PHYSICS OF GRAVITATIONAL WAVE DETECTION: RESONANT AND INTERFEROMETRIC DETECTORS

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ABSTRACT

I review the physics of ground-based gravitational wave detectors, and summarize the history of their development and use. Special attention is paid to the historical roots of today's detectors.

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1.3 A *gedanken* experiment to detect a gravitational wave

In the discussion in the preceding section, we took it for granted that the perturbations h_+ and $h_\times$ to the flat-space metric were, in some sense, real. But it is only by considering whether such effects are measurable that one can be convinced that a phenomenon like a gravitational wave is meaningful, rather than a mathematical artifact that could be transformed away by a suitable choice of coordinates.

To demonstrate the physical reality of gravitational waves, consider the example system of the previous section. We will concentrate our attention on three of the test masses, one chosen arbitrarily from the plane, along with its nearest neighbors in the $+x$ and $+y$ directions. Imagine that we have equipped the mass at the vertex of this "L" with a lamp that can be made to emit very brief pulses of light. Imagine also that the two masses at the ends of the "L" are fitted with mirrors aimed so that they will return the flashes of light back toward the vertex mass.

First, we will sketch how the apparatus can be properly set up, in the absence of a gravitational wave. Let the lamp emit a train of pulses, and observe when the reflected flashes of light are returned to the vertex mass by the mirrors on the two end masses. Adjust the distances from the vertex mass to the two end masses until the two reflected flashes arrive simultaneously.

Once the apparatus is nulled, let the lamp keep flashing, and wait for a burst of gravitational waves to arrive. When a wave of $\widehat{h}_+$ polarization passes through the apparatus along the z axis, it will disturb the balance between the lengths of the two arms of the "L". Imagine that the gravitational wave has a waveform given by

$$h^{\mu\nu} = h(t)\widehat{h}_+.$$

To see how this space-time perturbation changes the arrival times of the two returned flashes, let us carefully calculate the time it takes for light to travel along each of the two arms.

First, consider light in the arm along the x axis. The interval between two neigh-

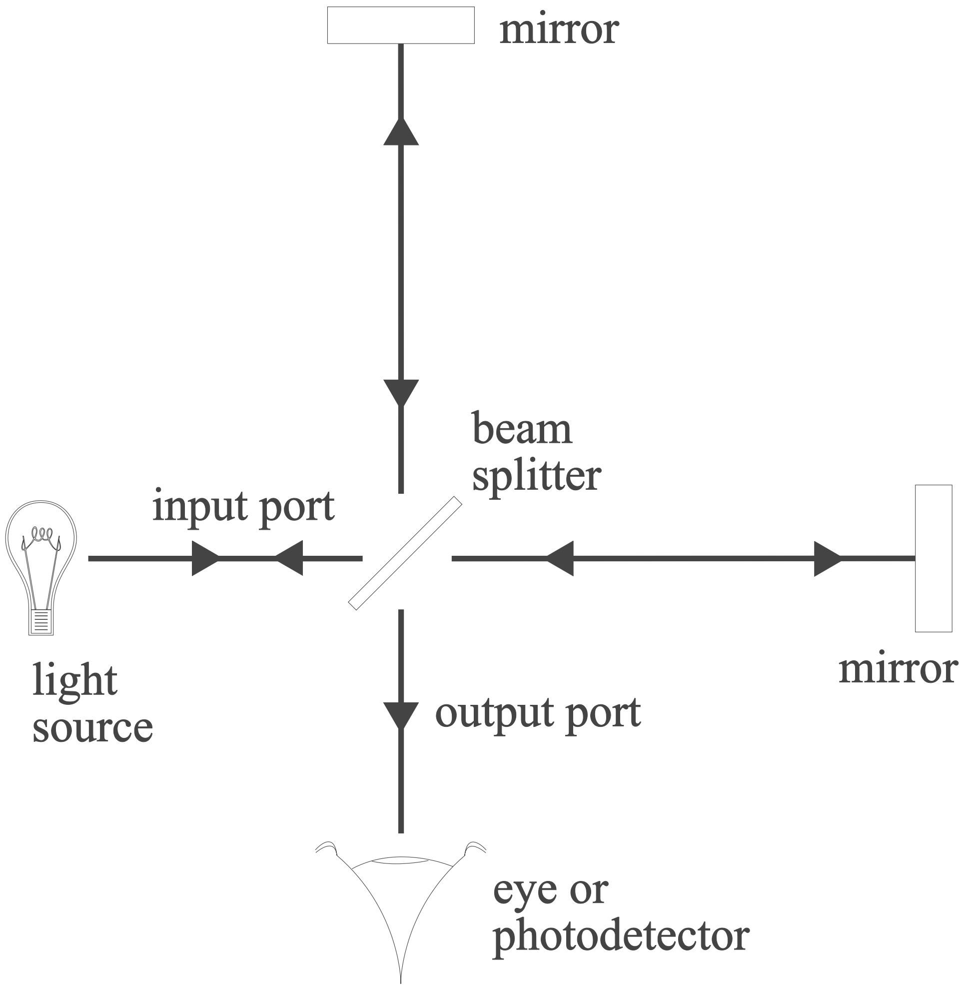

Fig. 2. A schematic diagram of an apparatus that can detect gravitational waves. It has the form of a Michelson interferometer.

boring space-time events linked by the light beam is given by

$$\begin{aligned} ds^2 \quad = 0 \quad &= g_{\mu\nu} dx^\mu dx^\nu \\ &= (\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu dx^\nu \\ &= -c^2 dt^2 + (1 + h_{11}(2\pi f t - kz))\, dx^2. \end{aligned} \tag{1}$$

This says that the effect of the gravitational wave is to modulate the square of the distance between two neighboring points of fixed coordinate separation dx (as marked, in this gauge, by freely-falling test particles) by a fractional amount h_{11}.

We can evaluate the light travel time from the beam splitter to the end of the x arm by integrating the square root of Eq. 1

$$\int_0^{\tau_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1 + h_{11}}dx \approx \frac{1}{c}\int_0^L \left(1 + \frac{1}{2} h_{11}\,(2\pi f t - kz)\right) dx, \tag{2}$$

where, because we will only encounter situations in which $h \ll 1$, we've used the binomial expansion of the square root, and dropped the utterly negligible terms with more than one power of h. We can write a similar equation for the return trip

$$\int_{\tau_{out}}^{\tau_{rt}} dt = -\frac{1}{c}\int_L^0 \left(1 + \frac{1}{2} h_{11}(2\pi f t - kz)\right) dx. \tag{3}$$

The total round trip time is thus

$$\tau_{rt} = \frac{2L}{c} + \frac{1}{2c}\int_0^L h_{11}(2\pi f t - kz)dx - \frac{1}{2c}\int_L^0 h_{11}(2\pi f t - kz)dx. \tag{4}$$

The integrals are to be evaluated by expressing the arguments as a function just of the position of a particular wavefront (the one that left the beam-splitter at $t = 0$) as it propagates through the apparatus. That is, we should make the substitution $t = x/c$ for the outbound leg, and $t = (2L - x)/c$ for the return leg. Corrections to these relations due to the effect of the gravitational wave itself are negligible.

A similar expression can be written for the light that travels through the y arm. The only differences are that it will depend on h_{22} instead of h_{11} and will involve a different substitution for t.

If $2\pi f_{gw}\tau_{rt} \ll 1$, then we can treat the metric perturbation as approximately constant during the time any given flash is present in the apparatus. There will be equal and opposite perturbations to the light travel time in the two arms. The total travel time difference will therefore be

$$\Delta\tau(t) = h(t)\frac{2L}{c} = h(t)\tau_{rt0}, \tag{5}$$

where we have defined $\tau_{rt0} \equiv 2L/c$.

