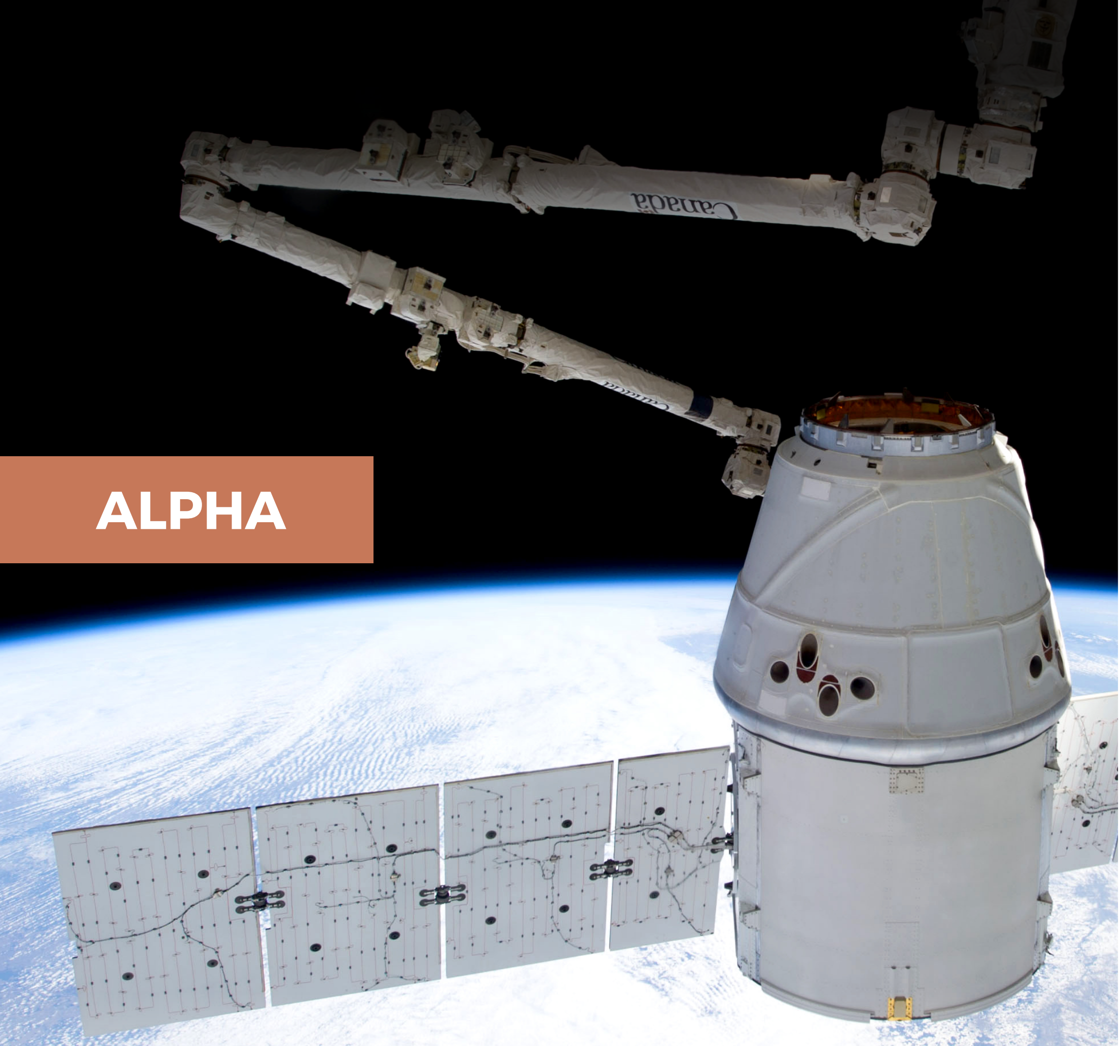
THIS ALL-IN-ONE GUIDE COVERS:

SPACECRAFT COMPONENTS
ORBITAL MECHANICS
ORBITAL RENDEZVOUS
MISSION OPERATIONS
PLANETARY OPERATIONS



ALPHA

ORBITAL VEHICLE OPERATIONS HANDBOOK

SEPTEMBER 9, 2016

ZLSA.GITHUB.IO/HANDBOOK

1. INTRODUCTION

Welcome to the Orbital Vehicle Operations Handbook! The Handbook will guide you through the basics of spacecraft operation and basic orbital mechanics, in the context of spacecraft operation and flight.

This Handbook covers spacecraft components, orbital mechanics, rendezvous and docking, aerocapture and reentry, and more. When you're finished reading this Handbook, you will know how spacecraft rendezvous with a space station, how capsules control their reentry, the entire launch process, and more.

I hope this Handbook helps you understand orbital mechanics and better appreciate the hundreds of thousands of hours that went into designing, building, and flying any spacecraft.

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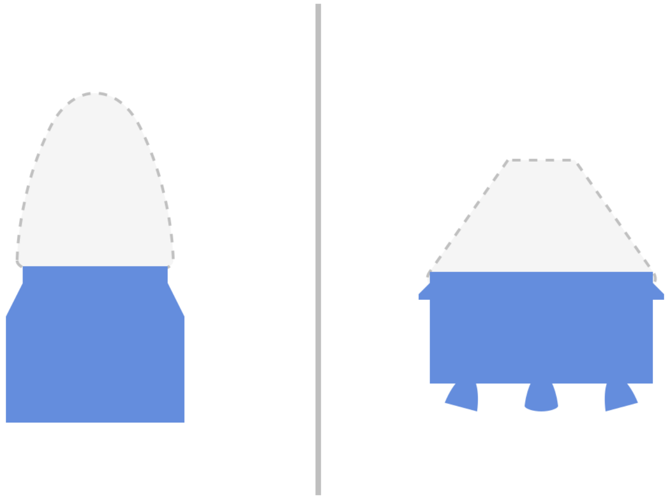
2. SPACECRAFT COMPONENTS

