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Note to Teachers:

In this series of activities, contributed by the Jet Propulsion Laboratory, students not only learn why the stars twinkle, but what is being done about it! The article describes a series of kinesthetic "games" that demonstrate the behavior of light from a star as it passes through the atmosphere, and how telescopes can correct for the resulting distortion using the computer-driven technology of adaptive optics.

In preparation, it is good to have students first carefully observe the night sky, taking notice of how the stars actually appear. If they have never noticed that the stars twinkle, they won't find the exercise very relevant. After their observations, you could give them the opportunity to describe what they saw (hopefully they will mention something about twinkling!) and discuss possible causes for the appearance of the stars. Students—and teachers—whose curiosity is piqued can go to some of the web sites listed at the end of the activity to find out more.

The four pages of the article are written to be photocopied and handed out to the students to supplement the activity.

Other space science and technology activities for children can be found on JPL's children's web site The Space Place, **http://spaceplace.jpl.nasa.gov**, also supported by ITEA.

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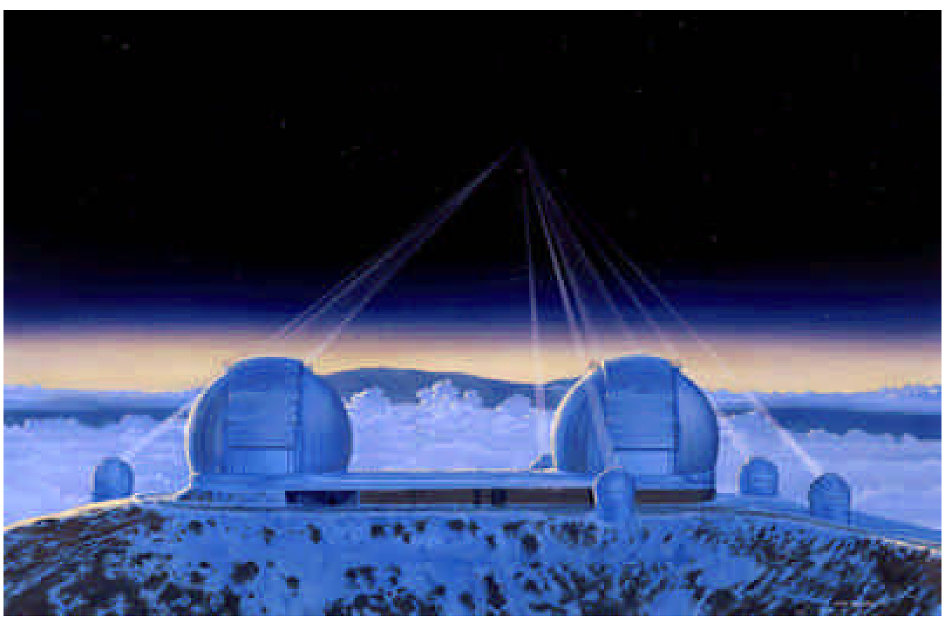

Artist's rendering of the Keck Interferometer on Mauna Kea in Hawaii, where the technique of adaptive optics is further enhancing the quality of the observations.

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How Astronomers "De-twinkle" the Stars

Twinkle, twinkle, little star . . .

The twinkling stars in the night sky are beautiful. If you live where there are no big cities nearby to pollute the night with their artificial light, you will see thousands of tiny points of light dancing against the blackness. If you live in the city, you may see only dozens or hundreds of stars, even on a clear night. But still, if you look carefully, you will see the points twinkle and dance.

Although the twinkling is a delight to our sense of beauty, it doesn't do a thing for astronomers trying to learn about the stars from the light that reaches us here on Earth. The twinkling is actually distortion caused by turbulence in Earth's atmosphere. As the starlight passes through the air, it is bent slightly. The denser (thicker) the air, the more it bends the light. Turbulent air is thick in some places and thin in others, and constantly moving and changing. The astronauts reports that, from above Earth's atmosphere, the stars look like brilliant, beautiful, *steady* points of light.

Your light has reached us from afar . . .

Light from the stars has been traveling a very long time and a very long distance. Our best telescopes can detect extremely faint starlight that has been traveling through space for billions of years to reach us! So, after the starlight has traveled all that way, astronomers don't want it to see it all messed up at the last instant by twinkling!

