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PREVIEW

Gravitational Waves

Detector (partial)

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

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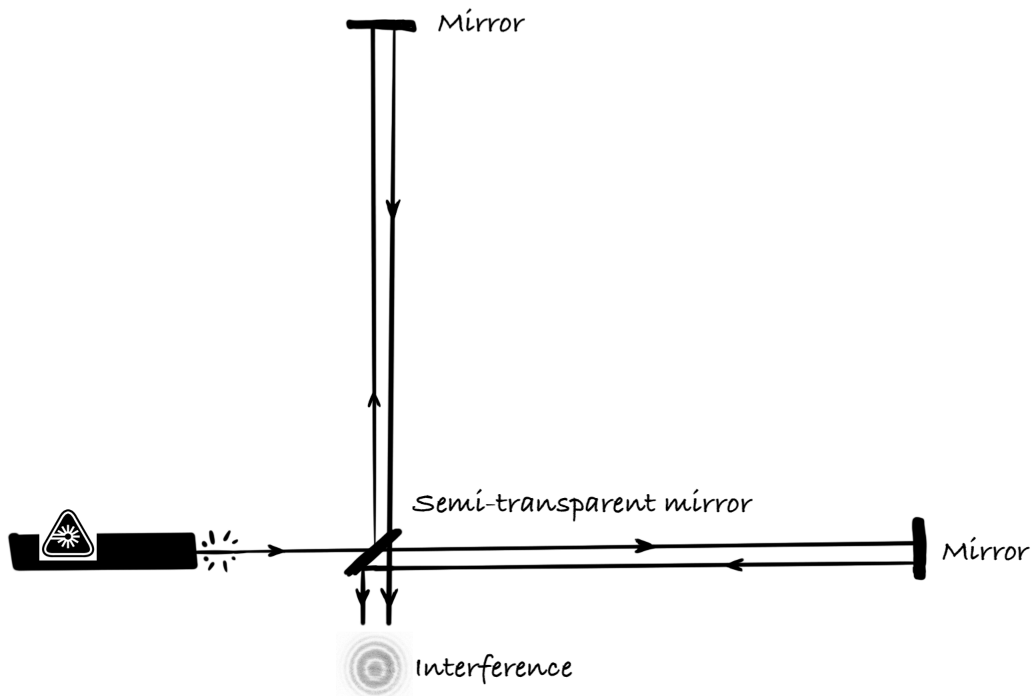
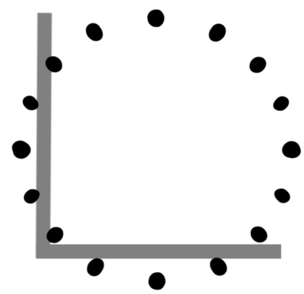
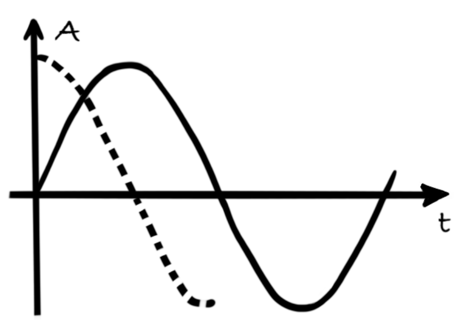
Basics of the detector. In 2017 I visited GEO600, an experiment set up to detect gravitational waves directly by measuring the distortion of space resulting from the passage of a wave. It is not the only such detector; several have been built worldwide, including LIGO in the US and VIRGO in Italy. They all rely on the same operational principle: the Michelson interferometer. A Michelson interferometer is not completely unlike my school experiment that imperiled the costly oscilloscope: you reflect a laser beam between two mirrors and measure its transit time. Based on the known and constant speed of light, you can then calculate the beam's path length. Any passing gravitational wave changes that length ever so slightly.



To measure this change in length precisely, you start with a single laser beam, which you then split into two beams using a beamsplitter, basically a semi-transparent mirror. You then send the two beams along the two roughly perpendicular arms: these are 600 meters long for GEO600 and 4,000 meters for LIGO. A mirror at the end of each arm reflects the light back. Because of the different orientations of the arms, a passing gravitational wave will shorten or lengthen the two arms differently, as illustrated by the next illustration that repeats the test particles from before:



To measure this length difference you let the two beams interfere with each other. As you probably remember from school, interference happens when two waves superpose. Depending on their phase difference, they arrive at the point of measurement with both waves at their peaks (which leads to constructive interference), both at their both troughs (destructive interference), or any combination between.