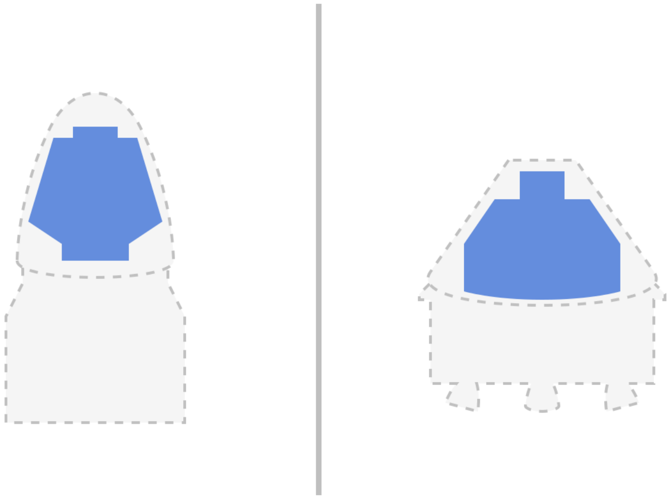
2.1. SERVICE MODULE

Most crewed spacecraft feature a service module. Much of the equipment used in space does not need to be safely returned to Earth, such as solar panels and orbital maneuvering engines. These are usually built into the service module instead; after the deorbit burn, the service module is jettisoned before reentry.



2.2. PRESSURE VESSEL

Every crewed spacecraft needs a pressurized compartment for its crew. The crew compartment must be pressurized to withstand the vacuum of space, and it must provide environmental controls and life support systems (ECLSS) for the long stay in space. The crew compartment usually contains custom-made seats, for the astronauts to sit in during launch and reentry, in addition to on-orbit sleeping when not docked to a space station. The crew compartment is not necessarily the same as the spacecraft's outer mold line (the "shape" of the vehicle).



2.2.1. ECLSS

Environmental controls and life support systems (ECLSS) are a required component of any crewed vehicle. Without ECLSS, exhaled carbon dioxide will displace the oxygen, and the crew compartment will overheat when the capsule is exposed to the sun. ECLSS is a very complicated mission-critical system, and redundancy is built-in so that an ECLSS subcomponent failure does not necessitate a mission cancellation.

2.3. POWER

Every spacecraft needs power; some spacecraft use fuel cells and some use batteries. Most battery-powered spacecraft also feature some form of recharging the batteries while the spacecraft is in space; these usually take the form of solar panel arrays.

Power is a critical system on any spacecraft since it powers many other critical systems, such as ECLSS. Because astronauts cannot simply perform an EVA to debug the power system, it must be very reliable and foolproof.

2.3.1. SOLAR ARRAYS

Solar arrays are used to recharge the onboard batteries. Solar arrays are almost always installed on the service module, as they're not needed during reentry and landing.

Usually, the solar arrays unfold once the spacecraft has reached orbit; however, some spacecraft feature fixed solar panels that are mounted to the service module. Fixed panels, unlike deployable solar arrays, cannot fail to deploy and usually weigh less; however, the maximum amount of power they generate is limited by the size of the service module.

2.4. CONTROL SYSTEMS

All spacecraft need to maneuver once in orbit, if only to deorbit at the end of the mission. Most spacecraft also need to keep themselves pointing in one direction to keep the solar panels facing towards the sun and to keep the thermal radiator facing away from the sun.

There are a few methods of controlling attitude on a spacecraft, but by far the most common is a reaction control system (RCS). A reaction control system is simply a network of small thrusters, that can produce small amounts of thrust quickly and accurately. With enough RCS thrusters pointed in different directions, the spacecraft can orient itself in any direction.

RCS thrusters are usually placed on the capsule or spaceplane, but some spacecraft feature RCS thrusters on the service module in addition to the capsule or spaceplane RCS thrusters. RCS propellant is sometimes stored in the service module as well.

Some spacecraft also feature a dedicated orbital engine, usually pointed directly backwards. This engine is usually more powerful and efficient than

RCS thrusters; these engines are used when performing long orbital maneuvering burns, such as the deorbit burn.

Space stations tend to be delicate; typically, visiting spacecraft must not use their RCS thrusters when in close proximity to the station. This is to prevent damage of delicate space station components, such as solar arrays and wiring.

3. ORBITAL MECHANICS

3.1. DELTA-V

Delta-v, dV, or ΔV (short for delta velocity), is simply the difference in velocity between two states. For example, imagine your spacecraft is floating in space, with no other bodies to affect it; to quantifiably measure ΔV , a part of the spacecraft is separated from the rest of the spacecraft. Because of Newton's first law, it will simply coast alongside the spacecraft; the current ΔV between the spacecraft and the part that was left behind is 0 meters per second.

Now imagine a rocket engine on the spacecraft is ignited. The spacecraft will start to fly away from the part that was left behind. When the engine is shut down, the ΔV of the burn is simply the difference in velocity between the piece of your spacecraft (which is equivalent to the velocity of the spacecraft before the burn) and your spacecraft after the burn. ΔV is almost always measured in meters per second.

ΔV does not measure distance; it measures only a difference in velocity. The energy required for maneuvers and engine burns is measured in ΔV , providing a vehicle-agnostic measurement of the amount of energy required.

3.2. GRAVITY

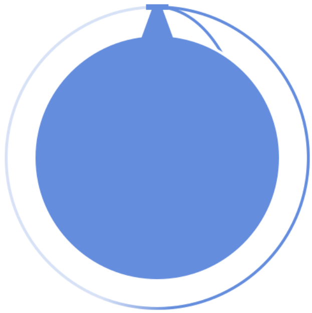
While a spacecraft is in orbit, gravity is still acting upon it even though it may appear to be "weightless". This is because the spacecraft, along with its crew and cargo, are all affected only by gravity, without any friction; since the external gravitational influence is identical for both the spacecraft and its contents; hence, the relative velocity between the spacecraft and its contents is zero, creating the illusion of zero-G.

