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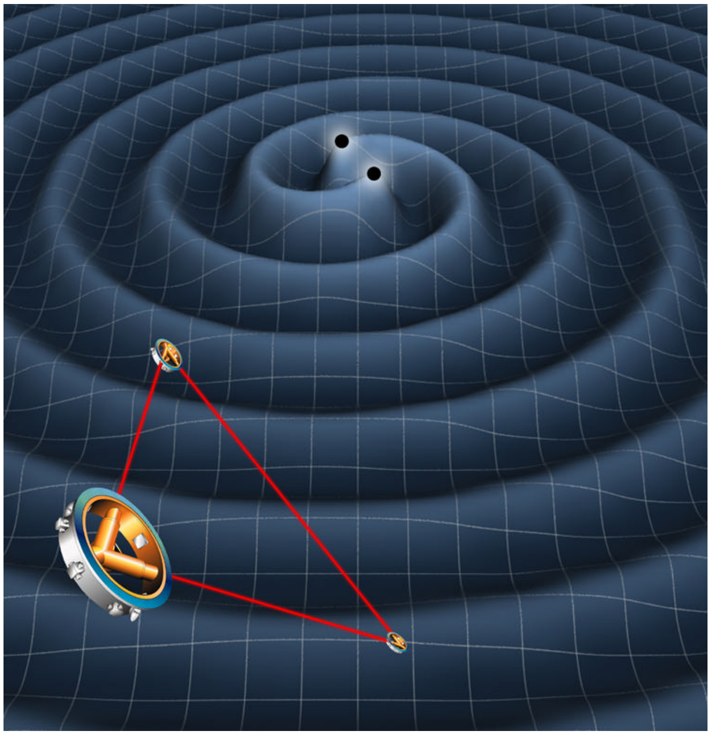
LISTENING FOR RINGS FROM SPACE

Did it ever occur to you how really amazing are your senses of vision and hearing? They allow you to understand objects and events in the world "remotely," without being in direct contact with them. While walking around, you can avoid running into things just by processing and understanding the information being carried to your brain by the light waves entering your eyes. Even in a room with no windows, you can understand that a thunderstorm is raging outside just by the sound waves entering your ears.

Light waves and sound waves are forms of energy. They carry information about whatever produced (and possibly reflected) them. Waves of candlelight that enter your eyes from your friend's face carry information not only about the candle that produced the light but also about the face that reflected it. Likewise, ocean waves are waves of energy moving through the water that carry information about the storm or the tides or Earth's rotation from which the energy originated. If there is an earthquake or suddenly erupting volcano at sea, a giant tsunami wave may form, carrying information about the cataclysmic event that has just occurred.



In this artist's concept, two black holes spiral around one another locked in a gravitational dance of doom. The three LISA spacecraft detect the waves of gravitational energy released by the motions of these massive bodies.

LOCKED IN A SHOCKING DEATH SPIRAL

Likewise, extremely fast motions by very massive objects in space produce waves of energy, not in air or water, but in the fabric of spacetime itself. For example, black holes are very massive and dense objects. They have so much matter packed into a small volume that their gravitational fields are too powerful for even light to escape. That's why they "appear" (or, actually, disappear) as black holes. When two of them get close enough together, they begin a spiraling dance of doom, their gravitational fields pulling each other in closer and closer. As they spiral through space, they release huge amounts of their gravitational energy. This energy radiates away in all directions in pulses, or waves—gravitational waves. Finally, spiraling faster and faster, and closer and closer, they collide and merge. The last few days and minutes of this dance release huge amounts of gravitational energy.

No one has detected a gravitational wave, but they are predicted by Einstein's theories and are certain to exist. Astronomers want to detect and study these waves of gravitational energy, because it would help them understand these very strange objects and events. Other violent cosmic events that produce gravitational waves are supernova explosions, and mergers of compact stars with each other or with black holes. Also, gravitational waves are still ringing from the Big Bang that started the universe. Those waves could tell us about our very beginnings.

So, how do we detect gravitational waves? No telescope or listening device ever invented would be able to detect gravitational waves. They are an entirely different form of energy from electromagnetic waves (light in all its visible and invisible forms).

What would we have to be able to measure in order to detect gravitational waves? To answer this question, we have to ask what happens when a gravitational wave passes by us and our gravitational wave detector.