If we imagine replacing the flashing lamp with a laser that emits a coherent beam of light, we can express the travel time difference as a phase shift by comparing the travel time difference to the (reduced) period of oscillation of the light, or

$$\Delta\phi(t) = h(t)\tau_{rt0}\frac{2\pi c}{\lambda}. \tag{6}$$

Another way to say this is that the phase shift between the light that traveled in the two arms is equal to a fraction h of the total phase a light beam accumulates as it traverses the apparatus. This immediately says that the longer the optical path in the apparatus, the larger will be the phase shift due to the gravitational wave.

Thus, this *gedanken* experiment has demonstrated that gravitational waves do indeed have physical reality, since they can (at least in principle) be measured. Furthermore, it suggests a straightforward interpretation of the dimensionless metric perturbation h. The gravitational wave amplitude gives the fractional change in the difference in light travel times along two perpendicular paths whose endpoints are marked by freely-falling test masses.

1.4 Another way to picture the effect of a gravitational wave on test bodies

In standard laboratory practice, it is not customary to define coordinates by the world-lines of freely-falling test masses. Instead, rigid rulers usually are used to do the job. The forces that make a rigid ruler rigid are something of a foreign concept in relativity, appearing ugly and awkward after the gravitational force has been made to disappear by expressing it as the curvature of space-time. On the other hand, non-gravitational forces are not only a fact of nature, but part of the familiar world of the laboratory. For many purposes, it is convenient to retreat from a purely relativistic picture and instead use a Newtonian picture in which gravity is treated as force on the same level as other forces.

What we are seeking is not a different theory of gravitational waves, but a translation of the theory discussed in the previous section into more familiar language. So let us reconsider the same *gedanken* experiment as before, but imagine that we have augmented the equipment with a rigid ruler along each axis. We saw that when a gravitational wave passed through our set of test masses, the amount of time it took for light to travel from the vertex mass to the end mass and back was made to vary. How can we describe how this came about in the standard language of the laboratory? If we imagine (notwithstanding their fixed coordinates in the transverse traceless gauge) that the test masses have moved in response to the gravitational wave, we can have a consistent picture of the effect. What is necessary is that the gravitational wave give a tidal force across the pair of masses that will cause them to move apart by the amount necessary to account for the change in light travel time through the system. It is as if the far masses felt forces whose magnitude were given by

$$F_{gw} = \frac{1}{2} m L \frac{\partial^2 h_{11}}{\partial t^2}, \tag{7}$$

where m is the mass of each of the two test bodies, and L is the separation between their centers of mass.

There are several features of this expression that are worthy of note. The force is proportional to the mass of the test bodies, as required by the Principle of Equivalence. The force is also proportional to the separation between the two test masses, making it akin to conventional gravitational tidal forces. The dependence of the gravitational wave force on the second time derivative of h is reminiscent of Newton's Second Law $F = m\ddot{x}$. A natural interpretation follows: in a conventional laboratory coordinate system, free masses actually change their separation by an amount $\Delta L = hL/2$.

Note how in two different coordinate systems the same phenomenon (and particularly the same measurement) is described in completely different language. In transverse traceless coordinates, the free test masses still just fall freely, each marking out its own coordinate (by definition) under any gravitational influence, but the light travel time between them changes as the metric of space-time varies. In standard laboratory coordinates, light travel time changes because the test masses move. Neither of these pictures is more "correct" than the other. The laboratory-coordinate picture is markedly more convenient for seeing how to combine the effect of a gravitational wave with the effects of noise forces of various kinds. The transverse traceless coordinates offer the most clarity when one wants to consider extreme cases, such as test masses separated by distances comparable to or longer than the gravitational wave's wavelength.

2 Generating gravitational waves

As mentioned above, the second time derivative of the mass quadrupole moment I plays the same role in gravitational wave emission as does the first derivative of the charge dipole moment in electromagnetic radiation problems, that of strongest source term in most situations. More specifically, the expression for gravitatonal wave generation is

$$h_{\mu\nu} = \frac{2G}{Rc^4}\ddot{I}_{\mu\nu}, \tag{8}$$

usually referred to as the “quadrupole formula”.[2]

Something about this expression should immediately give one pause — the prefactor of $2G/c^4$. In SI units, this has the value 1.6×10^{-44} sec^{2}kg^{-1}m^{-1}. It will take tremendously large values of $\ddot{I}/R$ in order for even modest values of h to be generated. *A priori*, one can think of two strategies that might work: make R small, or make $\ddot{I}$ large.

2.1 Laboratory generators of gravitational waves

To construct a source of gravitational waves in the laboratory would allow one to have the benefit of placing it as close as possible to one’s detector, thus exemplifying the first strategy in the previous paragraph. Of course, it would have other benefits as well. Control of the waveform, polarization, and other features would enable the detector to be carefully optimized to match the signal. At an even deeper level, confidence in the detection of gravitational waves could be assured by the requirement that they must be seen when, and only when, they were being emitted.

What one would really like to do is to replicate for gravitational waves what Hertz was able to accomplish for electromagnetic ones. His experiments of 1886-91 not only conclusively demonstrated the existence of electromagnetic waves, they validated Maxwell’s theory of electromagnetic radiation by exploring the rich phenomenology of polarization, reflection, and interference. They also began the process of harnessing the phenomenon for practical use. Marconi’s work started by his following closely in Hertz’s footsteps, and real long-distance communication via radio was not long in coming.

Unfortunately, no practicable way has been conceived to replicate Hertz’s success in the gravitational domain. Assume we could construct a dumbbell consisting of two masses of 1 ton each, at either end of a rod 2 meters long. Spin this quadrupole about an axis orthogonal to the connecting rod passing through its midpoint, at an angular frequency $f_{rot} = 1$ kHz. Neglecting for simplicity the contribution of the connecting rod, we have a system very similar to a binary star system. The amplitude of the gravitational waves generated by this device will be

$$h_{lab} = 2.6 \times 10^{-33}\mathrm{m} \times \frac{1}{R}. \tag{9}$$

Before we rush to plug in a distance R of a few meters, as Hertz was able to do for his experiment, we need to remember that wave phenomena are only distinguishable from near-field effects in the "wave zone", that is at distances from the source comparable to or larger than one wavelength. With $\omega_{rot} = 2\pi \times 1$ kHz, we have $\lambda = 300$ km! The receiver for our Hertzian experiment must be at least that far away from the transmitter. Hertz's electromagnetic experiments involved waves of 6 meters down to 60 cm in length, so the distance across the lab was fine for him.

At a distance of one wavelength, our laboratory generator gives gravitational waves of amplitude

$$h_{lab} = 9 \times 10^{-39}. \tag{10}$$

This is pretty small.

Even creating such a strong source as this may not be practicable. Consider the stress in the connecting rod of the dumbbell. It must supply the centripetal force necessary for the masses to move in a circle. If the rod were made of good steel, it would need a cross-sectional area substantially greater than that of a 1 ton sphere in order not to fail under the stresses in a device with the parameters we have assumed. So we'd have to reduce the rotation frequency to keep the generator from flying apart, with a consequent reduction in the transmitted wave amplitude.

3 Weber and the birth of gravitational wave detection

3.1 Weber's original vision

It is reasonable to ask the question whether even the astronomical signals are large enough to be detected by any conceivable device. On the face of it, the odds are daunting. A strain of 10^{-20}, for example, only generates relative motion of 10^{-20} meters between two test masses separated by one meter. Compare this with other characteristic length scales, and the challenge is clear: wavelength of visible light of 10^{-6} meter, atomic diameter of 10^{-10} meter, nuclear diameter of 10^{-15} meter. Nevertheless, it appears that gravitational wave signals from astronomical sources will probably soon be detected. It is the purpose of the rest of this review to show how this is possible.