3.3. BASIC CONCEPTS

3.3.1. ORBITS

The path that a body traces through space while under the gravitational influence of another body is called an orbit. It can be tricky to understand at first, since orbits, by necessity, do not work on the surface of a planet, so for most people, there is nothing to base orbital knowledge on.

A simple way to visualize an orbit is called Newton's Cannonball. The thought experiment involves a small planet with a large mountain; on the very top of this mountain is a cannon, pointed horizontally (not at the horizon; since the cannon is on a mountain, the horizon would be below horizontal). If you were to just drop a cannonball from the mountain, it would immediately fall down until it hit the mountain; if you threw it as hard as you could it would fly forwards a little, but it would still hit the mountain.

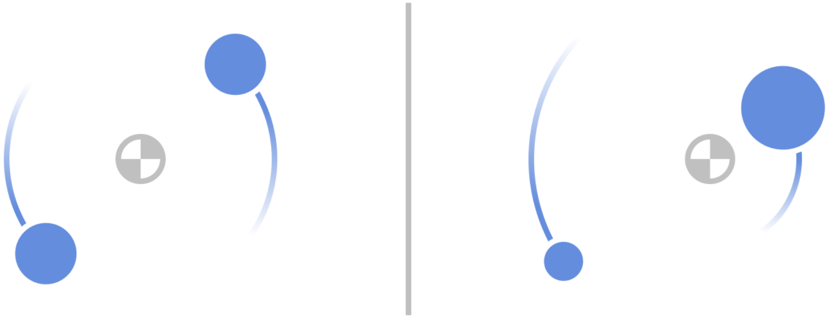


Now, if you put the cannonball into the cannon and fired the cannon, the cannonball would travel very far indeed, but it would eventually hit the ground, many miles downrange from the mountain. If you had a light enough cannonball and a small enough planet, you would be able to fire a cannonball so fast that it would travel forwards as it fell "around" the planet. As the cannonball falls towards the planet, its momentum carries it forwards. In the absence of an atmosphere, there would be no air friction; so the cannonball would stay in orbit forever. (However, as a side note, the cannonball would circle around the planet and strike the cannon from the other side. Since no forces have acted on the cannonball other than the planet, its path will not change during its orbit, so it will arrive exactly where it started from, but with a lot of velocity.)

Technically, when you throw a ball into the air, the ball is in a highly elliptical orbit with an apoapsis within the atmosphere; it has a definite periapsis and apoapsis. However, the Earth is so large that unless you're throwing things very fast, there will only be a tiny difference between an elliptical orbit and a simplified parabolic trajectory.

3.3.2. TWO-BODY SYSTEMS

In an ideal two-body system, both of the bodies will orbit around their common barycenter. This is because both bodies are affecting each other; no matter how heavy one is and how light the other is, the bodies will have a barycenter. As one body gets heavier and the other gets lighter, the barycenter will move towards the heavier body; however, unless the lighter body has zero mass, the heavier body will always be orbiting the shared barycenter.



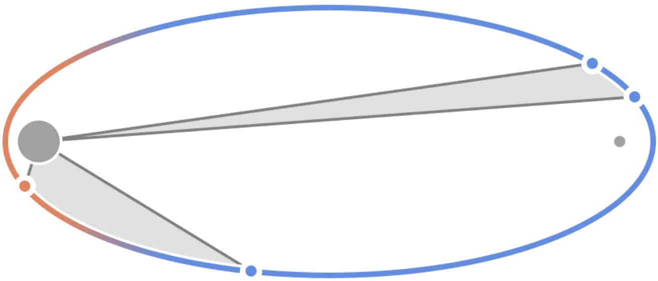
Despite this, in an ideal two-body system featuring a planet (such as the Earth or Mars) and a spacecraft, it can usually be simulated as a fixed, non-moving body and a spacecraft that orbits around it. For example, in an ideal two-body system with a typical crewed spacecraft weighing about 8 metric tons orbiting the Earth, the barycenter of the pair is only one 50,000th of an atom away from the Earth's center of mass (CoM). Realistically, the barycenter can be ignored when planning most spacecraft missions.

3.3.3. KEPLER'S THREE LAWS

Kepler's three laws describe the elliptical motion of a body orbiting a planet. (Note that these three laws only apply in the case of an orbit with an eccentricity less than one.)

1. The orbit of a body around a planet is an ellipse, with the planet being at one of the two foci of the ellipse.
2. A line segment connecting the body and the planet sweeps out equal areas during equal areas of time.
3. The square of the orbital period of a body is proportional to the cube of the semimajor axis of its orbit.

The first law simply describes the basic shape of any orbit; the second describes the time taken to travel around different parts of the orbit; and the third states that orbital speed is relative to the size of the ellipse.



3.3.4. MULTI-BODY SYSTEMS

The above information is only correct for an idealized two-body system. In reality, while your spacecraft may only be orbiting a single planet, that planet is orbiting another body, which may have dozens of bodies orbiting it, all of which also have other orbiting bodies.

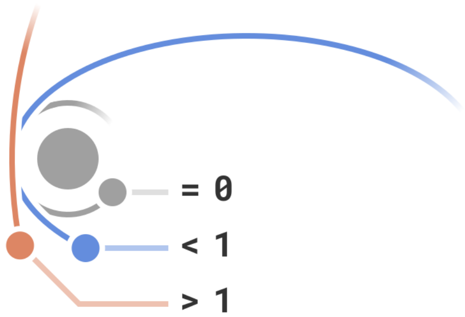
During Earth operations on-orbit, the strongest gravitational influences are the Earth, the Moon, the Sun, and Jupiter. The Earth and the Moon are high on the list for obvious reasons, as is the sun. Jupiter is also on the list because it's an exceptionally heavy planet (over three times heavier than Saturn, the next heaviest planet). Despite being so far away, it exerts a measurable influence on satellites orbiting the Earth, and it must be taken into account during the mission planning phase.

