the spacecraft varies irregularly with time, acting as a noise source for gravitational wave detection. The magnitude of the effect depends inversely on the radio frequency of the tracking link squared; thus, higher frequency radio links are much less affected. X-band uplinks will produce more than an order of magnitude improvement in sensitivity over S-band experiments. The first of the X-band uplink observations will be made with the Galileo spacecraft during the

cruise to Jupiter, with an expected sensitivity of approximately 5×10^{-15} for bursts and approximately 10^{-16} for periodic waves (cf. Fig. 3). The Mariner Mark II and Mars Observer spacecraft will also have X-band uplinks and will be appropriate for use in gravitational wave searches. Observations with very-high-frequency links such as K-band (31,000 MHz), or those with multiple-frequency links, can provide very high immunity to plasma noise and very sensitive gravitational wave experiments (about 10^{-17} for K-band). Improved timekeeping and precision tropospheric monitoring would also be necessary to fully exploit the benefits of higher frequencies.

The remarkably good sensitivities of current and near-future experiments are due to the explosion in precision measurement technology that has occurred over the past few decades. For both space- and ground-based detectors, a continued push of the state of the art in relevant advanced instrumentation is required for further progress. For the doppler tracking link, technological improvements that would increase sensitivities include:

(1) *Higher-precision timekeeping.* Timekeeping is at the heart of doppler gravitational wave experiments

(10^{-16}/1000-sec accuracy is currently the 1990 time-keeping goal for the DSN).

(2) *Higher RF links and dual-frequency uplinks.* Higher-frequency links (e.g., K-band) or dual-frequency uplinks and downlinks can substantially reduce plasma scintillation noise, currently the leading noise source for gravitational wave experiments.

(3) *Tropospheric monitoring technology.* The Earth's neutral atmosphere produces tropospheric scintillations that are at microwave frequencies independent of the radio frequency of the doppler link. As the plasma noise is reduced by higher-frequency links, tropospheric scintillation will become a leading noise source. Accurate monitoring of tropospheric scintillation with, for example, water vapor radiometry will be required to correct gravitational wave data for this effect.

(4) *Further transponder development.* Instrumental stability on the spacecraft is also central to a high-sensitivity doppler tracking experiment.

Acknowledgment

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Table 1. Gravitational waves: experimental limits in the LF and VLF bands

Burst Sources

("Raw" = Allan variance without matched filtering in the postprocessing.)

Frequency, Hz	Strain amplitude	Data type (date)	Data duration	Reference or comment
$\sim 10^{-3}$	$<3 \times 10^{-14}$	Voyager (1979)	2 days	[7]
$\sim 10^{-3}$	$<6 \times 10^{-14}$	Viking (1977)	2 days	[8]
$\sim 10^{-3}$	$<2 \times 10^{-13}$	Pioneer 10 (1981)	21 days	JPL group (in preparation)
10^{-2} to 5×10^{-4}	$<2 \times 10^{-13}$	Pioneer 11 (1983)	3 days	JPL group (in preparation)
10^{-1} to 10^{-4}	$\sim 3 \times 10^{-14}$	Ulysses (1990+)	28 days/year	Predicted performance
10^{-1} to 10^{-4}	$\sim 3 \times 10^{-15}$	Galileo (1990+)	40 days/year	Predicted (raw) performance

Sinusoidal Sources

Frequency, Hz	Amplitude (1σ)	Data type (date)	Comment	Reference or comment
1.04×10^{-4}	$<2 \times 10^{-14}$	Pioneer 10 (1981)	Geminga	[9]
0.005 to 0.033	$<1.5 \times 10^{-14}$	Pioneer 11 (1983)	broadband	[10]
10^{-1} to 10^{-4}	$\sim 5 \times 10^{-15}$	Ulysses (1990+)	28 days/year	Predicted performance
10^{-1} to 10^{-4}	$\sim 3 \times 10^{-16}$	Galileo (1990+)	40 days/year	Predicted performance

