



## Chapter 23

# ORBITS AND TRAJECTORIES

In this chapter, we will look at what happens when rocketry is used to send payloads into orbit or to destinations in space. Velocity is one major factor in this process. The other major factor is the direction of the trajectory. It is important to remember that these two factors always work with the forces of nature.



## Objectives

**Describe** orbits and trajectories.

**Define** inertia.

**Explain** how a satellite remains in orbit.

**Identify** the closest and farthest points of an object in orbit about Earth.

**Identify** the closest and farthest points of an object in orbit about another planet and about the Sun.

**Explain** what happens if the velocity of an object in orbit is increased.

**Identify** the components that comprise the takeoff mass of a rocket.

**Describe** escape velocity.

**Define** burnout velocity.

**Describe** the effect of Earth's rotational and orbital velocities on the launching of a satellite.

**Define** total velocity requirement.

**Describe** ballistic flight.

**Describe** a sounding-rocket flight.

**Name** the two basic types of orbits.

**Describe** why lower velocities are required for satellites to stay in orbit at higher altitudes.

**Describe** coplanar transfer.

**Explain** a circular orbit.

**Describe** a coplanar transfer.

**Explain** the Hohmann transfer.

**Explain** the fast transfer method for launching a vehicle.

**Describe** a non-coplanar transfer.

**Explain** a geostationary orbit.

**Explain** why a satellite might be placed into polar orbit.

**State** a reason for placing a satellite into sunsynchronous orbit.

**Describe** the *Titan IV* launch vehicle.

**Describe** the *Atlas* and *Delta* launch vehicles.



## Orbit and Trajectory Defined

The word orbit means a path described by one body in its revolution about another body. All matter within the universe is in motion. This motion begins somewhere down in what we might call the submicroscopic universe. An orbit is a balancing of forces. Where space is concerned, it is a compromise between gravitational attraction and the inertia of a movement. Inertia is the property that causes a body at rest to remain at rest and, a body in motion to remain in motion in a straight line at a constant velocity. This tendency toward motion in a straight line, when modified by gravitational forces, results in motion in a closed orbit, forming what is called an ellipse. The path described by an orbiting body may also be called a trajectory. Trajectory is the path of a body through space. In general, application of the term trajectory space includes the atmosphere. Thus, the terms orbit and trajectory are sometimes combined as orbital trajectory. A trajectory that does not result in an orbit (closed trajectory) must have a beginning and an ending. This is generally known as a ballistic trajectory, particularly if the flight of the object begins and ends on Earth.



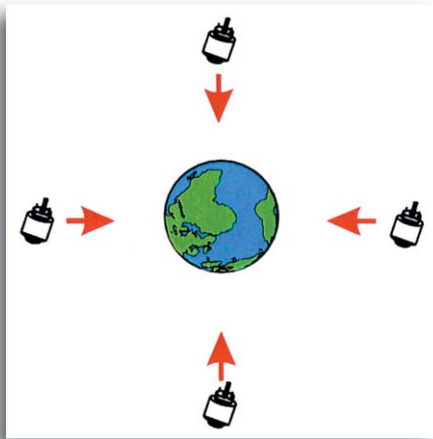
The Upper Atmosphere Research Satellite (UARS) in Orbit

### Basic Orbital Trajectories

An orbit effects a balance between the gravitational and inertial forces. Newton's law of universal gravitation states that the attraction between any two bodies is directly proportional to their masses



and inversely proportional to the square of the distance between them. Another way of saying the same thing is that the farther away two objects are from each other, the less effect their mutual gravitation will have. When applying this to Earth, the force of gravity on the planet itself is less on a mountaintop than it is at sea level. Granted, there is very little difference, but the difference exists.



The Earth's gravitational pull is always toward the center of the planet.

miles high and you climbed this tower equipped with a supply of baseballs. If you dropped a baseball from the top of the tower, gravity would cause it to fall to the Earth. If you threw a baseball from the tower, Newton's first law says that the ball would travel in a straight line (a-b) and at a constant velocity unless acted on by some outside force.

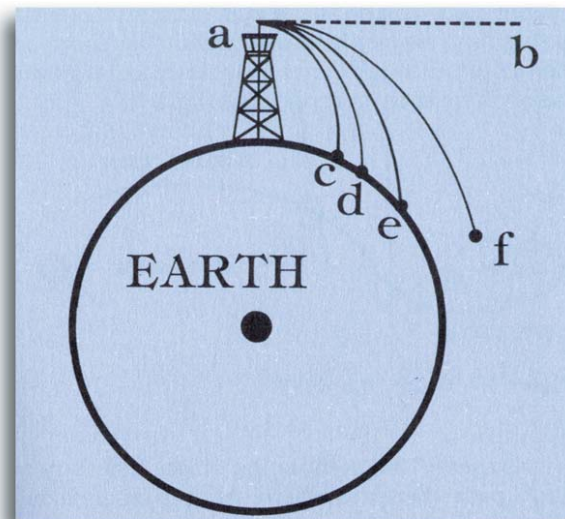
The outside force here is gravity. So the ball would start off traveling in a straight line, but gravity would pull it into a curved path and it would strike the Earth at point c. Throwing the ball harder gives it more inertia and changes the curved path. The ball then would strike the Earth farther from the tower (points d and e), but the result would be the same.

Eventually, it would strike the Earth. If it were possible to throw a ball from the tower at about 18,000 mph, it would have sufficient inertia to follow path f.

Gravity would pull it toward Earth's surface at about the same rate as Earth's surface curves. The result is that the ball remains at a fairly constant distance (altitude) from the surface even though it is constantly falling toward the surface. This balance of forces continues only as long as the velocity is maintained. Slow the ball by some means and gravity will get the upper hand and pull the ball to the surface. Add velocity to the ball and something else will happen. There could be several trajectories that the ball would follow depending on how much force was applied and the direction in which the force was applied. Enough force in the right direction would accelerate the ball on a trajectory that might force it

If an object is taken to an altitude of 100 or 1,000 miles above the Earth and dropped, it would fall to Earth. At 1,000 miles, the attraction would be even less than at 100 miles; therefore, the object would accelerate (or gain speed) more slowly. Nevertheless, it would still fall to Earth. The only way to keep the object from falling to Earth is to produce a force that is equal and opposite to the gravity and which balances the gravitational attraction. This is exactly what is done in keeping a satellite in orbit and the equal and opposite force is the inertial force or centrifugal effect. Inertia and centrifugal effects are both related to Newton's first and second laws of motion. The relationship between gravity and inertia in keeping a satellite in orbit can be visualized below.

Suppose you could build a tower on Earth that was 100



The Balancing of Inertial and Gravitational Forces to Achieve Orbit



out of the solar system. Less force in a different direction might place it in a trajectory that would eventually bring it crashing on to Earth again.

Listed below are definitions that will be used in future discussions:

**Circular orbit**—An orbit that maintains a virtually constant altitude above the Earth’s surface.

**Elliptical orbit**—Any closed orbit that is not circular. All elliptical orbits around Earth have an apogee and a perigee.

**Equatorial orbit**—The satellite travels from west to east over the Earth’s equator. Some satellite orbits incline to the Equator a certain number of degrees.

