The Deep Space Flight Manual

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An accompaniment to the Orbiter Space flight simulator.

This manual is all about how to plan a long-haul space flight. It covers the basic principles, and also how to package them together into typical manoevres that you'll perform to get where you're going. Once you've read it, you'll know everything that you need to visit planets in as fuel-efficient a manner as possible.

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1 Basic Orbits.

Here are a few things I'm going to assume you know. You've probably picked up most of this if you've taken a spacecraft to the ISS.

- **Periapsis.** This is the lowest point on an orbit, and the place where your velocity (relative to the central body) hits its maximum.

- **Apoapsis.** This is the highest point on an orbit, and the place where your velocity (relative to the central body) is at a minimum.
- **Prograde.** Directly forward along your orbit.
- **Retrograde.** Directly backward along your orbit.
- **All simple orbits are conic sections.** Either an orbit is elliptical, or hyperbolic.
- **All simple orbits fit into a plane (a flat surface.)** The flat surface always passes through the centre of the body being orbited. Two bodies in orbit are typically in different orbital planes. The planes intersect along a line.
- **Ellipses have eccentricities ranging from 0 to 1.** When eccentricity is close to 0, the orbit is virtually circular. As it approaches 1, the orbit becomes much longer than it is wide. Elliptical orbits are periodic – they take an exact length of time to go round.
- **Hyperbolic orbits have eccentricities greater than 1.** All hyperbolic orbits are unbound – they approach a planet from a distance, swing around it, and depart to great distance. Hyperbolic orbits with lower eccentricity swing the craft through a wide angle as it passes the planet. High eccentricity orbits are virtually straight lines.
- **Any orbit has a fixed energy, and a fixed angular momentum** – I'll say more about this later. The energy is also directly related to the distance between periapsis and apoapsis.

2 A potted description of the Solar system

The Solar system consists of the Sun, and a comparatively small amount of debris we call the planets. The Sun weighs more than a thousand times as much as all the planets put together. The background to your travels in Orbiter is the therefore the immense gravitational well of the Sun. Where you are sitting right now, Earth's escape velocity is about 11.3km/sec. But escaping from the Sun at this distance requires sixteen times as much energy – a velocity of 44 km/sec.

The planets themselves have also been described as consisting of Jupiter plus debris. It's almost true - Saturn is also quite large. Earth weighs three hundred times less than Jupiter, but is still the largest planet with a solid surface to land on.

The planets move fast – Earth travels around the Sun at around 29 kilometres per second – a speed that would require something like an 8 stage rocket to reach ! The only reason interplanetary travel is possible with our technology is that the solar system is shaped like a pancake. All the planets are more or less in the same orbital plane, and travel around the solar system in the same direction. This makes the Earth's speed an advantage rather than an obstacle.

The Solar system can broadly be divided into two parts – the inner and outer planets. Inner planets are Mercury, Venus, Earth and Mars. Outer planets are Jupiter, Saturn, Uranus and Neptune. (Pluto, as usual, doesn't count.) Inner planets are small and move fast. Where they live, the Sun's gravity dominates everything. It's important to use precise transfer orbits in this region if you want to avoid some very high speed encounters.

The outer planets, being further from the Sun, move more slowly. They are also ***much*** heavier. These two facts make it much easier to use slingshot trajectories. However, they are also a long way away – expect any journey to take years of simulated time, and hours of computer time! As you'll see, their weight makes it easier to stop when you reach them, so accurate Hohmann transfers are (fortunately!) not essential.

Jupiter is almost in a category by itself – its size makes it the ideal waypoint on quite a few journeys. A slingshot from Jupiter is worth more than two whole stages of rocket fuel.

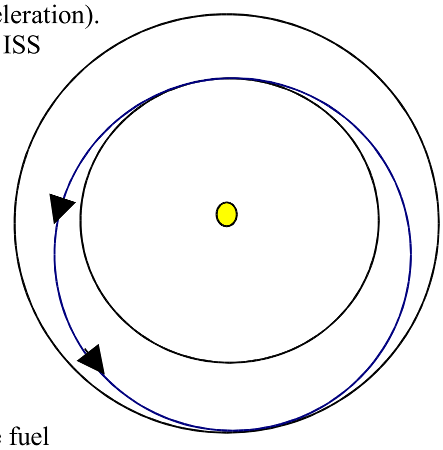
3 The principles of efficient flight

3.1 Three elliptical orbit experiments.

You probably have a few scenarios on your computer featuring a Deltaglider in low earth orbit – perhaps docked to ISS. Suppose you took one of these gliders, and carried out a long prograde burn.

