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Chasing Down a Satellite

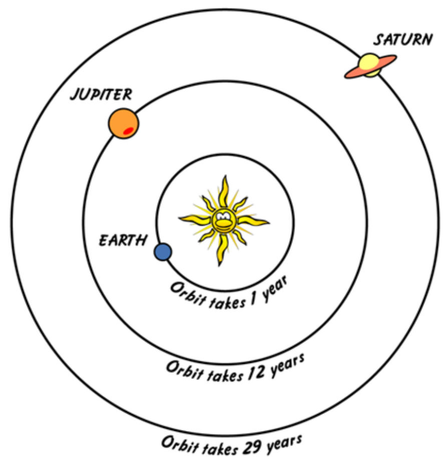
Have you ever spotted a satellite crossing the night sky over your town or city? Although it may have been a mere point of light like a star or planet, you could not mistake a visible satellite for a star, a planet, or even a high altitude plane. The reason? Even a plane does not move across the sky as fast as a satellite.

The International Space Station (ISS) is the easiest satellite to spot because it is by far the biggest and its orbit is low compared to many satellites. Take a look on NASA's list of ISS viewing opportunities at **www.hq.nasa.gov/osf/station/viewing/issvis.html** to see whether the Space Station might be visible from your location. If so, make plans to look for it.

Just how fast does the Space Station travel? And how do it and other satellites stay in orbit? Why doesn't Earth's gravity just bring them crashing down? Why and how do they travel so fast? And how do spacecraft engineers here on Earth control them?

Weightless? No Way!

Satellites take advantage of some basic laws of physics that two scientists figured out around 400 years ago. *Johannes Kepler*, a German astronomer and mathematician, discovered that the time it takes for one body to orbit another (like a planet to orbit the Sun) is directly related to the distance between the bodies. For example, he discovered that it takes Jupiter (the 5th planet from the Sun) 12 years for one orbit, while Saturn (the 6th planet) takes about 29 years for one orbit. *Isaac Newton*, English scientist and mathematician, came along few years later and discovered the direct relationship between mass and a force he called gravity, which acts to keep the planets in orbit about the Sun, rather than shooting off into space in a straight line.



Jupiter's orbit, which is much larger than Earth's, takes about 12 years to complete, while Saturn's takes about 29 years. (Orbit and planet sizes are not to scale in this diagram.)

Newton had a clever way to explain how one body could orbit another. Imagine a cannon mounted on top of a ridiculously tall mountain. The cannon is fired and the cannonball follows an arc (or trajectory), landing some distance away. If more gunpowder is used in the cannon, the cannonball will go even farther before crashing to the ground. Use enough gunpowder, and the cannonball will actually follow the curvature of Earth all the way around to where it started—and keep right on going! In other words, the cannonball will be in orbit.

An object in orbit around Earth is actually falling all the way around Earth. To put satellites into orbit, of course we don't use cannons on mountain tops! Instead, we use rockets to lift the satellite high enough and "throw" it hard enough that it will fall all the way around Earth. As Kepler noticed with the planets orbiting the Sun, the lower the satellite's orbit, the faster it will fall. The higher its

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orbit, the slower it will fall. Newton's discoveries help explain why. The force of gravity between objects is directly proportional to their masses and inversely proportional to the square of the distance between them. So, the force of gravity (F) between two masses (M_1 and M_2) is proportional to M_1 times M_2, with the result divided by the square of the distance (d) between them.

$$F \sim \frac{M_1 M_2}{d^2}$$

One thing missing in this formula is how to get force out of mass. Mass is the amount of matter in an object, which doesn't change whether it is on Earth's surface or in space or on the Moon. The force gravity exerts on it, does change, however. The *Universal Gravitational Constant*, or just G, is the actual measured, very weak gravitational force exerted between two 1-kilogram objects 1 meter apart. It is a mere .0000000000667 Newton. (A Newton is the force it takes to accelerate 1 kilogram by 1 meter per second per second. A Newton can also be expressed by the unit $kg \cdot m/s^2$). To avoid writing all these zeros, and trying to keep track of them in calculations, scientists use a mathematical shorthand called scientific notation. In scientific notation, G would be written

$$\mathbf{G = 6.67 \times 10^{-11}\ m^3/kg \cdot s^2}$$

The unit of G (**$m^3/kg \cdot s^2$**) might not seem to make much sense, but rather than explain it now, we hope you will accept it on faith!