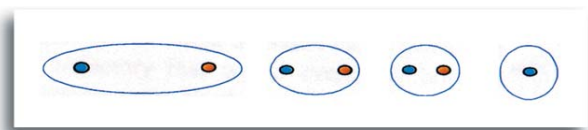
**Escape trajectory**—In launching a spacecraft to the Moon or to another heavenly body, it is necessary to accelerate the spacecraft to its escape velocity (about 25,000 mph). The velocity of the spacecraft is so high and the inertia is so great that the spacecraft comes under the influence of another body’s gravity before it reaches its apogee.

**Apogee**—That point in the orbital trajectory or flight path where the orbiting body is most distant from the body being orbited.

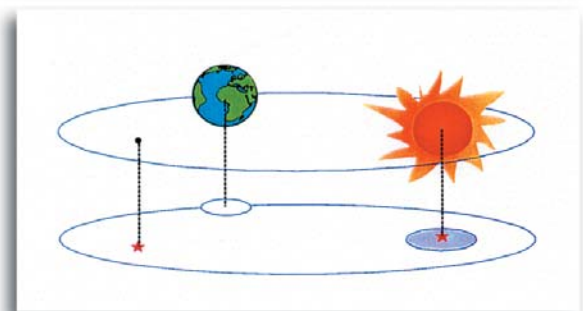
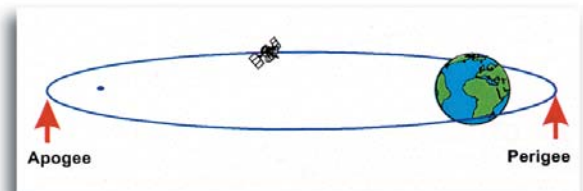
**Perigee**—The opposite of apogee—that point where the orbiting body is closest to the body being orbited. (Apogee and perigee are used only to describe orbits around Earth.)

The orbit of a satellite may be elliptical in shape. The ellipticity is expressed by its closest approach (p) to the Earth called perigee and its farthest point (a) called apogee. The orbit lies within a plane called the orbital plane. The line connecting apogee and perigee passes through the Earth’s mass center. The angle between the orbital plane and the Earth’s equatorial plane is the inclination (i).

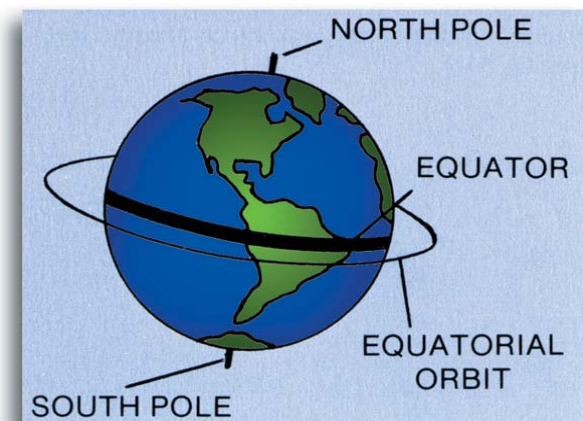
Earth rotates under the orbit, of course, making the satellite visible from many points on Earth in the period of a day. Because the Earth is slightly nonspherical, the orbital plane, while keeping its



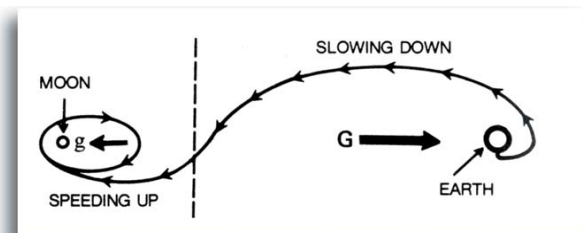
Orbital Shapes



Elliptical Orbit



Equatorial Orbit

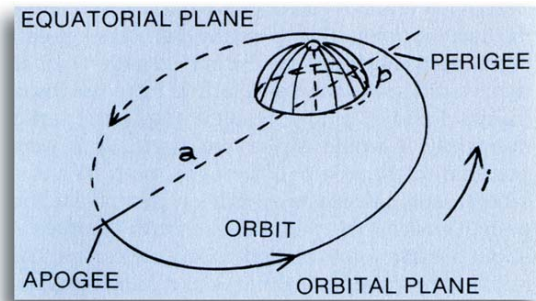


Escape Trajectory



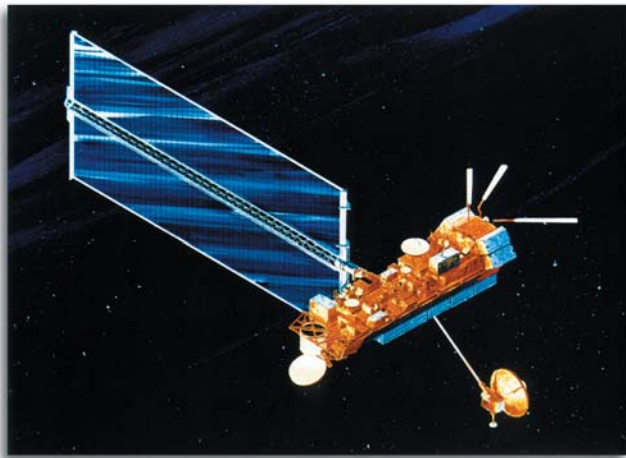
inclination constant, precesses slowly around the North Pole (with respect to the fixed stars) at a rate dependent upon inclination.

Elements for Describing a Geocentric Orbit —



## Velocity Requirements

Velocity requirement means the velocity required in order to travel a certain path. Here on Earth, the idea of such a velocity requirement may seem odd. On the highway, your destination may be 100 to 1,000 miles away, but you can take as much or as little time as you wish without fear of falling short of or overshooting your target. An airplane must achieve a certain velocity in order to keep flying. Within broad limits, it can also vary its airspeed without changing course. In space, on the other hand, how fast you go determines where you go.



Polar Orbiting Platform

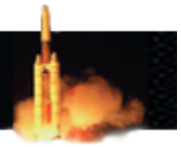
To reach the Moon in the shortest possible time, demands the complicated art of figuring the best trajectory to hit a moving target. Then apply exactly the right amount of thrust needed to propel the spacecraft along the chosen trajectory. Any increase in velocity is translated into a higher orbit instead of a faster orbit.

For example, let's suppose that we have a 90-minute circular orbit established. If we try to increase the vehicle's speed at any point in this orbit, the spacecraft is kicked out of the circular path and goes into an elliptical path. Though the spacecraft will travel faster than before at perigee, it will be considerably slower at apogee. The

total time for a complete circuit of Earth in this new orbit will be longer than 90 minutes.

In order to be used effectively in space missions, a rocket must have a satisfactory mass ratio. The payload, fuel load and deadweight (total weight of the rocket structure) make up the takeoff mass. After the fuel has been burned, the payload and empty rocket are the remaining mass. By dividing the takeoff mass by the remaining mass you obtain the mass ratio. A goal of good rocket engineering is to make the mass ratio large. Therefore, the deadweight must be kept comparatively low.

