Lagrange MFD

Official Tutorial

By: Nicholas Kang (Zheng Tien)

Lagrange MFD Design & Test Team:

- Andrew Stokes (ADSWNJ)
- Brian Jones (BrianJ)
- Dimitris Gatsoulis (dgatsoulis)
- Keith Gelling (KeiththG)
- Zheng Tien (Nicholas Kang)
- Szymon Ender (Enjo)

Contents

Pre-requisites

These are the mandatory installs for Lagrange MFD. Choose the version according to your version of Orbiter Space Flight Simulator:

1. Orbiter 2016 Space Flight Simulator/ Orbiter 2010 Space Flight Simulator
2. Lagrange MFD v1.0 for Orbiter 2016/Orbiter 2010
3. ModuleMessagingExt for Orbiter 2016 and ModuleMessagingExt for Orbiter 2010

These are additional pre-requisites for you to follow the tutorial steps below. Having a good grasp of those MFDs will ease orbinauts' trip to Lagrange points.

4. Launch MFD (2010/2016),
5. BurnTimeCalcMFD (2010/2016),
6. TransX (2010/2016) and
7. IMFD (2010/2016).

List of Abbreviations

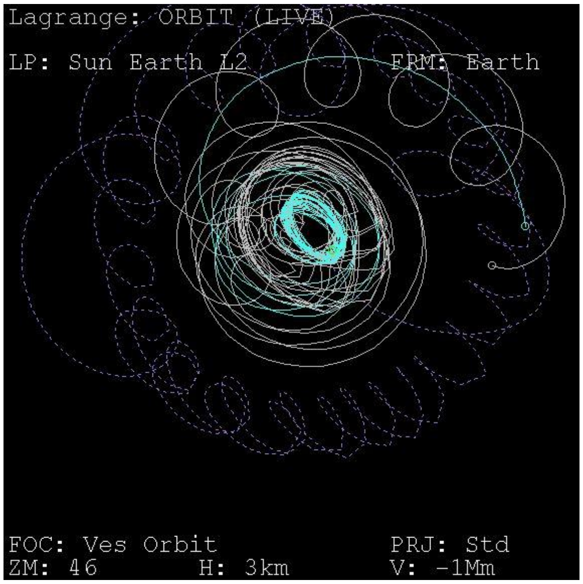
1. BB: Brighton Beach
2. EML: Earth-Moon Lagrange point
3. KSC: Kennedy Space Center
4. LEO: Low Earth Orbit
5. LLO: Low Lunar Orbit
6. MCC: Mid-Course Correction
7. SEL: Sun-Earth Lagrange point

About the Scenario Files

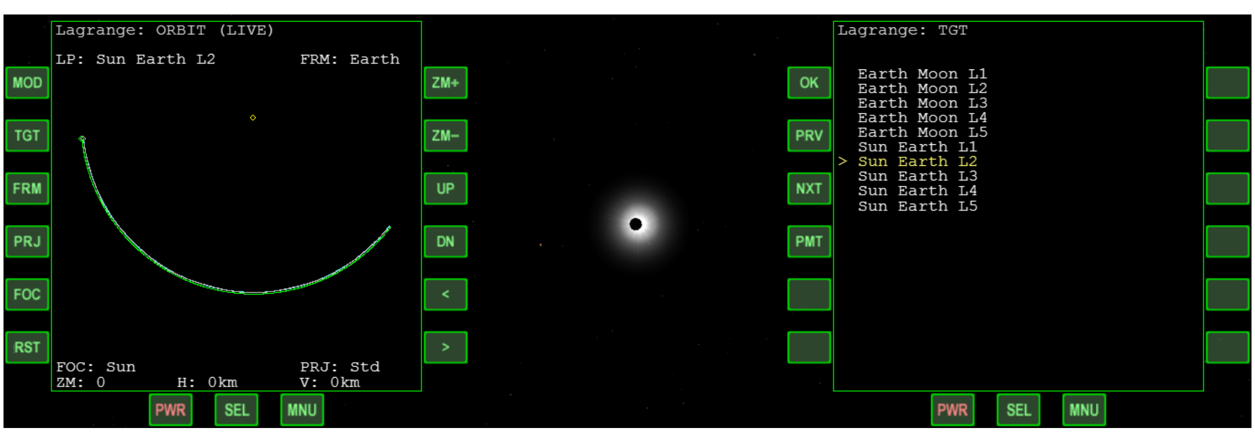
This tutorial document includes scenario files that are associated with the relevant scenarios mentioned in this tutorial document. Some of them are examples, but most of them are exercises for orbinauts to practice. In certain cases, the whole scenario folder will be intentionally left blank and orbinauts will be required to create their own scenarios. Hence, make sure you have mastered all the necessary skills before you proceed to these exercises.