Your orbit would gradually become more elliptical. Let's suppose you kept burning until the orbit MFD reports you now have an ellipse that takes between 100,000 and 150,000 seconds to go around. If you want to carry out these 'experiments' for real, set up an ellipse like this, and then save the scenario.

Experiment 1 – changing the inclination.



You go around the orbit to apoapsis (using careful time acceleration). You then (carefully!) change your relative inclination to the ISS by 20’. You have to be careful, as it doesn’t take long. You then return to Periapsis again. Once there, you carry out another burn, and change the relative inclination back to 0’ again. This will now require a much, much larger burn – probably about 30 times larger than the earlier one.

Result: The fuel required to change the inclination is directly proportional to your angular velocity around a planet. It can be very much cheaper to change it at apoapsis than at periapsis.

Space flight principle 1
Changing inclination is best done when moving slowly – the fuel required is proportional to the component of your velocity that's around the planet.

Experiment 2 – breaking away

You go around to apoapsis, and save the scenario. You then burn prograde, and time how long it takes before you reach escape velocity (your orbit becomes hyperbolic).
Using a saved scenario, you try the same thing on the same orbit at periapsis, and time how long it takes from there.

Result: This time the burn at periapsis is the shorter one, and by a large margin. The fuel required to increase your orbital energy is inversely proportional to your velocity.

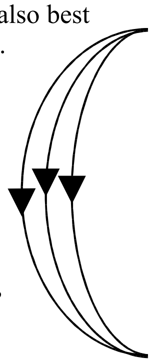
Space flight principle 2: Change your orbit’s energy when moving quickly. Energy increase is proportional to your velocity.

Experiment 3. The long and the short.

There’s one more result I’ll just tell you about. Suppose you create two scenarios, one with an ellipse reaching from low orbit to 50,000 kilometres, and another reaching from low orbit to 100,000 kilometres. Suppose you reach Apoapsis on both orbits. Which orbit can raise Periapsis with the shortest burn?

The answer here is that the longer orbit is twice as efficient as the short one. What you are doing here is changing angular momentum, and the efficiency of that process is directly proportional to your distance.

Space flight principle 3: Changing your periapsis height or position is also best done when far away – the cost is inversely proportional to your distance.



These three principles tell you most of what you need to plan efficient flight. There is only a one other principle I want to cover now.

Space flight principle 4. Only prograde acceleration changes your energy.
Changing the energy/size of your orbit requires you to thrust along your direction of travel. Thrusting at right angles to it changes your direction, but not your velocity, and, therefore, not your energy.

Let's put all of these principles together, and figure out some basic manoevres.

4 The Hohmann transfer

The inventor of the Hohmann transfer was a mathematician - Dr. Walter Hohmann, who realised its effectiveness back in 1925 – well before anyone was in a position to actually use such a thing. Perhaps he would be surprised to learn that his transfer is now the best-known of all spacecraft manoevres.

In its most basic form, a Hohmann transfer is a simple ellipse connecting two orbits. To travel from the inner planet to the outer one, all you need to do is to increase speed a bit. The craft will naturally coast outwards, and if done correctly, will encounter the other planet's orbit half an orbit later. There's then a need to match speeds with the target planet, and you're done.

If it was as simple as that, rocket science wouldn't be rocket science, but it's a good start. Let's see how it fits in with our principles of navigation.

Firstly, both manoevres that the spacecraft has to make are purely prograde. That makes them (by principle 4) pretty efficient at raising the energy of the spacecraft's orbit, and thus its size. The first manoevre raises the apoapsis out as far as the target orbit, and the second one (at the new apoapsis) raises periapsis. So, we already know that the manoevre's pretty efficient in what it does.

