Appendix 1 to Chapter 1

Useful Principles of Orbitology

Note: This appendix provides a basic explanation of how things move through space, particularly orbital space. It is meant to provide the non-expert with enough of an understanding of orbital mechanics to understand the capabilities and limitations of space operations as currently practiced. An understanding of current space operations will facilitate an understanding of the argument of the following chapters.

To illustrate the principles of orbital motion, Isaac Newton used the image of a cannon firing a shell horizontally from the top of a tall mountain. That was four hundred years ago. Since then, numerous other strained and stretched analogies have been offered: a weight whirling at the end of a string, or a motorcyclist zooming around inside a wide circus barrel, or even electric trains on circular tracks.

Some earthside principles are actually even helpful. Airmen know the technique of trading altitude for speed in a dive. Seamen appreciate the tremendous inertia of ships, which makes changing course a laborious process; they and artillerymen also know about correcting for crosstrack windage or current. Auto and horse racers know the value of the "inside track" in the turn.

These images—especially Newton's mountaintop cannon—turn out to be helpful in appreciating why satellites move through space the way they do, and how they can be controlled and steered. By applying very simple principles of motion through space, these unearthly concepts can become familiar and understandable.

History is also full of misjudgments caused by reliance on faulty analogies, on Earth as well as in space. Astronomers once constructed elaborate systems of cycles and epicycles to explain planetary motion. By imagining that space vehicles were "beyond Earth's gravity," early analysts conjured up images of satellites ominously hanging over surface points such as cities and military bases. Images from Hollywood show winged space vehicles swooping through arcs, or sometimes "stopping"—and always "right side up" relative to the camera angle. And even today, the greatest barrier to understanding spaceflight is often not technological or academic, but psychological.

Imagine You Are In Orbit

So now you've just been fired out of Newton's cannon from a mountain 200 km high. Imagine yourself moving horizontally across Earth's surface at about 8,000 meters per second, 200 km up in space. And imagine yourself still firmly in the grip of Earth's gravity, which relentlessly pulls you toward our planet's center. Although you feel that you are really high above the Earth, you are not so high when seen in context. If Earth were a peach, you would just be skimming the top of the fuzzy hairs.

In a single second, you move forward 8,000 meters (about 5 miles), and in that same second, you fall toward Earth's center by about 5 meters (16 feet). After this first second, you are on a slightly shifted course but at the same speed you were originally.

Meanwhile, you observe that Earth's surface below you is not flat. In keeping with the roundness of the planet, it gently recedes. In fact, if you have the proper forward speed, the surface recedes at the same rate as you fall towards it. You fall "over the horizon" in a continuous path that never reaches the ground. After about 90 minutes, you have completely circled the planet.

You are in "free fall," and since there is nothing to impede your free fall, you are weightless. You and everything loose in the vehicle float in midair. Even though some experts confusingly use the term "zero gravity" or "micro gravity" for this condition, they are only referring to the relative forces on the entire vehicle and its contents together. This common use term does NOT mean that the force of gravity is ZERO on the space vehicle.

This combination of very high SPEED and GRAVITY create the path you follow—the ORBIT. Without one or the other—that is, if you weren't moving forward at a high enough speed, or if Earth weren't pulling you DOWN—you would not be in orbit. You would hit the ground (not enough speed), or you'd fly straight off into deep space (no gravity).

The 10:1 Rule of Thumb

Consider two space vehicles in low, circular orbits around Earth. One satellite is at a higher altitude than the other. The satellite in the higher orbit takes longer to complete one lap, or "revolution." The higher the orbit, the longer it takes to complete one revolution. As a conceptual "rule of thumb," multiply the difference in altitude by ten to get a very rough idea of the relative speed difference between satellites (relative to the time to complete one orbit). For a small vertical separation—say, 1 km—between two satellites, the lower one will pull ahead of the higher one by about 10 km every revolution.

This "10:1 rule" is the result of two factors. It's mostly due to the higher satellite having a longer path to cover. But as a space vehicle's altitude increases, there is also a small drop-off in the force of gravity (you're farther from Earth's center) reducing the required forward speed that you need to stay in a circular orbit.

The rule can be applied over a wide range of near-Earth orbits. It also applies when the separation is averaged across the whole revolution, say when the vertical separation varies between 0 and 2 km every revolution, averaging a difference of 1 km.

The rule of thumb also tells us how the period of the orbit—the time it takes for one complete circuit of Earth—changes with respect to altitude. A satellite 4 km higher than another satellite will be 40 km behind it after one revolution, and since its speed is 8 km per second, it will take about 5 seconds longer to complete one revolution.