There are at least two questions that might be raised by consideration of the numbers listed in the previous paragraph. The first is whether measurements of a macroscopic body can be capable of resolving motions substantially smaller than nuclear diameters. The second question that one might ask is whether success might be easier if the scale of the apparatus were made substantially larger than a meter, in order to take advantage of the fact that test masses separated by a larger distance will move by a proportionally larger amount in response to a gravitational wave of a given strength.Pondering the answers to these questions will lead to understanding of the most promising techniques for gravitational wave detection.

The postwar atmosphere of optimism about astronomical progressmust have swept up Joseph Weber in the late 1950s. Weber became convinced that the time was right to try to extend the astronomical revolution beyond the electromagnetic spectrum. At that time, it was not obvious that strain sensitivities of 10^{-22} should be the goal. It was equally plausible that objects such as we discussed above might possibly be abundant enough that their typical distance might be the few kpc associated with galactic dimensions instead of 200 Mpc. So strains of 10^{-17} or perhaps even stronger might have been the proper goal to aim for. (Weber knew of a very optimistic estimate of wave strength by Wheeler,[5] which would allow an energy density of order the cosmological closure density.) Weber's thinking showed the way to achieve such strain sensitivities; indeed, devices following directly in a line of development from his first instrument have in the past few years approached rms sensitivities of 10^{-19}, with the prospect of extension to a new generartion of detectors sensitive to waves with amplitudes of order 10^{-20} or better.

Weber's early thinking is described in his *Physical Review* article of 1960,[6] and placed in the larger context of his thinking about general relativity in a small monograph published in 1961.[7] He describes a conceptual detector, in reciprocal relationship to a gravitational wave emitter, as a simple "mass quadrupole", sketched as two masses connected by a spring. Weber extends the general relativistic equation of geodesic deviation to include the non-gravitational forces applied by the elastic restoring force and the mechanical dissipation in the spring. The equation of motion of the system then becomes that of a simple harmonic oscillator, with the driving term given by the effective force from the gravitational wave (our Eq. 7).

Weber next shows how an extended elastic body behaves in such a way that each of its normal modes of vibration can be studied independently. (The gravest mode of a cylinder has a large quadrupole moment, and is the one that is usually used for detection.) He focuses attention on the use of a piezoelectric crystal as the detecting body, partly because he hopes that the electric field will make it a detector with effective size larger than half an acoustic wavelength, but also in large measure because the electric fields generated by the gravitational-wave-induced stress will give an integrated voltage between its ends that may be "large enough to be observed with a low-noise radio receiver." Weber calculates the amount of mechanical power that a sinusoidal gravitational wave can dissipate in the resonant detector as a function of frequency, then invokes the standard electrical network theorems to show what fraction of this power can be transferred to the input impedance of an amplifier.

A simple discussion of sensitivity follows. Weber first remarks that "in microwave spectroscopy it has been found that all spurious effects other than random fluctuations can be recognized." Then Weber states that the excitation of the detector must exceed the noise power associated with its thermal excitation.

Finally, Weber discusses possible practical experimental arrangements. In most of the discussion the devices are supposed to be made of large blocks of piezoelectric material. But in a footnote Weber states that the experimental work he is carrying out with David Zipoy and Robert L. Forward will probably make use of a large block of metal instead. (This is justified on the grounds that a half-wavelength at the 1 kHz frequency being contemplated is already large; thus the piezoelectric length-enhancement effect may not be necessary, and in any case such a large block of piezoelectric material "may not be obtainable as a single crystal".)

Two experimental strategies are foreseen: use of a single detector with examination of its output for a diurnal cycle associated with the scanning of its sensitivity pattern across the sky, and the cross-correlation of a pair of detectors so that external influences (presumably gravitational waves) can be distinguished from "internal fluctuations". He notes the necessity of preventing the excitation of the detector by "earth vibrations", and discusses an "ingenious" idea of Zipoy's for what is now called active vibration isolation.

Weber's very concise discussion is remarkable for the prescience with which it forshadowed not only his own work, but that of so many others. It also marks a watershed in the history of general relativity. In a single blow, Weber wrested consideration of gravitational waves from theorists concerned about issues such as exact solutions, and appropriated the subject instead for experimentalists trained in issues of radio engineering. The boldness and brilliance of this move are remarkable.

3.2 The logic of Weber's idea

Weber sweeps quickly over a variety of issues that are worthy of more leisurely consideration. We'll give an overview of the important issues in this section, then devote the rest of this review to discussing their implications.

The detector Weber outlined can be divided into several subsystems: a set of test masses that respond to the gravitational wave, a transduction system that converts this mechanical response to a convenient electrical signal, a low-noise pre-amplifier, and post-amplification averaging and recording mechanism. Notwithstanding the cleverness of Weber's original version, many variations on his basic scheme are possible, and indeed are responsible for much of the progress since he first announced the results of gravitational wave observations in 1969.[8]

Let's see how to analyze the original Weber design into these canonical subsystems. Weber explicitly pointed out how one could construct an analog of a pair of lumped test masses by monitoring an internal mode of vibration of an extended block of elastic material. In the version where this block is made of piezoelectric material, the same material serves both as test masses and as transducer from mechanical to electrical signal form. In the version in Weber's footnote (the one he actually built) a large aluminum cylinder serves as the set of test masses; piezoelectric strain gauges glued about the girth of the cylinder perform the transduction. The pre-amplifier is Weber's low-noise radio receiver. No averaging filter is shown in Weber's diagrams, but is implicit in his discussion.

Perhaps the most interesting choice that Weber made was to connect his test masses in a resonant system. It appears that Weber, at least in 1961, thought this was a necessity. In a footnote, he cites previous work by Pirani[9] in which the latter considered "measurement of the Riemann tensor by comparing accelerations of free test particles", but Weber continues, "The results of this chapter indicate that interacting particles must be used, in practice." In fact, it is not required either in principle or in practice, but it is interesting to consider why Weber may have thought so then, and what advantages still accrue to the use of resonant masses.

Weber couches a good deal of his discussion in terms of steady sinusoidal signals, still a common practice in much of engineering and even more so around 1960. If a gravitational wave did have this form, then masses connected by a spring give a resonant amplification of the response to a signal at the resonant frequency. The amount of this amplification is given by the resonator's quality factor Q, and can be substantial; Weber quotes an estimated $Q \sim 10^6$, still not a bad ballpark number.

On the other hand, there is essentially no resonant amplification if one has a sinusoidal signal whose frequency does not closely match the resonant frequency of the detector, or if the signal has a broad-band frequency content, as it would if it were a brief burst. Resonant amplification only comes about when the input force drives the resonant system with the proper phase for a substantial number of cycles; this can only occur when there is a good match between the signal frequency and the mechanical resonant frequency.

But even though the search for gravitational waves has come to focus mostly on burst-like signals, the resonant-mass configuration can still give a powerful advantage, albeit one not discussed by Weber in his 1961 book. A weak signal must compete for visibility against the noise in the pre-amplifier stage. This is why Weber made a point of calling for the lowest noise levels possible in this component. The noise in such amplifiers is generally of a broad-band character, best characterized by its power spectral density $S_v(f)$ which is typically roughly constant (or "white") over a wide range of frequencies. Usually there is an additional $1/f$ component that dominates at low frequencies.