The manoevre also makes excellent use of the existing motion of both planets. Both planets are already moving in the same direction as you wish to go, so in both cases the change in direction and speed is small. That's what makes the Hohmann transfer good.

4.1 Some complications to the Hohmann transfer

The planets aren't always aligned.

You can launch from Earth at any time and reach the orbit of Mars. However, the orbit of Mars is about 500 milion miles long. Reaching Mars's orbit is not much use if Mars itself is several hundred million miles away on the other side of the orbit.

Sensible Hohmann transfers are therefore timed in such a way that the craft will encounter Mars when it arrives, and not just a mathematical line in space. This requires the calculation of a launch window. If you start a Hohmann transfer at precisely the right time, you will also find Mars when you arrive at Mars's orbit. The right time to launch is usually when Mars is just in front of Earth on its orbit, and is about to be overtaken by it. These launch windows come along (in Mars's case) about every twenty months or so.

The orbits aren't circular.

Planet orbits aren't circular. This might seem like a major problem, but in practice it usually turns out not to be too troublesome. At least, not compared to the next problem.

The orbits aren't coplanar.

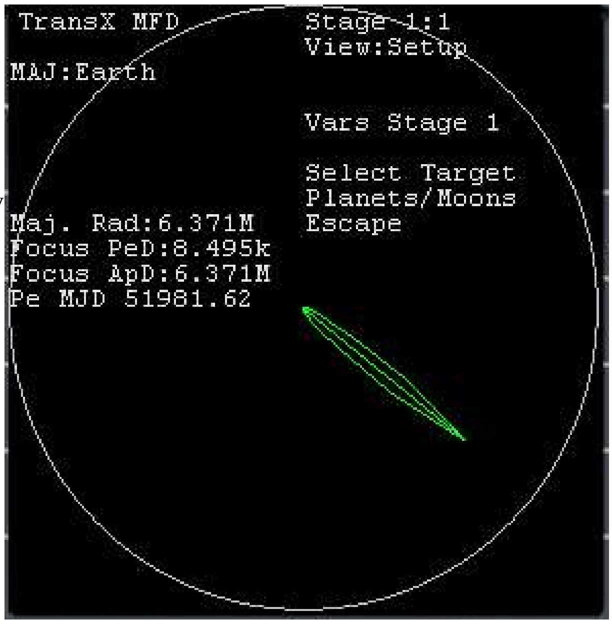
This one causes problems. The reason why it does can be seen by looking at a Hohmann transfer from a different angle. If you start from a given planet at a given time, all orbits of a certain size that start from there converge on the same spot 180' around from the start. The result is rather like that pictured over on the right.

In practice, this means that a pure Hohmann transfer also needs a plane change manoevre to be added in at some point during the journey. Sometimes this is actually done, but very often a better solution is not to do a perfect Hohmann transfer. If a slightly imperfect manoevre is carried out instead, the intercept with the target isn't 180' around from the start any more, and a plane change manoevre can be worked in from the beginning. The fact that planet orbits aren't completely circular also helps in this.

Another thing that really helps is that the orbits of the planets are acturally quite close to coplanar, and a modest plane change isn't usually too hard to fit in.

With these facts in mind, it's not too hard to plan a successful Hohmann (or close to Hohmann) transfer, but there's one other essential manoevre to learn about first.

5 Leaving a planet.



Just as with travelling between planets, there's a right and a wrong way to do this. The right way is to use space flight principle 2, and adjust energy when moving quickly. Therefore we want to do this when as much of our energy as possible is in the form of speed, and as little as practically possible is in the form of altitude. In short, the best method is to make the burn direct from low earth orbit. Any other method you may have come across isn't anything like as efficient, even if it sometimes works.

The result of doing this is a payoff that's almost the closest thing you get to a free lunch in space travel terms. This is what you get if you launch from the altitude where Escape Velocity is 11.2 km/sec

Escape velocity	***+45 m/sec***	***+180m/sec***	***+405m/sec***	***+2.56km/sec***
Velocity at infinity	1 km/sec	2 km/sec	3 km/sec	8 km/sec

The payoff is huge, particularly at first. A little bit of extra velocity low down, close to the Earth, pays off as a large amount of extra velocity at distance. This is why NASA does their main interplanetary launch burns in low earth orbit, and that's why you should too.