The 2:1 Rule of Thumb

Now, how can you move to a higher or lower orbit? Modifying your speed is the only way to change your altitude. Because of your tremendous forward speed, which means your movement has tremendous momentum, the most effective speed changes can only be made directly along your flight path. This will increase or decrease your total speed, which results in a different-shaped orbit.

A second rule-of-thumb, this time for orbital maneuvers, is called the "2:1 Rule." It was developed at NASA's Mission Control in Houston and so was first expressed in English units. The rule states that a velocity change—a "delta-V" in technical terms—of about 2 feet per second will result in the far side of the orbit changing by 1 nautical mile (6,076 feet) in altitude. Restating that slightly differently, a "delta-V" of 2 feet per second executed at a particular point along the orbital path will result in an altitude change of one nautical mile at a point halfway through the resulting orbital path. That's a ratio of about 1:3,000 and it also applies to the metric scale: a velocity change of 1 meter/sec causes an altitude change of about 3,000 meters at the far side of the orbit. However, the resulting orbit will be elliptical, or egg shaped, since one "delta-V" maneuver can only increase the altitude of part of the orbit. The altitude of the point at which the "delta-V" maneuver occurred did not change. More maneuvers are required to do that, so as to circularize the orbit.

One graphic application of this rule is in estimating how much velocity change is required to force an orbiting satellite to enter the atmosphere. Assuming an orbit 300 km high, if you desire to lower one end of the orbit to an altitude of zero (to guarantee atmospheric entry), you must perform a velocity change of about 300 divided by the 3000 factor, or 0.1 km/sec (i.e., 100 meters/sec). Of course, more precise computations must be made for the actual maneuver, but this kind of "rule of thumb" gives very useful qualitative results.

Note that this means the most efficient way to "deorbit" (get back into Earth's atmosphere) is to decelerate by applying propulsive thrust opposite your direction of travel ("a retrograde burn," or a negative "delta-V") half a revolution prior to landing. It turns out to be four times cheaper (in terms of applied energy, which is the same as propellant usage) than doing what might be "obvious" based on earthside experience and applying propulsion thrust to travel straight downwards toward Earth (as you'll soon learn how to estimate).

Results of Thrusting in Various Directions

You have mastered one way of looking at the relationship between speed and the shape of the satellite's orbit. From another point of view, it's informative to ask how much you change the shape of your orbit by making small rocket thrusts ("burns") in different directions. You would usually thrust along your flight path, taking advantage of momentum, but there’s no reason you couldn’t “burn” in other directions too: left or right, or up or down.

In each case, let’s compare your motion, after changing your velocity, to the motion of another satellite that remains in your original orbit (think of it as a deployed payload if you like). You are actually comparing your changed orbital path to your original orbital path before you changed your path. Let’s use a figure of 1 meter/sec as the velocity change you perform (other values will create proportionately different distances).

Thrusting Along Your Flight Path

Thrusting forward, for example, initially moves you forward as you might expect. But now you are moving faster than required to stay in your original circular orbit, and as you move forward MORE quickly than before, Earth’s curved surface “falls away” more rapidly. This means you are headed toward a higher orbit that (recall the 10:1 rule) takes longer to complete each revolution. So within a few minutes, you begin to rise above your original altitude. As you coast “uphill,” your forward motion relative to the original motion drops, then reverses, even as you continue to gain altitude. Within about 20 minutes you are passing your reference point (where you would have been) backwards and about 2,000 meters above your reference point (in its constant orbit), while still going forward relative to the Earth.

Half a revolution later, you are about 8,000 meters behind and about 3,000 meters above the original point. However, you are moving too slowly now to maintain a circular orbit at the higher altitude. You thus begin dropping down towards your original altitude, which you reach after an additional one half revolution. As you reach your original altitude, you are about 16,000 meters behind the original point, although you have picked up enough speed to briefly surge back towards your original location. The cycle continues until you make another velocity change.

Look how this is consistent with the 2:1 and 10:1 rules of thumb. The 1 meter/sec burn drove you to a point a little more than 3,000 meters higher after you traveled half a revolution. Your average height difference is half of this maximum, or just under 1,600 meters.

And every revolution moves you ten times that, or 16,000 meters, farther behind (horizontally) from the original point. Since your orbital speed was very slightly increased but is still close to 8,000 meters per second, it takes you an additional 2 seconds to complete each revolution. See Figure 1-2.