The extent to which this noise competes with a signal depends in an essential way on the duration of the signal. We use the term "burst" to refer to a signal of limited duration in time; call its length τ_s. A fundamental theorem of signal detection states that the optimum contrast between a given signal and white noise can be attained when the time series containing the noise plus any possible signals is convolved with a template of the same form as the signal. This is called the *matched filter* when it is implemented in real time by an analog device. The heuristic idea behind such an optimum is that the matched filter rejects all components of the noise that do not “look like” the signal for which one is searching. Still, some noise passes through the matched filter. How much? If the Fourier transform of the signal waveform $v(t)$ is given by $V(f)$, then it passes noise power of

$$N^2 = \int_{-\infty}^{\infty} |V(f)|^2 S_v(f) df.$$

Another very general theorem of Fourier analysis takes the form of a classical “uncertainty relation”. It states that there is an inverse relationship between the duration of a signal in the time domain and its width in the frequency domain:

$$\Delta f \Delta\tau \approx 1.$$

See what this implies for the question at hand. If we are looking for a brief signal, then its matched filter passes noise of a wide bandwidth. Thus, brief signals compete much less well against broad-band pre-amplifier noise than does a long-duration signal of the same amplitude.

Here is where a resonant detector of gravitational waves can make a difference even when one is looking for a broad-band signal. If the gravitational wave signal $h(t)$ contains substantial power in the vicinity of the detector’s resonant frequency, then it will excite the motion of the detector’s mode at an amplitude $\Delta L \sim hL$, not much different than if the test masses were free. But the subsequent behavior of the resonant detector is quite different than if the detector were made of free masses. The motions of free test masses only persist for the duration τ_s of the gravitational wave signal. But the resonant detector “rings” for a time of order the damping time of the resonance,

$$\tau_d = \frac{Q}{\pi f_0} \gg \tau_s,$$

where f_0 is the resonant frequency of the detector.

It is the motion of this resonant system, converted to electrical form by the transducer, that is presented to the input terminals of the pre-amplifier. So it is an electrical signal of long duration τ_d that competes with the amplifier noise. As a long duration deterministic signal, its matched filter has a much narrower width in frequency than had the original signal $h(t)$, and so passes a much smaller proportion of the amplifier noise. Thus, the resonant response of the test mass system allows a weak signal to compete more effectively against amplifier noise than would be the case with free masses.

3.3 The cost of resonant detection

This advantage of resonant-mass detectors is substantial; it is responsible for the continued vitality of the Weber style of detector over thirty years after it was first proposed. Still, it comes with a price that is not negligible. Implementing the matched filter described above, which is essential to attaining the advantage of the resonance, is tantamount to averaging the output of the amplifier for times of order τ_d. In the jargon of the field, such a system has a low *post-detection bandwidth* (usually shortened simply to "bandwidth".) The averaging washes out any details of the waveform $h(t)$ on time scales short compared to τ_d. What one gains in signal-to-noise ratio, one gives up in temporal resolution. Whether this is a price one ought to be willing to pay or not depends on the stakes: if it is absolutely necessary even to detect the signal, averaging with a matched filter is certainly worthwhile. If the signal could be detected anyway, averaging simply throws away information, and should be avoided. In the high signal-to-noise case, the resonance does not help, but neither does it hurt much either – a simple filtering operation could remove the resonant signature and allow reconstruction of the original signal waveform.

(N.B.: As we will show below, the actual choice of matched filter for a resonant detector is more subtle than that just described. Instead of τ_d, a shorter averaging time is almost always the optimum choice. Nevertheless, the qualitative thrust of the argument given in the previous paragraph still applies.)

3.4 Free-mass detectors as an alternative

Given the trade-off between sensitivity and bandwidth that resonant systems tempt one to make, it is worth exploring whether there are other entirely non-resonant detection schemes that can achieve high sensitivity to gravitational waves without sacrificing signal bandwidth. In fact, such free-mass detectors have been developed by a variety of workers, including the same Robert Forward who worked with Weber on the original resonant detector.[10,11] The essential advantage of free-mass detectors comes from the fact that the farther apart their test masses are placed, the larger is the relative displacement between them caused by a given gravitational wave amplitude $h(t)$. (This scaling relation holds true up to the point that the light travel time between the masses becomes comparable to the period of the wave, that is when separation of the masses becomes comparable to the wavelength of the wave.) But the resonance in a resonant detector comes roughly when the sound travel time across the bar matches the period of the wave. That is to say, resonant detectors reach their optimum sensitivity when the separation of the test masses is of order the acoustic wavelength at the gravitational wave frequency. Since the speed of sound in materials is of order 10^{-5} of the speed of light, a free-mass detector at its optimum length can have an advantage in signal size of 10^5 over a resonant-mass detector at its optimum length.

Another advantage is that no resonance is used to boost the signal. Thus, in principle a free-mass detector can have a completely white frequency response. This ideal can not be completely achieved in practice, since some of the noise sources discussed below have strong frequency dependences of their own. Still, it is possible to achieve useful bandwidths measured in decades rather than in fractions of an octave.

This signal size advantage would be a hollow one if there were no sensitive way to measure the relative displacement of test masses separated by many kilometers. Fortunately, there are such ways. As we saw above, the travel time of electromagnetic signals between the test masses can be measured with great precision. Interferometry using visible or near-infrared light to measure the separation of free masses has become a well developed technology that now is completely competitive with the best resonant-mass detectors, and which is about to undergo a great leap in sensitivity as new instruments of multi-kilometer scale come on line in the next couple of years. Radio ranging between interplanetary space probes separated by many millions of kilometers has been used for some time; optical interferometers in solar orbit, with million kilometer baselines, are now being planned.

The conceptually simpler free-mass detectors are in practice substantially more complicated devices; the freedom of the test masses must be tamed by servo systems to keep them operating properly. This is in part what is responsible for the time lag in their development, even though they were conceived not much later than resonant-mass detectors. In the remainder of the review, we will discuss both styles of gravitational wave detector.

6 History of interferometers

6.1 The work of Gertsenshtein and Pustovoit

Almost as soon as Weber had begun work on the first gravitational wave detector or the resonant-mass style, the idea arose to use interferometry to sense the motions induced by a gravitational wave. Weber and a student, Robert Forward, considered the idea in 1964.[10] We will discuss below how Forward later went about implementing the idea. But the first discussion of the idea is actually due to two Soviet physicists, M.E.

Gertsenshtein and V.I. Pustovoit. They wrote in 1962[57] a criticism of Weber's 1960 *Physical Review* article, claiming (incorrectly) that resonant gravitational wave detectors would be very insensitive. Then, they make a remarkable statement justified only by intuition, that "Since the reception of gravitational waves is a relativistic effect, one should expect that the use of an ultrarelativistic body — light — can lead to a more effective indication of the field of the gravitational wave."

Gertsenshtein and Pustovoit followed up this imaginative leap by noting that a Michelson interferometer has the appropriate symmetry to be sensitive to the strain pattern produced by gravitational waves. They give a simple and clear derivation of the arm length difference caused by a wave of amplitude h. Next, they note that L.L. Bernshtein had with ordinary light measured a path length differences of 10^{-11} cm in a 1 sec integration time. The newly invented laser, they claim, would "make it possible to decrease this factor by at least three orders of magnitude." (The concept of shot noise never appears explicitly here, so it is not clear what power levels are being anticipated.) They assume that one might make an interferometer with arm length of 10 m, thus leading to a sensitivity estimate of $10^{-14}/\sqrt{\mathrm{Hz}}$ for "ordinary" light, or as good as $10^{-17}/\sqrt{\mathrm{Hz}}$ for a laser-illuminated interferometer. This, Gertsenshtein and Pustovoit claim, is 10^7 to 10^{10} times better (it isn't clear whether they mean in amplitude or in power) than what would be possible with Weber-style detector. Putting aside their unjustified pessimism about resonant-mass detectors, their arguments about interferometric sensing are right on the mark, even conservative.