The bigger and heavier the planet you're close to, the bigger this effect is.

Arriving at a planet is just the inverse of leaving it, and slowing down ought to be done in the same place – close above the surface. This is obviously true if you intend to aerobrake on arrival, but makes sense even if you'd prefer to use retrorockets – it's more efficient to do the braking burn as close above the surface of the planet as you dare.

There's only one practical problem with this approach to departures – you have to calculate the correct hyperbola to depart in the direction that you intend. This is rather tedious to do by hand, but MFD's like TransX automate this calculation, and make it quite simple to plan.

6 Putting it together – TransX flight plan 1.

We now know everything that needs to be done to create a flight plan to another planet from Earth.

1. Calculate a suitable Hohmann transfer, including any variations needed to match inclinations. And find a suitable launch window to go.
2. Once that's been done, we'll have a requirement to leave Earth in a given direction, at a given speed, at a given time. So we need to plan a suitable Hyperbolic orbit that allows that.
3. Once we arrive at the target planet, we'll want to skim right above the surface, for three reasons.
   - It's fuel-efficient to retro-fire when we're low, and speed is high (rule 2)
   - It could allow aerobraking
   - It's cool to be that accurate.

How to get started

TransX divides all flights into stages – stages in which different central bodies are dominant. If you start up TransX for the first time, it will show your current trajectory around the body that's currently dominant for your spacecraft.

The best time to plan a flight is before you take off. Very often, there's a need to find a launch window in the early stages.

6.1Telling TransX the plan in outline.

To set up the very basic outline of your flight, you simply give TransX a sequence of 'Target''s to aim for. You do this using the 'Select Target' variable.

The "Select Target" variable normally comes up first in any stage. If it doesn't, it's in the "Setup" view, and can be selected using the VAR and -VR buttons (shift-V and B)

Let's look at some examples.

Going from Earth to Mars.

The first stage will be Earth-centred. Choose a target of 'Escape' and press FWD (shift-F) . A new stage, centred on the Sun, will be created.
This second stage is Sun-centred. You now have a list of planets to choose from! Choose 'Mars'. You don't have to do any more for now, but if you wish, you can press FWD again. This creates a Mars-centred stage.
In the third stage, don't choose a target.

Going from Earth to the Moon.

The first stage is Earth-centred. Choose 'Moon'.
The second stage will be moon centred. Don't choose a target.

Going from Earth to Titan.

The first stage is Earth-centred. Choose 'Escape'
The second stage is Sun-centred. Choose 'Saturn'
The third stage is Saturn-centred. Choose 'Titan'.
You may create a fourth, Titan centred stage.

Voyager

A complex flight like the Voyager grand tour, with multiple slingshots, could end up with a whole series of stages and targets.

Earth->Escape, Sun->Jupiter, Jupiter->Escape, Sun->Saturn, Saturn->Escape, Sun->Uranus, Uranus->Escape, Sun->Neptune, Neptune->?

By this means you can set out a very basic outline for any flight. In many cases there's no need to create all the stages at the beginning – you can always add them on later.

In this case, we're just doing a standard Hohmann transfer, so we only need two stages at first. Earth-centred, with a target of escape, and Sun-centred, with a target of Mars. Create this!

6.2 Creating the Hohmann transfer.

The actual Hohmann transfer needs to be created in the Sun-centred stage. Here's the process I use.