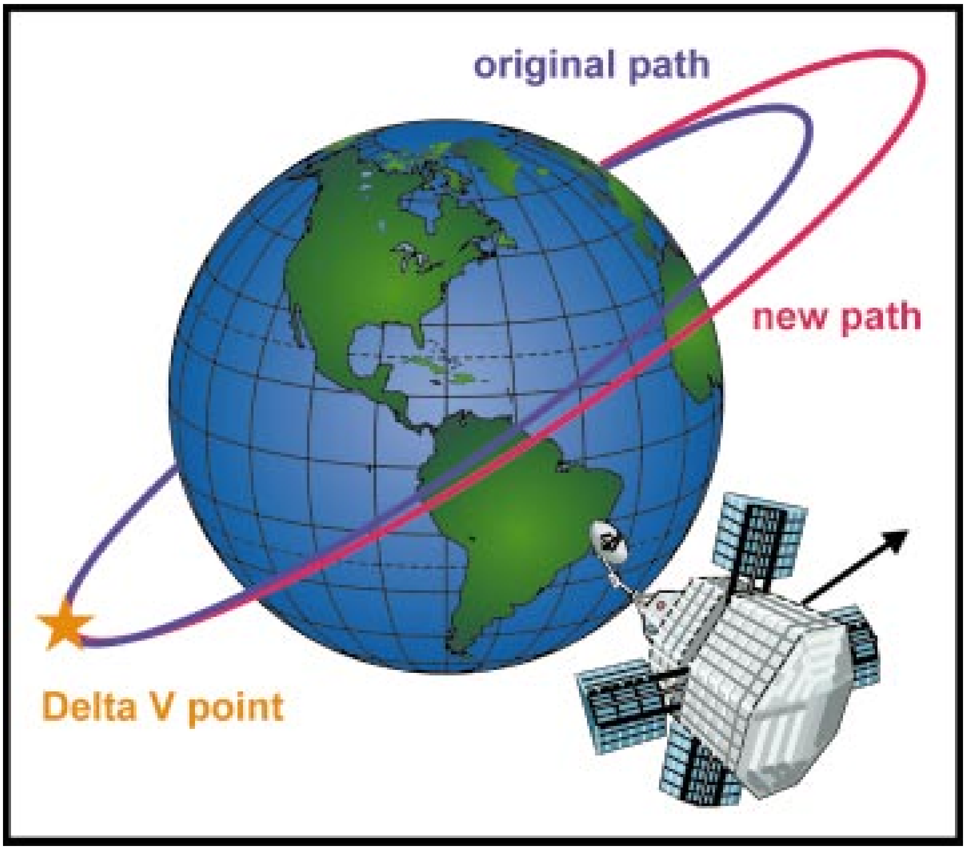

FIGURE 1-2. Thrusting Along the Flight Path.

Thrusting Upwards

On a different tack (literally), you can thrust crossways to your forward motion (vertically to your orbital path). Since the resulting vector is very small, your total speed is essentially unchanged. This means that your orbital period and average altitude would also remain unchanged. However, there would be small variations in your orbit that would repeat themselves every revolution, as follows.

A thrust upwards has the initial effect of doing what you would expect. You move upwards. But then you begin falling behind your constantly-moving reference point as your speed is no longer enough to keep pace with the lengthened orbital track.

Let's continue to use a figure of 1 meter/sec as the propulsive energy thrust you apply. After about a quarter of a revolution, your upward motion has died out, about 800 meters above and 1,600 meters behind where you started. You are still losing ground, slipping farther behind your original starting point, and then you begin falling back down towards your original altitude.

Half a revolution, about 45 minutes, after the upwards maneuver, you are about 3,200 meters behind where you started, on a mirror-image course, falling downwards at exactly the speed you first started upwards. Remember, without any change in your total orbital velocity, your motion will average out to keep you at the same average altitude.

Dropping below your original altitude, you pick up speed, and begin overtaking your original position. After exactly one complete revolution, you are precisely back where you started, moving upwards with the same speed you started with. It's deja vu all over again (Remember "Groundhog Day"—the Bill Murray movie) in orbit. Relative to your reference orbit, you follow the same path over and over again.

The only result of the vertical course change was to make the orbital path a bit lopsided, or in mathematical terms, more eccentric. Sometimes you are higher than your original orbit, and at other times you are lower. You didn't gain any permanent altitude increase by thrusting upwards. The only way to do that is to thrust forward. See Figure 1-3.

