Orbits

6.2

RADARSAT-1 and RADARSAT-2 are Earth-observation satellites designed and commissioned by the Canadian Space Agency. These "eyes in the skies" peer down from orbit, capturing images and data that help scientists monitor environmental changes and the planet's natural resources. Examples of satellite monitoring include detecting oil spills, tracking ice movements, identifying ships at sea, and monitoring natural disasters. **Figure 1** shows an image of RADARSAT-2.

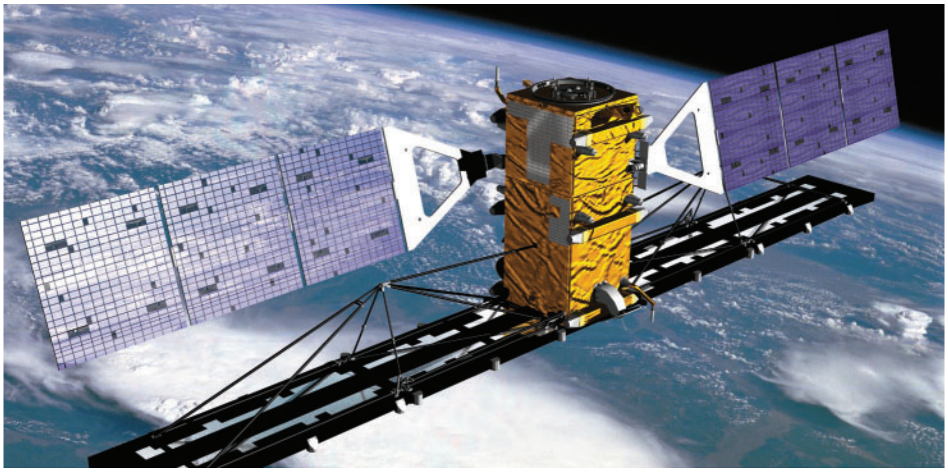

Figure 1 RADARSAT-2 uses sophisticated microwave-based radar to collect images of Earth day and night, even through cloud cover.

Satellites and Space Stations

A **satellite** is an object or a body that revolves around another body that usually has much more mass than the satellite. For example, the planets are natural satellites revolving around the Sun. Planetary moons, including Earth's moon, are natural satellites, too. **Artificial satellites**, on the other hand, are human-made objects that orbit Earth or other bodies in the solar system. CAREER LINK

RADARSAT-1 and RADARSAT-2 are examples of artificial satellites. Another well-known example of artificial satellites is the network of 24 satellites that make up the Global Positioning System (GPS). By coordinating several signals at once, as shown in **Figure 2**, the system can locate an object on Earth's surface to within 15 m of its actual position.

satellite an object or a body that revolves around another body due to gravitational attraction

artificial satellite an object that has been intentionally placed by humans into orbit around Earth or another body; referred to as "artificial" to distinguish from natural satellites such as the Moon