Introduction to Lagrange MFD

Before we start, let's explore what are the things that we can do with Lagrange MFD. First is a visualization of non-Keplerian orbits and trajectories. Have a look at the screenshot on the left below. You will notice that the orbit plot is rather chaotic. The orbits are jumbled up near the center and a series of helical and spiral trajectories appear at the outer part of the screenshot. Those trajectories represent the Moon, Earth, Lagrange point and your orbit over time, each with different colors. This is the beauty of non-Keplerian orbits, though it can be a bit confusing for orbinauts who are used to the standard 2-body problem orbits, where only conic sections such as circles, ellipses, parabolas and hyperbolas dictate the movement of celestial bodies in the heaven. In our tutorial though, we don't have to deal with crazy orbits like the one shown in the screenshot. The orbit plot can still project Keplerian orbits nicely, say for example, a Hohmann transfer Orbit.



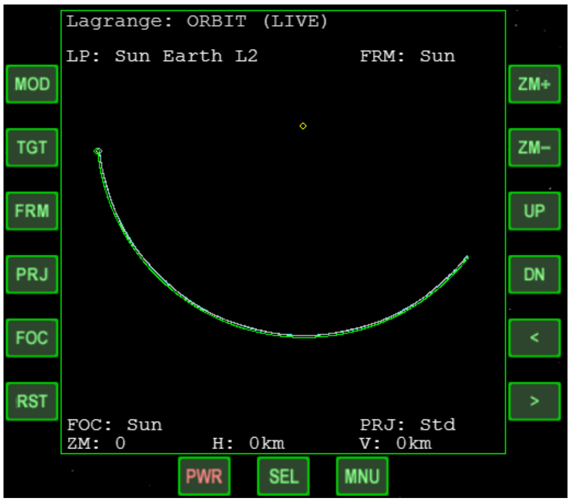
Next, Lagrange MFD will bring us to the Lagrange point! Lagrange MFD has a built-in PMT function (Put Me There) function. For beginners, make sure you have Lagrange MFD enabled in the modules tab in the Launchpad. Then, jump into any vessel in any Orbiter scenario. Bring up Lagrange MFD, hit the TGT button in the Orbit screen and select the Lagrange point you want to go by clicking PRV or NXT, then hit the PMT button and presto! You are at that Lagrange point. Try experimenting with different Lagrange points and have a look at the position of Earth, Moon and the Sun around you. Do you see the eclipse below? The black dot is Earth and we are behind Earth. Sun, Earth and us are in a straight line. Welcome to Sun-Earth Lagrange point 2!



Getting Started with Lagrange MFD

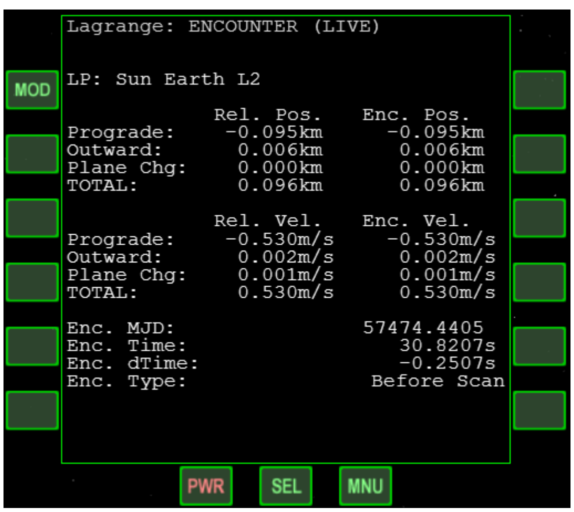
Before we begin, feel free to click MOD to cycle through the different screens in Lagrange MFD. There are 5 screens in Lagrange MFD, namely, Orbit, Encounter, Plan, Autopilot and S4I. Their names basically imply their functions.