Changes in the length of an arm of the interferometer will lead to a phase shift in the beam that travels along the arm. Because the arms change their length differently, and because the beams started out with zero phase difference because they were "split" from a single laser beam, the relative phasing of the two beams will change, and the resulting interference intensity will change accordingly. The particular interference pattern characterizes the relative length change of the two arms.

An interferometer naturally indicates changes in relative phase that is in the order of magnitude of the wavelength, between 10^{-7} and 10^{-6} meters for lasers in the visible spectrum. For larger differences the system has to count the sequence of intensity changes.

So far, so good. But here's the problem: gravitational waves are extremely weak. The relative length change caused by a gravitational wave is only 10^{-21} meters per meter of measurement distance. The distance traveled by the beams in GEO600 is on the order of 10^3 m, so the absolute change in length produced by a wave is 10^{-18} m, roughly 1/1000 of the diameter of a proton. This is very much less than the 10^{-7} m wavelength of the laser, so you'd only get a very very small change in phase, and thus intensity. You see the problem. Very high precision measurement is required—especially considering that the detector should not just record the fact that a wave has passed, but should also be able to capture the wave's evolution in frequency and amplitude over time, to be able to characterize the astronomical event that created it. So let's understand how to attack this problem.

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Passive seismic damping. Gravitational waves are made up of frequencies over a large range; a scientifically interesting band is between a few dozen and a few hundred Hertz. A passing wave will make space itself "vibrate" at those frequencies. To be able to detect such vibrations as phase shifts of the laser beams, you have to ensure that the mirrors that reflect the lasers do not vibrate at those frequencies for "earthly" reasons, relative to space—the detector would be merely a giant seismometer if the mirrors were not isolated from the environment. While the GEO600 detector is not near a railroad or a highway, it is also not outside of civilization: it's located next to a field midway between Hannover and Hildesheim. The unavoidable seismic background noise induced by civilization and the atmosphere has to be dealt with.

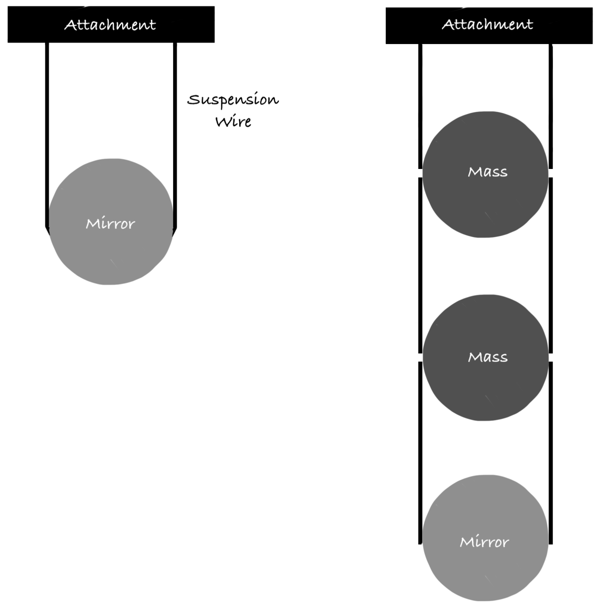
It is crucial to understand that a gravitational wave does not make the detector's mirrors vibrate in a classical way—that is, relative to the installation around them. Instead, space itself changes its shape. To detect this, any classical vibration of the mirror has to be extremely well damped in the relevant frequency range. To achieve this, the interferometer's mirrors are suspended from a pendulum.

Let's try to understand the necessary damping characteristics using seismic microtremors as an example. These are man-made vibrations above 1 Hz with an amplitude on the scale of micrometers, 10^{-6} m. We know from above that the relative length change induced by a gravitational wave is of the order of 10^{-18} m for the roughly 1,000 meter light path in GEO600. To isolate the mirrors from microtremors, therefore, we have to achieve damping of the order of 10^{12}. Let's look at the damping characteristics of pendulums:

$$\delta = \left(\frac{f}{f_r}\right)^2 \qquad f_r = \frac{1}{2\,\pi}\sqrt{\frac{g}{L}} \qquad L = \frac{\delta\, g}{4\,\pi^2 f^2}$$

The first formula shows a pendulum's damping, δ. This is frequency-dependent, as we can see from the f in the formula; this simple formula applies for $f >> f_r$, where f_r is the resonant frequency of the pendulum. As the second formula shows, f_r depends on the geometry of the pendulum, and in particular on its length L. Let's say that we want to damp vibration at 100 Hz, a frequency that is right in the middle of where interesting astronomical phenomena occur, and let's assume we have a pendulum with $f_r = 1$ Hz. The reduction in vibration amplitude is then $\delta = 10^4$. How long would such a pendulum have to be? Solving the second formula above for L, we get around 25 centimeters for a resonance frequency of 1 Hz—a feasible size.