The rocket must achieve circular velocity if its payload is to go into orbit, without further expenditure of fuel, around a planet such as the Earth. The escape velocity is required for the payload to escape from the gravitational attraction of that planet. The circular velocity and escape velocity differ for each planet because they depend on the planet's mass. In the case of Earth, the circular velocity is



approximately 8 kilometers per second (17,856 miles per hour) and the escape velocity is 11 kilometers per second (25,560 miles per hour).

### ***Burnout Velocity***

At the moment a rocket engine ceases to produce thrust, it is at burnout. The velocity that is required to place a spacecraft on its intended trajectory must be attained at burnout. If something goes wrong and the proper velocity has not been reached by the time burnout occurs (either the propellant is exhausted or automatic cutoff is activated to cause burnout), the payload is not going to reach its intended destination—orbit, Moon, planet and so on.

Today, this type failure is not likely to occur unless there is a major breakdown in the system because rocketry systems have been perfected to the point where there is a great deal of control over what happens. Whether or not direct control exists, the required velocity must be present upon reaching a certain point and/or time.

It is possible to start, stop and change the thrust of some rocket engines. This gives a great deal of flexibility to adjust the flight of a satellite or spacecraft. Suppose, however, that we had several one-shot, solid-propellant rockets and we wanted to use them to launch different types of space missions. In addition, let's consider each rocket capable of reaching a different velocity at burnout. The following velocities would be required to:

- a. place a satellite into a circular orbit at an altitude of 100 nautical miles (NM) (17,454 mph),
- b. place a satellite into orbit with 1,000-NM apogee and 100-NM perigee (18,409 mph),
- c. place a satellite into orbit with 10,000-NM apogee and 100-NM perigee (21,954 mph) and
- d. place a satellite into orbit with 100,000-NM apogee and 100-NM perigee (24,273 mph).

The above examples could be carried further, but suppose we wanted to send a payload somewhere other than into orbit about Earth. What would be the velocity requirement? Of course, it would depend on the ultimate destination of the payload, but the minimum velocity to the Moon is 24,409 mph—with burnout at 100-NM altitude. Such velocity requirements continue to increase until a velocity of more than 36,000 mph is required to leave the solar system.

Now, 36,000 mph is a respectable velocity, but it could take a velocity of almost twice this much to send a payload crashing into the Sun. We tend to forget that Earth's orbital velocity about the Sun is more than 66,000 mph. Before any rocket is launched, we must remember that its initial velocity is the same as that of Earth. To get a payload to the Sun really means that the Earth's velocity must be counteracted so that the Sun's gravitational field will pull the payload into the Sun.

All the velocity requirements stated previously are for a given set of conditions. No allowances were made for several variables. One variable is the velocity that can be added according to the direction of launch and another variable is the location of the launch site. If a launch vehicle is fired toward the east, it will have the velocity of the Earth's rotation added to whatever velocity it obtains from the vehicle's propulsion system.

At Earth's equator, this velocity is roughly 1,000 mph. A launch north or south of the Equator would reduce this added velocity. How much reduction there would be depends on the distance from the Equator of the launch site. The azimuth, or angle in relation to true east, would also affect how much natural velocity would be added.



Suppose the mission of a payload required that it be launched toward the west. Everything that we said about a to-the-east launch is reversed. Finally, what about a true-north or true-south launch direction? The specialists responsible for calculating the desired trajectory would still have to consider Earth's rotational velocity because it would be more of a deflecting force instead of a force with a plus- or minus-velocity change.

## **Total Velocity Requirement**

In planning a space mission, it is necessary to calculate total velocity requirements. This total figure represents the adding together of all the velocity requirements for all stages of the mission. It does not represent the velocity at which the vehicle travels at any one moment in its journey, but it would be in excess of that velocity. All the velocities in such a sum would not be in the same direction. Nevertheless, the sum is essential in computing the needed propellant for the mission.

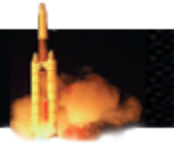
Placing a payload into a low orbit about Earth might be a one-shot deal. That is, the total required velocity would be realized at burnout, and the payload would be injected into the proper orbit. This could very well be the case for certain types of elliptical orbits. On the other hand, a trajectory for a very long spaceflight, or the need to change the shape of an object's orbit, will require a change in velocity—in other words, the application of thrust.

Perhaps we can better demonstrate the concept of the need to know the total velocity requirement by examining a flight to the Moon and return. Injection into a trajectory that will take the spacecraft to the Moon could require a burnout velocity of 36,000 feet per second (fps) (or 24,545 mph, with variables considered). To land the vehicle on the Moon would require 8,700 fps (5,932 mph) of retrothrust (opposite-direction thrust). Another 8,700 fps would be required for liftoff and insertion into a return-to-Earth trajectory.

In this example, we will go along with the technique of using Earth's



The space shuttle *Challenger* lifts off.



atmosphere to slow a returning spacecraft to soft-landing velocity, so no velocity requirements exist for the return trip. The Earth's gravitational force has provided most of the velocity requirements. Thus, we have a total velocity requirement of 53,400 fps (36,409 mph).

If the flight plan did call for a slowing of the spacecraft prior to entering Earth's atmosphere, this velocity requirement would have to be included. So would any velocity requirements for changing or correcting the vehicle's course on the way to or from the Moon.

*Saturn V*, a three-stage vehicle, was used for manned *Apollo* lunar flights. In flying to the Moon, *Saturn's* first stage, weighing nearly 5,000,000 pounds, lifted the second and third stages along with the spacecraft to a speed of 5,400 mph and to a point 41 miles above the Earth. The second stage, weighing more than 1,000,000 pounds, then took over, increasing speed to more than 14,000 mph. At a point 120 miles above the Earth, the second stage was jettisoned.

The third stage ignited briefly to accelerate the spacecraft to 17,000 mph, putting the spacecraft into Earth orbit. The astronauts then reignited the single engine of the third stage, which burned for 5 1/2 minutes. This single engine cut off at an altitude of about 190 miles and a speed of 24,300 mph. From that point, the rocket traveled through space until it reached a Moon orbit.

The total velocity requirement tells flight planners how much thrust is going to be needed for the trip. This thrust, and the vehicle and payload masses determine what kinds and sizes of engines will be needed and how much propellant will have to be used. The actual amount of propellant used will probably be slightly more than is calculated as the bare minimum.

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## Ballistic Trajectories

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The term ballistic pertains to the science of ballistics. Ballistics is the study of the arc of a nonorbiting body. Ballistic flight is primarily concerned with propelling an object from one place on Earth's surface to another place or target on Earth's surface. The moment a bullet leaves the barrel of a rifle, the bullet is in ballistic flight. It is no longer powered so it is under the influence of natural forces only—primarily gravity.

The same ballistic-type flight occurs with rocket-propelled missiles used to hit a distant target. If there is no way to change the payload's flight path after main rocket burnout, the remainder of the flight is ballistic. On the other hand, if the missile is guided all the way to impact with the target, its trajectory cannot be considered ballistic. This is because any ballistic influences will be counteracted by the guidance and control systems.

All ballistic trajectories behave as if they were going into an elliptical orbit around Earth's center of gravity. What keeps them from doing this is the presence of Earth's surface. We can see this tendency to orbit the center of gravity if we examine the trajectory of a large ballistic missile.