Orbit screen:



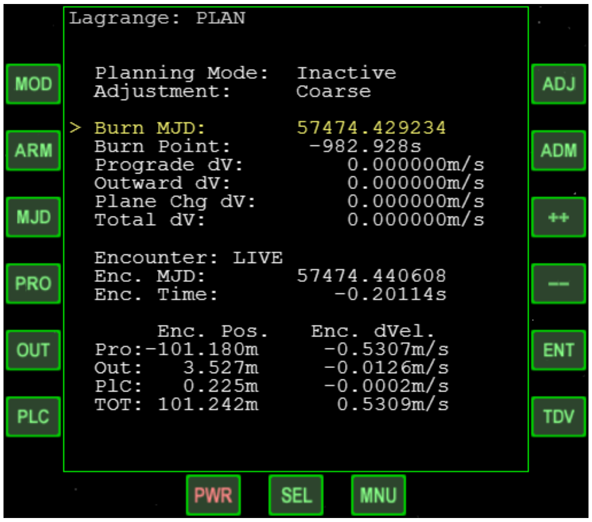
Use the Orbit screen to assist you with planning trajectories to Lagrange points. Whenever you want to go to Lagrange points, click TGT and select that Lagrange point and orbit plot will display your current orbit and the Lagrange point's orbit with respect to the frame you choose. Click FRM to change the frame. For trips from LEO to SEL points, FRM should be set to Sun; for trips from LLO to EML points, FRM should be set to Moon while for trips from LEO to EML points, FRM should be set to Earth.

Encounter screen:



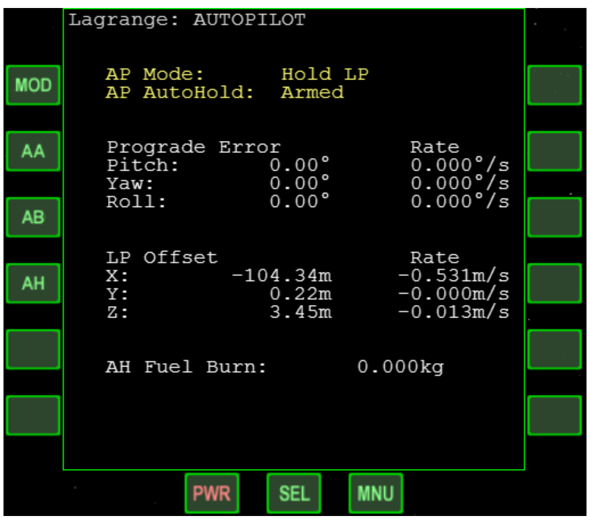
The Encounter screen is useful for looking at your vessel's current position and velocity relative to the Lagrange point, your closest approach to the Lagrange point and its velocity and time to interception. Rel. Pos. and Rel. Vel. will be your current vessel's position and velocity relative to the Lagrange point you targeted in the Orbit screen while Enc. Pos. and Enc. Vel. will be your vessel's relative position and velocity at its nearest point to the Lagrange point. You can see your Enc. Pos. and Rel. Vel. in the Plan screen as well.

Plan screen:



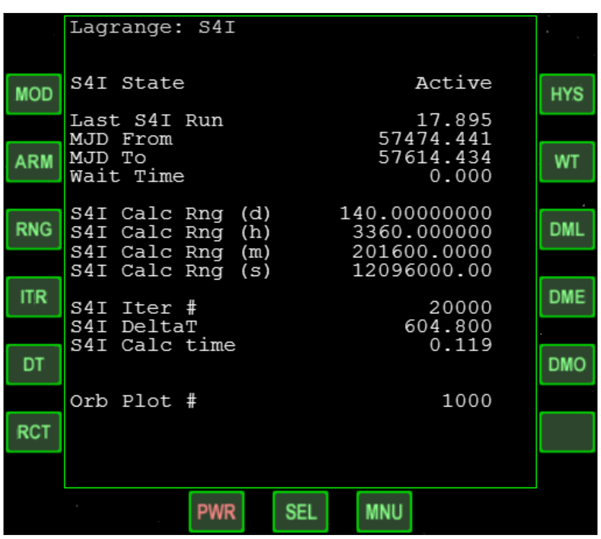
This heavily used screen in Lagrange MFD is where orbinauts will input the required dV and date to get to the Lagrange point. Those familiar with TransX will probably use this screen with ease. After entering the required dV and maneuver date, one needs to arm the plan by clicking the ARM button to show the final Enc. Pos. and Enc. dVel (encounter mode: PLAN). Otherwise, the encounter mode is set to LIVE, which displays your current vessel's orbit. TDV can set the burn magnitude, or lock your dV to allow you to adjust the burn direction without changing the magnitude.

Autopilot screen:



Once your plan is armed, you can bring up this screen and hit the AB button to engage the AutoBurn autopilot. This is simply the combination of TransX's Auto-Center function and BurnTimeCalc's function and similar to IMFD's AB button. The autopilot will reorient the vessel to point at the burn vector and commence the burn armed in the Plan screen. Once you arrive at a Lagrange point, engage AutoHold for station-keeping. Current fuel consumption for station-keeping is quite high and will be improved in future releases.