However, if we try to achieve the necessary damping of 10^{12} , the pendulum would become humongous—do the calculation and see for yourself using the third formula above. Fortunately there is an alternative: stacking them. This means that the wires of pendulum two are attached to the mass of pendulum one, as the following illustration shows:



If pendulums are stacked, their attenuation is additive. So by stacking three pendulums with a damping factor of 10^4, we can achieve an attenuation of $10^{(4+4+4)} = 10^{12}$. Now we're getting somewhere.

The specific setup of the pendulums differs between the various detectors. GEO600 uses exactly this kind of triple-stacked pendulum. LIGO uses four stacked pendulums and VIRGO seven, but they all rely on the idea of stacked pendulums to achieve large damping values without requiring huge size. We'll discuss a few more details about GEO600's pendulums later.

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Vacuum. The arms in which the laser beams travel are evacuated. This is necessary for several reasons. First and foremost, air in the arms would transmit outside vibrations as sound waves. All the sophisticated suspension-based 10^{12} damping would not be of much use if air transmitted external disturbances.

Less obviously, the vacuum is also crucial to maintain all the optical components at the same constant temperature to prevent them expanding or shrinking. Thermal expansion varies widely for different materials, but even the best exhibit in the order of 10^{-6} meters of expansion per (cubic) meter of material per Kelvin of temperature change. This would clearly be another no-go for a detector that is supposed to resolve to 10^{-18}. Long-term temperature variations can be a problem for the mirror suspensions, causing them to sag and change the alignment of the optics. More critical are shorter-term variation that affect only part of the system; air currents could produce such variations. Finally, the movement of the air in the tunnel—thermal turbulence and sound waves—would refract the laser beams and potentially disturb their collimation, the perfectly parallel orientation of the waves. This could make the laser diverge.

The final argument in favor of a vacuum is mirror cleanliness. As we will see, very high laser power circulates in the arm cavities, which can burn any specks of dust onto the optics, destroying their surface.

Creating and maintaining a vacuum is a technical challenge in itself. The process starts by mechanically pumping out the air with turbo pumps or scroll pumps. Scroll pumps use meshed spirals to produce a continuously decreasing volume that compresses gas and then expels it through an exhaust. Turbo-molecular pumps work roughly like jet engines: rotors accelerate air molecules into successively higher-pressure stages, until the pressure is high enough for more traditional pumps to deal with it. LIGO uses ion pumps to get to the required ultra-high vacuum quality of 10^{-6} Pascal. Ion pumps ionize the gas in a vacuum vessel and then use a strong electric field to accelerate the ions towards, and then stick to, a solid electrode. Water molecules are extracted with liquid nitrogen cryo-pumps that condense water vapor onto a cold surface. The vacuum is continuously monitored by computers and actively maintained with the various pumps.

Operating all the optical equipment necessary for the detector in this vacuum is an additional engineering challenge. Operation has to be reliable, with absolutely minimal manual intervention, because every opening of the vacuum vessel requires “rebuilding” the vacuum from ambient pressure. For LIGO this takes over a month!

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Thermal noise and the Q factor. Every material has internal friction that transforms kinetic energy into thermal energy. For example, when you move a pendulum, the internal friction of the suspension wires damps the pendulum slightly; in exchange, the wires get slightly warmer. The quality factor Q of a material characterizes this behavior: the higher the Q-factor, the lower the dissipation, the lower the damping. However, as we have said, the pendulum does not actually move when a wave passes (it is space itself that expands and shrinks), so why is the effect relevant?

Every material exhibits internal random fluctuations of its electrons as a result of its temperature. This is called thermal or Nyquist noise. It's basically the electrical equivalent of Brownian motion in gases. The energy of these fluctuations depends on the square root of the temperature, as well as on properties of the material. These internal fluctuations can have a (very small) macroscopic effect: the mass starts to vibrate a tiny bit. At the precision gravitational wave detectors operate, these mechanical vibrations might disturb the detection, so they have to be avoided.