Any missile that has a range of several hundred miles or more, rises above the Earth's atmosphere in its trajectory and is designed to reach its target in the shortest time possible is a long-range ballistic missile. It must obey certain laws in its flight. Such a missile cannot be under continuous propulsion and guidance during the entire course of its flight. Its launch and trajectory, during the time the propulsion system is functioning, will be guided.





Burnout of the propellant system will occur well below the top of the missile's trajectory. The rest of the payload's flight will be like that of a bullet or an orbiting space vehicle—unpowered and determined primarily by the force of gravity.

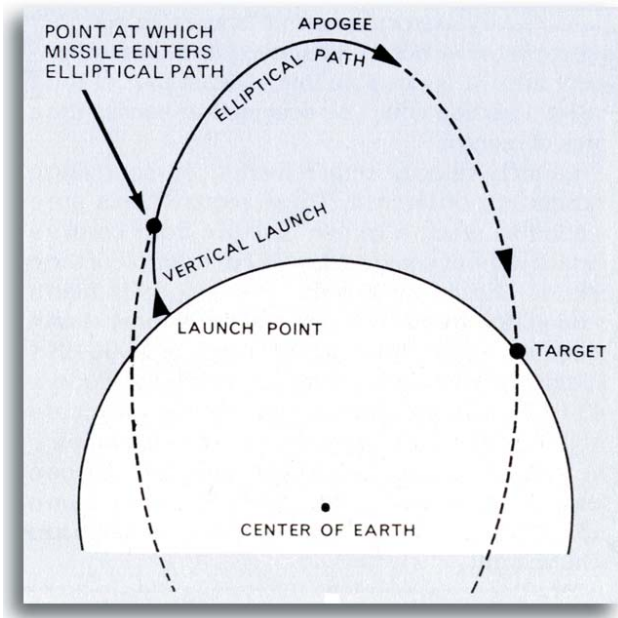
It will describe a high, arching trajectory toward target, possibly reaching a peak of several hundred miles above the surface of the Earth. The atmosphere will affect the path of the reentry portion of the flight.

The launch velocity of a ballistic missile is less than that required for an orbit, although in the case of a missile with a 10,000-NM range, it is only a little less. The missile is also launched into a higher flight-path angle than the more horizontal angle that is usual for orbital launches. Lacking the velocity to clear the Earth, it will fall back to Earth along a path determined by gravity. If it could continue falling—that is, follow an imaginary path within the sphere of Earth—it would fall faster and faster to a perigee point and be carried by its own momentum right up through the Earth back to the point where it started. This trajectory is impossible, but the fact remains that the actual flight of the missile does

describe the exterior portion of such an imaginary orbit around the center of the Earth.

Therefore, the missile's ground track—that is, the route of its trajectory projected downward and plotted on the surface of the Earth—would be a part of a great circle, somewhat modified by the effect of the Earth's rotation. The missile could not follow a trajectory due east or due west along some parallel of latitude other than the Equator (which is a great circle) nor could it follow an eccentric or irregular path designed to fool an enemy defense system.

These facts tell us two things about ballistic missiles. One is that propulsion and guidance are available to place a missile into a trajectory toward any target on Earth with great accuracy. The second is that since the route the ballistic missile must fly is predictable, defense measures can be taken against it.

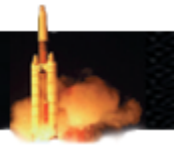


**A Ballistic Missile's Imaginary Orbit About Earth's Center**

## **Sounding-rocket Flights**

If the trajectory of a rocket does not send its payload into orbit, or to some destination well beyond Earth or to another point on Earth's surface, where does the rocket send its payload? The only direction left is straight up. Essentially, this is the trajectory of a sounding rocket—straight up.

Sounding is an old term associated with measuring or sampling the depths of a body of water. Somehow, and at some time, this same term was applied to sampling Earth's ocean of air. Thus, a



rocket sent into, or even beyond the atmosphere, on a one-way trip to gather information is now identified as a sounding rocket.

Instruments carried aboard a sounding rocket are designed to observe and measure various natural phenomena at different altitudes above the surface and transmit these findings to ground stations. After reaching its maximum altitude, the rocket simply falls back to Earth and is destroyed by either reentry and/or impact forces. The total sounding rocket may not be destroyed in this manner every time. It is possible that at least part of the payload section could be designed to survive the force of reentry.

Launch velocity requirements for sounding rockets are of interest. These requirements are needed to reach a certain distance from Earth's surface without going into orbit. For example, if the altitude chosen for the rocket's apogee is high enough, the thrust/burnout velocity is more than adequate to go into orbit. To reach a 1,000 NM altitude (100-NM altitude burnout) requires a velocity of 11,114 mph. This isn't enough velocity to achieve orbit (17,454 mph). Suppose a mission to sample the magnetosphere at 10,000-NM altitude had to be flown. The burnout velocity required for this mission is 31,000 fps or 21,136 mph—more than enough to achieve orbit.

Why does this very high-altitude sounding rocket not go into orbit? The reason is that a sounding rocket is launched at a very steep angle and does not have the horizontal velocity needed to put it into orbit. Like any other sounding vehicle, it eventually reaches a point where gravity overcomes its upward momentum, and it will return to Earth. Its trajectory is not necessarily straight up and down, but is rather like a high, narrow arch with a return path that would not carry it beyond the Earth. If the complete path of the sounding-rocket trajectory were plotted, it would show an extremely narrow ellipse within the Earth, around the center of the Earth's mass.

It does not require 10 times as much velocity to reach 10,000 miles as it does to reach 1,000 miles. Gravity's effect weakens with distance from its center.

Some economic factors can also be noted. Since the sounding-rocket velocity for 1,000 miles is suborbital, it is the cheapest way of reaching such an altitude. Using a sounding rocket to reach a height of 10,000 miles, however, is questionable. For reaching still higher altitudes, it is definitely more economical to put the vehicle into orbit.

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## Types of Orbits

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As far as satellites of Earth are concerned, there are two basic orbital flight paths involved: the elliptical and the circular. If you think about our previous introductory discussions on trajectories and orbital velocities, you will realize that an elliptical orbit can be achieved with one shot provided the angle used (to the vertical) is correct. Get away from the one-shot-type approach to orbital insertion and thrust will again be needed.

The lowest Earth orbit that has been discussed is an approximate circular one at 100 NM altitude, for which an injection velocity (the velocity that will place it into orbit) of 17,454 mph is required. Therefore, let us use this orbit as a starting point for learning more about Earth orbits. In this one instance, the injection velocity, the apogee velocity and the circular-orbit velocity are all the same. At this altitude, the pull of gravity is only slightly less than it is at the surface of the Earth. The velocity represents the speed at which the vehicle must outrace the horizon as it "falls" around the curving



Earth, always maintaining the same altitude above it. It is important to note that the injection into orbit must be horizontal (tangent to the orbit). Any effort to extend range by giving the vehicle an upward trajectory without added thrust would only rob it of some of its vital forward velocity and bring it to Earth before one orbit was completed.