For improvements beyond the quoted level, they make suggestions that are somewhat misguided. They say that observation time could be lengthened beyond 1 sec, which would be obvious for some sources (such as "monochromatic sinusoidal signals" or signals of long period) and hopeless for short bursts. Their other suggestion is to use "known methods for the separation of a weak signal from the noise background"; this suggestion is curious because known methods appear to be already built into their estimates that are referenced to a specific observing time. The other lack that is obvious in hindsight is any mention of mechanical noise sources. Still, the gist of the idea of interferometric detection of gravitational waves is clearly present, as is a demonstration that the idea can have interesting sensitivity.

6.2 The origins of today's interferometric detectors

For a variety of reasons, not least of which must have been the fact that it was written too early (before Weber's work had progressed beyond design studies), the proposal of Gertsenshtein and Pustovoit had little influence. The activity that began the by-now flourishing field of interferometric gravitational wave detection started independently in the West. In fact, it began semi-independently at several places in the United States at around the same time. The roots of this work can be seen in a pair of papers, written in 1971-2, by two teams linked in an unusual collaboration that is acknowledged in the bodies of the papers, although not in the author lists. The first to be published was that of the Hughes Research Lab team, whose most committed member was Robert L. Forward, the former Weber student mentioned above. Later to appear, and not in a refereed journal, was the work of Rainer Weiss, an MIT physicist who had spent an influential postdoctoral stint with Robert H. Dicke at Princeton. Linking the two groups was someone who never published anything on the subject under his own name, but whose activity is mentioned in both papers — Philip K. Chapman, who had earned a doctorate in Instrumentation at MIT's Department of Aeronautics and Astronautics before joining NASA as a scientist-astronaut.

6.2.1 Interferometer studies at Hughes Research Lab

An account of the idea for an interferometric detector of gravitational waves, and of the performance of an early-model prototype, is found in the 1971 paper of Moss, Miller, and Forward.[10] The authors cite a program to develop "long wideband" gravitational wave detectors that had started at Hughes in 1966, around the time of Weber's first account of a working resonant detector. The motivations for a wideband detector were 1) to allow detailed meaurement of waveforms which would in turn give insight into the nature of the sources, 2) "to allow the phasing of spaced antennas to form a phased array" (in other words to allow good temporal resolution so that the direction of the wave can be determined by arrival time differences), and 3) to allow matched filters to be used to optimize the signal to noise ratio of a complex waveform "in addition to the use of standard narrowband frequency filtering for sinusoidal signals, which is the natural filtering action of a resonant antenna." The motivation for the use of a long detector is the larger test mass displacement, which, all else being equal, should directly translate into improved signal to noise ratio.

The authors credit the original idea for this way to achieve a long wideband detector to P.K. Chapman, and go on to state that "Our work has benefited from many discussions with Dr. Chapman as well as R. Weiss, who is involved in the design and construction of his own design at MIT."

The interferometer described by Moss *et al.* was "constructed to set experimental limits on the various noise sources in the laser transducer." It is a classic one-bounce Michelson interferometer, in which both output beams are detected "in a balanced bridge to reduce sensitivity to laser amplitude noise." The operating point for this arrangement was equal photocurrents from the photodetectors at the two output ports of the interferometer. (This is to be distinguished from the use of a photodetector at a single output port of the interferometer that is dithered about the dark fringe. See our discussion of this alternative below.) The interferometer is to be held at this balanced operating point by "slowly acting servo loops ... so that the effects of laser amplitude and phase noise are minimized." The flat mirrors were rigidly mounted to an optical table, which was in turn supported on air-filled rubber tubes to give a resonant frequency of 2 Hz. (Other isolation schemes for the rigid interferometer were tried without success, causing the authors to lament that "vibration isolation is still an art rather than a science.") One of the mirrors was mounted on piezoelectric elements, which provided control of the operating point as well as a means of calibration.

The main result presented in the paper is the noise level that was achieved in this prototype interferometer, equivalent to a mirror displacement sensitivity of 1.3×10^{-14} m/$\sqrt{\mathrm{Hz}}$ at a signal frequency of 5 kHz. This was about a factor of $\sqrt{2}$ larger than the calculated shot noise sensitivity, which the authors state is consistent with other indications that "the sensitivity limits were set by acoustic and ground noise." This noise level was "to date ... the smallest vibrational displacement directly measured with a laser". No translation of the sensitivity into strain units was given, either directly or by specification of the arm length. This is perhaps appropriate, since the rigid mirror mounts made this test instrument ill-suited for actually searching for gravitational waves.

The last section of the paper lists the improvements intended to follow this initial work. Firstly, a more powerful laser was proposed; at the then impressive power level of 75 mW, the displacement sensitivity due to shot noise would be "close to that obtained in the present resonant antennas" that were at the date of writing appearing to give significant detections. A final paragraph listed the other proposed improvements: mirrors attached to masses that were large (to reduce thermal noise) and independently suspended from vibration isolation mounts, placed in a vacuum system whose initial length of several meters could be extended "to several kilometers by adding additional evacuated tubes." This section can be read as a telegraphic summary of the plans described at greater length by Weiss in his report written the following year.

6.2.2 The vision of Rainer Weiss

The other paper that gave birth to the massive worldwide effort to detect gravitational waves using interferometers, Rainer Weiss' 1972 "Electromagnetically Coupled Broadband Gravitational Antenna", appeared only as an unpublished research progress report of the organization at MIT that administered the umbrella research grant supporting his work.[11] Weber's claimed detection of gravitational waves was very much on Weiss' mind in 1972, reported as possibly correct but with the recognition that the energy flux the waves appeared to carry would dominate the luminosity of the Galaxy. Weiss states that he had been inspired by a 1956 paper by F.A.E. Pirani (that discussed the identification of measurable quantities in general relativity)[9] to consider the possibility that measurements of the light travel time between freely-falling test masses would make the best probes of spacetime structure. He further states that he had realized several years prior to writing (while teaching an undergraduate seminar) that the newly developed lasers could turn Pirani's *gedanken* experiment into a practical measurement strategy. Weiss also notes that the idea "has been independently discovered by Dr. Philip Chapman of the National Aeronautics and Space Administration, Houston."

Many of the ideas that appear in the breathless final paragraph of Moss *et al.* are elaborated at substantially greater length in Weiss' report, which should be considered the first serious design study of the concept of interferometric gravitational wave detection. After the review of Weber's claims, Weiss continues with a clear summary of the physical meaning of gravitational waves in general relativity, and an examination of the possible strength of gravitational waves from the then newly discovered pulsars. He then gives a summary of the key ideas of the proposed system:

- a Michelson interferometer used as a sensor of "differential strain induced in the arms",
- operated "on a fixed fringe by a servo system" in a modulated system very much in the tradition of Dicke's improved Eötvös experiment[58]
- "mirrors and beam splitter mounted on horizontal seismometer suspensions" that "must have resonant frequencies far below the frequencies in the gravitational wave" and "a high Q"

- arms that “can be made as large as is consistent with the condition that the travel time of light in the arm is less than one-half the period of the gravitational wave”, in part by being arranged as “optical delay lines”of the style described by Herriott.

Weiss is quite clear about the advantage that accrues from the last point. He says

> This points out the principal feature of electromagnetically coupled antennas relative to acoustically coupled ones such as bars; that an electromagnetic antenna can be longer than its acoustic counterpart in the ratio of the speed of light to the speed of sound in materials, a factor of 10^5. Since it is not the strain but rather the differential displacement that is measured in these gravitational antennas, the proposed antenna can offer a distinct advantage in sensitivity relative to detecting both broadband and single-frequency gravitational radiation. A significant improvement in thermal noise can also be realized.