Just as a sound wave causes air molecules to be momentarily squeezed together as it passes, a gravitational wave actually causes space itself to be squeezed! This squeezing has the effect of changing the distance between objects—for example, the distance between the spacecraft in the LISA mission.

Gravitational waves that reach our neighborhood of space from millions of light years away are extremely weak. So in order to be able to measure them, we need a technology that can measure distances with extreme precision.

AN EAR FOR THE GRAVITATIONAL MUSIC

LISA (for Laser Interferometer Space Antenna) is a mission to measure gravitational waves in space. It will consist of three spacecraft flying in the form of a triangle 5 million kilometers (3 million miles) on a side! These three spacecraft will use laser beams to keep in touch. The laser beams will form the sides of this virtual triangle and enable the three spacecraft to remain a very precise distance apart and be able to detect any squeezing or stretching of the distance between them caused by a passing gravitational wave. With three spacecraft, LISA will be able to pinpoint from which direction the gravitational wave originated.

Because the waves are so weak, LISA must be able to measure distance so precisely that it could detect a change the diameter of a human hair in the distance from here to the nearest star, Alpha Centauri. This precision is what the lasers will provide.

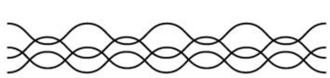
THE POWER OF LASERS

Remember that electromagnetic energy (light) travels in waves. The length of the wave is what determines whether the electromagnetic energy is, for example, a radio wave, a visible light wave, an infrared wave, or an x-ray.

Laser stands for "**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation." Laser beams have three characteristics that make them different from ordinary beams of light:

First, the light from a laser contains exactly one color or wavelength rather than a lot of different wavelengths. Scientists say that laser light is "**monochromatic**," meaning of one color.

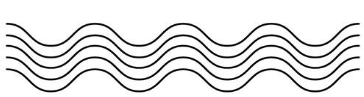
Mixed wavelength
(white light)



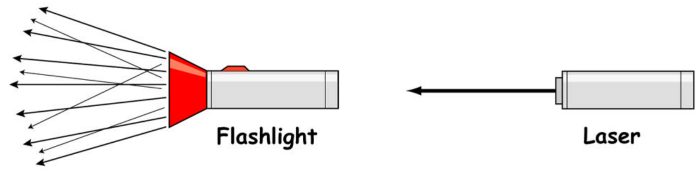
Monochromatic light
(but not in phase)

Second, all the wavelengths are in phase. That is, they are all "waving" in unison. All the wave crests (high points) and troughs (low points) are lined up. Scientists say the laser light is "**coherent**."

Same wavelength
(and in phase)



And third, the particles of light, or photons in the laser light waves are all traveling in the same direction, exactly parallel to one another. They are not headed off in different directions. This means that laser light beams are very narrow and can be concentrated on one tiny spot. Scientists say the laser light is "**collimated**."

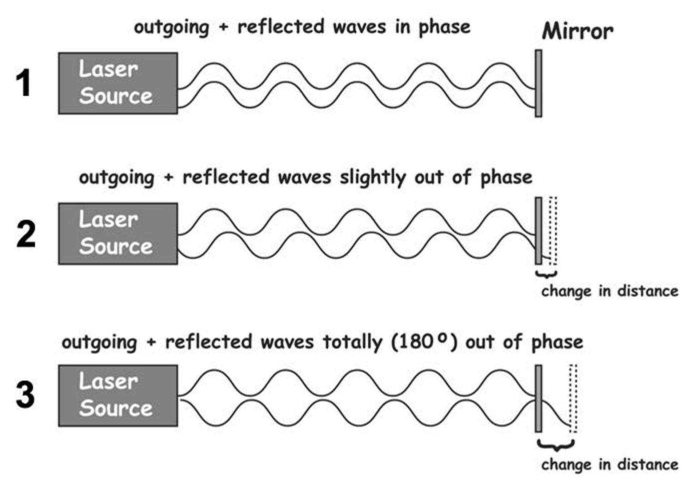


Because the laser light is monochromatic, coherent, and collimated, all of its energy is focused to produce a small point of intense power. This also means that a laser beam can shine a very long distance without losing a lot of its power, since it doesn't spread out much. This characteristic makes lasers perfect for LISA, since the beam generated by one spacecraft has to travel a 5-million-kilometer straight line through space to "connect" with another spacecraft.