For any higher orbit, we have this basic paradox. Higher and higher velocities are required to reach successively higher altitudes, but lower and lower velocities are required to stay in orbit at successively higher altitudes. This phenomenon is due to the weakening of Earth's gravitational effect with distance.

A boost velocity of about 18,400 mph is needed to hurl a vehicle to an apogee of 1,000 NM. After burnout, the vehicle coasts outward along an elliptical path, moving slower and slower as gravitational pull gradually overcomes the force of the launch. At its planned 1,000-NM apogee, it will have a speed somewhat less than 15,000 mph and will begin to lose altitude. Sliding down the far side of the ellipse, it will move faster and faster as it approaches closer and closer to Earth. It will then whip around perigee at top speed. Perigee in this case will be at the injection altitude of 100 NM and at the injection velocity of 18,400 mph. The vehicle will then begin another climb toward its 1,000 NM apogee. Discounting the slowing effect of faint atmospheric resistance at perigee, it will keep on swinging around this ellipse indefinitely without need for burning an ounce of propellant.

Let us continue to assume that injection and perigee are at 100 NM. More and more launch power will shoot the vehicle out to more and more distant apogees. The orbits would describe successively longer ellipses.

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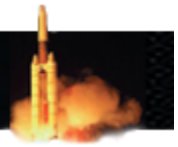
## Circular Orbits and Transfers

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To change what is certain to be an elliptical orbit into a circular orbit when the satellite reaches an after-launch apogee requires the addition of thrust. This thrust must be applied toward a specific direction. That is, when the vehicle reaches apogee, its engine is restarted to give it some additional velocity to thrust it outward and circularize the orbit. Circular velocity minus apogee velocity gives the amount of kick needed to circularize an orbit at a given altitude.

To show how to figure the total velocity required attaining a circular orbit, let's work a problem using simple arithmetic. The velocity required to boost a vehicle to an apogee of 300 NM is 17,659 mph. To this number add the difference between apogee velocity and circular velocity at 300 NM (273 mph). The sum 17,932 mph is the total velocity requirement—that required for launching a vehicle into a 300-NM circular orbit in two steps—but the vehicle never travels that fast. The total velocity requirement is merely an engineer's figure which is useful in determining how much energy is needed to perform a given task with a given payload weight. Spaceflight velocity usually is not given in miles per hour but in feet per second. However, to visualize the fantastic velocities required in spaceflight, we expressed it in miles per hour (an expression of measure with which everyone is familiar).

The velocities we have given are ballpark figures. In actual flight situations, much more precision is necessary. The amount and the point at which thrust is applied to an orbiting vehicle are critical. For

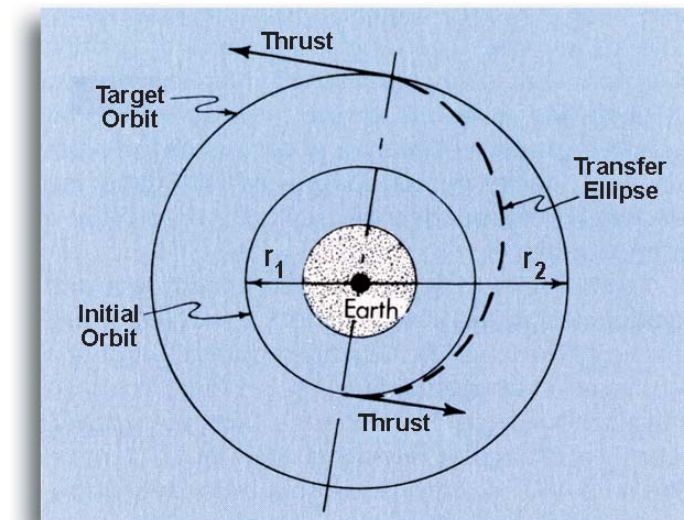


example, if thrust applied at apogee is a little less than that required for circularizing the orbit, the result will be a wider ellipse with the same apogee and a higher perigee. If it is thrust a little more, the vehicle will be boosted to a higher apogee.

Achieving a circular orbit at any height above that of launch burnout (original perigee) is done in two steps—launching into an elliptical trajectory and applying another spurt of rocket energy at the desired altitude to circularize the orbit. It might also be done in three steps—the vehicle could be launched into a lower orbit called a parking orbit, then boosted to a higher apogee and then circularized at that apogee. Moving a vehicle from one orbit to another is called a transfer. Such maneuvers accomplished within the same orbital plane are called coplanar (same plane) transfers. All the movements are on the same plane, like the sheet of paper on which you see them. If viewed from the side, the plane would appear as a line.

### **The Hohmann Transfer**

Back in 1925, when space travel was only a theoretical dream, the city engineer of Essen, Germany, published a scientific paper on the most economical way to boost a satellite into a chosen circular orbit. The method proposed by Walter Hohmann is quite similar to the one described above. It has been called the minimum energy transfer. The Hohmann transfer, or slight variations of it, is a practical method of space maneuver to this day. In a Hohmann transfer, the vehicle is first placed in a low-elliptical parking orbit. When the vehicle swings around to perigee, sufficient thrust is applied to push the vehicle to apogee at the desired altitude. When the vehicle reaches the high point of this transfer ellipse, thrust is applied again, and the vehicle moves out on a circle that is tangent to the transfer ellipse.



**The Hohmann Transfer**

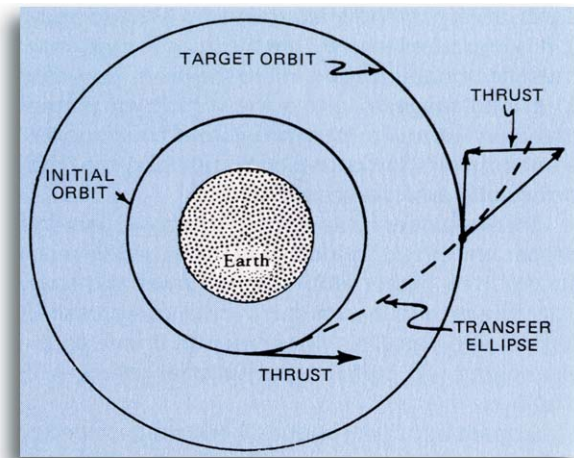
Discussion of ellipses, circles and tangents should remind us that all space travel is in curves. Moving in a straight line in space would require constant application of deflected thrust, a tremendous and wasteful expenditure of propellant. The curves that Hohmann chose are those that actually permit thrust to be applied in a straight line. A vehicle with a rigid engine or nozzle, incapable of changing direction of thrust would be able to accomplish a Hohmann transfer by thrusting straight ahead at the proper transfer points. Momentarily, the vehicle would move out on a straight-line tangent to its former course, but, almost immediately, the particular new balance achieved between the forward momentum and the pull of gravity would set the vehicle on a new curved trajectory.



