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DAMPEN THAT DRIFT!

How would you like to go to Mars or some other alien world? Well, NASA would love to send you there! However, it will take quite a few years to reach that goal. Meanwhile, there is much we can do and find out using robotic spacecraft and space telescopes. Imaging and other scientific instruments in space can reveal mysteries of the universe that reach far beyond any distance that would ever be practical for human space travel.

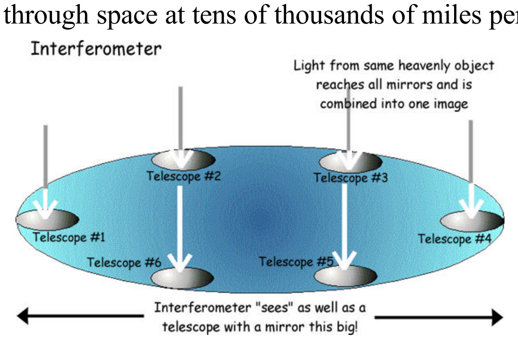
As far back as the 1600's, Galileo used the crudest possible telescope technology to see the largest moons of Jupiter. His view using even this ancient technology was much better than our eyes can see. Now our telescopes, especially those boosted into space well above the distortions caused by Earth's atmosphere, can see nearly to the edge of the universe.

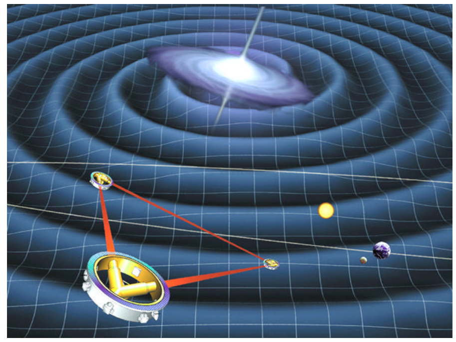
The secret to making telescopes better and better is to make their apertures (that is, their mirrors that collect the light) bigger and bigger. The bigger the aperture, the farther the telescope can see. The bigger the aperture, the fainter the objects it can see. The bigger the aperture, the more details it can see.

One very practical way to make huge telescope apertures is to use a technique called interferometry. With interferometry, several telescopes work together to make an image as good as could be made by a telescope whose aperture is as large as the greatest distance between the individual telescopes. By putting these telescopes in space, we can put them much farther apart than they could be on the surface of Earth. They can be farther apart than the whole diameter of Earth! In the bargain, we get the telescopes up above the starlight-distorting and blurring effects of Earth's atmosphere.

MAKING ONE GIANT VIRTUAL APERTURE

The trick is to get several telescopes to work together as a fixed, rigid telescope aperture even though they are flying through space at tens of thousands of miles per hour!





The three-spacecraft LISA (Laser Interferometer Space Antenna) will detect gravitational waves, the ripples in space-time caused by such violent events as the merger of two black holes. Lasers will help keep the three spacecraft perfectly aligned. But lasers will not be enough!

If we could fly the telescopes in precise formation, say three spacecraft in a triangle, controlling the distances between them with great accuracy, then they would act as a single, huge telescope. This multi-spacecraft telescope would be so powerful it could actually see whether there were any Earth-sized planets around other stars!

If multiple spacecraft could fly in precise formation, eager scientists could use special sensors to do other types of space missions. They could—

- Find evidence of massive objects such as black holes by detecting those ripples they create in space-time—cosmic gravitational waves.
- Learn more about planetary crusts and ocean currents by mapping gravity fields around Earth and other planets.
- Test Einstein's general relativity theory, as well as other theories of gravity.

Some of the planned missions will require the spacecraft to maintain their positions to within a fraction of the wavelength of light. Around 1000 wavelengths of light would fit on a speck of dust; so a fraction of one wavelength is unimaginably small. Any jiggling around beyond that tiny amount would prevent space telescopes using interferometry from seeing tiny, faint objects such as Earth-like planets around other stars. Nor could space antennas work using interferometry to detect the minute ripples in space-time caused by passing gravitational waves.