S4I screen:

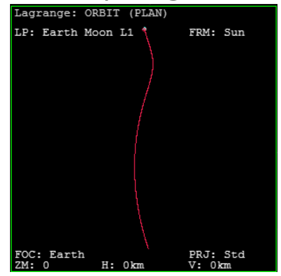


This is where all S4I settings are located. Lagrange MFD is based on a fourth-order Symplectic Integrator calculation engine (hence S4I) concept from Dr. Keith Gelling. It is a highly accurate prediction engine for determining future positions and velocities of celestial bodies and vessels. For beginners, there are 2 buttons of most interest, namely RNG (controls S4I Calc Rng) and RCT (controls S4I Calc time).

Before we begin, we need to make just one adjustment to Lagrange MFD, which is the S4I engine setting. The setting differs from one computer to another and is dependent on mission length. It is worth spending time to experiment with your computer's optimal S4I engine setting before you begin. Also, a warm-up exercise is included to get orbinauts familiarize themselves with Lagrange MFD. (Note: No scenarios are provided for this warm-up exercise.)

Steps of adjusting RCT and RNG setting in the S4I screen and some warm-up exercises:

1.		Start with the default "Lagrange at SEL2" scenario that in the Lagrange folder. Bring up Lagrange MFD on both sides. Bring up the S4I screen on one side and the Orbit screen on the other side. Bring up the Plan screen in an external MFD as well. Start by experimenting with the RNG value. Click RNG and enter different values of time such as 4d (4 days), 30m (30 minutes) or 500s (500 seconds).
2.		Watch how the orbit screen responds. A shorter calculation range (lower RNG value) will result in a shorter orbit plot in the orbit screen and vice versa. Return your RNG value to its default setting. Again, click RNG, enter 140d (You have to remember your original setting in this case, but this is just for the sake of this exercise. Once you have mastered the skills to change RCT and RNG, you can set both values without memorizing them.)
3.		Put in some 3000m/s of prograde dV in the Plan screen. Arm the plan and watch how your orbit plot, the Enc. Pos. and Enc. Vel. changes in the orbit and plan screen. Note how fast the Enc. Pos. and Enc. dVel. value changes in the Plan screen. Now, increase RCT to 3-5 seconds and watch the speed in which the Enc. Pos. and Enc .dVel. change. It should slow down, but what you get should be more accurate than before.

4.		Now, use the PMT function to put you in EML1. (Click TGT in orbit screen, click Nxt/Prv until EML1 is highlighted, then click PMT). Notice that when you click OK in the orbit screen, you get a strange orbit. Why? 
5.		Three things cause this. Firstly, you haven't disarmed your plan in the Plan screen, so Lagrange MFD assumes you want to conduct a 3 km/s burn from EML1 some 500-600 seconds later, but you just want to stay at EML1. So, disarm your plan by clicking the ARM button. You should see some orbits now. But this is still not preferable. Obviously EML1's orbit should look more like a circle/ellipse between Earth and Moon, but definitely not the trajectory that you see on the left.
6.		The problem is your large calc. range*. Reduce your RNG value to just 5 days (hit RNG button in S4I screen, enter "5d".) Now you should see something nice. The blue dot is Earth, the green curve line is your vessel's current orbit at EML1 and the white line is the Moon. You probably have noticed that Lagrange MFD took longer to respond to your inputs ever since you increase the RCT value (i.e. longer to change the orbit plot view in Orbit screen and Plan screen's data).
*Perhaps you are wondering why in step 6, a large calculation range will result in such peculiar trajectories. The answer is Earth-Moon Lagrange point 1 is a dynamically unstable point (this is true for Lagrange 1-3, but not 4 or 5). Without station-keeping burns, any perturbation from this Lagrange point will accelerate the vessel away from the Lagrange point, possibly with enough dV o exit cislunar space entirely. This is shown in Step 5's screenshot, with a long curvy green line extending out to the outer region of the plot. That indicates the vessel's final fate of bring "thrown" away from the Earth-Moon region, but in a short calc. range like 5 days, the orbit remains well-defined.		

7.		The slow response is due to the high RCT rate of 3 seconds we set earlier. Go ahead and reduce that to 0.25-0.333 seconds. Now Lagrange MFD should respond faster. Do you notice that FRM is set to Sun and not Earth/Moon in the Orbit screen? Click FRM in Orbit screen click Nxt/Prv to select Earth (or Moon) and click OK. Up to this point, everything has returned to normal. Notice you are still some 13 meters away from EML1 (Enc. Pos. in Plan screen is some 13m). Go ahead and use linear thrusters to get closer to EML1. When you are very near there, cancel out all Enc. dVel and engage AutoHold by pressing the AH button in the autopilot screen (press MOD to cycle through the 5 screens). Good luck!