If you were in an orbit 300 km high, could you reach an altitude of zero kilometers by thrusting downwards toward Earth? The ratio described above—one meter/sec upward/downward thrust creates a changed altitude of 800 meters one quarter of a revolution later—means that you'd need a delta-V of about 400 meters/sec towards the

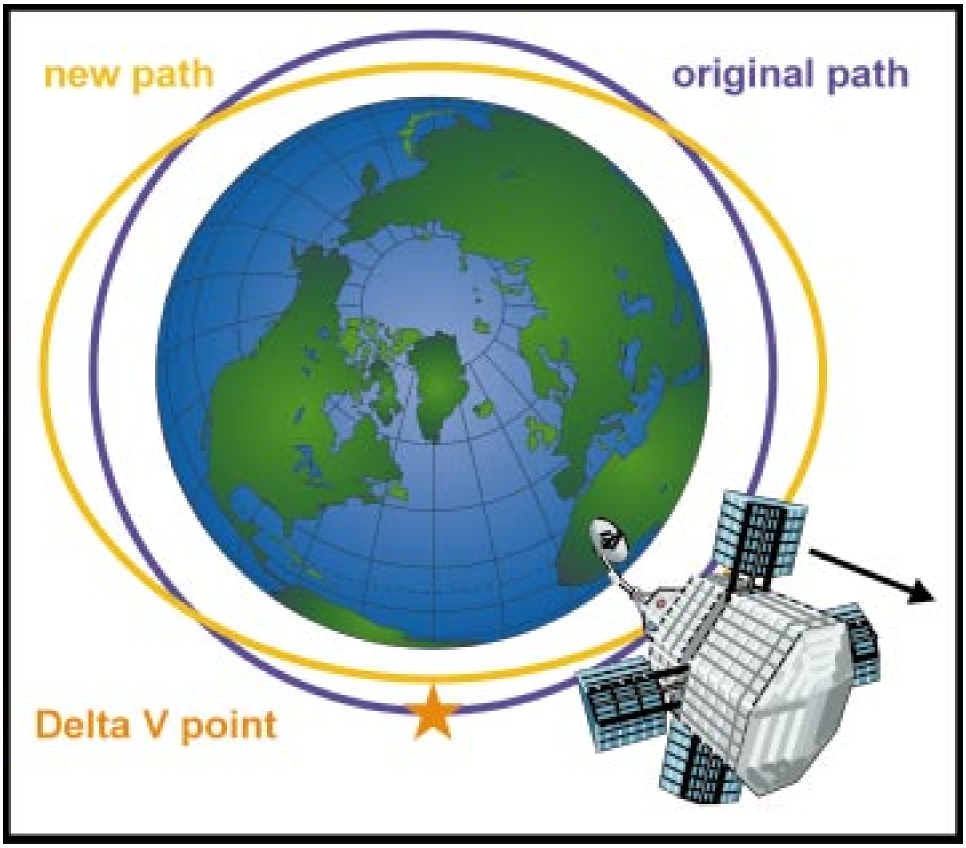

FIGURE 1-3. Thrusting Upwards.

Earth to achieve this. Compare this with the 100 meters / sec delta-V to deorbit in the most efficient manner, using a braking thrust along your flight path.

Inclination or Plane of an Orbit

Before we go any further, we need to talk about another technical characteristic of an orbit: inclination, which is very important to the usefulness of a satellite. Suppose your space vehicle was fired due east from a mountain on the Equator. Your orbital path follows the Equator. Your orbital path would not be inclined to the Equator and, therefore, would have a "0-degree" inclination. You will pass over only that part of the Earth's surface that lies on the Equator; you will never pass over Switzerland or New Zealand. If you could change the inclination, or plane, of your orbit to 45 degrees in relation to the plane of the Equator, then you will eventually pass over all of the Earth's surface between 45 degrees North and 45 degrees South latitude. You would pass over Switzerland and New Zealand, but not on each orbit. Because the Earth is slowly rotating underneath your satellite's orbit, at a rate of one revolution per day while your orbital path is revolving around the Earth every 90 minutes, from the point of view of Earth's surface, your orbital plane is shifting westward. Every time you pass over the equator heading northbound, you hit a farther west longitude.

Thrusting Sideways

Let's go back to operating your space vehicle. A horizontal sideways thrust—in orbitological terms, a thrust "out of plane"—has a similar periodic result as thrusting upwards. Initially, you move in the direction that "common sense" indicates.

Since you retain essentially the same overall forward speed you started with, your orbital period doesn't change, and so you must wind up one revolution later exactly back at your starting point. So after about a quarter revolution of travel, your off-to-the-side motion has died out, after you have gotten about 900 meters away from your starting point. You then start slipping back towards your original reference point. Half a revolution later, you pass right back through your reference point (the place where you would be if you hadn't thrusted) going in the exact opposite direction (left/right) you started to go. After this mirror image motion to the other side of your orbital plane, you wind up after one full revolution exactly back where you started. See Figure 1-4.