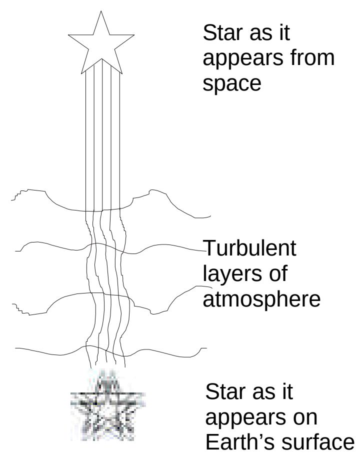
It helps to put telescopes on high mountains where at least there is less atmosphere above them through which the starlight must pass. It also helps to find places where the air is very calm, with little turbulence.

The Keck Observatory, along with eleven other international observatories, is high atop a mountain on the Big Island of Hawaii. At 4,205 meters (13,796 feet) above sea level, Mauna Kea is the highest island mountain in the world. It is usually above the weather, with the clouds down below. The skies above are usually clear, dry, still—and dark. From Mauna Kea, telescopes can see the faintest galaxies at the very edge of the observable universe.

A little blurred, but that's OK . . .

But still there is some twinkling. What can we do about the twinkling, short of launching the giant Keck and other observatories into space, well above the atmosphere?

Most of the turbulence in the atmosphere occurs in thin layers at different altitudes. Each layer has a different amount of turbulence, which we can measure. Is it possible to predict how the light will behave as it passes through these different layers? If the twinkling doesn't happen by pure random chance, but is predictable in some way, then we may be able to correct for it.



Stars are spheres and they beam their light in all directions. But even though the light waves spread out from the star in a sphere, by the time they reach us, they are, for all practical purposes, flat—just as to us on the ground, the spherical Earth seems flat, because we can see only a tiny part of it. What atmospheric turbulence does is make the wave "unflat" by the time it reaches the ground.

Adaptive optics will clear the way!

In 1953, astronomer Horace Babcock described a method, called **adaptive optics**, of correcting for atmospheric disturbances of light waves at the time they occur. First, you would have to measure the distortions in the wave front and then correct them very quickly so as to follow the rapidly changing patterns of atmospheric turbulence.

In 1957, physicist Robert Leighton partially corrected the atmospheric blurring at the 60-inch telescope on Mount Wilson (above Pasadena, California) to produce the sharpest photographs up to that time of Jupiter and Saturn. This was done by tilting the secondary mirror several times a second (called a "tip-tilt" correction) to eliminate or reduce the dancing motion of the image. Tip-tilt made the image two or three times sharper. However, to get rid of atmospheric blurring altogether, it needed to be another ten times better.

In another adaptive optics system built for the100-inch telescope at Mt. Wilson, the light reflected from the telescope mirror is divided into several hundred smaller beams or regions. Looking at the beam of light from a star, the system sees hundreds of separate beams that are going in different directions because of the atmospheric effects. The electronic circuits in the system compute the bent shape of a mirror surface that would straighten out the separate beams so that they are all going in the same direction. Then a signal is sent to the deformable mirror to change its shape in accordance with these electronic signals. In other words, a crooked beam of light hits a crooked mirror and a straight beam is reflected!

It is only in the last 5 to 10 years that computers have been able to do these complex calculations fast enough to make adaptive optics work really well.

Activity #1: Some "random" events are more random than others

1. Get a partner and stand facing each other, about two arm-lengths apart. One person is the "actor" and the other person is the "mirror." The actor begins making big, slow movements—for example moving arms, turning sideways (but still looking at the "mirror"), stepping slowly sideways or back. The mirror tries to reflect (match) every movement of the actor, as closely and with as little delay as possible. As the actor, keep the movements slow so your mirror can "predict" what you will do next and match your movements. After a minute or so, switch roles.
2. Now, as the actor, speed up your movements and make them as unpredictable as you can. Try not to do the same thing twice. As the mirror, try to predict and match the actor's movements. After a minute or so, switch roles.
3. This time, as the actor, go ahead and move fairly fast, but make up a pattern of maybe 3-5 movements that you repeat over and over. As the mirror, you might not be able to reflect the actor's movements right at first, but you will soon learn the pattern and be a perfect mirror image! Switch roles and try it again with a different pattern of movements.

Here are some terms that scientists use to describe how predictable an event is:

An **unpredictable** event happens at random, no regular pattern.

A **linearly predictable** event happens with a regular pattern.

A **non-linearly predictable** event happens with a statistical pattern. That is you can estimate how likely it is that your prediction is going to be correct.

Which term would describe each of the parts of the activity?