Our warm-up exercise ends here. Finally, here are some tips on using Lagrange MFD. Then, our tutorial journey will begin.

A portrait of all 5 Lagrange MFD screens. (Starting from top left, in clockwise direction: Autopilot, Plan, S4I, Encounter, Orbit)

Tips on Using Lagrange MFD

1. Make use of other MFDs to guide you through your journey to the Lagrange point. Common ones include TransX, IMFD, Orbit MFD, Align Plane MFD, Map MFD and Launch MFD. Make use of external MFDs whenever possible.
2. Adjust the RNG setting first, followed by the RCT setting according to your computer's specification and mission as described before.
3. Consider deoptimizing your approach to a Lagrange point by conducting the approach burn earlier or adjust the component dV setting to overshoot/undershoot the Lagrange point. While conducting MCCs, allow an offset of several hundred km to the Lagrange point in question. This give you space to make fine adjustments for the actual encounter.
4. Always quicksave your current scenario. Make it a habit to do so because the AutoAlign and AutoBurn feature may lead to inaccurate/imprecise burns. This happens the most in approach burns, as you will encounter in this tutorial later. Hence quicksave your scenario every time before you conduct an approach burn to a Lagrange point.
5. Remember to disengage all Lagrange MFD autopilots before you quicksave your scenarios. Failing to do so will result in your vessel automatically spinning when you start up your quicksaved scenario.
6. To save time, instead of launching from surface bases such as KSC or BB, you may want to use the scenario editor to put you directly in orbit and you can proceed from there.
7. Engage AutoHold only when you are very near a Lagrange point and of low encounter velocity (Enc. Vel.) and use linear thrusters to help the Autohold as you see appropriate, in order to preserve fuel (Autohold is a bit fuel-hungry in this release).
8. If you are using the DeltaGlider, remember to open the retro doors once you are in orbit, so that you can apply retro thrusts when required, especially during mid-course corrections (MCCs).
9. When engaging the AutoAlign autopilot, allow the vessel to align before changing time warp settings. Occasionally, if you change time warp during alignment, the vessel will come to rest in a non-zero alignment. If this happens, switch to ROT autopilot and give the vessel a single tap of thrust on the non-zero axis. The AutoAlign autopilot will then complete the job.
10. If your orbit is bouncing around erratically, this is because you are very close to a Lagrange point, and your calculation RCT is too low. Try increasing RCT to stabilize the plot.

Tutorial Guide

Lagrange MFD tutorial is intended to help inexperienced orbinauts who are eager to understand how to use Lagrange MFD to fly to Lagrange points.

The tutorial is arranged from easy missions to hard ones, starting from a simple transfer from LEO (coplanar with the Moon) to Earth-Moon Lagrange point 1 (EML1) to off-plane transfer from ISS or from surface bases on Earth and Moon to those Lagrange points.

Future versions of this tutorial will include tutorials in uncommon trips such as Weak Stability Bound Transfer (WSBT).

Disclaimer

The methods mentioned in this document to get to Lagrange points are by no means optimized for delta-V or Flight Time. The author has searched for the best available method thus far with minimal dV requirement. Better solutions, if found, are welcomed from the community and will be included in this tutorial in the future. Feel free to drop a Private Message to the author in Orbiter Forum about your findings or discuss it in the thread of this tutorial in Orbiter Forum. Thank you.