When a spacecraft is affected by forces not taken into account in an ideal two-body system, the orbital trajectory includes perturbations. These can be caused by a non-spherical planet (such as the earth), an uneven mass distribution of the planet, or other planets. Perturbations manifest as slight drifts to the orbit over time; the spacecraft may need to perform correction burns as a result. The Earth itself isn't perfectly spherical; its gravitational force varies depending on the spacecraft's inclination. Of other planets, the Earth's moon is very large relative to the Earth for a moon; its effects on orbiting spacecraft is marked, and special care must be taken during mission planning for lunar perturbations.

Mathematical equations have been developed to quantify the influence the moon has on Earth-based spacecraft orbits; together, they are called lunar theory. Taking into account lunar theory is an important part of planning Earth-based missions since the moon strongly affects any satellite or spacecraft orbiting Earth due to its high mass and relatively close proximity to the Earth.

3.3.5. ECCENTRICITY

So far, we have only investigated perfectly circular orbits. In reality, no orbit is perfectly circular; such an ideal orbit has an eccentricity of zero. The more elliptical an orbit is, the higher its eccentricity; an orbit with an eccentricity of one is a parabolic escape trajectory; and an orbit with an eccentricity greater than one is a hyperbolic trajectory.



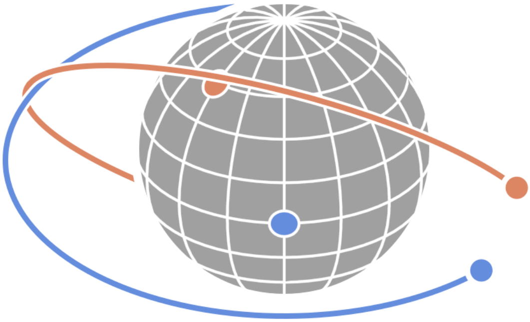
When a body is orbiting around its parent with a parabolic escape trajectory, its speed is the absolute minimum required to escape the gravitational influence of its parent; if its speed were any lower, the eccentricity would be less than one, and it would remain in orbit instead of being flung out.

A hyperbolic trajectory is simply a parabolic escape trajectory, but with a higher velocity. In reality, any spacecraft traveling between two bodies will use a hyperbolic trajectory, both when departing the first body and when arriving at the second.

3.3.6. INCLINATION

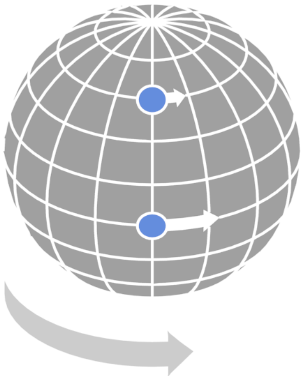
Unlike the orbits explained in these diagrams, reality is not two-dimensional. Spacecraft must deal with a third dimension: inclination.

When launching from an ideal equatorial launch site, the inclination of the resulting orbit can be as low as zero degrees. The ground track of a zero-inclination orbit would follow along the equator; if you mounted a camera onboard the spacecraft and aimed it at the Earth, the equator would always cross through the center of the frame.



However, no launch sites currently in operation are situated on the equator. Cape Canaveral is at 28 degrees north of the equator, while Russia's Baikonur Cosmodrome is nearly 46 degrees north of the equator. When a spacecraft is launched into orbit, the minimum inclination is the same as that of its launch site. This is a large part of the decision to build the ISS at 51.6 degrees inclination, since Russia's launch site is located at 46 degrees north; if the inclination of the ISS was lower than 46 degrees, Russia would not be able to easily launch their spacecraft to the ISS.

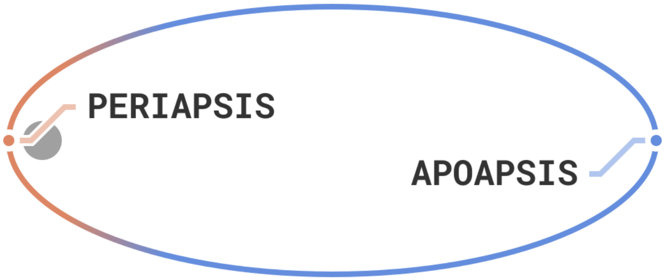
There's another factor that must be taken into consideration in conjunction with orbital inclination, and that's the velocity of the planet's surface at the launch site. Since the Earth spins along its axis once every 23 hours and 56 minutes (one sidereal day), some velocity can be taken from the Earth's rotation when launching spacecraft. At the equator, the Earth's surface velocity (relative to the Sun and Earth's center of mass) is 464 meters per second (m/s). The further the launch site is from the equator, the less surface velocity is present. To launch into orbit from a high inclination launch site requires more energy from the launch vehicle as compared to an equatorial launch site.



This is why most launch sites are located as close as possible to the Earth's equator: the closer the launch site is to the equator, the less fuel a launch vehicle will need to reach Earth orbit (and beyond).

3.3.7. PERIAPSIS AND APOAPSIS

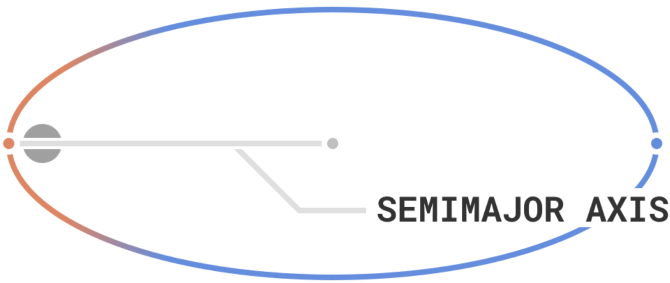
The periapsis of an orbit is the point at which the spacecraft and body are the closest to each other; the apoapsis is simply the furthest point. Any orbit with an eccentricity greater than one will have an apoapsis and a periapsis. The periapsis and apoapsis are typically measured from the spacecraft to the surface of the body, to simplify matters for the astronauts; however, mathematically, the periapsis and apoapsis are measured relative to the barycenter.