As light enters Earth's atmosphere, turbulence at upper layers produces a small effect. Turbulence increases as the light moves closer to Earth. If the turbulence were totally random, we would not have much of a chance to anticipate and correct for distortions. The actual behavior of the turbulence is more statistically predictable. Upper atmospheric patterns tend to be more predictable than at lower altitudes. Thus, astronomers seek out high altitude locations—mountains! On mountaintops, adaptive optics can compensate for distortion and greatly improve the accuracy of star images.

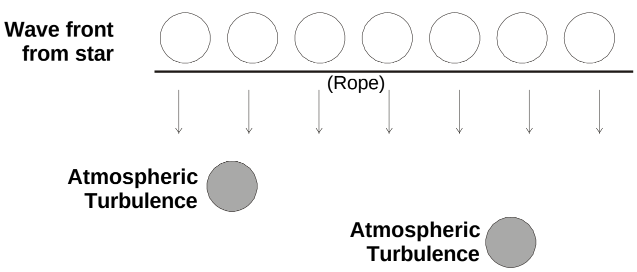
Activity #2. Mirror a wave front with no turbulence

Get about six friends (seven of you altogether) and line up side-by-side. You can all hold onto a rope to help keep your line straight, or you can hold hands. Make your line very straight, for you are a flat wave front of starlight approaching Earth's atmosphere!

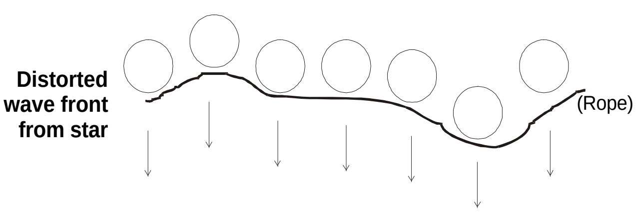
Now, you are moving through space, undisturbed by anything. Walk forward ten steps, keeping your line absolutely straight. (You might count off the steps, so everyone stays together.)

Activity #3. Mirror the turbulence

Find two more friends to be Earth's turbulent atmosphere. Put these "disturbing" friends a few paces in front of your flat wave front. Walk your wave front ahead ten paces, this time right into Earth's atmosphere, where each of the turbulent people gets in the way a little and makes your line crooked. Don't knock anybody down! The atmosphere isn't *that* turbulent!



Now, as your wave front reaches Earth's surface, it isn't flat anymore. It's a little distorted.

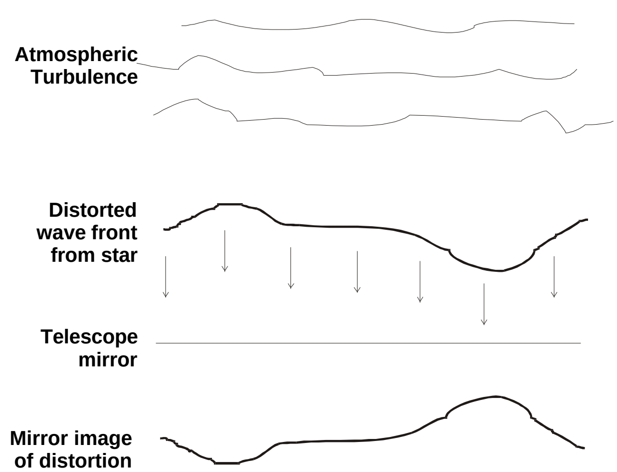


Imagine other wave fronts following you very closely through the atmosphere, and when they reach the ground, they are also distorted, but in a little bit different way, because the air turbulence pushed them in different ways. Thus, the twinkling!

Activity #4: "De-twinkle" the stars!

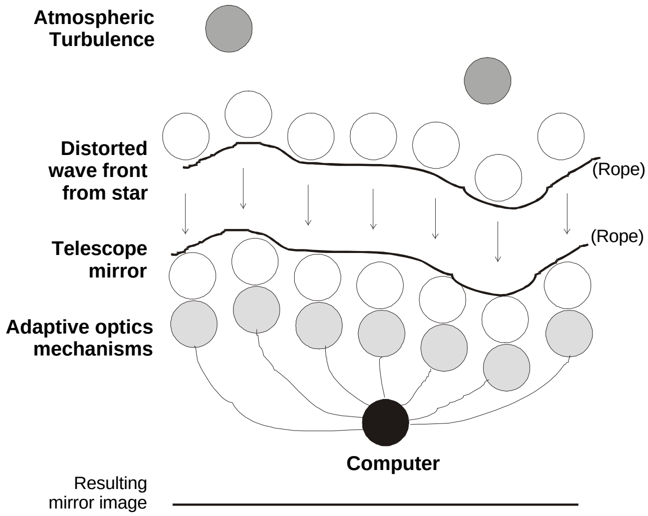
Keep your "wave front" lineup and atmospheric turbulence people intact. Line up seven more people facing your wave front and about 15 paces away. This is the telescope mirror that will catch your starlight.