## Other Coplanar Transfers

There are other ways of accomplishing transfers and maneuvers within a given plane of orbit. One is the fast transfer applied in modern satellite maneuvering. Instead of choosing a transfer ellipse tangent to both the lower and higher orbits, a trajectory is chosen that intersects or crosses the two orbits. In a direct ascent, more launch velocity than needed would be built up to reach a given apogee. At the desired altitude, the kick would thus be applied lower than apogee, with deflected thrust, to aim it into the desired circle. Because all the energy would not be working in a straight line, extra energy would be needed to make the desired turn. The maneuver boosts the vehicle into higher orbit faster than a Hohmann transfer does. Actually, most fast transfers are only slightly different from Hohmann transfers. The turn is not very sharp at either transfer point.

Moving down from a higher to a lower orbit should also be mentioned. To do this, negative thrust (or retrothrust) must be applied to kill off some of the velocity that keeps the vehicle in the higher orbit. The vehicle is then drawn by gravity into an orbital path that matches its new velocity. As it moves lower, however, it moves faster. This is another interesting paradox—putting on the brakes in order to go faster. Actually, it is a practical maneuver. Suppose that two vehicles are attempting to meet (rendezvous) in the same orbit and one is a thousand miles ahead of the other. The chase vehicle can never hope to catch up with the target vehicle while both are in the same orbit. Therefore, the chase vehicle



The Fast Transfer

applies retrothrust to get drawn into a downward transfer ellipse. This allows it not only to follow a shortcut route but also to be moved by gravitational pull faster along that shorter, lower route to a point where the two orbits are again tangent. At this point, the two vehicles will come within maneuvering range of a rendezvous. The precomputed route selection, as well as the guidance and control mechanisms, used to accomplish the rendezvous itself must be extremely precise.

## Non-Coplanar Transfers

Up to this point, discussion has been given to satellites being in the same plane. In actual satellite flight, this is not true. We have Earth satellites at many different altitudes and at various angles to the Equator. Some have circular orbits, but others are in elliptical orbits with apogees and perigees of varying distances.

The plane of any orbit around Earth must pass through the center of Earth. If a satellite is launched due east from Cape Canaveral in Florida (the launch site of many space vehicles), which has a latitude of  $28.5^\circ$  N, it is impossible for it to keep traveling due east around the world at the same latitude. Its orbital path will bring it south across the Equator to reach a latitude of  $28.5^\circ$  S before it swings north again. The orbital plane of such a launch is said to have an angle of inclination (slant) of  $28.5^\circ$  with



respect to the plane of the Equator. Aiming the satellite at launch in any direction other than due east will produce a steeper angle of inclination, causing the satellite to overfly latitudes higher than  $28.5^\circ$  on either side of the Equator. A northward or southward injection will put the satellite into a polar orbit.

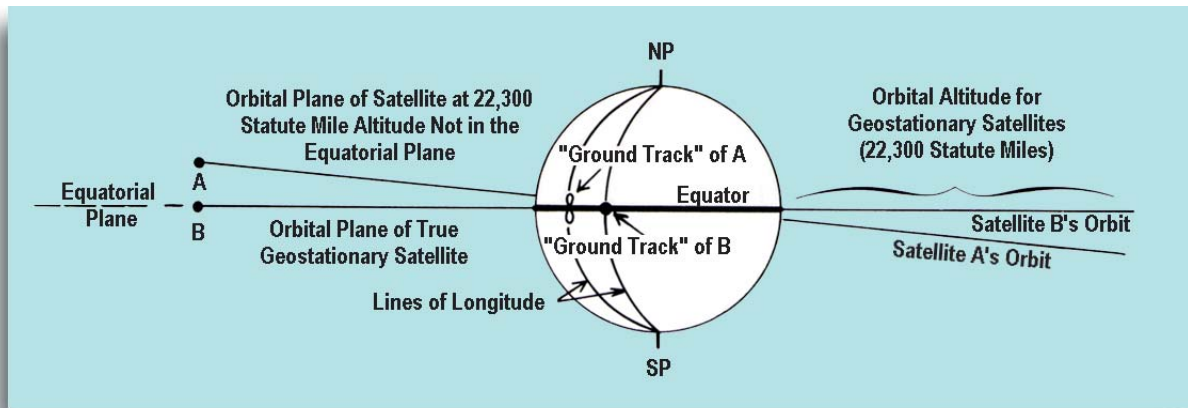
Obviously, no launch from Cape Canaveral could put a vehicle directly into an orbit around the Equator or at any angle of inclination less than the latitude of Cape Canaveral itself. To put a vehicle into equatorial orbit requires a non-coplanar transfer. The vehicle would first be launched at its minimum angle of inclination of  $28.5^\circ$ . Then, on either its first or a later revolution at one of two points where it crosses the Equator, thrust would be applied at the proper angle to put the vehicle into an orbit coplanar with the Equator. Think of this transfer maneuver as kicking the vehicle sideways instead of upward, as in the coplanar transfer. Similarly, any angle of inclination can be achieved by means of non-coplanar transfer, but not necessarily in one such transfer. If the angle of change is too extreme, the vehicle may have to orbit Earth two or more times, changing its angle of inclination by a certain amount at each intersection of planes, before the desired inclination is achieved. If both a change of inclination and a change of orbital altitude are desired, the non-coplanar and altitude transfers can be achieved in one orbit by calculating the thrust angles three-dimensionally.

## Special Orbits

A special orbit is our term for those orbits in which a satellite must be placed to accomplish a special mission. These orbits are mostly circular. This is especially true for those satellites that provide services in the forms of communications, environmental monitoring and navigation.

### Geostationary Orbit

There are certain tasks which satellites can do best if they are in an orbit that will keep them stationed above one point on Earth's surface. These are called geostationary satellites. The term means that the satellite is in an equatorial orbit at a distance where the satellite's period of revolution is the



Examples of Geostationary Orbits



same as the Earth's period of rotation—24 hours. Three geostationary satellites, spaced 120 degrees of longitude apart can give 24-hour around-the-world service over most of the surface of the globe.

For a satellite to be geostationary with the Earth (that is, keep time with the rotation of the Earth so perfectly that it always remains directly above a certain point along the Equator), it must have a circular orbit at one altitude. That altitude is 19,351 NM (or 22,300 statute miles), which gives it a period of 24 hours.

If such a satellite is launched from Cape Canaveral without a non-coplanar transfer, it will have an inclination of  $28.5^\circ$  and will not appear perfectly stationary over the Earth. It can be timed to reach the right orbit at the desired point, but its inclination will take it above and below the plane of the Equator by  $28.5^\circ$  in the course of its 1-day orbit. In other words, its ground track would describe a narrow figure eight crossing at the Equator and its top and bottom touching both  $28.5^\circ$  parallels. In order to make it remain stationary over one point on Earth, it is necessary to plan for a non-coplanar transfer into the equatorial plane. The one point over which it hovers must be on the Equator and at no other latitude. This type of orbit is called a geosynchronous orbit.

These are the major maneuvers for positioning a geostationary satellite. However, once the satellite is in the desired orbital position, further and continuing adjustments to its position are necessary. After all, the satellite is subjected to varying gravitational influences of the Sun-Earth-Moon system. In addition, the pressure of the Sun's radiation disturbs the satellite's position. This means that station-keeping maneuvers have to be made periodically. The satellite's small-reaction control devices or thrusters effect such maneuvers.