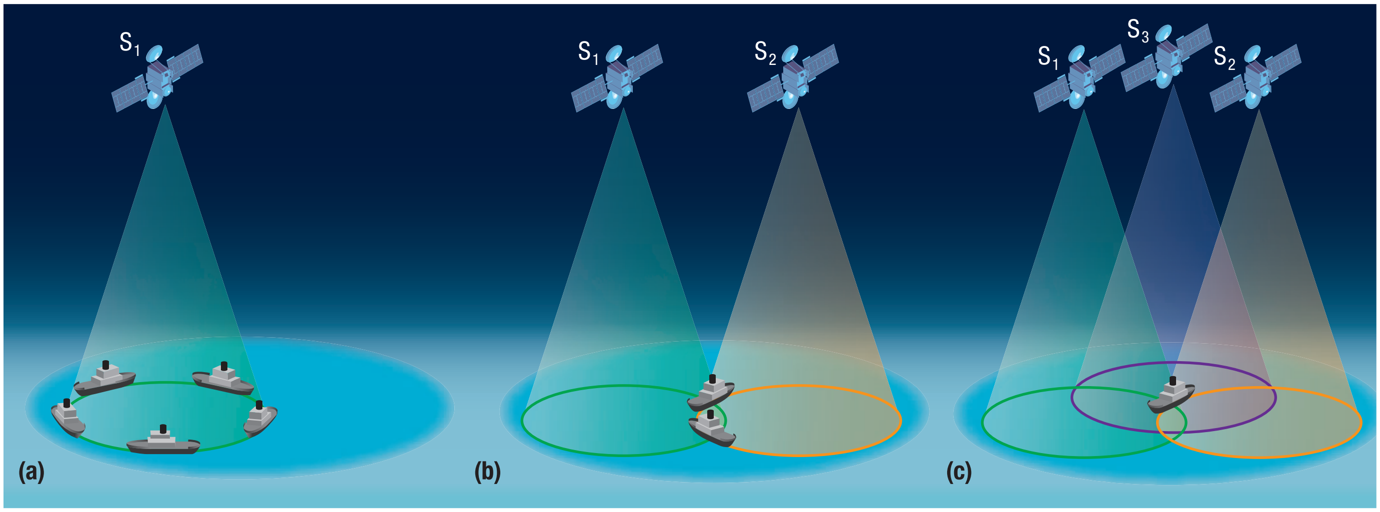

Figure 2 GPS satellites can determine the location of an object, in this case a boat. (a) The data from one satellite will show that the location is somewhere along the circumference of a circle. (b) Two satellites consulted simultaneously will refine the location to one of two intersection spots. (c) With three satellites consulted simultaneously, the intersection of three circles will give the location of the boat to within 15 m of its actual position.

The boat shown in Figure 2 on the previous page has a computer-controlled GPS receiver that detects signals from three satellites simultaneously. The system calculates distances based on signal speeds and transmission times. A single satellite can identify the boat's location somewhere along the circumference of a circle. Two simultaneous satellite signals can pinpoint the location at one of two intersecting spots where two circles intersect. With a third satellite—and therefore three intersecting circles—the boat's location can be pinpointed. This is referred to as triangulation.

space station a spacecraft in which people live and work

Another example of an artificial satellite in Earth orbit is a **space station**, a spacecraft in which people live and work. An example is the International Space Station (ISS), shown in **Figure 3**. The ISS is a permanent orbiting laboratory that supports many different research projects. In the process, scientists are also able to study human responses to space travel and "zero" gravity or, more accurately, microgravity: 1×10^{-6} times the value of g. A microgravity environment is present when any object is in free fall. So when you dive from a dive tower into a swimming pool, you are in microgravity until you hit the water. Similarly, astronauts aboard the ISS are in a constant state of free fall and are thus in a microgravity environment. It is important to note the difference between microgravity and the gravitational field strength, since the value of g at the altitude of the ISS is approximately 8.7 N/kg. Clearly, there is still a significant gravitational force at that altitude and it is incorrect to say that the astronauts are in zero gravity. A gravitational force of approximately zero would only occur if you were extremely far away from any mass.

Figure 3 The International Space Station is an orbiting spacecraft in which astronauts live and work in space.

The knowledge gained from research by orbiting space stations enables scientists to design spacecraft that can safely transport people through space and perform experiments in microgravity environments. These microgravity experiments can lead to breakthroughs in medicine and chemistry. CAREER LINK

Mini Investigation

Exploring Gravity and Orbits

Skills: Performing, Observing, Analyzing, Communicating

In this investigation, you will use a simulation to create and explore different configurations of orbiting bodies. Move the planets, moons, or the Sun to see how the orbital paths change. Change the sizes of the objects and the distances between them. Explore the variations that occur as the force of gravity is changed or when gravity is removed from the model.