So, how is it that LISA will be able to measure this huge distance so precisely?

THE POWER OF INTERFEROMETRY

As we mentioned, waves have crests and troughs, and in a laser beam they are all lined up, or coherent. The following explanation is a bit simplified. In principle, one LISA spacecraft sends a laser beam toward another spacecraft. The other spacecraft reflects that laser beam right back. If the distance between them has not changed, the returning laser beam should still be in phase (coherent) with the sent laser beam. If their distance has changed even a fraction of a wavelength, then the two laser beams will be out of phase with one another and the LISA electronics will detect and measure how much out of phase they are. Since about 1000 wavelengths of laser light would fit



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on a speck of dust, a part of a wavelength is unimaginably tiny. This explains the amazing precision of LISA's measurements of very long distances.

This measurement technique is called interferometry, because the measurement is based on the interference of electromagnetic waves. When waves that are in phase encounter one another, the energy of their crests and troughs add together.

When waves are totally (180°) out of phase, the crest of one wave cancels out the trough of the other.

MAKE A SIMPLE "MINI-LISA"

We can mimic in a simple way LISA's precision laser interferometer technology using ordinary materials and three students to stand in for the three LISA spacecraft. You will be making three "laser beam interferometer" models for the entire class. Each of these models will represent one side of the triangle formed by the three LISA spacecraft, and the three students will each be "attached" to two of its sides.

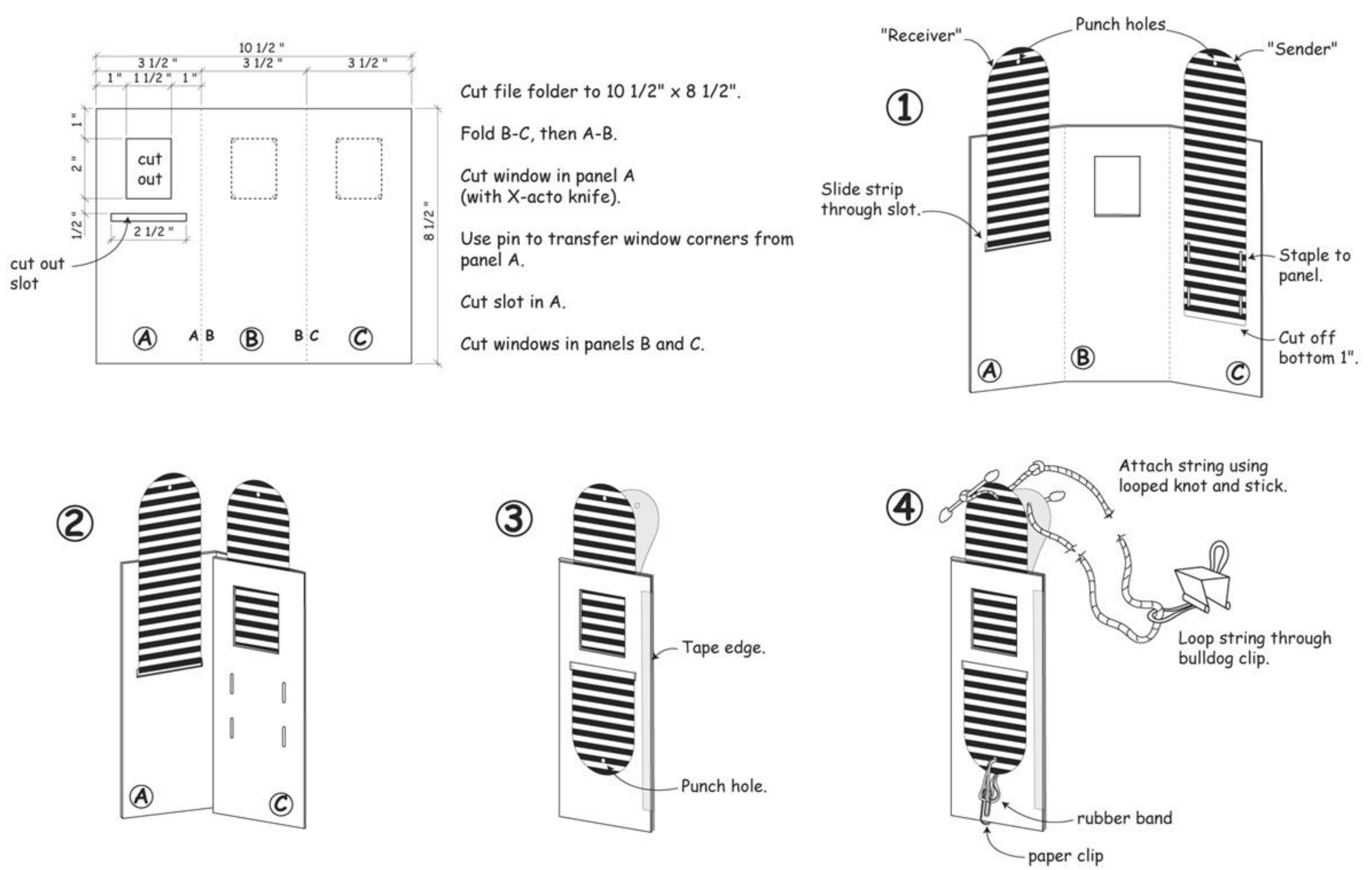
MATERIALS:

- 3 file folders
- 6 photocopies on transparency film of the strip on the last page of this article
- String or twine (non-stretchable), about 30 meters (about 99 feet), (3 10-meter or 33-foot lengths)
- 3 paper clips
- 3 rubber bands
- Scissors
- X-acto knife
- Stapler
- Tape
- Cotton swabs, matchsticks, or toothpicks (6)

CONSTRUCTION:

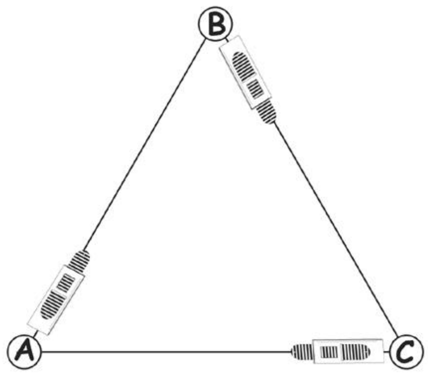
Cut out, fold, and construct the interferometer model as shown (see illustration).

Constructing the Interferometer



The stripes on the transparent strips represent laser beam wavelengths. Each dark line stands for a trough and each "bright" line stands for a crest. In this case, your "laser beam" has a wavelength of 1 centimeter, or about 10,000 times longer than LISA's laser beams.

On each of the model interferometers you have made, the "interferometer window" represents one of the spacecraft sending out a laser beam toward one of the other spacecraft. The clip at the other end represents a mirror reflecting the laser beam (thus the loop in the string) back to the originating spacecraft.

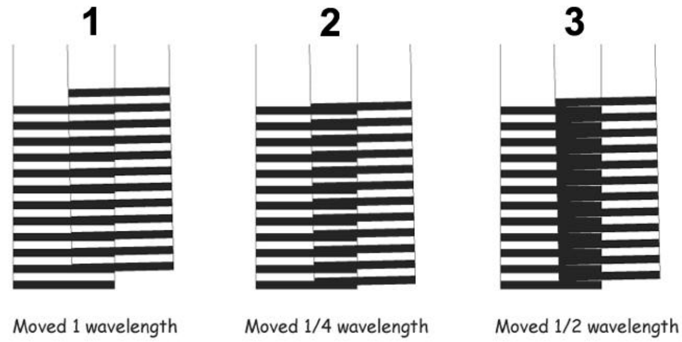


Now, let's put it all together. One student (A) holds the "interferometer window" end of the "laser beam interferometer." Another student (B) clips the other end onto his or her clothes. In turn, B holds the "Interferometer window" end of the second model and a third student (C) clips the other end onto his or her clothes. All that's left to complete the triangle is for C to hold the window end of the third model and A to clip the end onto his or her clothes.

Now everyone moves into a position so that there is no slack and just a bit of tension in the strings. You now represent the three LISA spacecraft flying in formation, connected by laser beams. You are only about 5 meters apart, but the LISA spacecraft will be a billion times farther apart!