These figures show that changing a satellite's orbital plane in space is extremely difficult. That's because you are attempting to shift the momentum of an object traveling at a tremendous forward speed (about 8,000 meters per second) off in a different direction by making a crosswise thrust. Since a degree of latitude is 60 nautical miles, or 110

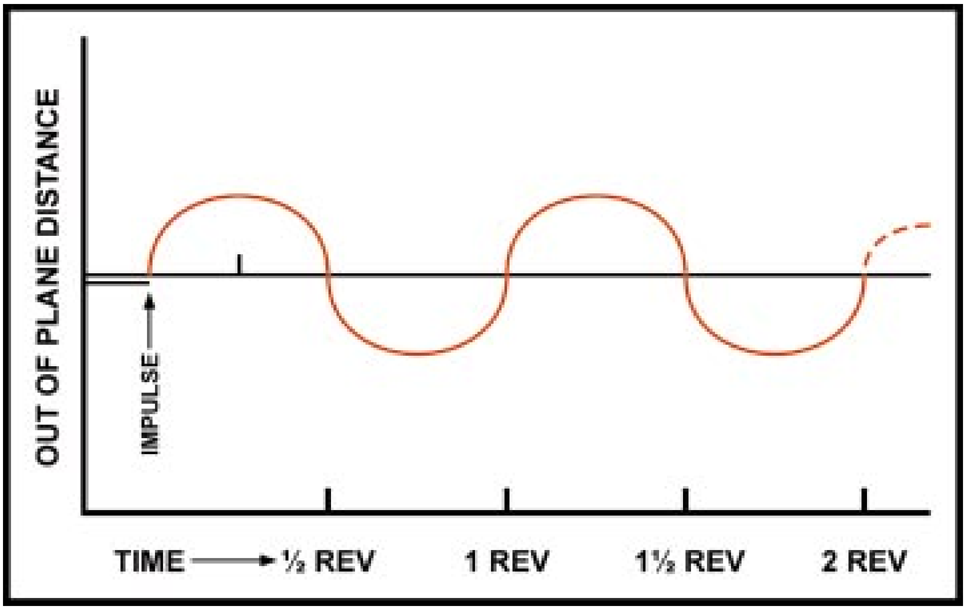

FIGURE 1-4. Thrusting out of Plane.

km, and 1 meter per second only moves you 900 meters, to get a full 110 km off to the side (to change your plane by one degree), you would have needed a burn out of plane of more than 120 meters per second. Compare that to the 100 meters per second which is enough to return to Earth.

Maneuvering in Space

Now that you are in control of your orbit, how can you change your path to get to where you want to be? Specifically, you may want to maneuver to rendezvous with another satellite, or to a specific location relative to a point on the ground. By the way, only a few nations have succeeded in accomplishing a space rendezvous. It seems easier than it really is in practice.

Solving the "rendezvous problem" depends on knowing what kind of solution you need. If it is merely to bring two objects together at any speed, there is one set of constraints. If the requirement is to bring two objects together at near-zero speed, an entirely different set of problems exists.

The first problem is one of “intercept” (deliberate collision), and aside from the tremendous speeds involved, it is not substantially different from air-to-air interception. The path of the target must be measured and predicted, and an interceptor must be steered into position close enough for the kill.

The “gentle rendezvous” problem, however, involves all the principles of orbital motion we have already discussed, including orbital planes and changing the shape of one’s orbit. It is therefore a useful mental exercise.

Because changing one’s orbital plane in space is prohibitively expensive, it is required to begin the rendezvous maneuver nearly in plane with the target. This means that the launching can occur only near those brief moments when Earth’s rotation carries the launch site through the orbital plane of the target satellite. This immediately places severe scheduling constraints on the rendezvous mission.

The preferred geometry for a rendezvous profile is for the chaser to approach the target from behind and below, which gives you an overtaking rate (remember the 10:1 rule). The desired time of arrival is picked to optimize lighting conditions and perhaps communications periods. To achieve this, the chaser’s approach rate is controlled by raising its orbit in small steps.

Some eccentricity (“wobble”) in the chaser’s orbit is desired to allow the line of sight to the target to shift back and forth during each revolution. This provides geometric visual cues as to the true range. And the closer the chaser gets, the more it must depend on its onboard sensors—visual, radar (passive or with transponder), even laser—since ground tracking doesn’t provide the required accuracy or timeliness. This is especially true for a noncooperating target, either one that is passive, or broken, or even potentially hostile.