Equipment and Materials: computer with Internet access

1. Go to the Nelson Science website.
2. Load the supporting software, if necessary.
3. Select the option to view the Sun, Earth, and Moon and the options to show Gravity Force and the Path.
4. Play the simulation and allow Earth to complete one full revolution around the Sun.
5. Pause the simulation.
6. Using the slider bar, increase the size of the Sun and start the simulation again. Observe the motion of Earth and the Moon around the Sun for one full revolution.
7. Pause the simulation again. Return the Sun to its original size and then increase the size of Earth.
8. Start the simulation again and observe Earth's revolution.

A. What happens to the orbit of Earth when you increase the size of the Sun? T/I A

B. What happens to the Moon when you increase the size of the Sun? What happens when you increase the size of Earth? T/I A

C. What happens to Earth's orbit when you increase the size of Earth? T/I A

D. The MESSENGER probe mentioned at the beginning of this chapter made use of several gravity assists to reach Mercury without using too much of its own energy. This method is also known as a gravitational slingshot. It works by using the gravity of a celestial body to accelerate, slow down, or redirect the path of a spacecraft. Gravity assists can save fuel, time, and expense. Try to design a system of orbiting elements within the simulation that demonstrates this effect. K/U T/I C A

WEB LINK

Satellites in Circular Orbits

When Newton developed the idea of universal gravitation, he also theorized that the same force that pulls objects to Earth also keeps the Moon in its orbit. One difference, of course, is that the Moon does not hit Earth's surface. The Moon orbits Earth at a distance from Earth's centre—called the **orbital radius**. The orbit of the Moon about Earth is another example of centripetal motion, which you studied in Chapter 3. The force of gravity on the Moon due to Earth is a centripetal force that pulls the Moon toward Earth's centre. As the Moon orbits Earth, the Moon has velocity perpendicular to the radius vector. Without gravity, the Moon would fly off in a straight line. Without its orbital velocity, however, the force of gravity would pull the Moon straight to Earth's surface. The orbital motion of the Moon depends on both the centripetal force due to gravity and the Moon's orbital velocity.

orbital radius the distance between the centre of a satellite and the centre of its parent body

The Moon's orbit, similar to the orbits of the planets around the Sun, is actually elliptical. We can closely approximate the orbits, however, by assuming that they are circular. This approximation is useful for most problem-solving purposes. To analyze the motion of a satellite in uniform circular motion, combine Newton's law of universal gravitation with the mathematical expression describing centripetal acceleration. Using the universal law of gravitation from Section 6.1, we can say that the gravitational field strength of Earth with mass m_E at the location of a satellite at height r above Earth's centre is

$$g = \frac{Gm_E}{r^2}$$

Recall from Chapter 3 that the formula for centripetal acceleration based on the orbiting object's speed v is

$$a_c = \frac{v^2}{r}$$

For a satellite in a circular orbit, the gravitational force provides the centripetal force. Combining the above two equations gives

$$a_c = g$$

$$\frac{v^2}{r} = \frac{Gm_E}{r^2}$$

Solving for the speed of the satellite and using only the positive square root gives

$$\boxed{v = \sqrt{\frac{Gm_E}{r}}}$$

This equation holds for an orbiting body in a central gravitational field. If a satellite orbits around any other large body with mass m, we can replace the mass of Earth in this equation and generalize it to

$$\boxed{v = \sqrt{\frac{Gm}{r}}}$$

This equation indicates that the speed of a satellite depends on its orbital radius and is independent of the satellite's own mass. For a satellite to maintain an orbit of radius r, its speed v must be constant.