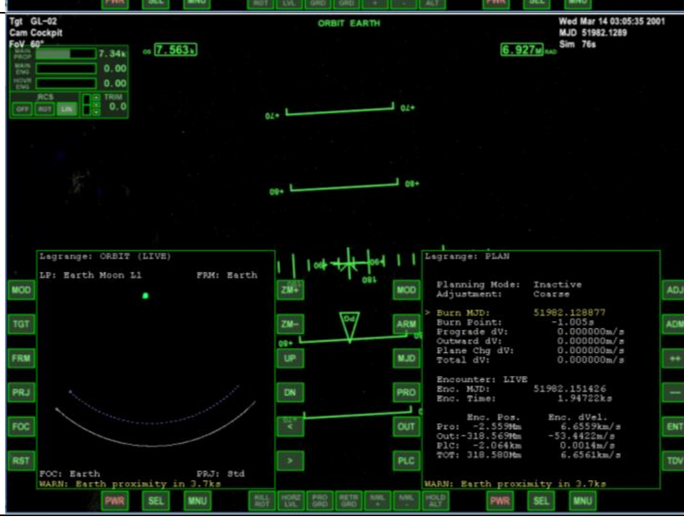
Flight Lessons/Tutorials

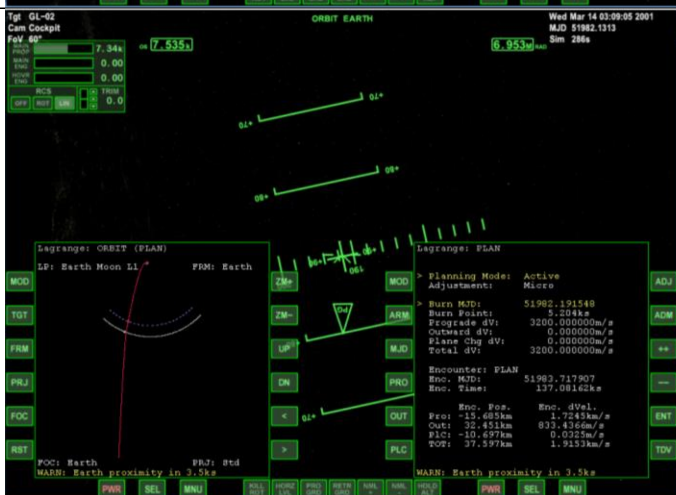
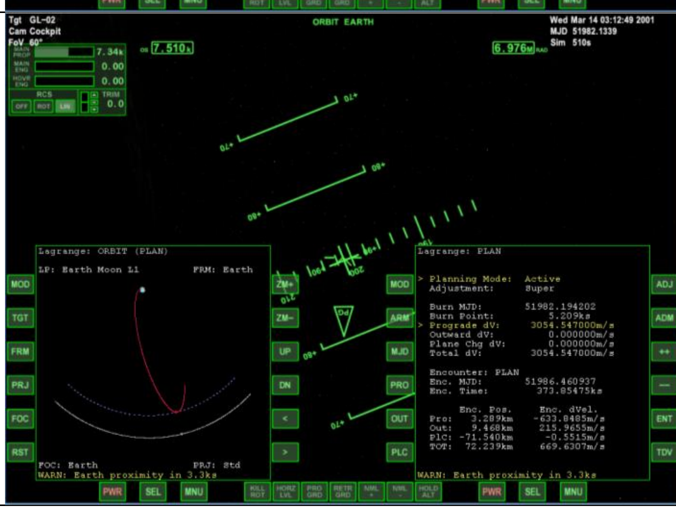
Coplanar Transfer

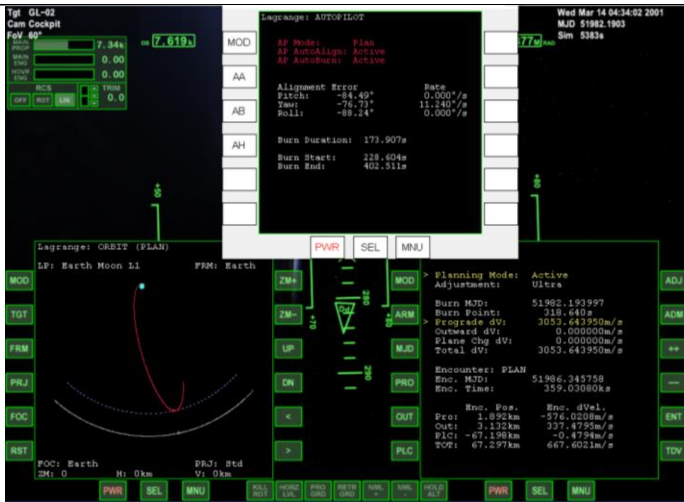
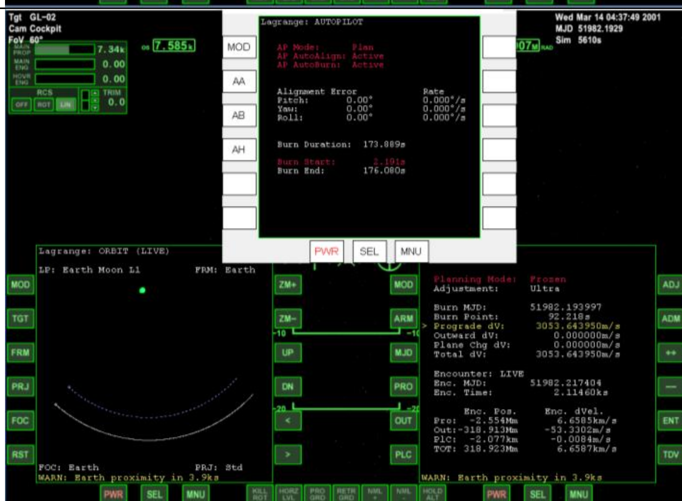
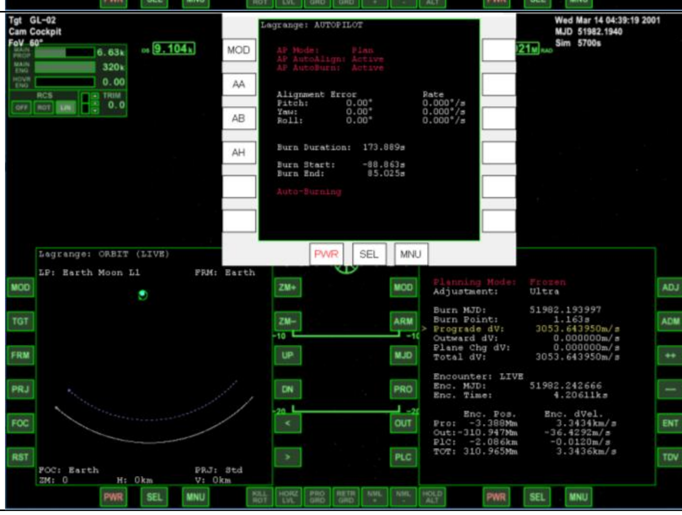
From Lunar-coplanar LEO to EML1/2/3/4/5