The theoretically perfect approach paths are most economical in terms of fuel usage only if the chaser has perfect knowledge of its relative position and can perform its required course corrections precisely. Of course, this doesn’t correspond to reality, so in practice, an approach path is designed to be able to tolerate some position uncertainty and thrusting sloppiness.

Both automated and manual approach systems prefer simple control laws, which specify what corrections need to be made under what detected course deviations. They also usually contain a series of range-dependent “gates” at which the chaser must slow its approach down to specified rates. By this point, we have left the realm of pure orbitology and are using design principles from operational control theory.

Earth Surface Targets

Satellites do not, of course, fly across a uniform, featureless globe. There are specific points on the Earth’s surface of tremendous interest to the satellite’s operators. These may be communications stations, observational targets, planned landing zones, or other mission-relevant locations. It is highly desirable to optimize the changing relative position of the passing satellite to the ground locations.

Earth itself is in motion, rotating eastwards at a rate of 1,600 km per hour at the Equator, or about 15 degrees per hour. After a low-orbit satellite completes a 90-minute revolution, a point on the Equator will have rotated about 2,400 km eastward. If the satellite were in a polar orbit (one that is inclined 90 degrees to the Equator and passes over the North and South Poles), it would pass over the Equator exactly 2,400 km west of the point it crossed the Equator on the previous orbit. Each succeeding track across the Earth’s surface is thus displaced farther and farther west. This explains how you can be fired out of Newton’s cannon from a mountaintop 200 km high and not hit the mountain after only one Earth orbit (except for our equatorial orbit example earlier).

If there were a particular point on the surface that you wanted to pass over, you will need to adjust your groundtrack. It makes no sense to steer to the left or right, since we’ve seen that out-of-plane burns are tremendously expensive and of limited value. Instead, since Earth is moving sideways below your orbit, you want to give Earth more (or less) time to bring the point of interest directly below you when you reach the right point in your orbit.

You do that by delaying (or advancing) your arrival at the point in the orbit where the target passes underneath. That requires you to change the period of your orbit, and that requires you to raise (or lower) your average altitude.

Say, three days from now, you expect to pass 200 km east of a target of interest near the Equator—but you want to be directly overhead. So you want to give the target enough time to be carried eastward by Earth's rotation until it is directly below your track.

These are the steps you go through to estimate the maneuver required. Each one of these has already been explained.

Step 1. Since your satellite is traveling at 1,600 km / hour, you will need to let the Earth rotate underneath your satellite for an additional eight minutes, which essentially shifts your orbital ground track 200 km more or less, and should place your satellite over your target point.

Step 2. In three days you will be making 48 revolutions, you thus want to make each revolution last about one sixth of a minute, or 10 seconds, longer. This will give you a total of 8 minutes of delay after 48 revolutions.

Step 3. Since your satellite's speed is 8 km / sec velocity, you want to increase the distance covered on each revolution by about 80 km, so that it will take about 10 seconds longer for each revolution of the Earth.

Step 4. By the "10:1 rule" you thus want to increase the average altitude by 8 km.

Step 5. If you want to do this as cheaply as possible and use just one propulsive rocket burn, you can keep one end of the orbit the same and raise the other end by 16 km, or 16,000 meters.

Step 6. By the "2:1 rule," which actually specifies a 1:3,000 ratio of velocity change to altitude change, you will need a delta-V of about 5 meters per second to achieve this higher, slower orbit.

In summary, the best way to place yourself over a desired ground target is to exploit Earth's own rotational rate. You don't turn, you let the Earth turn. But this requires that you adjust your orbital speed by raising (or lowering) your orbit. The notion that you can get access to targets off to the side of your path by adjusting your forward speed is truly unearthly, but it's a straightforward consequence of the simple principles of orbital motion.

Geosynchronous Orbits

There are many reasons to want to control your ground track and make it fit into a pattern. You may want to repeat your track over the same ground targets every few days. You may want to maintain position with other related satellites which form a network in space, a "constellation." Any orbit which has a repetitive groundtrack is called "geosynchronous," that is, synchronized in some way with an Earth-surface reference frame.

The most famous kind of geosynchronous orbit—so famous that it often is thought to be the only kind—is one that is high above the Earth's surface (about 36,000 km) and is also in the same plane as the Equator (the equatorial plane of the Earth). A satellite at that specific altitude and at that inclination (0 degrees) circles the Earth exactly once a day. The resulting matched eastward rates of the satellite in this orbit and Earth's surface leads to the satellite holding a stationary position in the sky relative to a desired specific point on Earth. This is the so-called "geostationary" orbit, which is just a geosynchronous equatorial orbit with a period of one day.