UNIT TASK **BOOKMARK**

You can apply what you have learned about orbits and satellites to the Unit Task on page 422.

geosynchronous orbit the orbit around Earth of an object with an orbital speed matching the rate of Earth's rotation; the period of such an orbit is exactly one Earth day

A communications satellite in **geosynchronous orbit**—that is, a satellite orbiting Earth with a speed matching that of Earth's own rotation—is an example of an artificial satellite with a constant orbital radius (**Figure 4**). The orbital period, represented by the symbol *T*, is the time it takes an object to complete one orbit around another object. A geosynchronous satellite's orbital speed leads to an orbital period that exactly matches Earth's rotational period. To an observer on Earth, the satellite will appear to travel through the same point in the sky every 24 h. A geostationary orbit is a type of geosynchronous orbit in which the satellite orbits directly over the equator. To an observer on Earth, a geostationary satellite will appear to remain fixed in the same point in the sky at all times. CAREER LINK

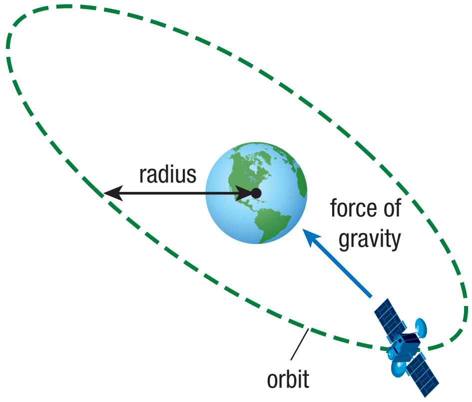

Figure 4 A satellite with a geosynchronous orbit travels at the same speed as Earth's rotation. Its orbital period is one Earth day.

In the following Tutorial you will explore how you can use the equation for orbital speed in problem solving.

Tutorial 1 Solving Problems Relating to Circular Orbits

The Sample Problems in this Tutorial show how to determine the properties of an object in a circular orbit within a gravitational field around a larger object.

Sample Problem 1: Calculating the Speed and Orbital Period of a Satellite

The International Space Station (ISS) orbits Earth at an altitude of about 350 km above Earth's surface.

(a) Determine the speed needed by the ISS to maintain its orbit.

(b) Determine the orbital period of the ISS in minutes.

Solution

(a) **Given:** $G = 6.67 \times 10^{-11}\ \text{N·m}^2/\text{kg}^2$; $m_E = 5.98 \times 10^{24}$ kg; $r_E = 6.38 \times 10^6$ m; $h_{ISS} = 350\ \text{km} = 3.5 \times 10^5$ m

Required: v

Analysis: $v = \sqrt{\dfrac{Gm_E}{r}}$; $r = r_E + h_{ISS} = 6.73 \times 10^6$ m

Solution: $v = \sqrt{\dfrac{Gm_E}{r}}$

$$= \sqrt{\frac{\left(6.67 \times 10^{-11} \dfrac{\cancel{\text{kg}} \cdot \dfrac{\cancel{\text{m}}}{\text{s}^2} \cdot \text{m}^2}{\cancel{\text{kg}^2}}\right)(5.98 \times 10^{24}\ \cancel{\text{kg}})}{6.73 \times 10^6\ \cancel{\text{m}}}}$$

$v = 7.698 \times 10^3$ m/s (two extra digits carried)

Statement: The ISS requires a speed of 7.7×10^3 m/s to maintain its orbit.

(b) **Given:** $v = 7.698 \times 10^3$ m/s; $r = 6.73 \times 10^6$ m

Required: T

Analysis: The distance travelled in one period is $2\pi r$. The orbital period, T, is the time it takes for the space station to travel this distance, so it is the distance divided by the speed, $T = \frac{2\pi r}{v}$.

Solution:

$$T = \frac{2\pi r}{v}$$

$$= \frac{2\pi(6.73 \times 10^6\ \cancel{\text{m}})}{7.698 \times 10^3\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}} \times \frac{1\ \text{min}}{60\ \cancel{\text{s}}}$$

$$T = 92\ \text{min}$$

Statement: The ISS has an orbital period of 92 min.

Sample Problem 2: Calculating the Speeds of Planets around the Sun

Determine the speeds of Venus and Earth as they orbit the Sun. The Sun's mass is 1.99×10^{30} kg. Venus has an orbital radius of 1.08×10^{11} m, and Earth has an orbital radius of 1.49×10^{11} m.