Stochastic Background

(Amplitude expressed as energy density in gravitational waves in bandwidth equal to the center frequency, except for the normal mode data, normalized by the energy density required to close the universe.)

| Frequency, Hz	Energy density/ closure density	Data type (date)	Reference or comment
$\sim 10^{-8}$	$<1.4 \times 10^{-4}$	pulsars	[11]
$\sim 10^{-7}$	$<5 \times 10^{-4}$	pulsars	[12]
$\sim 10^{-6}$	<18	Pioneer 10 (1981)	[13]
$\sim 4 \times 10^{-6}$	<38	Pioneer 10	[13]
$\sim 7 \times 10^{-5}$	<260	Pioneer 10	[13]
$\sim 4 \times 10^{-4}$	<40	Voyager (1979)	[7]
$\sim 3 \times 10^{-4}$	<100	Sun's normal modes	[14]
$\sim 3.1 \times 10^{-4}$	<1	Earth's normal modes	[14]
1.2×10^{-4}	<9	Pioneer 11 (1983)	JPL group (in preparation)
10^{-1} to 10^{-4}	~ 5	Ulysses (1990+)	28 days/year, predicted performance
10^{-1} to 10^{-4}	~ 0.01	Galileo (1990+)	40 days/year, predicted performance
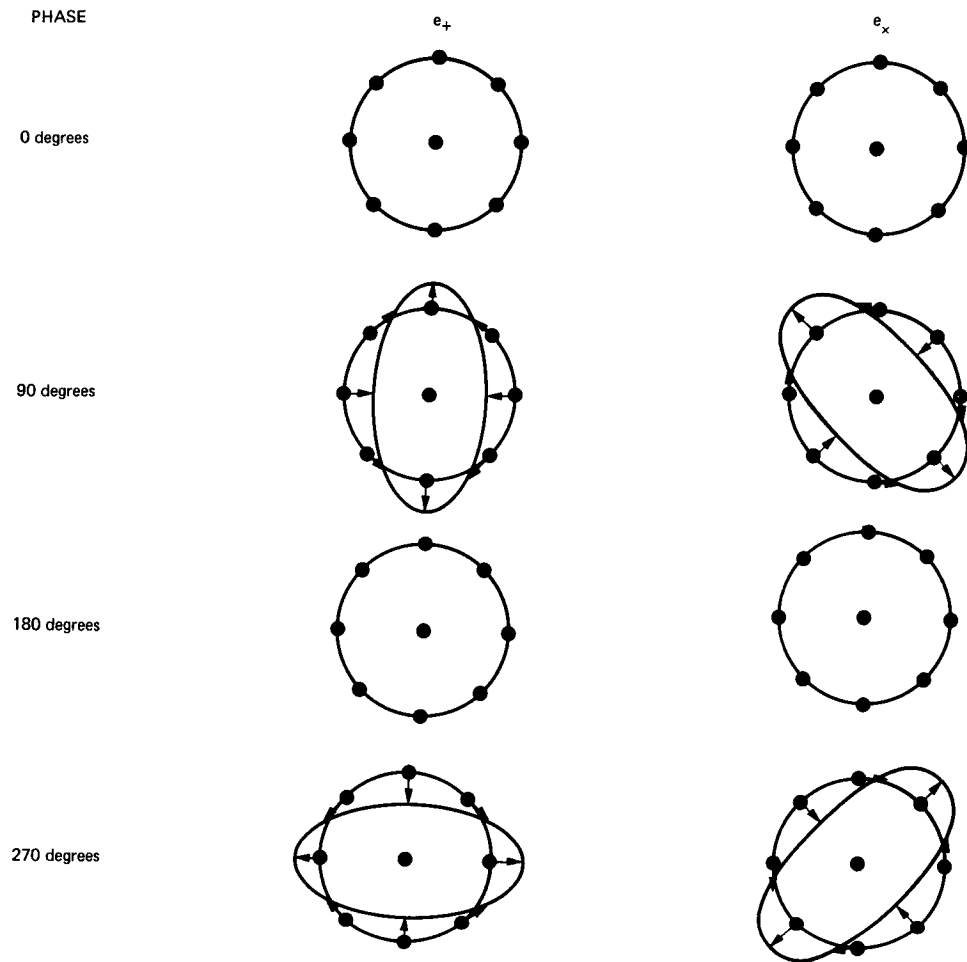