This last sentence points out one of the key insights of this report, expanded upon at much greater length in the remainder of the text. As a sensitive mechanical measurement, the interferometric detection of gravitational waves is prey to a host of mechanical noise sources whose strengths need to be minimized if success is to be achieved. By far the largest section of the paper is devoted to estimates of the magnitudes of a long list of noise sources of various kinds. They include: amplitude noise in the laser (the only place where the work of the Hughes group is cited, as an example of a shot noise limited measurement), phase noise in the laser, mechanical thermal noise, radiation pressure noise, seismic noise, thermal gradient (“radiometer effect”) noise, cosmic ray impacts, “gravitational-gradient” noise, and fluctuating forces from electric and magnetic fields. This looks almost (with a few omissions) like the list of noise sources that contemporary workers are grappling with as they strive to make the new kilometer scale interferometers work; by contrast, the other earlier treatments of the subject look myopic and unbalanced. And this insight is what led to the recognition that interferometers of the greatest practical length, with the resulting dilution of displacement noise terms as compared with a strain signal, would be the way to achieve the promise of good gravitational wave sensitivity, and would be worth the substantial investments needed to build them.

6.7 Designs for kilometer-class interferometers

As noted above, laboratory work on interferometers was almost from the beginning considered an engineering exercise preparatory to the construction of instruments with arms of kilometer scale. With several such devices now under construction, it is worth reviewing their distinctive features. Here, even more so than for the other cases we have been discussing, the refereed literature is a poor source of information, and so are conference proceedings. For most projects the only detailed descriptions are those contained in funding proposals. (The one redeeming feature of this form of publication is that, since the reviewers of such documents were typically not expected to be experts in the field, they contain an abundance of carefully written tutorial material, and well-reasoned justifications for most design choices.)

The three largest approved projects today, (LIGO,[72] VIRGO,[73] and GEO[74]) all went through similar parallel processes of design study, proposal, and now construction. This was a fruitful period, with a rich interchange of ideas. For pedagogical purposes, we choose to focus in this review on a single line of development, that of the U.S. LIGO Project.

6.7.1 The "Blue Book"

In almost the same sense as the early table-top interferometers were prototypes of larger instruments, so too did the proposals for kilometer-scale interferometers have a prototype. This was the report called "A Study of a Long Baseline Gravitational Wave Antenna System", submitted to the U.S. National Science Foundation in October 1983.[75] (It has since its presentation been called the "Blue Book" because of the color of the cheap paper cover in which it was bound.) It was prepared primarily by Weiss and two colleagues at MIT (Paul S. Linsay and the present author), as the product of a planning exercise funded by the NSF starting in 1981. The report also contained a section by Stan Whitcomb of Caltech on Fabry-Perot systems (as a partial counter to Weiss' emphasis on Herriott delay lines), as well as extensive sections written by industrial consultants from Stone & Webster Engineering Corporation and from Arthur D. Little, Inc. These latter contributors were essential, because this document contains, for the first time anywhere, an extensive discussion of the engineering details specific to the problems of the construction and siting of a large interferometer. The report was presented, by both Weiss' MIT group and that of Drever at Caltech, at a meeting of the NSF's Advisory Council for Physics late in 1983. While not a formal proposal, it served as a sort of "white paper", suggesting the directions that subsequent proposals might (and in large measure did) take.

The first half of the report is devoted to the physics of gravitational wave interferometers. This section reads much like Weiss' 1972 design study, except that many issues only touched on briefly in the first paper are here discussed at substantially greater length. In the eleven years that elapsed between the two documents there had been real progress on several fronts. There are chapters on sources of gravitational waves, the basic physics of the response of a free-mass interferometer to a gravitational wave, a discussion of beam-folding schemes and a summary of the current prototype interferometers, and another extensive discussion of noise sources. The report is bracketed by an introductory section outlining a history of the field to 1983 and by a pair of appendices, one of which compares the quantum limits of bars and interferometers and the other showing why the interferometer beams must travel through an evacuated space instead of through optical fibers.

The main emphasis of the Blue Book was less a discussion of physics *per se* than it was a consideration of the practical aspects of the experiment as an engineering and construction project. The completely new material appears in the second half of the Blue Book, in the chapters summarizing the work of the industrial consultants. Weiss believed that the only significant impediment to achieving astrophysically interesting sensitivity was the expense of building an interferometer with long arms (the issue that had brought the Hughes group's progress to a halt.) The industrial study was undertaken with the aim of identifying what design trade-offs would allow for a large system to be built at minimum cost, and to establish a rough estimate of that cost (along with cost scaling laws) so that the NSF could consider whether it might be feasible to proceed with a full-scale project.

Before such an engineering exercise could be meaningful, though, it was necessary to define what was meant by "full-scale". The Blue Book approaches this question by first modeling the total noise budget as a function of frequency, then evaluating the model as a function of arm lengths ranging from 50 meters (not much longer than the Caltech prototype) to 50 km. The design space embodied in this model was then explored in a process guided by three principles:

- "The antenna should not be so small that the fundamental limits of performance can not be attained with realistic estimates of technical capability." This was taken to mean that the length ought to be long enough that one could achieve shot noise limited performance for laser power of 100 W, without being limited instead by displacement noise sources, over a band of interesting frequencies. The length resulting from this criterion strongly depended on whether one took that band to begin around 1 kHz (in which case $L = 500$ m was adequate), 100 Hz (where $L = 5$ km was only approaching the required length), or lower still (in which case even $L = 50$ km would not suffice.) Evidently, this strictly physics-based criterion was too elastic to be definitive.
- "The scale of the system should be large enough so that further improvement of the performance by a significant factor requires cost increments by a substantial factor." In other words, the system should be long enough so that the cost is not dominated by the length-independent costs of the remote installation.
- "Within reason no choice in external parameters of the present antenna design

should preclude future internal design changes which, with advances in technology, will substantially improve performance." This was a justification for investing in a large-diameter beam tube, and for making sure that the vacuum system could achieve pressures as low as 10^{-8} torr.

In an iterative process, rough application of these principles was used to set the scope of options explored by the industrial consultants. Then at the end of the process, the principles were used again to select a preferred design. Arm lengths as long as 10 km were explored, and tube diameters as large as 48 inches. An extensive site survey was also carried out by the consultants. It was aimed at establishing that sites existed that were suitable for a trenched installation (which put stringent requirements on flatness of the ground) of a 5 km interferometer. The survey covered Federal land across the United States, and a study of maps of all land in the Northeastern United States, along with North Carolina, Colorado, and Nebraska. Thirteen "suitable" sites were identified. Evaluation criteria also included land use (specifically that the site not be crossed by roads, railroads, or oil and gas pipelines), earthquake risk, drainage, and accessibility.

The site survey also attempted to identify possibilities of locating an interferometer in a subsurface mine, which would give a more stable thermal environment and perhaps also reduced seismic noise (if it were located deep enough, and if it were inactive.) No mines were found in the United States with two straight orthogonal tunnels even 2 km in length.

The conclusion of the exercise was a "proposed design" with the following features:

- Two interferometer installations separated by "continental" distances.
- Interferometer arm length of $L = 5$ km.
- Beam tubes of 48 inch diameter made of aluminum (chosen for an expected cost savings over stainless steel) pumped by a combination of Roots-blowers for roughing and ion-pumps for achieving and maintaining the high vacuum. A delay line interferometer would require a diameter of almost the proposed size. Drever's beam-interchange scheme for improved narrow-band sensitivity was also listed as one justification for preferring large tubes, as was the possibility of multiple interferometers (presumably based on Fabry-Perot cavities) side by side.
- The proposed installation method was to enclose the tube in a 7' by 12' cover constructed of a "multi-plate pipe-arch", in turn installed 4 feet below grade in a trench that was subsequently back-filled with soil.

The total estimated cost for such a system was given as $58M.

Note that there were no specific recommendations for the design of the interferometers themselves, beyond the "straw man" used for estimating the noise budget.