TINY SPOILERS

Out in space, the wind doesn't blow as on Earth and gravity is either extremely weak or is balanced by centripetal force as an orbiting body (that is, a satellite) goes around a planet or moon. However, there are still extremely small forces at work that can push any one of the several

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spacecraft in a formation out of position. Some of the sources of these disturbing forces might be

- Solar radiation (pressure from sunlight)
- Thermal radiation (heat radiating from one side of the spacecraft more than the others)
- Impacts from particles in space (tiny meteoroids) and occasional gas molecules or atoms of this or that.
- Distortions from equipment heating up and cooling off unevenly inside the spacecraft

These forces are so small, that correcting for them becomes an giant exercise in gentleness.

So NASA's New Millennium Program is developing and testing a technology to help with this problem. Space Technology 7 is a mission to test a new Disturbance Reduction System (DRS) in space. This technology has two tasks:

(1) Detect the slightest movement of a spacecraft from its position in the formation.
(2) Immediately correct that movement to restore the precise formation.

We will describe more about these amazing technologies later. For now, let's get a feel for the problem and play a game.

Be a Vector Inspector

Say your skis are 50 inches long. It doesn't matter which way they are pointing, they are still 50 inches long. However, your weight, 120 pounds, has a direction to it. Weight is a measure of the force of gravitational pull between Earth and your body. The force acts downward toward Earth's center. It doesn't pull or push your body toward the North Pole or the North Star. It pushes you down, down, down. To counteract it, your muscles exert force to hold you up and allow you to walk, jump, and get up out of bed in the morning.

Quantities with no associated direction, such as the length of your skis, are called *scalar* quantities. Other examples of scalar quantities are mass, speed, and electrical charge.

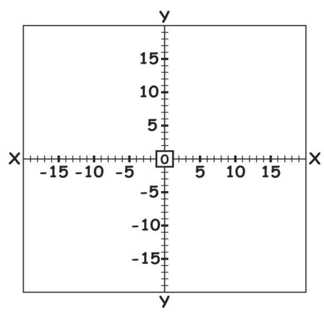
Quantities that do have direction associated with them are called vector quantities, or just *vectors*. Weight is just one example of a force. Force is always a vector. Other examples are velocity (which is speed in a particular direction) and acceleration (rate of increase of speed in a particular direction).

So, let's go back to our problem of flying spacecraft in formation. If forces from solar radiation, impacts of tiny particles, etc., are pushing on different sides of the spacecraft, how do we know how much force the thrusters need to exert to counteract those forces and keep the spacecraft in the correct position?

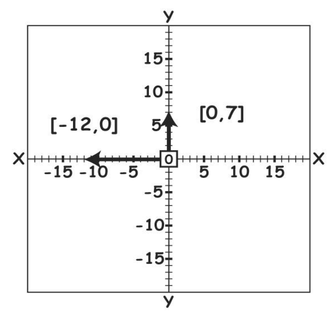
This simplified explanation will give you an inkling of how it's done.

Let's pretend we have a two-dimensional (that is, flat) spacecraft moving across a two-dimensional space. Let's put the spacecraft at the center of a grid, as in the diagram called **Grid 1**. Random forces may move the spacecraft any distance and in any direction on this grid, as it goes zipping through space at thousands of miles per hour. We want to keep the spacecraft centered on the zero point, where the X and Y axes cross.

Let's say solar radiation pushes the spacecraft toward the top of the grid with a force of 7 units (which in the case of ST7, might stand for micro-Newtons, extremely tiny units of force). We would represent this force on our grid as shown below in **Grid 2.**



Grid 1



Grid 2

The [0,7] describes the force vector. The first number in the brackets tells how far along the X axis the force acts, while the second number shows how far along the Y axis the force acts. You plot the point represented by the two numbers, then draw an arrow from the zero point to the plotted point. The arrow from the zero point to the point described by the numbers in square brackets represents the vector.

Suppose another force due to a swarm of small particles pushes the spacecraft toward the left side of our grid. This force vector can be described as [-12, 0]. On the X axis, count 12 units to the left of 0 and place a dot exactly on the X axis, since it represents the Y=0 component (neither above or below the 0 line). Draw an arrow from 0 to this point to show the vector. (See Grid 2.)

Now, if both these forces act on the spacecraft at the same time, you might guess that the spacecraft is pushed toward the upper left-hand corner of the grid. You would be right. **But exactly how hard would this resulting force**

push and at exactly what angle? You can guess, but a guess wouldn't be good enough.