But even as close together as you are, notice what happens in the interferometer windows when someone moves the slightest amount, thus changing the length of the "laser beam."

Look back at the drawings labelled 1, 2, and 3 of laser light waves in and out of phase. If the outgoing and reflected waves are *in phase* (1), the interference pattern on your interferometer will look like the Drawing 1 below. This could mean that the distance the laser beams had traversed either had not changed at all, or had changed by one or more whole wavelengths. Similarly, if the outgoing and reflected laser beams are 1/4 wavelength out of phase, the bands of the interference pattern will overlap as in Drawing 2. If the outgoing and reflected waves are totally



(180°) out of phase, the bands will appear to cancel each other out as in Drawing 3. If a computer (or you, in this demonstation) records all the shifts in the interference patterns as they take place, it (or you) can then calculate to the nearest 1/4 wavelength the total distance moved.

In the case of your interferometer, a "wavelength" is 1 centimeter. So, how accurate is your interferometer?

At 5 meters, you can easily see a shift of as little as one-quarter of a wavelength. Since 1 wavelength is 1 cm,

¼ wavelength = .25 cm

And the

Total distance = 5 m x 100 cm = 500 cm

To find the accuracy, we divide the total distance by the smallest change in distance that we can measure, or

500 cm / .25 cm = 2000

So your interferometer is accurate to 1 part in 2000. You can measure a change of as little as 1/2000th of the distance between the "spacecraft." Not bad!

Now, how accurate is LISA's interferometer? For LISA,

1 wavelength = 1 micron (one-millionth of a meter)

Total distance = 5,000,000 kilometers (multiply by 1,000 to get total meters)

Total Meters / .25 micron = ? (answer at bottom of page)

Now, how can LISA detect a passing gravitational wave? And how will LISA know from which direction it comes? As the gravitational wave passes, it will stretch and squeeze the space along the three arms of the interferometer, depending on the direction it is moving. LISA's computers will be able to calculate this direction, as well as the strength and wavelength of the gravitational wave based on these tiny measurement differences.

How accurate is LISA? 1 part in 20,000,000,000,000,000 , or 20 x 10^{15}.

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PUSHING THE TECHNOLOGY OF PRECISION

The “gravitational wave detecting antenna” you’ve made demonstrates some fundamentals of interferometry, with no technological tricks to make it cheaper, faster, better. Your system, with suitable software to process the data from the three lasers, could be used to measure the presence of gravitational waves.

But you would encounter some problems; at the enormous distances, even laser beams become weakened. Instead of reflecting a weak signal to the transmitting spacecraft, you might have the target spacecraft re-transmit a return beam at full power, with waves in the same sequence as though reflected.

With your system, data about distance change has to be collected from laser systems on three legs, then calculated to determine what moved and in which direction. It would be more efficient to measure two legs at once; use one laser and shine it through a piece of special glass at 45 degrees to split the laser beam, sending half to each of the other spacecraft. The reflected beams return through the same glass and both can be seen from a single point (on the other side of the glass). Waves from the two reflections come together to create the same kind of interference patterns as shown in your demonstration system. Changes of the interference pattern reveal movements, but only in two legs. Data from all three legs is needed to accurately measure distance and motion of the spacecraft.

LISA’s system solves that in this way: The transmitting spacecraft (A) splits the laser beam, sending half to spacecraft (B) and half to spacecraft (C). Instead of returning the “reflected” laser beam to the transmitting spacecraft (A), receiving spacecraft (B) transmits the beam to the spacecraft (C), which in turn transmits it back to (A). Similarly, (C) sends to (B) which returns to (A).

Interference of waves in the returning beams represent movements in all three legs of the LISA triangle. If the two arms of the interferometer are exactly the same length, a bright spot will appear on the detector, giving the maximum electrical signal. This indicates no gravitational wave has passed. If the difference in the arm lengths is one half of the wavelength of the laser light, then the two light beams will cancel each other out and the detector output will be a minimum.

This can indicate a passing gravitational wave. Because the wavelength of laser light is very small, an interferometer is a very sensitive instrument for measuring small changes in length and is thus ideal for use in detecting gravitational waves.

Find out more about gravitational waves and do a LISA online crossword at spaceplace.nasa.gov/lisa_fact2.htm .

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