Fig. 1. A plane gravitational wave produces changes in the separation of test masses transverse to the direction of propagation. This figure, adapted from [1], shows schematically how an initially circular ring of test masses is distorted by the passage of waves in each of the two independent polarizations ("+" and "×" polarizations). Gravitational wave detectors attempt to sense some manifestation of these (very small) deviations in test particle separation.
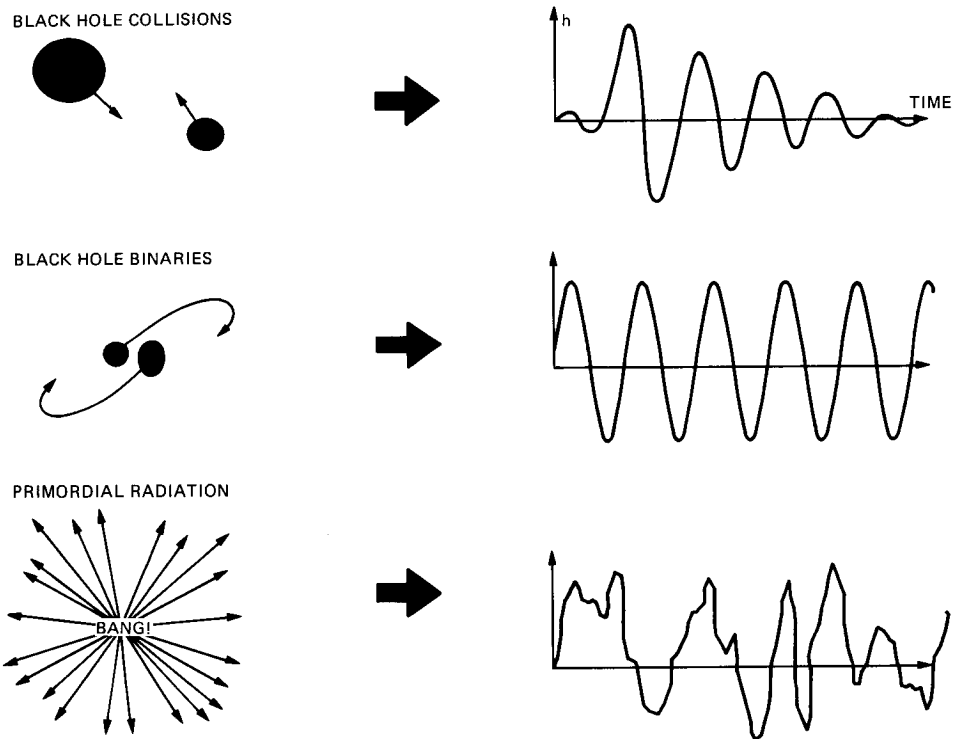
Fig. 2. Gravitational waves are conventionally classified by their temporal waveforms. Burst waves are "on" for at most a few cycles and might be produced by, for example, black hole collisions. Periodic waves, the prototype of which is the indicated sinusoid, could be generated by binary black holes. Stochastic waves, irregular variations in the wave strength on time scales that are long compared to an experimental time scale, might be generated by an ensemble of incoherent radiators or by the Big Bang.