To calculate the result of these two forces acting together, we need to add the vectors. We add them by first adding together the X components, and then adding together the Y components. The result is a new vector that combines the two forces. In this case,

```
   [  0,   +7]
 + [-12,    0]
   ----------
   [-12,  +7]
```

This new vector would look like that shown in **Grid 3**.

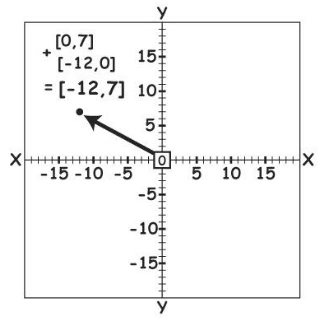
So [-12,+7] on our grid represents where the spacecraft would be.

Now, let's say our little 2-D spacecraft in its 2-D space has tiny thrusters on each of its four sides. So if you wanted to fire the spacecraft's thrusters to counteract the external forces pushing the spacecraft out of position, you need to figure out which thrusters to fire and for how long in order to produce the resulting vector that will compensate.

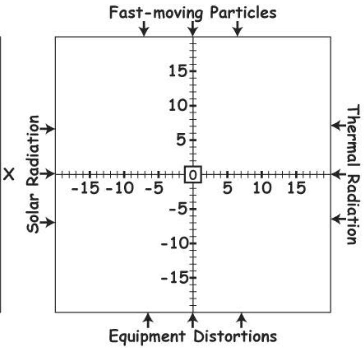
> ***Reminder**: When a spacecraft must correct its course or maneuver into orbit, it fires thrusters in a very precise way to change its direction, speed, or orientation. Newton's Third Law of motion says that every action produces an equal and opposite reaction. All rockets depend on this law. A rocket shoots hot gases out its tail with great velocity, and the rocket moves off in the opposition direction.*

Back to our problem—which thrusters shall we fire and with what amount of force? We must compensate for forces that add up to the vector [-12,7]. So, because of Newton's Third Law, we want our compensating force to be equal and opposite. In other words, they should add up to [+12, -7], so that the end result will, once again, be [0,0], putting the spacecraft back at the center of our grid where it belongs.

How will we get this compensating vector? Since we have just four thrusters and each can fire in only one direction, we must break our desired resulting vector into two vectors, one for each of two thrusters. So we could achieve the [+12, -7] by adding together a [+12,0] vector and a [0,-7] vector. Now all we have to remember is to fire the thrusters exactly in the opposite direction of where we want the spacecraft to go. So to get the [+12,0] component, we would fire the left thruster to make the spacecraft go to the right. To get the [0,-7] component, we would fire the top (up) thruster to make the spacecraft go down. Fired together, the spacecraft would end up back where we want it, at [0,0].



Grid 3



Grid 4

DISTURBANCE AND ANTI-DISTURBANCE

Form one **Disturbance Team** of five members. Form one or more **Spacecraft Teams** of three members. It's OK to have different numbers of people on a team, but you will have to modify the roles a bit to fit. Each Spacecraft represents one flying in tight formation with the others to make a giant space interferometer and look for Earth-like planets in other solar systems.

The **Disturbance Team,** will represent the forces in space acting on the spacecraft to spoil the precise positioning needed for formation flying with the other spacecraft. Each **Spacecraft Team** will figure out how to compensate for the Disturbances and bring the spacecraft back into its correct position in the formation.

(The teacher should photocopy **Grid 4** or redraw it and then photocopy it, with several copies for each team.)

Four members of the Disturbance Team each represents a force. We will call them the **Disturbers**. The fifth member will be the Disturbance Summarizer. On **Grid 4**, for simplicity's sake, we are going to assume that each force is acting directly up, down, left or right.

GAME 1:

Each **Disturber** thinks of a number from 1-20, and draws a vector that represents the force with which it pushes on the spacecraft. For example, if "SOLAR RADIATION" picked 15, it would be pushing from left to right, described as [+15,0]. If "FAST-MOVING PARTICLES" picked 6, it would be pushing from top toward bottom, described as [0,-6].

The fifth Team Member, the **Disturbance Summarizer**, adds up the vectors to come up with the resulting force on the spacecraft from all these disturbances acting together, and draws this resulting vector on the grid. The Summarizer then announces the summary vector numbers to all Spacecraft Teams.