Given: $G = 6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$; $m_S = 1.99 \times 10^{30}$ kg; $r_V = 1.08 \times 10^{11}$ m; $r_E = 1.49 \times 10^{11}$ m

Required: v_V; v_E

Analysis: $v = \sqrt{\frac{Gm}{r}}$

Solution:

$$v_V = \sqrt{\frac{Gm_S}{r_V}}$$

$$= \sqrt{\frac{\left(6.67 \times 10^{-11} \frac{\cancel{\text{kg}} \cdot \frac{\cancel{\text{m}}}{\text{s}^2} \cdot \text{m}^2}{\cancel{\text{kg}^2}}\right)(1.99 \times 10^{30}\ \cancel{\text{kg}})}{1.08 \times 10^{11}\ \cancel{\text{m}}}}$$

$$v_V = 3.51 \times 10^4\ \text{m/s}$$

$$v_E = \sqrt{\frac{Gm_S}{r_E}}$$

$$= \sqrt{\frac{\left(6.67 \times 10^{-11} \frac{\cancel{\text{kg}} \cdot \frac{\cancel{\text{m}}}{\text{s}^2} \cdot \text{m}^2}{\cancel{\text{kg}^2}}\right)(1.99 \times 10^{30}\ \cancel{\text{kg}})}{1.49 \times 10^{11}\ \cancel{\text{m}}}}$$

$$v_E = 2.98 \times 10^4\ \text{m/s}$$

Statement: Venus orbits the Sun at a speed of 3.51×10^4 m/s, and Earth orbits the Sun at a speed of 2.98×10^4 m/s.

Practice

1. Astronomers have determined that a black hole sits at the centre of galaxy M87 (**Figure 5**). Observations show matter at a distance of 5.34×10^{17} m from the black hole and travelling at speeds of 7.5×10^5 m/s. Calculate the mass of the black hole, assuming the matter being observed moves in a circular orbit around it. T/I A [ans: 4.5×10^{39} kg]

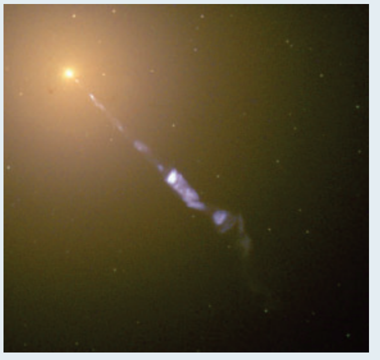

Figure 5

2. Mars orbits the Sun in a nearly circular orbit of radius 2.28×10^{11} m. The mass of Mars is 6.42×10^{23} kg. Mars experiences a gravitational force from the Sun of magnitude 1.63×10^{21} N. Calculate the speed of Mars and the period of revolution for Mars in terms of Earth years. T/I A [ans: 2.41×10^4 m/s; 1.90 Earth years]
3. Calculate the speed of a satellite in a circular orbit 600.0 km above Earth's surface. Determine the orbital period of the satellite to two significant digits. T/I A [ans: 7.56×10^3 m/s; 97 min]
4. Satellites can orbit the Moon very close to the Moon's surface because the Moon has no atmosphere to slow the satellite through air resistance. Determine the speed of a satellite that orbits the Moon just 25 m above the surface. (Hint: Refer to Appendix B for radius and mass data for the Moon.) T/I A [ans: 1.7×10^3 m/s]

Investigation 6.2.1

Design a Solar System (page 309)
With what you have learned about orbits and the movement of planetary bodies, you are ready to take the next step. This investigation will give you an opportunity to create your own solar system with a sun, several planets, and moons.

Research This

Space Junk

Skills: Researching, Analyzing, Communicating

SKILLS HANDBOOK A4.1

Space junk is debris from artificial objects orbiting Earth. It is just one example of how beneficial technology can have unwanted environmental effects. In this activity, you will research space junk and discover how an orbiting body can go from being a functioning satellite to being space junk.