Since periapsis and apoapsis describe locations relative to the orbit, not the parent body, any changes to the orbit will also change the periapsis and apoapsis.

SEMI-MAJOR AXIS

The semimajor axis of an orbit is the distance from the periapsis to the apoapsis, divided by two. Despite appearing to be derived from the periapsis and apoapsis, the semimajor axis is the root from which those are derived; since an orbit with an eccentricity less than one is an ellipse with the parent body at one of the foci, the semimajor axis is generally more useful for orbital calculations than the periapsis and apoapsis are.



ORBITAL PERIOD

The period of an orbit is the amount of time it takes to complete one full orbit. It can be calculated from the semimajor axis and the mass of the parent body. Due to Newton's laws, a higher orbit (with a larger semimajor axis) will have a longer period than that of a lower orbit. To adjust the orbital period, the semimajor axis must change; this is done by changing the apoapsis and the periapsis by burning prograde or retrograde.

3.3.8. ASCENDING AND DESCENDING NODES

Every object orbiting a body with an inclination greater than zero will have both an ascending node and a descending node in its orbit. Like the periapsis and apoapsis, the ascending and descending nodes are located relative to the orbit and the parent body, so any changes to the orbit will also change the ascending and descending node.

Ascending and descending nodes only work if the parent body has an equator. The imaginary plane extending out in all directions from the equator of the parent body is called the plane of reference; it applies to any satellites orbiting the body.

The ascending node is the point where the orbit crosses the plane of reference, travelling south to north. The descending node simply delineates the opposite side of the orbit, where it crosses the plane of reference, travelling north to south.

ARGUMENT OF PERIAPSIS

The argument of periapsis is the angle, measured starting from the ascending node and travelling northwards, to the periapsis. The argument of periapsis orients the orbit's semimajor axis within its orbital plane.

LONGITUDE OF THE ASCENDING NODE

The longitude of the ascending node is the longitude, relative to the parent body's center of mass, is the longitude directly underneath the ascending node. It is measured relative to the parent body's center of mass, not its surface; this means that the longitude of the ascending node will not change as the parent body spins on its axis.

The longitude of the ascending node is used to orient the orbit relative to the parent body.

3.3.9. MEAN ANOMALY AT EPOCH

The mean anomaly at epoch describes the virtual angular position of the satellite at a predetermined time (the epoch). The mean anomaly does not describe a physical angle, except in the case of a perfectly circular orbit; because of Kepler's third law, any orbit with an eccentricity greater than zero will have a non-uniform orbital velocity. Mean anomaly will therefore "drift" during the orbit; so it must first be converted into true anomaly. True anomaly takes into account the eccentricity of the orbit, and so provides the direct physical angle between the periapsis and the orbiting object at a given point in time.

3.3.10. KEPLERIAN ELEMENTS

When the values for eccentricity, inclination, semimajor axis, the argument of periapsis, the longitude of the ascending node, and mean anomaly at epoch are combined, the exact position of the spacecraft in space can be calculated at any time. Together, these six values are called the orbit's Keplerian elements. They only apply to an ideal two-body system, with no external gravitational influences. Since external gravitational influences affect the orbit over time, Keplerian elements cannot be accurately used for anything beyond an ideal two-body system.

3.4. ORBITAL MANEUVERING

Maneuvering in orbit is a critical component of any spacecraft operation, and is required for orbital rendezvous and docking as well as deorbit operations. It is also essential during any mission that flies beyond low earth orbit.

Orbital mechanics make maneuvering difficult and counter-intuitive.

All orbital maneuvers simply adjust your orbit, albeit in different directions. There are a few main categories of orbital maneuvering:

1. Periapsis and apoapsis adjustments (changing your altitude)
2. Orbit phasing (adjusting the duration, or period, of your orbit)
3. Plane changes (also known as inclination changes)

3.4.1. IMPULSIVE VS. FINITE MANEUVERS

Any maneuver can be ideally simulated as an impulsive maneuver, a maneuver which is completed instantly. In reality, an impulsive maneuver is impossible as it would require infinite thrust; however, it's a good approximation during mission planning. The analogous non-instant maneuver is called a finite maneuver, as it takes a finite amount of time to complete.

There are methods to convert an impulsive maneuver into a nearly equivalent finite maneuver; thus, most of the mission planning can be accomplished with impulse maneuvers, to be converted into finite maneuvers after verifying the intermediate orbits.

The following sections will assume impulse maneuvers for simplicity. In reality, these maneuvers will take a finite amount of time, so the start of the maneuver must be shifted backwards in time so that the midpoint of the maneuver is at the proper location.

3.4.2. ORIENTATION

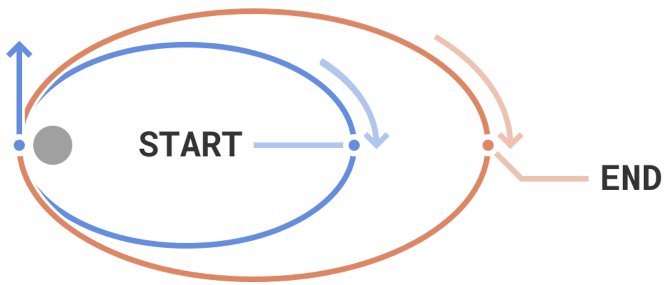
As you might guess, orientation is critical during orbital maneuvers, because most spacecraft have an optimum direction to thrust in. Some spacecraft have engines that are specifically designed for orbital maneuvers, but they only point in one direction. For these reasons, spacecraft need to orient themselves while performing orbital maneuvers.

Most maneuvers involve orienting the ship either prograde (in the direction of movement) or retrograde (the exact opposite of prograde). Inclination changes, however, require orientations that point transversely relative to the orbital plane (i.e. "north" or "south", but relative to the orbital plane). These are called normal (for north-facing) and anti-normal (for south-facing).