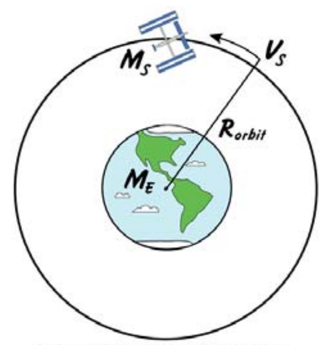
Let's Figure It Out

If you spot the Space Station, you will see it really moves! Just how fast is it going?

Based on Kepler's and Newton's discoveries, you can figure out the speed of a satellite in a circular orbit. (The orbit of the Space Station isn't exactly circular, but it's close enough that we will ignore its slight elongation.)

You need to know the mass of Earth (which was easy to figure out once the value of G was measured accurately), the mass of the satellite, and its altitude above Earth's surface. Their relationships can be expressed mathematically like this:

$$\frac{m_s v_s^2}{R_{orbit}} = \frac{G M_E m_s}{R_{orbit}^2}$$



(This diagram does not represent the true orbital plane of the Space Station.)

This equation says that the mass of the satellite (**m_s**) times the square of the velocity of the satellite (**v_s^2**) divided by the radius of the satellite's orbit (**R_{orbit}**) (measured from the center of Earth) is equal to **G** times the mass of Earth (**M_E**) times the mass of the satellite (**m_s**) divided by the square of radius of the satellite's orbit. Then, if we solve for the velocity, we get

$$v_s = \sqrt{\frac{G M_E}{R_{orbit}}}$$

This equation says that to find the velocity of a satellite, multiply **G** times the mass of Earth, then divide the product by the radius of the satellite's orbit. (The radius of its orbit is the radius of Earth plus the altitude of the satellite above Earth's surface.) Then take the square root of the result. But notice that the mass of the satellite has disappeared from the equation! Just as *Galileo* is said to have noticed when he leaned out of the Tower of Pisa and dropped a heavy object and a light object, mass has no bearing on the speed with which objects fall.

From the equation for $\mathbf{v}_s$, calculate the velocity of the Space Station. Here are the (approximate) numbers you will need for all the calculations:

G	=	6.67×10^{-11} m³/kg·s²
M_E	=	6×10^{24} kilograms
Radius of Earth	=	6,371 kilometers
Average altitude of ISS orbit	=	385 kilometers (as of 10/8/02)

Remember, to get the radius of the ISS's orbit, you have to add the radius of Earth to the altitude of the ISS above Earth.

So, how fast is the Space Station moving? How long would it take to cross the United States from one coast to the other at this speed? (Answer is on the last page of this article.)

Bonus Problem!

Would it be possible to put a satellite into an orbit so that it would seem to hover over one spot on Earth all the time? Absolutely. This type of orbit is called a *geosynchronous* or *geostationary* orbit. The satellite must orbit in (or very near) the same plane as Earth's equator, and must be at an altitude that will let it make just one orbit per day. Thus, it will be as if it is on a long string running down to Earth's surface and being swung around as Earth rotates on its axis. What would be altitude of this satellite's orbit? Here's how to figure it out.

Let's call the radius of the satellite's geosynchronous orbit R_{geo}. We know that whatever its orbit, it will have to make it all the way around in 24 hours (86,400 seconds). The circumference (distance around) the orbit is $2\pi R_{geo}$. So the velocity of the satellite will be