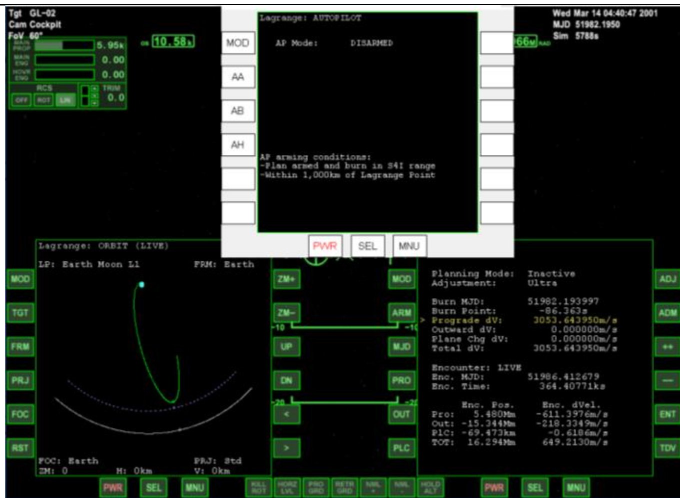
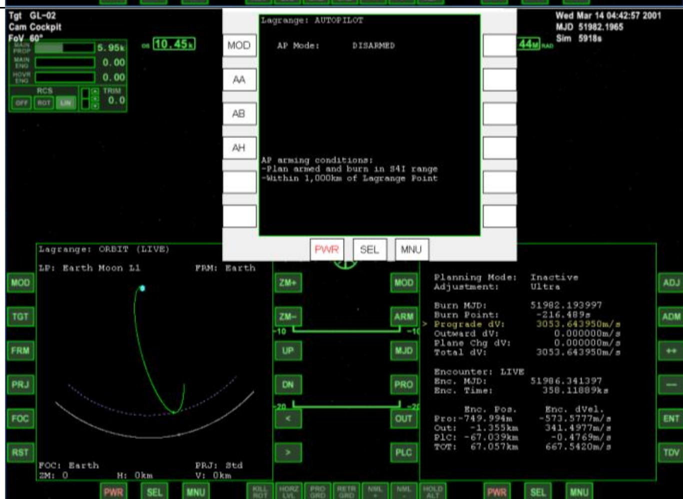
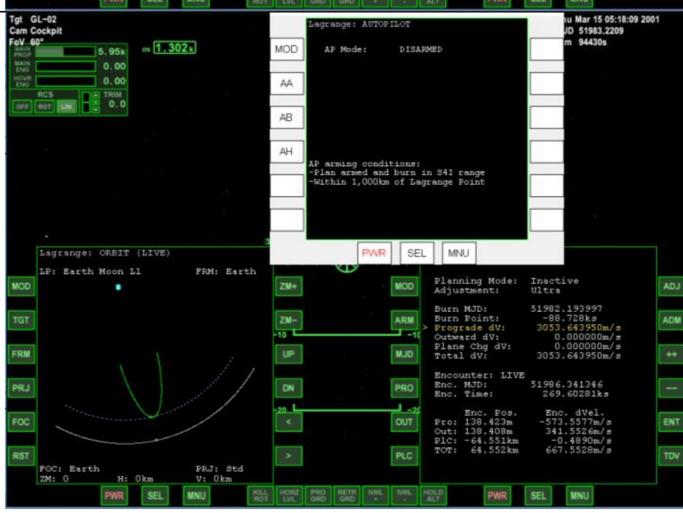
*Have a look at ADSWNJ's tutorial here and dgatsoulis' video tutorial here.