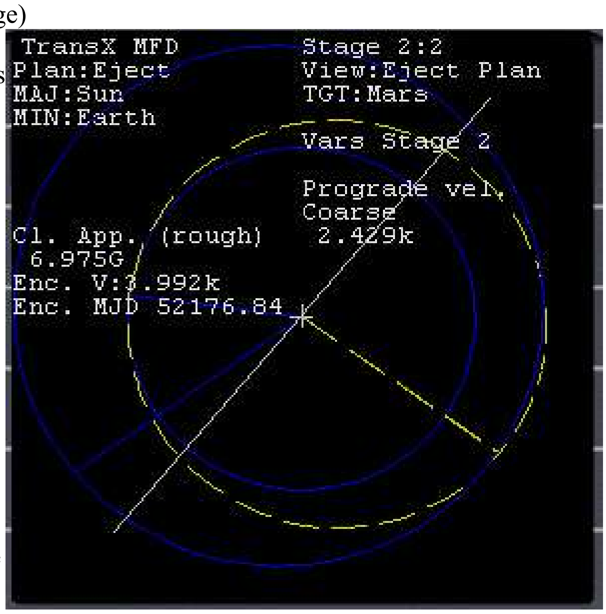
- Go to the Sun-centred stage. (sh-F). Select View – Plan Eject.

- Select the "Prograde Vel" variable, and increase its value. You will see a yellow, hypothetical orbit displayed.

TransX has a colour scheme.

Your orbit, (or any orbit that's been passed forward from a previous stage) is in green.

Orbits of planets are blue (this is a recent change)
Hypothetical orbits are a hatched yellow.
The line of intersect of two inclination planes is grey, as is the surface of a planet.



Increase the size of the yellow orbit until it touches the blue orbit of the target planet. You can increase its size by increasing the value of "Prograde Vel".

Once you have done this, you will see two hatched yellow lines, and a line on the MFD saying "Cl. App (rough)". This is measured in metres – k=kilometres, m=megametres (1000 km) G= Gigametres (1 million km) T = Terametres (1 billion km). This line gives a rough estimate of how close you will pass to the target planet. Your actual pass will normally be closer – this figure doesn't take the planet's gravity into account.

Typically the two yellow hatched lines will be some distance apart. This is because TransX assumes your takeoff will be immediate. You need to find a suitable launch window.
Select the "Eject Date" variable, and change it. You'll see the yellow orbit tumble around, and the closest approach distance will change. Move it until you reach what seems like a minimum value. This is your launch window! The TransX graph above shows what it looks like at a launch window.

You may at this stage wish to stop planning, close Orbiter, and manually edit a scenario to a few days before your selected launch window. This can save a lot of waiting !

As you can see, TransX still thinks you will miss Mars by nearly 7 million kilometres. This is because we have done nothing about the differing inclinations of Earth and Mars. We can deal with that now.

Select "Ch. Plane Velocity". Add some velocity here. You will see the grey inclination line swing around. Line it up with the two yellow ones. You'll see the closest approach drop significantly.

You can fine-tune the approach by playing with the variables. There's no need to get it perfect at this stage – you will need course corrections later in any case.

The final variable "Outward velocity" is useful if you for some reason want to leave earlier or later in the launch window than the absolute optimum day. Positive outward velocity allows you to leave later, negative allows an earlier departure.

Once you're happy with your setup, you've successfully planned the Hohmann transfer part of the trip. Now we need to plan the departure from Earth.

7 Departing from Earth.

In the course of planning your Hohmann transfer, you have effectively decided on the date, direction and velocity of your departure from Earth. With this information, TransX can plan an appropriate departure orbit, given two further pieces of information.

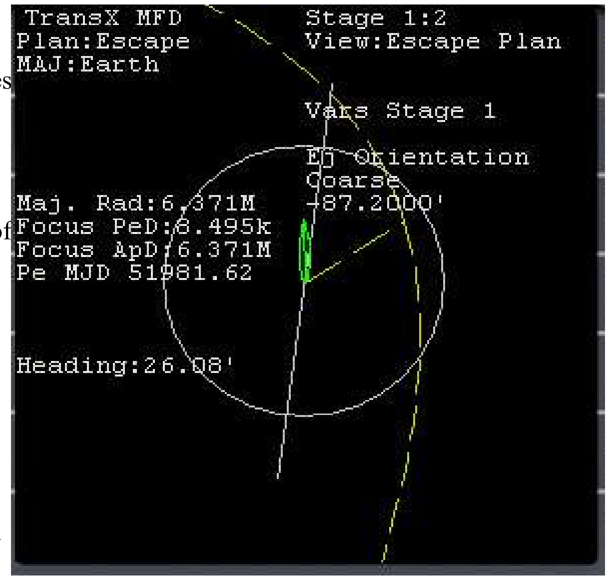
1. The distance of Pe (Periapsis) above the planet core. Because of principle 2 (faster is better) the best place for this is right above the atmosphere. At around 6.455 M

2. The second thing to plan is the orientation of your departure hyperbola. The hyperbola can be rotated around the departure vector using this variable. Most values should be OK.