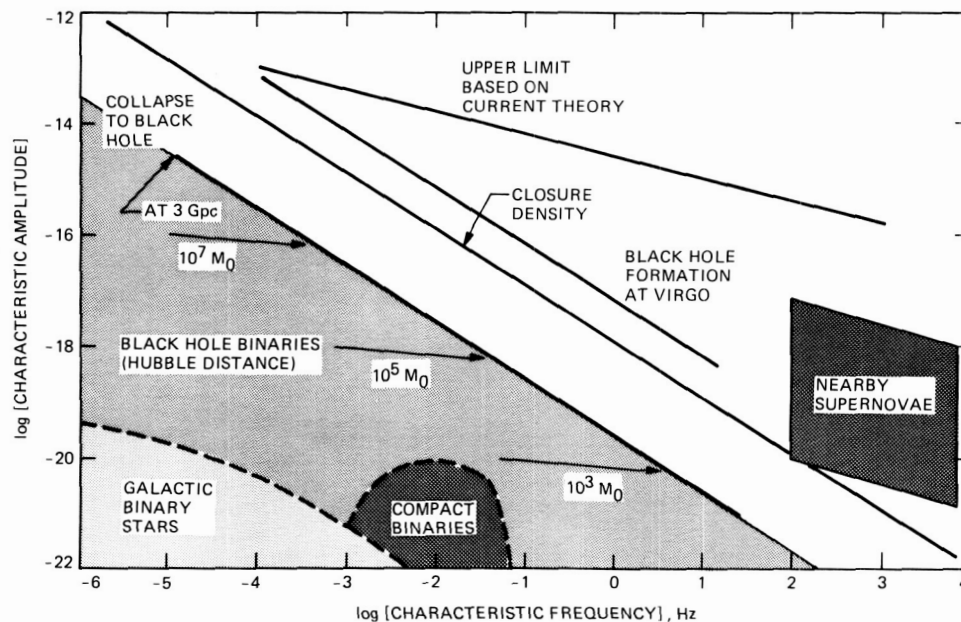
Fig. 3. Theoretical estimates of amplitudes and time scales for gravitational waves from some sources, adapted from [3]. It should be understood that these estimates are highly uncertain and many caveats apply; see [3]. "Upper limit based on current theory" is for the anticipated strength of burst radiation based on current understanding of the galaxy and general physical considerations. "Closure density" is the envelope of a family of curves having bandwidths equal to center frequency which represents the level of a gravitational wave background that would be sufficient to gravitationally close the universe. "Collapse to black hole" is the anticipated strength for burst radiation from black hole formation, assuming the mass of the hole (indicated) and assuming the source is at the Hubble distance (3 Gpc) or the Virgo cluster (where the amplitudes would be about 200 times larger). Shaded area labeled "black hole binaries (Hubble distance)" indicates