Orbital Twist or Equatorial Shift

In practice, there are some other significant influences on the orbit of a satellite. One of those is the influence of the equatorial gravitational "bulge." Since the Earth rotates, it flattens slightly at the poles and bulges outward at the Equator. Probably the most significant and mysterious impact of the equatorial bulge is how it causes the path of an orbit to "twist" in space. Twist isn't really the right word; it's more like a long, gentle "S" turn. However, "twist" is the term used by most space operators. It's as hard to understand and as complicated as the not-right terminology indicates. But, orbital twist is important enough to be explained. For better and more detailed explanations, there are several good textbooks on orbital mechanics.

Various analogies have been suggested in orbital mechanics textbooks, having to do with right-angle forces on spinning wheels, and other strained parallels with earthside experience. But the most useful way to grasp the concept is to keep visualizing your space vehicle moving under the influence of gravity and its own forward speed—with extra localized gravitational pull as your satellite crosses the equator. Think of Earth's equatorial bulge as a ring around the planet's waist. It has its own mass, and will pull anything nearby towards it.

Now imagine your satellite approaching Earth's equator, say, from the southwest, at an angle (remember that angle with which it crosses the Equator is called the orbital inclination) greater than a few degrees. It's just been over a point well away and south of the Equator. It's aimed straight ahead for a spot above the Equator.

As it approaches the Equator, the nearest portion of the "bulge" is also pulling on it, directly toward the Equator. Its path will veer slightly toward the bulge, to the left. It will reach the Equator at a point somewhat to the left of where it had originally been headed.

North of the Equator the process is symmetrical but in the opposite direction. Now the nearest parts of this extra equatorial bulge are on the right, and it is in this direction that the satellite veers. As it finally distances itself from the Equator, the two effects—the veer to the left (south of the Equator) and the veer to the right (north of the Equator)—have balanced out to return the satellite to its original direction.

However, the original swerve to the left (westwards) is NOT counterbalanced, so the satellite's orbital plane has been effectively shifted a small amount. For a typical space shuttle flight from Florida, this shift per Equator crossing amounts to about 20 to 25 km. That's not much on an orbit that is 40,000 km long per revolution, but it can add up. For space shuttle flights, it can amount to a westwards plane shift of about five to seven degrees per day.

Now, if we apply the principles of gravitation to this effect, we can see how it works for different altitudes and inclinations. Since it is caused by the extra gravity from the equatorial bulge, the closer you are and the longer you stay close to this bulge, the bigger you should expect the effect to be.

This is exactly the case. The lower the inclination of an orbit, the longer it skirts "near" the Equator and the more it is twisted. The higher the orbital altitude, the more distant its approach to the extra mass, and so the less its orbital plane is twisted. See Figure 1-5.

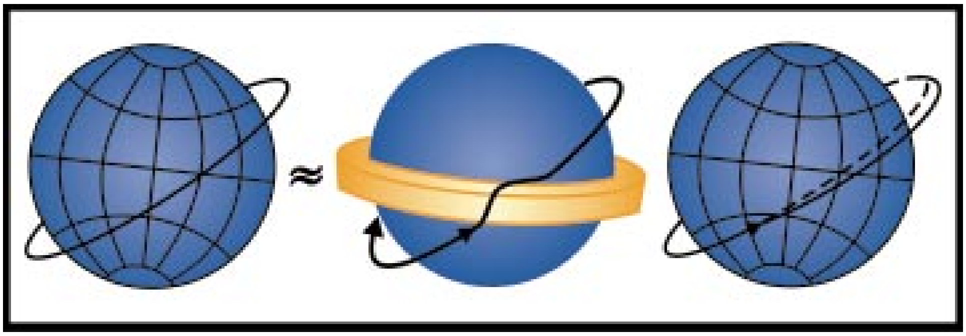

FIGURE 1-5. **Orbital Twist.**

An interesting and very useful application of this orbital twisting is connected with those orbits that are nearly perfectly north-south (near-polar) orbits that are slightly "retrograde"—that is, they approach the Equator from slightly east of south when northbound. The twisting still occurs, but this time (think of where the extra mass is closest), it is first to the right, towards the east and then to the left. Sketch this out to convince yourself.

As Earth circles the Sun once per year, it moves in its orbit and the Sun appears to move through the constellations. The rate is a little less than one degree per day, which works out to be 360 degrees in 365 days plus some hours.

If a satellite is placed in a slightly retrograde near-polar orbit, the equatorial bulge will twist the plane eastwards. The ideal situation is that the orbital plane shifts ("twists") eastward at the same rate as the Sun appears to move against the background stars, and as a result, the relationship of the orbital plane and the Earth-Sun line remains the same. This means that as the satellite passes over ground locations, the angle of sunlight—and the resulting shadows—remain fairly uniform, no matter how much time, or how many orbits, have gone by.