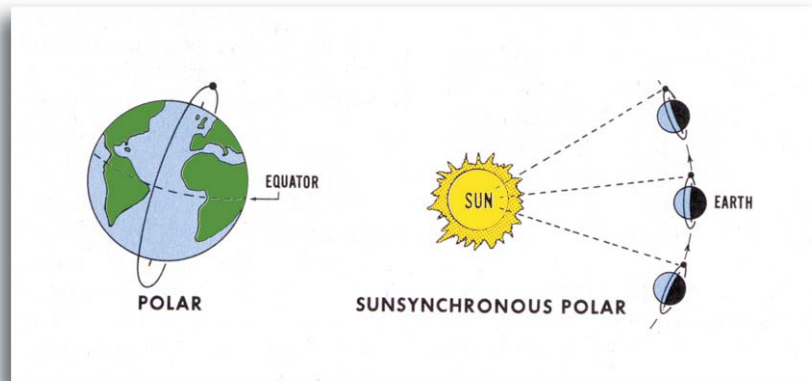
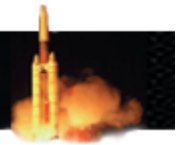
## ***Polar Orbit***

As the name implies, a polar orbit involves a path that crosses or nearly crosses the North and South Poles during each orbit. This type orbit offers a satellite's cameras a chance to photograph Earth's entire surface. The reason this is true is that Earth is turning on its axis as the satellite sweeps over the poles and each orbit of the satellite puts it west of its previous sweep. (Earth is rotating toward the east.)

## ***Sunsynchronous Orbit***

This is another form of polar orbit that keeps a satellite exposed to constant sunlight. The Earth is not a perfect sphere. It bulges slightly at the Equator and is flattened slightly at the poles. The resulting imperfect sphere contributes to the fact that Earth's gravitational force is not constant at all points of a satellite's orbit.

A satellite placed into the proper polar orbit (direction and altitude) will remain exposed to constant sunlight as Earth revolves around the Sun. The sunsynchronous orbit is appropriate for those satellites that need constant sunlight to generate power for on-board operations. This orbit could also be used for those satellites that monitor the Sun's activities, and the sunsynchronous orbit may be one of those chosen for in-space electrical power generation.



Polar and Sun-synchronous Orbits

## Launch Vehicles

There is often confusion about the difference between a rocket, a missile and a launch vehicle. Many people will use one term when they are talking about the other. For example, many people use the term missile when talking about the *Saturn* rockets that carried people into space. Although there are no firm written rules that tell you when to use these terms, there are rules that are generally accepted by people who work in the field of rocketry. We are going to use these generally accepted rules in this textbook.

A rocket is a type of power plant that is used to propel something (payload). It produces its power by the principle of action and reaction (Newton's third law of motion). The exhaust gases that are expelled from the rocket at a very high velocity produce the action. The equal and opposite reaction forces the rocket and its payload in the opposite direction. Burning some type of fuel in the common types of rockets produces the exhaust gases. Some of the more advanced rockets produce the action in other ways.

In general usage, a missile is a rocket-propelled vehicle with a weapon or warhead as the payload. This warhead may be a nuclear weapon or a simple explosive charge. If the payload of a rocket is a satellite or a spacecraft rather than a warhead, the vehicle is called a launch vehicle or a booster. The same rocket may be used to carry either a warhead or a satellite. A rocket is called a missile while carrying a warhead and a launch vehicle when carrying a satellite. For example, the *Titan II* rocket was originally designed to carry a nuclear warhead and was called the *Titan II* missile. Later, NASA began using the *Titan II* to launch the *Gemini* spacecraft. It was then called the *Titan II* booster or the *Titan II* launch vehicle.

There are two basic categories of launch vehicles—expendable launch vehicles and reusable launch vehicles. Rockets that are only used once are considered expendable launch vehicles. These include *Titan*, *Atlas* and *Delta*. The space shuttle is the only reusable launch vehicle we have.

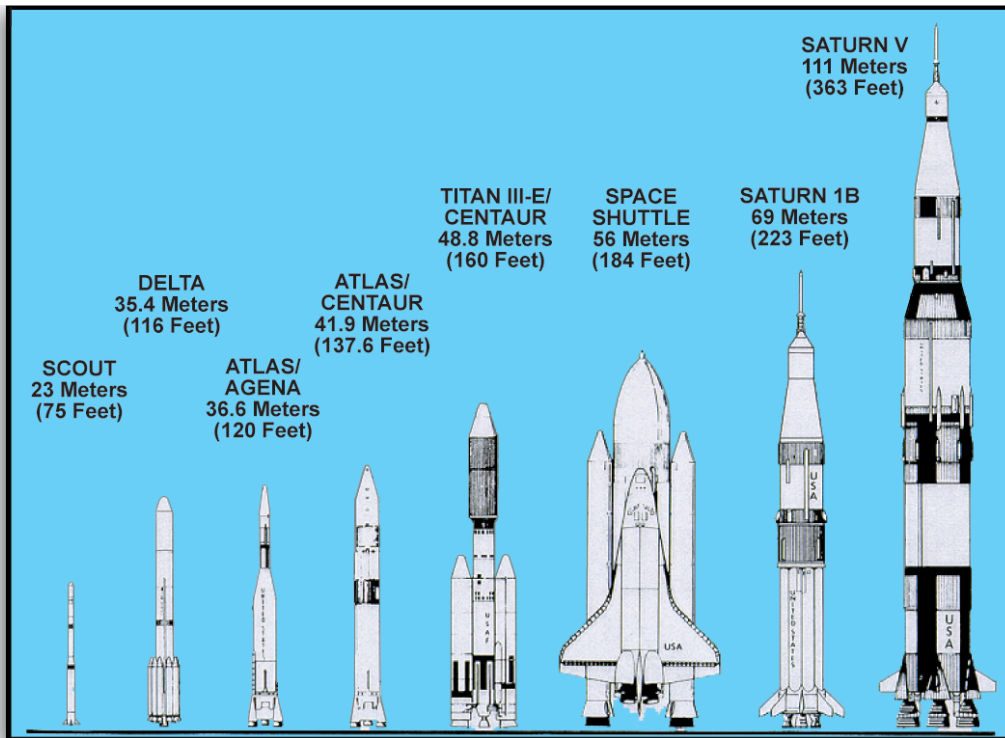
The satellites launched by the military are used to ensure our national security. They include navigational satellites to improve the navigation of military aircraft and ships, communications satellites, surveillance satellites and nuclear-detection satellites.





The launch vehicles used by the military to place their satellites into space are the same as those used by NASA. The one exception to this is the *Titan* series of boosters. The *Titan* was developed by the military and only a few civilian spacecraft have ever been launched by it. The *Titan* was first launched in 1964, and since that time, it has been produced in several versions. All *Titan* vehicles start out as a two-stage *Titan II* ICBM. The *Titan IV* has a stretched first and second stage, two seven-segment, solid strap-on boosters and a *Centaur G* third stage. The *Titan IV* can place 10,200 pounds into geosynchronous orbit or 31,100 pounds into near Earth orbit. The *Titans* are the largest and most powerful launch vehicles in the United States. The only rocket ever built which was larger than the *Titan III* was the giant *Saturn V* Moon rocket that is no longer being used.