The displayed heading gives an indication of the right direction to launch in, but is only accurate when it's time to launch.

It IS time to launch when your current location is just a bit west of the plane of the orbit you want to be in. TransX provides an equatorial projection to help you judge this. The following picture is an equatorial projection (North Pole at the top, equator across the centre), and shows that your current position will be rotated (by the Earth) across the plane of your target orbit in a short time. It's a good moment to take off.

At this point, the takeoff heading will be 26'. This value also doesn't take accound of the rotation of the Earth – in this case a few degrees west of that – 21', perhaps, will probably work out well.



Once you have actually taken off, the heading label disappears, and is replaced by a readout of the relative inclination of your orbit to the target. This gives you a chance to adjust your heading during takeoff to get an excellent alignment with your target orbit.

If all goes well, you should end up in a low earth orbit that is close to coplanar to your planned hypothetical one. You can tidy up any error in your inclination by a suitable burn as you cross the grey inclination line – just as you would with the align orbit MFD.

As you approach the periapsis of the planned orbit, you can then carry out a prograde burn to put you precisely into the planned trajectory. You are on your way !

8 Course corrections in TransX

After you've got close onto a course close to the planned one, it's best to then coast away from Earth. Even if the angle's are slightly wrong, it'll be cheaper to fix them once your velocity has dropped a bit (most non-energy errors should be fixed when you move slowly!). As you coast away, TransX will eventually detect that you've left Earth's influence, and will delete the first stage. The first stage will now be the Sun-centred one. Coast for a bit longer until you're sure that the remaining dregs of Earth's influence are well behind you. Now is a good time for a course correction.

When should I make course corrections?

To a degree it's up to you. However, the longer you leave an error, the larger the course correction you're likely to ultimately need. A good rule of thumb is to correct your trajectory every time the remaining distance to your target halves until you are certain where you're going. That, and a bit of practice is all you need.

Is there an easier way to do course corrections?

Maybe. If the course correction is quite small, you can forget about planning it, and just use RCS thrusters in linear mode in various directions until you're happy with the retargeting.

Making course corrections.

Change the view to “Manoevre”. Use the “Manoevre mode” variable to switch manoevre mode on. You can always reset manoevre mode by toggling this variable off and on again.

Following this, you have four variables you can use to create a manoevre. You can set the time, prograde, outward and change plane velocities, in much the same manner as in the Eject plan.You can adjust this manoevre, whilst watching the Closest approach variable, until you're entirely happy with it.

If you open a second TransX MFD window, you can look at the consequences in any following stages of your adjustments in the current one.

Once you're happy with the accuracy of your retargeting, press the VW button to change to the "Crosshair" view. Change the orientation of your ship to line up the crosshairs in the middle. Then carry out the burn, watching how much delta-V is left to burn. Once you're close, you will have made your planned course correction! Go back and switch off manoevre mode to see what your actual course now looks like.

This mode is also useful for planning some types of larger burns. Anytime you want to use TransX to plan a change to an existing orbit, the manoevre view is possibly the way to go.

9 The standard (Pioneer style) slingshot orbit.

A traditional gravitational slingshot (or gravity assist) manoevre is rather like the interaction between a ball and a bat. From the bat's point of view, the ball just bounces off it, and in fact energy is lost due to the fact that the ball isn't perfectly elastic. But the ball in fact gains plenty of energy. Why? Because the bat is moving.

A typical gravitational slingshot is just the same. A planet plays the part of the bat, and the spacecraft is the ball. Instead of a bounce, there's a hyperbolic orbit. But the effect is just the same. From the planets point of view, the spacecraft arrives in one direction, and departs in another at the same speed – the 'bounce' in gravitational slingshots is virtually perfectly elastic. And because the planet is actually moving, the spacecraft can gain plenty of energy in the process.