This is called a "sun-synchronous" orbit. It has many obvious applications to different types of observation platforms. The applications are so obvious that any object in such an orbit is presumed to be in some sort of Earth surface observation. There are a few other satellites in the same type of orbit to remain in continuous sunlight for reasons such as power, astronomical work, etc.

Recall that because the degree of orbital twisting depends on the satellite's altitude above the Earth, achieving the same amount of orbital twisting (the technical term is "precession") requires the selection of different inclinations for different operational altitudes. As the orbit gets higher (and farther from the Equatorial bulge), it must have a lower inclination so as to spend a proportionately longer time "close" to the bulge to accumulate the same amount of twisting. As a result, it will pass over a lessened north to south range of the Earth's surface; therefore, sun synchronous orbits can't be very high.

Using Orbits

Satellites in low earth orbits (LEO) have altitudes from about 150 km to 1,500 km. A satellite orbiting at an altitude of 150 km will require regular propulsive thrusting to stay in its orbit. It is slowed by the drag of the Earth's extremely thin atmosphere at this altitude. A satellite in an orbit of 150 km could stay in orbit at this altitude for only one day before decaying back, unless raised higher. Higher up, a satellite at 400 km could remain in orbit for a year without intervention, but it too would be slowed to a speed that could not keep it in orbit after about one year. For LEO orbits, drag is a significant problem. But LEO orbits are very important because the lower the satellite, the closer it is to objects on the Earth's surface. That means it can see those objects better with a telescope or pick up a less powerful radio signal from an object on the Earth. Satellites in LEO orbits do not see large areas relative to other orbital views. During a typical orbit by a satellite at LEO altitude, its field of view is a narrow ribbon of the Earth's surface about as wide as a large metropolitan city, and equal in area to less than one percent of the Earth's surface. The most valuable aspect of LEO is its proximity to the Earth for observation and low-powered communications.

Satellites in medium altitude orbits (MEO - medium earth orbit) between 1,500 km and 35,800 km, take from 2 to 24 hours to circle the Earth. The only valued orbit, at present, at MEO is the "semi-synchronous" orbit with an altitude of 20,700 km. Satellites at this altitude, because they revolve around the Earth in exactly 12 hours, repeat an identical track or ground trace over the Earth every 24 hours (if they have the proper inclination as well) and are therefore uniquely suited for some communications and navigation missions.

One particular semi-synchronous orbit, named the “Molniya Orbit” after the Russian satellite which first used it, is worth mentioning because of yet another gravitational disturbance on satellite orbits. The Molniya orbit is highly eccentric—that is, its high and low points are very different. In practice, the low points are about 800 km high, and the high points are about 40,000 km.

For such elongated orbits, a subtle new kind of twisting is caused by irregularities in Earth’s gravity field (it’s not just bulgy at the equator, it’s lumpy at various spots as well). The line running from the low point to the high point is (depending on orbital inclination) shifted clockwise or counterclockwise along the orbital plane. So over a period of weeks, a satellite with a high point over Norway, say, will see that high point shift to be over Italy, then over Libya, and so forth. This interferes with the planned application of such satellites for communications relay functions over far northern areas.

At one particular orbital inclination, these kinds of gravitational disturbances cancel out, and the orbit keeps its high point pointed in the original direction. That inclination happens to be about 62 degrees, and that’s why all satellites in Molniya-type orbits use this inclination.

Geostationary earth orbits (GEO) are at a very high altitude (35,800 km). As already explained, satellites at this orbital altitude appear motionless to an observer on Earth. Their field of view includes large expanses of the Earth, so much so that three of these satellites equally spaced over the Equator theoretically provides total coverage of the Earth’s surface, except the North and South Poles. GEO (really a misnomer) positions (“slots”) are controlled by the International Telecommunications Union (ITU) and are highly prized for communications uses, including television broadcast. Some warning systems are put at GEO altitude for their wide view of the Earth.

Conclusions

Motion through space is the ultimate “unearthly trip.” Attempts to lean on “common sense” analogies often fail us. Mathematical approaches often are severely intimidating. This appendix introduces a qualitative approach using a few rules of thumb and a few basic principles. It then tries to use those rules and principles to show how they explain the essentials of orbital motion. The desired result is an improved understanding by non-experts of how and why satellites move. That understanding can then provide insight into the uses of various orbits and orbital altitudes to provide space-based services. After all, for the critical functions of space operations, the scientific and precise answers can be left to the experts in orbital mechanics.