NASA is responsible for launching all nonmilitary spacecraft for the United States. In addition, NASA has a cooperative program with more than 30 foreign countries to launch their spacecraft on a contract basis. NASA also launches a few military spacecraft on some of their rockets if they have room. The rockets used by NASA in its space exploration program include the boosters used to place spacecraft into orbit and the sounding rockets which carry their payloads to high altitudes, but not into orbit.



The United States' Rocket Launch Vehicles

1950s as an intermediate-range ballistic missile and placed in service in Europe. When the *Atlas* ICBM became operational, the *Thors* were dismantled and returned to the United States. All were eventually converted into space boosters.

Beginning in 1959, Douglas Aircraft (now McDonnell-Douglas) was awarded a contract to develop a second and third stage for the basic *Thor*. The *Thor*, with its second and third stages, became

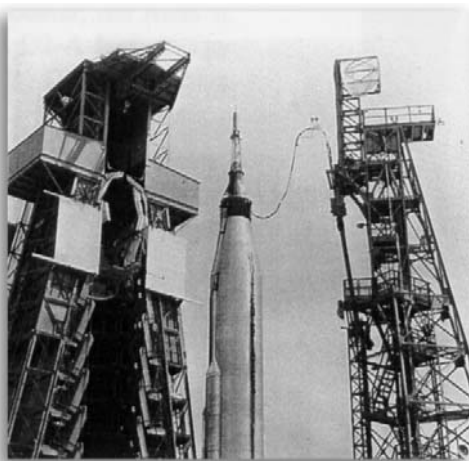
In addition to the *Titan IV* series, space launches are carried by two basic launch vehicles. Both vehicles are modified military missiles, the *Thor* and the *Atlas*. These two boosters, with different second stages and solid strap-ons, can carry 95 percent of all US satellites into space. The *Thor* was developed in the



known as the *Thor-Delta*, and this rocket launched many of our famous satellites. The first *Delta* could put a 480-pound payload into orbit about 300 miles above the Earth. The most current version of the *Delta*, the *Delta II*, is a three-stage booster that can place a 2,000-pound payload into orbit 22,000 miles high. This has been accomplished by making the first stage longer (to hold more fuel) and by adding more powerful upper stages. Also the *Delta II* uses nine solid-fuel, strap-on rockets added to the first stage.

The *Atlas* became a launch vehicle in the same way as the *Thor*. When the *Atlas* ICBMs were phased out in 1965, the missiles became available for other use. As they were needed, the Convair Division of General Dynamics Corporation at Vandenberg Air Force Base, California, refurbished them. More than 500 *Atlas* launches have taken place, including some very famous firsts. An *Atlas* launched the world's first communications satellite in 1958. The first US manned orbital flights in Project Mercury were boosted into space by the *Atlas*. The *Atlas* was also used to launch the first US spacecraft to Venus, Mercury, Mars and Jupiter.

In its use as a space booster, the *Atlas II* is used with the *Centaur D2-A* high-energy upper stage. The *Atlas-Centaur* rocket stands 131 feet in height. Using the *Centaur D2-A* second stage, the *Atlas* is capable of placing 11,200 pounds into a 115 mile-high orbit, 4,100 pounds into a synchronous orbit, or 1,300 pounds to a near planet. The *Centaur G-prime* modified upper stage is used with the *Titan IV* launch vehicle.



In 1962, an early version of *Atlas* thrusts a *Mercury* capsule into orbit.



The *Atlas IIAS* launched the AT&T *Telstar* satellite.



A *Titan IV* with *Centaur* Upper Stage



## Key Terms and Concepts

- orbits
- trajectories
- inertia
- circular orbit
- elliptical orbit
- equatorial orbit
- escape trajectory
- apogee
- perigee
- escape velocity
- burnout velocity
- total velocity requirement
- retrothrust
- ballistics
- sounding rocket flight
- Hohmann transfer
- coplanar transfer
- non-coplanar transfer
- geostationary orbit
- polar orbit
- sunsynchronous orbit
- rocket
- missile

## ? Test Your Knowledge ?

### SELECT THE CORRECT ANSWER

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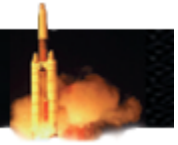
1. To take advantage of the speed from Earth's rotation, rockets should be fired to the **(north, south, east or west)**. If the launch is at the Equator, this adds roughly **(500/1000/1500/2000)** mph.
2. A **(re-usable launch vehicle/ sounding rocket)** is sent on a one-way trip to gather information.
3. If the velocity of an object in orbit is increased, it **(goes into a higher orbit/takes less time to travel the same orbit)**.
4. Moving from a higher orbit to a lower orbit requires the use of **(thrust/ retrothrust)** causing the vehicle to **(speed up/ slow down)** making it more subject to **(gravity/ centrifugal force)**, but as a result of the lower orbit, the vehicle actually goes **(faster/ slower)**.
5. **(Polar/ Geostationary)** orbits allow a satellite's cameras a chance to photograph the Earth's entire surface.

### MATCHING

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6. Match the terms

- |               |   |
|---------------|---|
| a. orbit      | (1) Satellite travels west to east around the 0 degree latitude     |
| b. trajectory | (2) Path described by one body in its revolution about another body |
| c. inertia    | (3) Path a body takes, accelerating enough to escape gravity's pull |



- d. circular orbit (4) **Point where a body orbiting Earth is closest to it**
- e. elliptical orbit (5) **Property that causes a body in motion to remain in motion**
- f. equatorial orbit (6) **A non-circular path around a body**
- g. escape trajectory (7) **Path of a body through space**
- h. apogee (8) **Maintained at a virtually constant altitude above the Earth's surface**
- i. perigee (9) **Point where a body orbiting the Earth is farthest from it**

- 7. Escape velocity is defined as \_\_\_\_\_.
- 8. The \_\_\_\_\_ \_\_\_\_\_ \_\_\_\_\_ represents adding together all the velocity requirements for all stages of the mission.
- 9. The moment a rocket engine ceases to produce thrust, \_\_\_\_\_ is said to have occurred and the velocity required to achieve the intended \_\_\_\_\_ must be attained.
- 10. Ballistics is the study of \_\_\_\_\_.
- 11. The trajectory of a \_\_\_\_\_ \_\_\_\_\_ is straight up.
- 12. Moving a vehicle from one orbit to another is called a \_\_\_\_\_; if accomplished within the same orbital plane, it is called \_\_\_\_\_.
- 13. A Hohmann transfer is also known as a \_\_\_\_\_ \_\_\_\_\_ \_\_\_\_\_.

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### TRUE OR FALSE

- 14. The payload, fuel load and deadweight make up takeoff mass.
- 15. Retrothrust is defined as thrust in the opposite direction usually used to slow a vehicle.
- 16. Ballistic flight is concerned with propelling an object from the Earth's surface to non-orbital space flight.
- 17. A bullet is a good example of ballistic flight.
- 18. Most fast transfers are only slightly different from Hohmann transfers.

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### SHORT ANSWER

- 19. Why are lower velocities required for satellites to stay in orbit at higher altitudes?
- 20. Briefly describe the Hohmann transfer.