There are two criteria for a good planet for gravitational slingshots. One is that the planet must be heavy and dense enough to turn the spacecraft's path through a sizeable angle. The second is that the planet itself should be moving at a good speed. The combination of these two criteria means that Jupiter is by far the best planet for slingshots - it's really big and heavy, and it moves pretty quickly. Saturn comes in second place as it's still heavy enough for most things, but it is beginning to move more slowly. The most plausible third place candidate is Earth itself. It's on the small size for slingshots, but it is the largest terrestrial planet, its very high density makes up for its light weight to a degree, and it does have the advantage of moving quickly. Venus also has its uses. Mars is too small for most things, and Mercury is also rather small, and since it isn't on the way to anywhere else, you only use it when you have to. Uranus and Neptune are slow, but heavy, so slingshots there alter direction quite well, but have less impact on the energy. Pluto, as you may have guessed, is completely useless.

This type of slingshot is all about accuracy. You aim for a single, unique pathway past a planet that will flick you off in a precise direction – to get to the next place you're going. There is always just one trajectory that will do this. Nearby trajectories all achieve spectacularly different (and probably unhelpful) results.

The outstandingly good characteristics of Jupiter mean that a Jupiter slingshot is a component of many flight plans. If you ever want to go to the Sun, for example, the most fuel-efficient route is to go to Jupiter first.

9.1 The periapsis burn refinement.

As you swing past a planet, your velocity can increase considerably, peaking at periapsis at values as high as 50 kilometres per second in the case of Jupiter. These high speeds make the periapsis of the pass a perfect place to add (or remove) some orbital energy using engines.

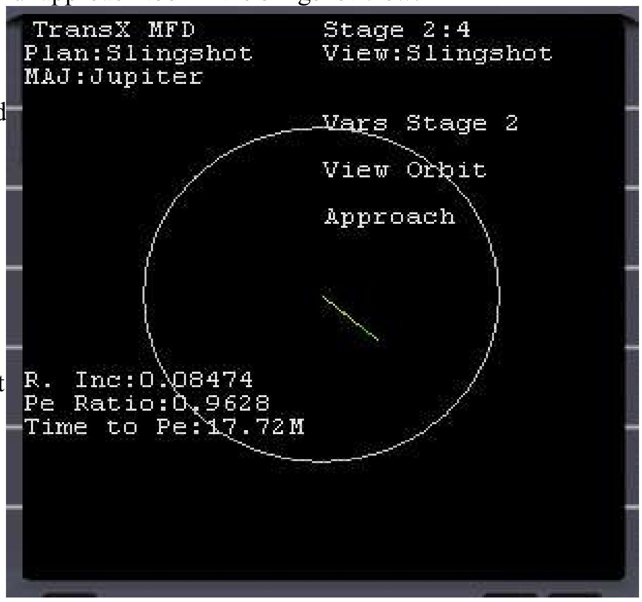
9.2 Doing slingshots with TransX.

If you select a target of escape from a planet, and it's not the first place you started, TransX will select the slingshot plan for the planet stage, and sling direct for the stage afterward.

The sling direct plan is rather like the eject plan, except that it uses different variables. You are invited to direct the path of your craft using angles, rather than setting three different velocities. Your path is chosen this way to reflect the fact that you probably won't do a major burn as you pass the planet. Using angles makes it easy to see what you can do with the velocity you have.

After you've selected your angles, you also need to check that your trajectory safely clears the planet. You can do this in the “Sling Direct” stage by looking at the “Sling Direct” view. This view contains the ratio of your Periapsis above the planet to the planet's radius. Figures above 1 mean you'll be able to fly by. Figures below 1 imply the opposite! You may have to allow a bit of space for the atmosphere as well, so don't cut it too fine.

On the slingshot stage itself, there's a powerful approach tool in the slingshot view.



The grey circle represents the disk of the planet, and the two lines on the diagram represent the periapsis of your actual orbit (or the one a manoevre may get you to), and the periapsis of the orbit you require.To get an optimal slingshot past a planet on your planned course, you need to keep the lines aligned. To align the lines perfectly, the Pe Ratio (the ratio of the distances from the planet core) must be 1, and the relative inclination should be zero.