Enter the fluctuation–dissipation theorem. This states that the magnitude of spontaneous temperature-induced thermal fluctuations is proportional to the material's damping of an external disturbance—that is, materials with a high quality factor macroscopically vibrate less for a given temperature. This is why the components of the pendulum are made from fused silica, a type of glass; its Q-factor is several orders of magnitude higher than, for example, steel, while it still has sufficient mechanical strength to hold the heavy masses. In addition to the wires, thermal vibration can also originate from the pendulum masses themselves, so they are also made from fused silica as well. Even the connection between the wires and the masses might be a source of internal friction, so the two are bonded together. Bonding is a way of chemically joining two parts such that they basically share free electrons. It results in a strong, thin, vacuum-compatible connection that is free from internal stresses. Finally, it turns out that for the pendulum as a whole, the Q-factor can also be increased by making the mass heavier. GEO600 uses 10 kg, LIGO uses 40 kg.

It is important to point out that understanding all these processes and coming up with the kind of suspensions used in today's detectors is the result of decades of basic research and experimental refinement. The Institute for Gravitational Research at the University of Glasgow specializes in building these suspensions; GEO600's and LIGO's suspensions were built by this group. They are continuously optimized. For example, LIGO was offline between 2010 and 2015 to be upgraded to the Advanced LIGO configuration which, among other enhancements, added a fourth level of pendulums. They also replaced their original steel attachments with high-Q monolithic glass. Both updates were instrumental in the first detection of gravitational waves in 2017.

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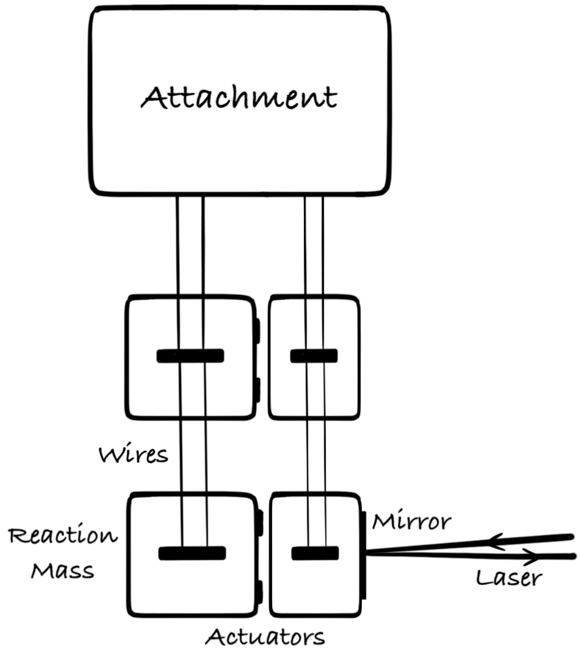
Active damping. We have seen that the passive damping system based on three stacked pendulums achieves a factor of 10^{12} for frequencies at around 100 Hz. But a lot of the action in gravitational waves occurs at low frequencies, where the dampening is less because we get closer to the resonance frequency of the pendulums. On the other hand, these frequencies are easier to compensate with actively controlled damping, which is exactly what is done. However, it is important to ensure that the active control is not relative to a base that itself vibrates because it is connected to the "outside world". To achieve this, the overall mirror mounting system in fact consists of two pendulums, located right next to each other. Sensors mounted on the masses that ultimately hold the mirrors detect movement. Actuators mounted on the reaction masses then create stabilizing forces. Each level is damped separately.



The measurement detects relative movements of the masses. This can be done with electric fields or with shadow sensors, in which a photodiode is partially shadowed from an LED on the opposing mass depending on the relative movement. However, it is not unlikely that both mass "chains" are disturbed similarly—after all, they are ultimately installed in the same environment. To detect "joint" movement, accelerometers are used; those measure absolute acceleration in inertial space, rather than relative to a reference surface. In particular, this prevents any coupling with seismic noise. The sensitivity of these sensors is limited by electronics noise and the problem that they measure acceleration, and ultimately, relative displacement, so errors are cumulative.

The actuators' forces are created with electric and magnetic fields: coils and magnets, not unlike the fine drive in SOFIA. In total, GEO600 uses more than 250 active control loops in various elements of the optical path.

All this passive and active damping leads to very stable mirrors. As Christoph Affeldt, operations manager of GEO600, says "Because the ground also just moves at sub-micrometer range, [the damping ensures that] our mirrors basically don't move at all." But there are other issues that limit the resolution of the detector, several of them related to the laser.

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