Now if the mirror just stood there and reflected exactly what came toward it, it would look just as distorted as your wave front after being pushed around by the air turbulence.



But how can we make the reflected wave front flat again? Adaptive optics!

Have another person stand behind each piece (person) of the mirror, with hands on the shoulders of the "mirror piece." These are the mechanisms that move the pieces of the mirror to correct the distortions in the wave front.



Mirror "distorts the distortion" so that the resulting image is again undistorted!

Behind these two layers of the mirror, put one last person to be the all important computer. Imagine the computer is wired to each of the mirror-moving mechanisms. The computer can sort of extend and wave its arms and fingers toward the mirror "system" to send the commands telling the mirror how to move.

Now, action! The wave front again approaches the turbulent atmosphere of Earth and gets pushed out of alignment a little. As it approaches the mirror, each piece (person) of the mirror notices whether the part (person) of the wave front coming directly toward it is slightly ahead or slightly behind the rest of the wave front. With the help of the computer and its movement mechanism, it moves in exactly the opposite way so that when the wave front reaches the mirror, all the distortions will cancel out and the wave front reflected by the mirror will be flat again. Actually, adaptive optics is distorting the distortions in exactly the right way to cancel them out.

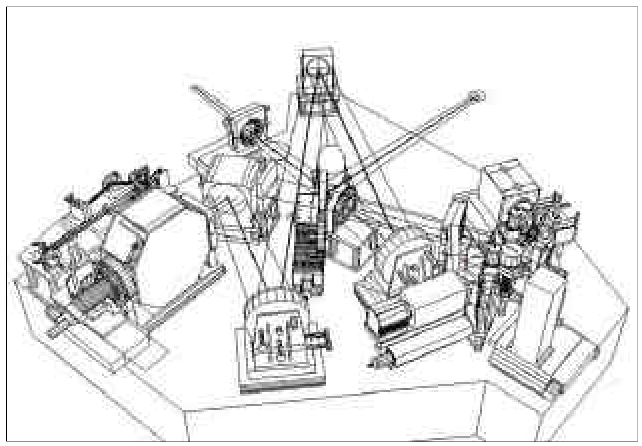
For example, if you are a piece of the mirror, and the part of the wave coming toward you is slightly ahead of the line, you would step back to be slightly behind the line. (If you were a true reflection of the distorted wave, you would step forward.)

For more about adaptive optics, visit some of these web sites:

http://www2.keck.hawaii.edu:3636/realpublic/ao/overview-2.html#HEADING2-0
http://www2.keck.hawaii.edu:3636/realpublic/ao/aolight.html (great image here!)
http://www.pha.jhu.edu/~jlotz/aoptics/empaper2.html
http://astro.uchicago.edu/chaos/
http://www.mtwilson.edu/Science/AdapOpt/
http://www.ifa.hawaii.edu/ao/
http://op.ph.ic.ac.uk/lcao/lowcost.html
http://op.ph.ic.ac.uk/ao/overview.html

The Great Keck Telescopes

The Keck Observatory high atop Mauna Kea has developed an adaptive optics system for the Keck-2 telescope and will soon have one for Keck-1. These two telescopes are the largest optical and infrared telescopes on Earth. Because of their size, their location, and advanced technologies like adaptive optics used to build and operate them, they can see farther and gather scientific data beyond the reach of any other Earth-bound telescope.



This is a drawing of the adaptive optics system of the Keck-2 telescope. As you can see, it is very complicated--but the activities you have just done still show the basic idea.

The National Aeronautics and Space Administration (NASA) plans to make the Keck telescopes even more useful by adding several "outrigger" mirrors to create a huge "virtual telescope." Using a technique called *interferometry*, images from all the mirrors will be combined into one. The resulting image will be even clearer and enable astronomers to more precisely pinpoint the locations and motions of the stars, and see even deeper into space, to the very edges of the visible universe.

To find out more about the Keck Interferometer, see http://huey.jpl.nasa.gov/keck.