For large planets like Jupiter, this alignment process should start a long way out. This screenshot is from the GT6 scenario that comes with Orbiter's standard TransX install. At this point, I'm still about six months distant from Jupiter. It's worth aligning very early in Jupiter's case.

If the lines are perfectly aligned, you will pass precisely through the required slingshot with an accuracy measured in mere tens of miles or less. The accuracy of slingshots is just as good as regular launches.

10 The giant planet arrival ellipse.

Here's another manoevre that NASA does that you can emulate – this one allows you to land on the moons of the giant planets. Let's assume we're heading for Jupiter.

The trick is in the first manoevre. You line up a low pass, close to the Jovian surface. Because Jupiter is 300 times the mass of Earth, this means we'll be going fast – nearly 60 km/sec at closest approach. This speed means that this Jovian periapsis is a great place to adjust orbital energy. If we're arriving at Jupiter at 7km/sec, it's going to take a burn of only 400 metres/second to lose it all, and get captured into Jovian orbit. It's space flight principle 2 at work – adjust energy when moving fast. Because of this, it really doesn't hurt too much to encounter Jupiter at high speed – it's pretty fuel-efficient to sort it out when you arrive.

But there's more to this manoevre than that. When you're at some distance from Jupiter, you can efficiently choose which part of the planet you want to swoop around. ***Do it so that Periapsis is also the place where you cross the orbital plane of your target moon.*** If you do that, when you make the retro burn, you'll create a long elliptical orbit. And, up at the other end, at Apoapsis, will be the other place where you cross your target moon's orbital plane !

The second part of the manoevre is therefore to go around the ellipse to apoapsis. There, perform two manoevres.

1. Match inclination with your target orbit. At the top of this long ellipse, you'll be moving slowly, and the burn will be cheap.
2. Raise periapsis to match up with your target moon. This burn will be comparatively cheap too.

Someday there may be an MFD mode that can amalgamate these two manoevres into a single burn.

The third part of the manoevre is to go around to the new periapsis, and there do a retro burn to reduce the orbit length. You can use either the default Sync orbit MFD or TransX to line up an encounter with the moon itself on the following orbit.

To see the required manoevres in TransX, all you need to do is to set the moon as the next target. The inclination line will then be displayed.

Reversing the process?

This manoevre ought to be carried out in reverse to plan a return trip to Earth. However, it is currently rather difficult to plan this manoevre in reverse – this is likely to be the subject of a future TransX plan.

11 Resonant encounters

There aren't any TransX plans to support these manoevres yet. But NASA does them, and they're quite cunning.

11.1 The simple resonant encounter.

If one pass of a planet doesn't give enough of a twist to a slingshot, you can always try using several. The trick is to get yourself into an orbit which is resonant with the orbit of the planet you encounter. If, for example, you swing past Earth and enter an orbit that takes 2 years, the Earth will go around its orbit twice for every orbit your craft makes. This means that when you get back to the location of your first encounter with Earth, the planet will be there again as well. So you can then swing past it again, and perhaps move on to a different resonance, perhaps 3:2, or 3:1 allowing yet another encounter at that same location later. By hopping from resonance to resonance, you can encounter a planet repeatedly in the same location, and progressively change your orbit into something quite different. NASA did this repeatedly with the moons of Jupiter during Galileo's grand tour.

11.2 The 'apoapsis burn' variant.

If you're in an orbit that's coplanar with your target as well as close to resonant, there's another neat trick that's available.

1. Encounter the planet, and leave it in a more-or-less prograde direction.
2. At your apoapsis, lower Periapsis somewhat. Plan to do this in such a way that you'll re-encounter the same planet, but in a different place, and at more of an angle.
3. You then encounter the planet, but at a much higher relative velocity, due to the angle change. On swinging back to prograde, you significantly increase the energy of your orbit. Or you can use the extra energy for some other purpose.

This process can be used to pump the orbit size up (with retro burns at apoapsis) or down, by following the process backwards.

It's planned that TransX will support both of these someday....

12 Feedback

Email any comments on this back to duncan.sharpe@pixel-21.co.uk

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