The Blue Book was received respectfully by the NSF's Advisory Committee for Physics. As a result, the MIT and Caltech research groups were encouraged to combine their forces to develop a complete specific design. Subsequently, both groups received funding with the eventual goal of a joint proposal for construction of a large interferometer system.

6.7.2 The LIGO proposal of December 1987

By 1987, substantial progress had been made on lab-scale interferometers by research groups around the world. And, encouraged by the NSF's reception of the Blue Book, more thinking had gone into the best way to construct and exploit large interferometers. Much of this progress is evident in the proposal submitted to the U.S. National Science Foundation in December of 1987 by a formal Caltech-MIT collaboration that had adopted the name of LIGO, for Laser Interferometer Gravitational wave Observatory.[76] Since September 1987 it had been led by Rochus E. ("Robbie") Vogt as Project Director, with Drever and Weiss as science team leaders. The proposal requested funds for a three-year program of R&D and engineering studies, the outcome of which was intended to be another proposal (to be submitted in 1989) requesting authorization to build a pair of 4 km long interferometers.

Prototype interferometers were functioning at respectable sensitivities, after years of assembly, debugging, analysis, and redesign. The Caltech 40-meter interferometer was the showpiece of the proposal. It employed high-finesse Fabry-Perot cavities, arranged in the simplified non-recombined configuration for ease of testing. An impressive graph shows the improvement in strain sensitivity since its first operation in May 1983, by a factor of over 10^3 in amplitude. In that interval, ultra-low loss "supermirrors" were installed, first on an early optical-bench style of test mass and then on separated compact test masses (eventually ones made of fused silica), and a variety of improvements were made to the Argon laser and to the locking servos. The noise spectrum above 1 kHz was nearly white, with a level of $h(f) \approx 2 \times 10^{-19}/\sqrt{\mathrm{Hz}}$. This was consistent with the expected level of shot noise.

Results were also presented from the table-top (1.5 meter arm length) prototype interferometer at MIT. It employed Herriott delay lines of 56 bounces between conventional high quality mirrors that were clamped to aluminum test masses. Unlike the Caltech instrument which could not function without sophisticated frequency stabilization of its laser, MIT used an unstabilized Argon laser to which phase noise was actually added to help suppress scattered light. Pointing, damping, and slow feedback were accomplished with electrostatic actuators. Strain sensitivity could of course not compete with the much longer Caltech instrument, but even the displacement noise was nearly an order of magnitude worse, given as 4.6×10^{-17} m/$\sqrt{\mathrm{Hz}}$, for frequencies above 4 kHz. That level was a factor of 2 in excess of the expected shot noise in the 60 mW of light, diagnosed as insufficiently suppressed noise from scattered light. At lower frequencies acoustic noise drove the interferometer via a variety of coupling paths through the injection optics as well as the test mass suspensions.

The proposal records substantial progress toward design of a full-scale interferometer. It states that the collaboration had adopted the Fabry-Perot beam-folding system. A preliminary design is presented in an appendix of the proposal. It envisioned use of 5 to 6 W of light at 514 nm from an Argon laser employed in a power recycled configuration. An elaborate schematic diagram gave a hint of the complexity of the servos necessary to control the large number degrees of freedom that need to be kept locked for such an instrument to function. These include lengths of the arm cavities, the separation of their input mirrors from the beam splitter, the location of the power recycling mirror, and the lengths of various “mode cleaning” resonant cavities used for spatial filtering of the laser beam. In addition to these lengths, control of a number of angular degrees of freedom also needs to be included. Four separate RF modulation frequencies are specified to drive these servos. Special features are designed into the main cavity locking servo so that the phase modulation can be injected with a small Pockels cell without the inevitable losses dominating the performance of the recycling system.

Another appendix describes an alternate optical configuration based on Herriott delay lines. It employed 86 cm diameter silicon test masses of 450 kg. The simplicity of the servos was listed as one of its major advantages. A “closed-path” variation of this design was also presented, in which light leaving one arm is injected into the other. This is like a single-interchange version of Drever’s system for improving sensitivity to periodic waves. Here it was employed mainly to relax the tolerances on matching the curvature of the large mirrors. (The virtues of this design have recently been explored again by the Stanford group.[77])

On the engineering and site issues there had also been some progress since the Blue

Book study, mostly made by engineers at Caltech's Jet Propulsion Laboratory, but this was not considered complete enough to highlight in the proposal. Instead, one of the first proposed tasks was to complete a preliminary engineering design. Nevertheless, a mature understanding had been achieved of what LIGO ought to *be*. This insight was expressed in a list of "Essential Features of the LIGO":

1. "Two widely separated sites under common management." Two sites had been a feature of Weiss' earliest thinking, to allow coincidence observations to search for transient signals. The new feature was the commitment to truly have them managed as a single entity, "to guarantee that two receivers of nearly equal sensitivity are on line simultaneously at two sites, with a high live time."

2. "Arm lengths of order 4 kilometers at each site," a slight scaling back of the 5 km considered previously, but still long enough to strongly dilute the effects of displacement noise.

3. "The ability to operate simultaneously several receiver systems at each site." In a way, this was the most ambitious feature of the LIGO concept. In part it grew out of a kind of conservatism that was not clearly spelled out, but that was nevertheless real. The early LIGO interferometers, if they were not to be extremely risky extrapolations from known technology, were unlikely to have sufficient sensitivity to be assured of detecting astrophysical signals. Even if that weren't so, the project would have had to wrestle with the competition between time devoted to observation and time devoted to improving the performance of the instrument. This competition had bedeviled workers on resonant-mass detectors. The key new idea for LIGO was that the precious commodity, an evacuated beam pipe, might be available with abundant cross-sectional area since the Fabry-Perot geometry had been adopted. All that was required was an arrangement of tanks at the ends of the pipe to install the test masses of various interferometers, both operational and experimental. This actually called for substantial cleverness in developing an airlock system, so that installation and operation could take place with "a minimum of mutual interference".

4. "The capability for receivers of two different arm lengths." Drever urged the adoption of this feature, to allow a clean test of the gravitational origin of candidate signals, which should show up as the tidal signature that a longer interferometer sees twice the signal.

5. "A vacuum tube diameter of order 48 inches." This had the conservative justifica-

tion that it would be necessary if one had to switch from Fabry-Perot cavities to delay lines, and the great benefit of allowing multiple Fabry-Perot interferometers, as mentioned above.

6. "The capability of a vacuum level of 10^{-8} torr." This would be needed, not for the first LIGO instrument, but to avoid having fluctuations in the index of refraction of the residual gas dominate shot noise in a more sensitive "advanced" receiver.
7. "A minimum lifetime of the facilities of 20 years." This was to be not just a one-shot discovery experiment, but a laboratory to exploit the gravitational wave window in astronomy.
8. "Adequate support instrumentation."

The heritage of the Blue Book should be evident in the above list, but so too should be the progress in thinking beyond that point.

Because of a Federal budget crisis, this proposal was not funded. However, the two groups were encouraged to continue their work, and to submit a more complete proposal in a subsequent year.

6.7.3 The LIGO proposal of December 1989

Many of the features only hinted out in the 1987 proposal are spelled out in much greater detail in the proposal for engineering design and construction of LIGO (now with a hyphen in Laser Interferometer Gravitational-Wave Observatory) that was submitted to the NSF in December 1989.[78] It fleshes out the design of a system that would embody the eight Essential Features of LIGO first described in the 1987 proposal. (The only differences are that the vacuum tube diameter is now specified as a "clear optical diameter of approximately 1 meter", and the vacuum spec is given as "10^{-9} torr of hydrogen and 10^{-10} of other gases.")