Very rarely used are radial orientations; a radial-in orientation is perpendicular to the orbital trajectory, pointing in the general direction of the planet; a radial-out orientation is the opposite.

3.4.3. PERIAPSIS AND APOAPSIS ADJUSTMENTS

To adjust the periapsis or apoapsis, the spacecraft must be at the opposite point in the orbit. For example, to increase the apoapsis, the spacecraft must be at the periapsis, then burn prograde until the apoapsis reaches the target value. The reverse is true to lower the apoapsis.



Since the orbital period depends on the length of the semimajor axis, with a larger orbit having a longer orbital period, adjusting the periapsis and apoapsis will by necessity also adjust the orbital period.

Often, a spacecraft needs to adjust both its periapsis and apoapsis by the same amount. Usually, the most efficient method is a Hohmann transfer. To perform a Hohmann transfer, the spacecraft first performs an orbit adjustment maneuver to change the altitude of the other side of its orbit; then, when it reaches the new altitude at the other side of its orbit, it performs another orbit adjustment burn to bring the first point to the proper altitude as well.

3.4.4. ORBIT PHASING

Orbit phasing refers to the timing of a spacecraft within its orbit. This is usually required during rendezvous; even if the semimajor axes, orbital planes, and eccentricities of the two spacecraft are the same, the spacecraft may be a half-orbit apart.

Orbit phasing needs to be performed on every mission that includes a rendezvous. However, with the proper planning, it can be performed alongside the spacecraft's altitude adjustment maneuvers.

3.4.5. PLANE CHANGES

A plane change maneuver adjusts the inclination of the spacecraft's orbit. To do so, it must burn in the normal or anti-normal directions. Plane change maneuvers are the most expensive maneuver, ΔV wise. To adjust the inclination of a circular orbit by 90 degrees requires nearly as much ΔV as it took to reach orbit in the first place. Plane changes are only performed when they are absolutely necessary, such as for satellites that must be in geostationary equatorial orbit (GEO). Such satellites must be on the equator, and since no launch site is on the equator, they must perform a plane change once in orbit.

Since all orbital maneuvering ΔV is relative to your existing ΔV , plane changes are more efficient the more eccentric your orbit is, provided the plane change maneuver is performed at the apoapsis. It's often more efficient to dramatically increase the apoapsis, perform a plane change, then lower the apoapsis again instead of performing a plane change in-place. Some launch providers will launch GEO satellites into a super-synchronous orbit, with an apoapsis much higher than necessary, to reduce the ΔV requirements of the satellite itself.

3.4.6. OBERTH EFFECT

The Oberth effect describes the counterintuitive fact that a prograde burn at periapsis imparts more energy to the spacecraft than one performed at the apoapsis. This is because the kinetic energy in an object is the square of its velocity; therefore, adding a fixed amount of velocity while the spacecraft is moving rapidly will add more kinetic energy than if the velocity was added while the spacecraft was moving slowly.

3.5. ORBITAL RENDEZVOUS

One of the most difficult tasks is rendezvous and docking with another spacecraft. It requires a deep understanding of orbital maneuvering, the capabilities of your spacecraft, and the ability to precisely target another spacecraft in orbit.

To understand orbital rendezvous, it's simpler to first work backwards from a spacecraft that's already docked to a space station. Their orbits are completely identical, and their speeds are matched up perfectly.

First, the spacecraft must undock from the space station. This is usually performed by sealing the hatch from both sides, unlocking the docking port, then using electromechanical pushers to mechanically separate the two. After some coast time, the spacecraft is far enough away from the space station to use its RCS thrusters.

At this point, the spacecraft will begin a series of Hohmann transfers, reducing its altitude (and increasing its distance to the space station at the same time). This is done to minimize RCS thruster usage while the spacecraft is still near the space station. From an observer on the space station, the spacecraft will appear to fall towards the planet and start moving retrograde.

Now, the spacecraft is in a separate orbit, lower and faster than that of the space station. The spacecraft has just performed the opposite of a rendezvous; the only difference is that a departure is typically faster than a rendezvous, as there's less chance of approaching the space station too closely.

The reverse of spacecraft departure is spacecraft rendezvous. Now, the spacecraft is in the exact same low, fast orbit that is needed to begin orbital rendezvous; with the space station in a higher, slower orbit. The orbital planes are parallel; if not, a plane change maneuver will have to be made.

The spacecraft now performs a series of Hohmann transfers, to raise its orbit to that of the space station. The timing of these transfers is critical, since the orbital phasing is being adjusted at the same time. During the maneuvering, the spacecraft is communicating with both the space station and ground controllers, who watch the position to make sure the spacecraft will not pass too close to the space station.

As the spacecraft approaches the space station from below, it performs several small burns to match orbits nearly perfectly, then maneuvers itself around the space station to a docking port; despite the close proximity of the spacecraft and the space station, orbital mechanics still applies, and care must be taken that the spacecraft remains in the same position relative to the space station.

The only thing that remains is to dock with the space station; this is usually fully automated, like rendezvous; during the docking procedure, the spacecraft will use its onboard docking camera to track visual targets on the space station's docking port.

When the spacecraft contacts the docking port, petal-shaped flaps align the two docking ports; hooks extend to lock the two together, and connectors for air and electricity are connected and opened. Soon afterwards, the hatches on both sides are opened and crewmembers may board the space station.

4. MISSION OPERATIONS

In reality, a crewed mission is much more complex than the orbital maneuvers described above. In fact, with a mission that may only last a few days, mission planners on the ground have been preparing the mission for several years.

4.1. LAUNCH OPERATIONS

4.1.1. PRELAUNCH OPERATIONS

Months before the launch of your spacecraft, mission planners will begin to plan out your mission. If your mission is to a space station such as the International Space Station, the mission planners will need to secure approval for a visiting spacecraft as well as preparing for the rendezvous procedure.