1. Research the mechanisms that satellites have to maintain speed and orbital radius.
2. Research methods of dealing with different forms of space junk.
3. Explore one story of space junk that catches your interest.

A. Review this chapter's formulas pertaining to the relationship between orbital speed and orbital radius. Describe effects that could make a satellite slow down in its orbit and slip into a lower orbit. C A

B. Describe what happens when a satellite drifts so low that it enters Earth's atmosphere. C A

C. Are there any ways to avoid creating space junk? T/I C

D. Are there any effective ways to get rid of existing space junk? C A

E. Compose an email to a friend describing what space junk is. Include the interesting example you researched in Step 3. C

WEB LINK

6.2 Review

Summary

- Satellites can be natural, such as moons around planets, or artificial, such as the RADARSAT satellites and the International Space Station.
- The speed, v, of a satellite in uniform circular motion around a central body depends on the mass of the central body, m, and the radius of the orbit, r:

$$v = \sqrt{\frac{Gm}{r}}$$

- For a given orbital radius, a satellite in circular orbit has a constant speed.

Questions

1. What is the difference between natural and artificial satellites? Give an example of each. K/U
2. Explain what microgravity is. K/U
3. Explain in your own words how GPS satellites work. K/U
4. (a) What is a geosynchronous orbit?
   (b) How does a satellite in geosynchronous orbit appear to an observer on Earth?
   (c) How does a satellite in geostationary orbit appear to an observer on Earth? K/U C
5. Calculate the orbital radius of a satellite in geosynchronous orbit. K/U T/I A
6. Neptune orbits the Sun in 164.5 Earth years in an approximately circular orbit at a radius of 4.5×10^9 km. T/I A
   (a) Determine the orbital speed of Neptune.
   (b) Determine the mass of the Sun.
7. Saturn makes one complete orbit of the Sun every 29 Earth years with a speed of 9.69 km/s. Calculate the radius of the orbit of Saturn. Assume a circular orbit. T/I A
8. The region of the solar system between Mars and Jupiter, called the Asteroid Belt, contains many asteroids that orbit the Sun. Consider an asteroid in a circular orbit of radius 5.03×10^{11} m. T/I A
   (a) Calculate the speed of the asteroid around the Sun.
   (b) Calculate the period of the orbit in years.
9. In recent years, astronomers have discovered that a number of nearby stars have planets of their own, called exoplanets. A newly discovered exoplanet orbits a star with our Sun's mass (1.99×10^{30} kg) in a circular orbit with an orbital radius of 4.05×10^{12} m. What is the orbital speed of the exoplanet in kilometres per hour? T/I A
10. The orbital radius of one exoplanet is 4.03×10^{11} m, with a period of 1100 Earth days. Calculate the mass of the star around which the exoplanet revolves. T/I A
11. Phobos (**Figure 6**), one of Mars's moons, has an elliptical orbit around Mars with an orbital radius that varies between 9200 km and 9500 km. Calculate the orbital period of Phobos in Earth days, assuming a circular orbit of radius 9.38×10^6 m. The mass of Mars is 6.42×10^{23} kg. T/I A

Figure 6

12. Determine the speed of a satellite, in kilometres per hour, that is in a geosynchronous orbit about Earth. (Hint: Use the equation for the speed of an object in circular motion and equate that to the speed of a satellite in orbit around a central body. Rearrange the equation to solve for the radius. Use the radius to calculate the speed.) K/U T/I A
13. (a) Calculate the orbital speeds of the planets Mercury, Venus, Earth, and Mars using the solar system data in Appendix B.
    (b) What can you conclude about the speed of the planets in orbit farther from the Sun? T/I A
14. Scientists wish to place a geosynchronous satellite near a moon at an altitude of 410 km. The mass of the moon is 7.36×10^{22} kg and it has a radius of 1.74×10^6 m. Calculate the velocity and the period of the satellite. T/I A