A single detector system would require three interferometers — a 4 km interferometer at each of two widely separated remote sites, plus a 2 km interferometer at one of the sites. This shorter interferometer played two related roles: a check that a candidate signal had the tidal signature of a gravitational wave, and the simpler but crucial requirement that a real signal should appear in all three interferometers. A calculation presented here shows that an accidental event rate of around 100/hour/interferometer can be tolerated without accidental 3-way coincidences occurring more frequently than once in ten years, an improvement of about two orders of magnitude over what could be tolerated with only a single interferometer at each site.

The features described above are part of a plan that is aimed at accomplishing “three primary objectives”:

- “observation”, or a continuous “gravitational-wave watch”,
- “development”, or “full functional testing of new and advanced interferometer-based detector concepts”, and
- “special investigations” using detectors optimized for “particular phenomena”.

These missions are “to be conducted without mutual interference.”

It would take a substantial investment (of money, ideas, and energy of scientists) to accomplish all of these goals, and so for this reason full implementation of this strategy was to be accomplished in a series of phases.

- “Phase A, The Exploration/Discovery Phase”, with one three-interferometer detector system, suitable for observation or development, but not both simultaneously.
- “Phase B, The Discovery/Observation Phase”, with two three-interferometer detector systems, allowing “concurrent observation *and* development or specialized search.”
- “Phase C, The Observatory Phase”, room for three full detector systems, “allows concurrent observation, development, special investigations, and optimal access for the scientific community at large. It completes the LIGO evolution to its presently conceived full-design capability.”

Because of the cost involved in elaborate vacuum chambers with airlocks, the 1989 proposal asked only for the funds to complete Phase A. The single important investment in the capability to upgrade to Phases B and C was the design of buildings large enough to accomodate all of the vacuum tanks that would be eventually required.

It should be emphasized that, to a large degree, this agressive planning for an elaborate facility was a necessary consequence of a simple fact — that it looked difficult to build an interferometer that would have sufficient sensitivity to assure detection of gravitational waves. Hence the need to plan for ongoing interferometer development and specially optimized instruments. Of course, these activities would also be useful even if some signals proved easier to detect than expected, since carrying out gravitational wave astronomy would call for the highest achievable signal to noise ratios. For example, angular position errors are inversely proportional to the signal to noise ratio, and are as large as 10 arcmin or more when the SNR= 10, even when observations are made with a three-detector U.S.-Europe network.

The 1989 proposal is much more explicit about the details of the design of the first interferometer. The design is based on the Fabry-Perot interferometer of the 1987 proposal's appendix. It has been fleshed out with specifications of laser power, finesse, test mass parameters and vibration isolation performance, so that a specific noise budget could be presented. The 1989 proposal also contains a preliminary discussion of what sorts of improvements would be necessary to push the noise to levels low enough to guarantee detection of signals. This includes laser power of 60 W recycled by a factor of 100, a much more aggressive vibration isolation system, and final pendulum suspensions with a quality factor of 10^9 carrying 1-ton fused silica mirrors.

6.7.4 The situation today

Construction of LIGO was approved in 1991. By mid-1998 (the time of the writing of this review), construction of the two facilities in Hanford WA and Livingston LA was over three-quarters complete. The schedule calls for construction to be completed soon. Roughly speaking, 1999 is to be devoted to installation of the scientific equipment in the completed facilities, 2000 to shakedown of the interferometers, and 2001 to engineering activities to bring the performance up to the design specifications. Then, data will be collected during 2002-3. Beginning in 2004, upgrades to improve the performance will be carried out, interspersed with additional periods of observation.

The first instrument to be installed is expected to have a noise spectrum like that shown in Figure 4. The high frequency noise spectrum should be dominated by shot noise, as determined from an input power of 6 W, multiplied by a power recycling gain of 30. Thermal noise from the 1 Hz pendulum mode will dominate the intermediate frequency band; the oscillations of the 10 kg test masses should achieve a quality factor of 1.6×10^5. (Internal thermal noise will dominate the spectrum only in a narrow band, due to test mass modal quality factors of about 10^6.) Low frequency noise will be governed of course by seismic noise that passes through the multi-layer stack.

Performance of the VIRGO 3 km interferometer will be similar at medium and high frequencies. At low frequencies, seismic noise should be much lower in VIRGO than in LIGO, since a much more aggresive filter has been designed. This should allow the noise to be dominated by pendulum thermal noise down to 10 Hz or a bit lower.

The GEO 600 meter interferometer is not expected to reach quite such low levels,

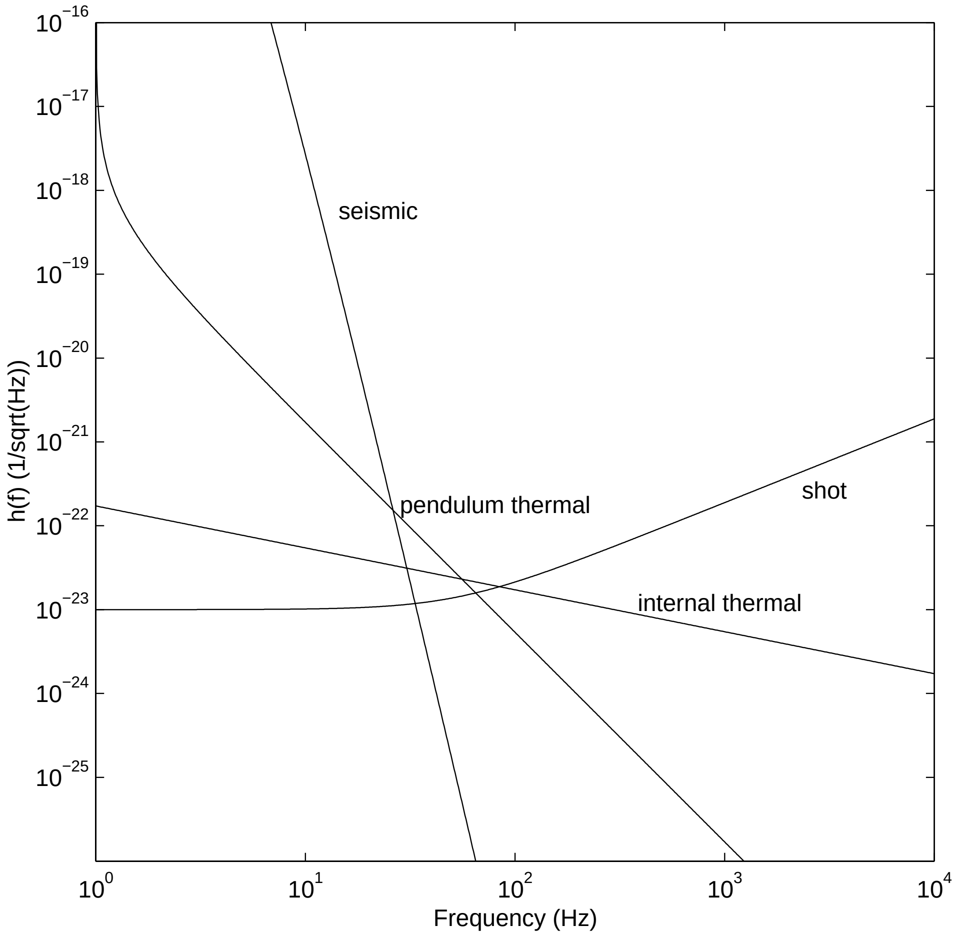

Fig. 4. An estimate of the noise spectrum of the LIGO I interferometers. The four most important noise sources are shown: seismic noise, pendulum mode thermal noise, thermal noise of internal vibrations of the mirror, and shot noise.

but it will be surprisingly close. To make up for the shorter length, advanced technologies (including signal recycling) will be pursued aggressively from an early date. Thus this instrument will play a dual role as part of the global network of interferometers and as a prototype for features that will later be incorporated into other interferometers.

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