Your mission planners will formulate a mission plan. This includes:

- Cargo manifest and center of mass calculations
- Astronaut scheduling
- Launch profile and orbital trajectory
- Space station approach, rendezvous, and docking
- Space station undocking and departure
- Deorbit planning and entry trajectory
- Recovery vessel positioning

While your mission is being prepared by the mission planners, you and your crew will train for spacecraft operations and zero-g movement, in addition to whatever specialized training your mission may require. Crew training is considered one of the more strenuous and difficult parts of being an astronaut, but just remember: what you learn in crew training will possibly save your life in the future.

4.1.2. LAUNCH OPERATIONS

The spacecraft will arrive at the launch site integration hangar a few weeks before launch. During this time, it is loaded with cargo, with the exception of late-load cargo. Checks are done on the spacecraft, and it's integrated to the launch vehicle and readied for rollout and erection.

The launch vehicle is usually rolled out to the launchpad a few days in advance of T-0. Different launch providers have different launch vehicle designs, and hence have different rollout and erection schedules and guidelines.

You and your crew will board the spacecraft only a few hours before launch, before fueling has occurred. Typically, you will board the spacecraft via the crew arm, which is swung away after ground crew have strapped you into your seats and closed the spacecraft ground door.

After the launchpad is cleared of all personnel and the command is given, launch vehicle fueling will begin. Once again, precise timing depends on the launch provider's choice of vehicle.

If your mission includes rendezvous with a space station, the launch window is very short or instantaneous. If the launch occurs too far from the optimal launch time, the spacecraft will need to perform an expensive on-orbit inclination change. Most spacecraft do not have enough onboard delta-v to perform this maneuver themselves.

Fueling is usually completed a few minutes to an hour before the planned liftoff time. The crew access arm retracts, and the launch vehicle and spacecraft switch to internal power (instead of power provided from the launch pad) in preparation for flight.

A few minutes before liftoff, the fueling valves are closed, and any excess gases in the tanks are vented until seconds before engine ignition. This is only an issue with cryogenic propellants, such as liquid oxygen or liquid methane; kerosene, with a boiling temperature well above the boiling point of water, does not boil off while in the tanks.

A few seconds before liftoff, the engine ignition command is given. Engine startup is a long and complicated process, and auto-aborts during the ignition sequence are not rare. After the vehicle has determined that all of the engines are operating properly and at the right thrust levels, the command is given to release the hold-downs.

As soon as the hold-downs are released, the launch vehicle will begin to ascend. A few seconds after liftoff, the launch vehicle will have cleared the tower; soon afterwards, the vehicle will perform a pitch kick to begin the gravity turn.

As the propellants are burned in the engines to produce thrust, the launch vehicle will lose mass; however, since the thrust level of the engines does not decrease, the thrust-to-weight ratio (TWR) will increase during first-stage flight. To compensate for increased acceleration, launch vehicles need to reduce thrust. There are two primary ways to reduce thrust; the method depends on the throttleability of the launch vehicle's chosen rocket engine.

On launch vehicles whose engines cannot throttle (or if the engines do not have the necessary throttle range), one or more engines are shut down to reduce total thrust. This method only works if you have three or more engines, and if they are arranged to allow for shutdowns without adversely affecting the thrust vector.

The other, more common method is to throttle all of the engines down equally. This is the preferred method for many reasons: first, throttling engines is much smoother than shutting them down; second, engine shutdown is nearly as complex as engine ignition; and third, shutting down engines changes the thrust distribution. All currently-flying human-rated launch vehicles throttle their engines during the ascent.

During the atmospheric portion of ascent, the launch vehicle must fly in the direction it's travelling; even slight deviations will cause a rapid loss of control due to aerodynamic forces and necessitate a launch abort.

As the vehicle ascends, there will be a point of maximum dynamic pressure (MaxQ) on the vehicle; this is the point of highest aerodynamic stress on the vehicle and is one of critical points during a launch. In most launch vehicles, MaxQ occurs shortly after the launch vehicle goes supersonic.

When the target velocity and altitude are reached, the first stage engines shut down; this is called main engine cutoff (MECO). Shortly afterwards, the first stage is separated and the second stage engine is ignited.

Depending on how many stages the launch vehicle has, this cycle continues until the spacecraft has reached its desired orbit (or in the case of a mission to a space station, a preliminary parking orbit). At this point, the engine on the final stage is shut down and the spacecraft is separated from the launch vehicle.

4.1.3. POSTLAUNCH OPERATIONS

The primary concern after reaching orbit is power. Most spacecraft feature unfolding solar arrays, but some spacecraft, such as the SpaceX Crew Dragon, feature integrated solar panels that do not require any action to provide power. On the other hand, the Boeing Starliner does not feature any type of power generation; as such, the Starliner is only capable of visiting space stations that can provide power to visiting vehicles.

Once the spacecraft is in the correct attitude and is generating power, less important systems can be checked for proper functionality.

5. PLANETARY LANDING

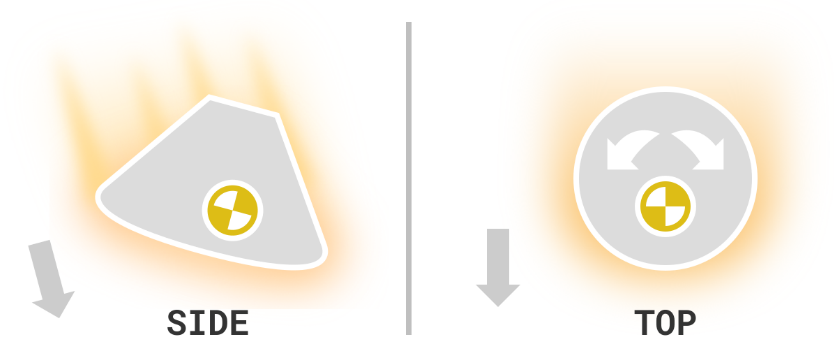
Successfully landing on a planet requires a set of steps to be performed with precise timing. First, the spacecraft's periapsis must be low enough to capture the spacecraft as it descends to the atmosphere; second, the spacecraft must control itself during reentry to target a landing point; and third, the spacecraft must provide some form of deceleration to allow for a smooth touchdown.