$$v = \frac{2\pi R_{geo}}{86{,}400 \text{ sec}}$$

Solving for R_{geo}, we have

$$\frac{2\pi R_{geo}}{86{,}400 \text{ sec}} = \sqrt{\frac{GM_E}{R_{geo}}}$$

$$\frac{4\pi^2 R_{geo}^{\;2}}{(86{,}400 \text{ sec})^2} = \frac{GM_E}{R_{geo}}$$

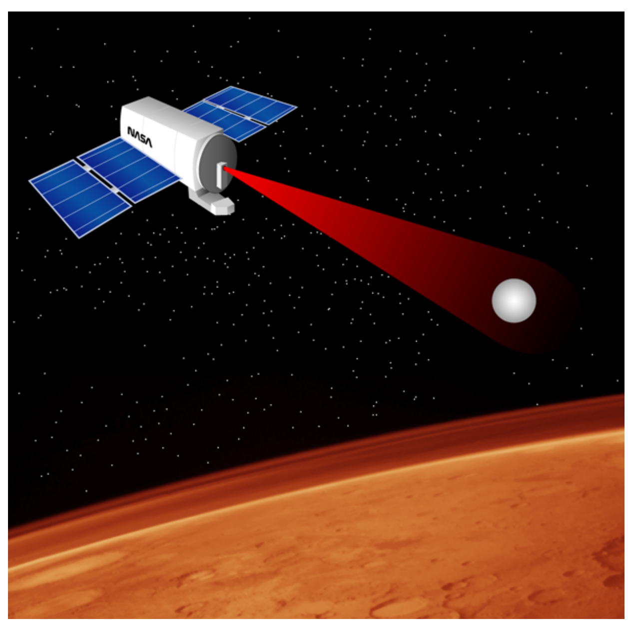
$$R_{geo} = \sqrt[3]{\frac{GM_E(86{,}400 \text{ sec})^2}{4\pi^2}}$$

So, using the values given before for G and M_E, and using 3.1416 for π, what will the altitude be of a satellite in geosynchronous orbit? (Answer is on the last page of this article.)

Just Imagine this Problem!

Even in very high altitude orbits, satellites are moving very fast. Every time the Space Shuttle makes a trip to the Space Station to deliver cargo or ferry astronauts, the Space Shuttle has to catch up, rendezvous, and dock with the Space Station. Astronauts train for months to learn how to do this.

Now, imagine this problem: One spacecraft needs to catch up and rendezvous with another spacecraft and neither one of them has a human aboard. What's more, the mission controllers on Earth are so far away it takes a command signal several minutes to travel from Earth to the spacecraft. This is exactly the problem to be solved when NASA does its first Mars Sample Return mission. The Mars soil and rock samples will have been placed in a small canister and blasted into orbit around Mars by a robotic Mars lander. Another spacecraft that has been orbiting Mars needs to find the orbiting sample canister, rendezvous with it, and bring it home to Earth.



NASA's New Millennium Program Space Technology 6 mission will test advanced autonomous rendezvous technology.

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What is needed is an *autonomous rendezvous* technology. NASA's New Millennium Program has the job of identifying new technologies that will be needed for future NASA missions and then testing them in space to make sure they will work. Part of New Millennium's Space Technology 6 mission is to test an Autonomous Rendezvous system in Earth orbit. The rendezvous system will fly in 2004 as part of the payload onboard an Air Force satellite.

The rendezvous system includes a laser radar sensor (called *LIDAR*) that will act as the eyes to find and detect the distance to a target spacecraft (which will be one that is no longer operating). The LIDAR will feed direction and distance information to the computer and software part of the rendezvous system. The software will then calculate the steps necessary to reach the target and give instructions to the thrusters on the spacecraft to change its attitude (orientation in space) and velocity so that the spacecraft will move toward the target. The LIDAR will continue to give feedback to the computer and the software will continuously check and update its calculations and instructions to the spacecraft to close in on the target.

If you think calculating the velocity of a satellite is difficult, imagine the calculations needed to figure out how to change your velocity and orientation to rendezvous with another spacecraft (also moving at tens of thousands of kilometers per hour) in a different orbit. Of course, your calculations have to keep in mind that a change in your velocity is going to bring a change in your own altitude and it might not be in the right direction!

In the next Space Place column, we'll explore further how software engineers tackle hard problems like that of ST6's Autonomous Rendezvous software.

Learn more about ST6 at nmp.jpl.nasa.gov/st6 . For another fun activity and more about another new Space Technology 6 technology, see The Space Place web site at spaceplace.nasa.gov/st6starfinder/st6starfinder.htm .

This article was written by Diane Fisher, writer and designer of The Space Place website at ***spaceplace.nasa.gov****. Thanks to Jack Stocky, New Millennium Program Chief Technologist, for technical help. Alex Novati drew the illustrations. 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.*

Answers:

At an altitude of 385 kilometers, the ISS travels at about 27,707 kilometers per hour. Since it goes all the way around Earth once every 92 minutes, no wonder it doesn't seem to stick around very long overhead.

The geosynchronous orbit is about 35,800 kilometers above the equator. Your answer may vary a bit, depending on how you rounded your numbers during the calculating.