amplitudes of periodic radiation from black hole binaries of indicated mass at 3 Gpc. The nearly horizontal arrows indicate evolutionary tracks. Amplitudes scale upward by about 200 if the source is in the Virgo cluster. "Galactic binary stars" shows the calculated strength of periodic waves from known binary stars in our galaxy. "Compact binaries" shows the calculated amplitudes for compact binaries, e.g., neutron star binaries, in our galaxy.
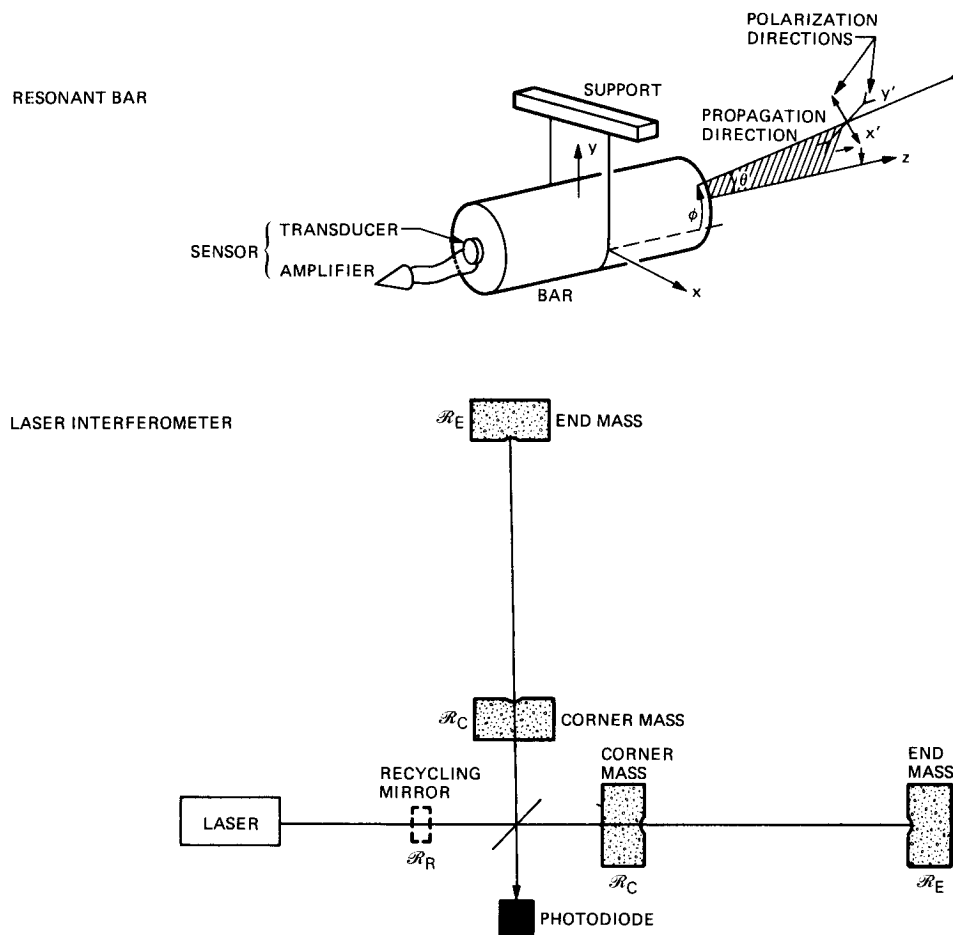
Fig. 4. Schematic diagrams of ground-based detectors—resonant bars and laser interferometers; see text for discussion.
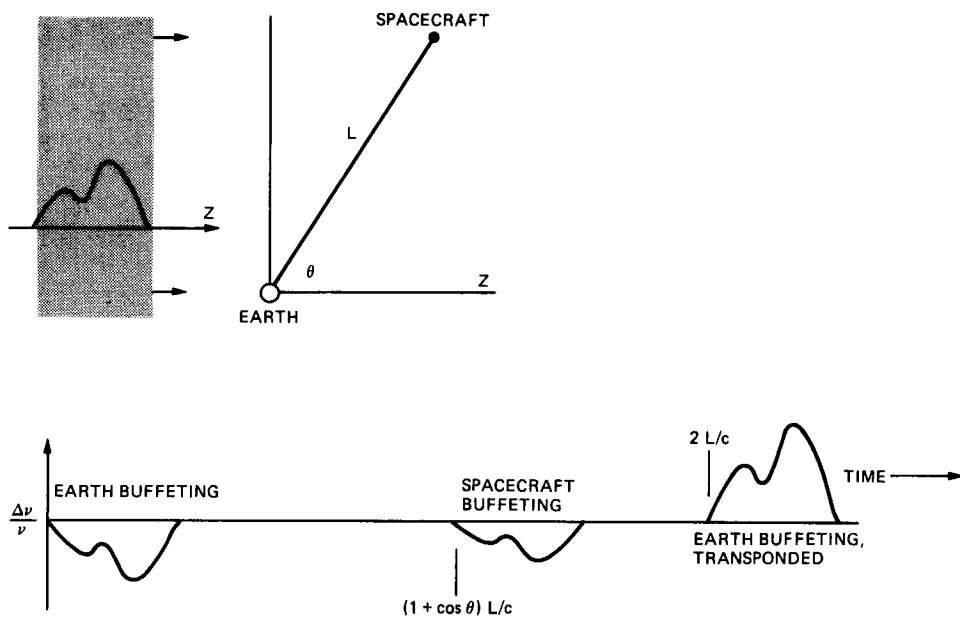
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Fig. 5. Schematic diagram of spacecraft doppler tracking detector. Upper diagram shows a plane gravitational wave incident on the Earth–spacecraft system. Lower diagram shows "three-pulse" mapping of a gravitational waveform into the doppler tracking time series (see text and [6]).