5.1. DEORBIT

Deorbiting a spacecraft is relatively simple: you just perform a maneuver at the apoapsis that lowers the periapsis and fine-tunes the entry trajectory. When the perigee is deep enough in the atmosphere, deorbit is assured. Once the spacecraft maneuvers are complete, the service module, if present, is jettisoned, and the spacecraft reorients itself in preparation for atmospheric entry.

5.2. ATMOSPHERIC ENTRY

After less than a half-orbit, the spacecraft will reach the atmospheric entry interface and engage active entry guidance. Every modern crewed spacecraft is capable of guided entry; even capsule-derived spacecraft can control their trajectory with an offset center of mass and precisely controlled roll around the vertical axis. Most spaceplanes perform wide S-turns to decrease peak G-forces.



During the time of peak heating and G-forces on the spacecraft, communications will cut out as a consequence of the superheated plasma surrounding the spacecraft; communications blackout typically lasts only a few minutes. During this time, the spacecraft experiences high G-forces, typically in the range of 3-5 Gs (that is, 3-5 times more force than on Earth); spaceplanes usually experience less G-force as a virtue of their increased lift-to-drag ratio. Every crewed spacecraft is designed for these forces, and furthermore, they're designed to safely and comfortably secure the astronauts during this time.

5.3. LANDING

5.3.1. PARACHUTE SPLASHDOWN/AIRBAG ASSIST

Most modern capsule-derived spacecraft use parachutes for a splashdown in the ocean or an airbag or rocket-assisted land landing. This method is reliable and proven, and is relatively simple compared to other choices. This method deploys drogue chutes after the capsule decelerates to subsonic velocities, then uses the drogue chutes to pull out the main chutes, of which there are usually three or four. After a few minutes of slow descent under the parachute canopy, the capsule either splashes down in the ocean or deploys airbags or rocket motors, to soften a land-based touchdown.

Parachute landings are the tried-and-true technique, but they suffer from difficult recoveries (in the case of ocean splashdowns) and hard landings, even when airbag or rocket-assisted (in the case of land landings). Ocean splashdowns also expose the spacecraft to salty ocean water only minutes after the spacecraft has been exposed to the extreme temperatures of atmospheric entry.

5.3.2. PROPULSIVE LANDING

Some next-generation spacecraft feature propulsive landing. Instead of using a parachute to reduce their speed, they use multiple onboard rocket motors to slow the vehicle down in a precise, computer-controlled manner. The primary advantage of propulsive landing is the increased accuracy and no chance of tangled parachutes; on the other hand, propulsive landing is a relatively new addition to crewed capsules, and reliability hasn't been proven yet. In addition, propulsive landing does not depend on an atmosphere; propulsive landing works just as well on Mars as it does on Earth.

Propulsively-landed spacecraft cannot be landed manually; humans simply cannot control the spacecraft quickly or accurately enough for a manual landing. Spacecraft with propulsive landing will need to have a parachute backup in the near future until the reliability of propulsive landing is proven.

5.3.3. SPACEPLANE RUNWAY LANDING

Currently, there are no crewed spaceplane designs; but in the future, Sierra Nevada Corporation's DreamChaser vehicle might change this. Nevertheless, we will provide a description of what to expect when landing a spaceplane on a runway.

Unlike the far simpler parachute splashdowns in the ocean, a runway landing requires highly accurate computerized entry guidance, to ensure the spacecraft is able to reach the target runway. Furthermore, no spaceplane currently in service features atmospheric engines; therefore, the flight must be flown unpowered.

As airplanes cannot gain altitude without losing speed, all spaceplane entry trajectories must place the spaceplane on a trajectory that overflies the runway; after reentry, as the spaceplane slows down from hypersonic speeds, it will perform wide S-turns to bleed off speed and altitude without gaining as much ground as a direct glide would.

When the spaceplane reaches the appropriate altitude and is aligned to the runway, the spaceplane will autonomously descend along the glideslope, deploy its landing gear, and rollout along the runway automatically. Modern spaceplanes are difficult to control manually, so the pilot will only take over in the case of an anomaly with the autopilot.

6. PLANETARY OPERATIONS

6.1. DEPARTING FROM A PLANET

To depart from a planet, the spacecraft must be in an orbit with an eccentricity greater or equal to one; i.e. a hyperbolic orbit. The maneuver used to raise the apogee beyond the planet's sphere of influence is called an escape burn.

Escape burns are more efficient at the periapsis of the spacecraft's orbit due to the Oberth effect; to perform an escape burn, the spacecraft simply raises its apogee until the eccentricity of its orbit is greater than or equal to one. Escape burns must be precisely plotted ahead-of-time to ensure the escape trajectory intersects the destination planet at the right time, angle, and speed.

6.2. ARRIVING AT A PLANET

When arriving at a planet, the spacecraft will be on a hyperbolic trajectory; to enter an orbit, it must perform a capture maneuver which slows the vehicle down at its periapsis. To do so, it must use some combination of a retrograde engine burn and aerobraking.

6.2.1. RETROGRADE ENGINE BURN

A retrograde engine burn capture is performed by orienting the spacecraft retrograde, then performing a long engine burn at periapsis to reduce the spacecraft's apoapsis. This method does not require a heatshield and works on planets without atmospheres.

6.2.2. AEROBRAKING

Aerobraking is a maneuver which uses the atmosphere of a planet to lower the spacecraft's apogee without landing. The spacecraft must have a shield of some sort to dissipate the heat generated during atmospheric flight, and the planet must have an atmosphere to brake against.

This method is far superior to an engine burn in terms of mass penalty, but it imposes strict limits on the spacecraft's design, as it must withstand very high G-forces. In addition, the spacecraft trajectory must be accurately controlled to ensure a precise orbit after the maneuver. This is because atmospheres vary over time, and the overall braking force can't be calculated accurately beforehand.

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