One person on each Spacecraft Team is the **Spacecraft Analyst**. It is the Spacecraft Analyst's job to plot the announced vector on the spacecraft grid, then draw the correction vector required to bring the spacecraft back to the center. The two other members are **X Thrust Navigator** and **Y Thrust Navigator**. From the Analyst's correction vector, each Navigator calculates how much force will be needed from which of their two opposed thrusters to compensate for the disturbance. To fire, each Navigator draws the component vectors that their thrusters produce on the grid. Thrusters are fired by turns, starting with X.

GAME 2:

All spacecraft can use the same Disturbance Team vector. Or, the **Disturbance Summarizer** can easily generate individual disturbance vectors for up to four spacecraft by reversing coordinate signs. Using disturbance coordinates [+3, -7], for example, the Summarizer can change the signs to [-3, +7], [+3, +7] , [-3, -7]. The Summarizer can supply disturbance coordinates to four additional spacecraft by then reversing vector numbers: [+7, -3], [-7, +3], [+7, +3], [-7, -3].

Spacecraft hardware must be simple, lightweight, and reliable. To meet these requirements, we have simplified how our two dimensional spacecraft thrusters operate. Each thruster will produce force in increments of 4 units on its first firing. On its second firing, however, it will produce a force of just 1 unit. Each thruster then alternates firing in increments of 4 units, then just 1 unit.

In other words, any thruster can produce a force of 4, 8, 12, 16, or 20 on its first, third, fifth, etc., firing.. But the second (or fourth, sixth, etc.) time it fires, it produces force increments of 1 unit. Navigators must figure out the exact X or Y vector needed to compensate for the disturbance vector. If the correction vector is not divisible by 4, the Navigator can overshoot or undershoot on the first firing and correct the difference with additional firing. For example, if a [-11, 0] thrust is needed to compensate for a [+11, 0] disturbance vector, the X Navigator could command the minus-X thruster to fire at [-16, 0], then the plus-X thruster to fire at [+4, 0], and the plus-X thruster to fire again at [+1, 0].

Can you see other strategies?

How would you compensate for a [+10, 0] disturbance?

The X Navigator fires first, followed by the Y Navigator. Each fires once per turn. If the spacecraft is not brought back to zero at the last firing, look for the error and make corrective firings, as needed.

ADDING DIMENSION AND PRECISION

Of course, the real problem that the Space Technology 7 Disturbance Reduction System must solve has a few more complications. For one thing, it must operate in three dimensions, and it has to be able to measure and correct for changes in position that are a fraction of one wavelength of light. When you really think about it, this is an amazing technology, far beyond what any technology has so far been able to do.

To measure the slightest shift in position due to external forces on the spacecraft, the DRS contains two freely floating masses that do not touch any part of the spacecraft. It is as if the spacecraft and the floating masses inside it are also flying in formation, but very, very closely. A measurement system (based on measuring electrical charge) detects when the spacecraft moves with respect to the floating test mass inside. The test masses are protected from solar radiation, impacting particles, and other disturbances coming from outside the spacecraft. If movement of the spacecraft is detected, microthrusters on the outside of the spacecraft fire just enough to correct for the detected movement.

Of course, in the case of the DRS, all the calculations are done at blinding speed by a computer, which also controls the thrusters. It is a continuously operating system of constant measuring and thrusting to keep the spacecraft nearly perfectly unperturbed in its formation position.

The DRS will be tested first on a spacecraft called LISA Pathfinder to be flown by the European Space Agency. This mission will pave the way for the LISA (Laser Interferometer Space Antenna) mission planned for launch in 2011.

The Disturbance Reduction System is one of the highly advanced technologies that will allow us to learn fascinating new things about Earth and the universe and reveal the answers to some of its deepest mysteries: Are we alone? How did the Universe begin?

Find out more about Space Technology 7 and the Disturbance Reduction System at **nmp.nasa.gov/st7 .**

This article was written by Diane Fisher, writer and designer of The Space Place website at ***spaceplace.nasa.gov****. Alex Novati drew the illustrations. Thanks to Gene Schugart, Space Place advisor, for activity concept and helpful advice. The article was provided through the courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under a contract with the National Aeronautics and Space Administration.*