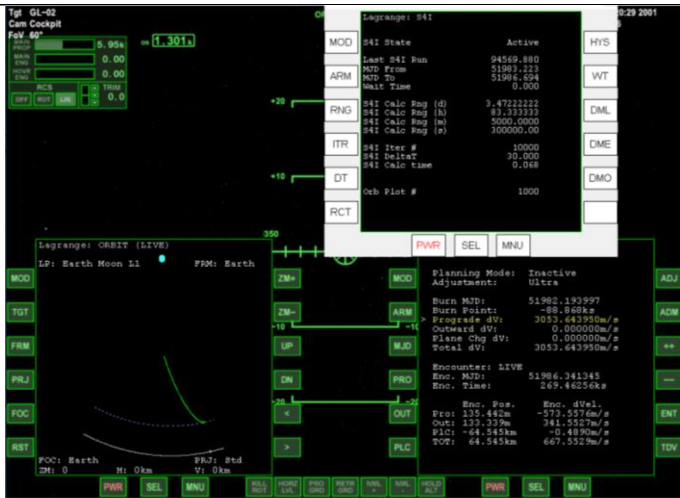
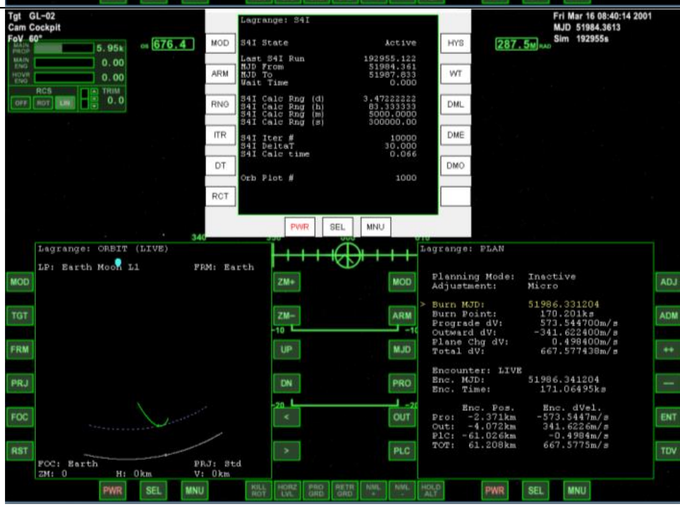
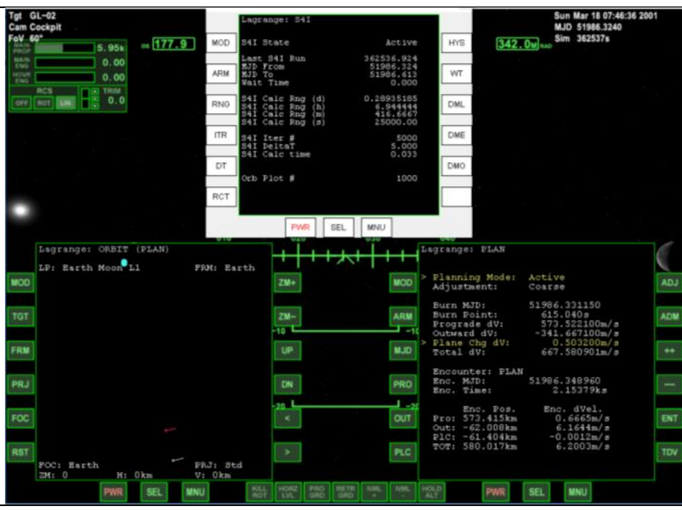
In this simple tutorial, you want to get to EML1 from LEO and you are already in an orbit coplanar with the Moon (and hence all Earth-Moon Lagrange points). You can get to EML2/3/4/5 using the same method. An ecliptic LEO trip (scenario provided) to SEL1/2 and a trip from LLO to EML1/2 will just be the same. Here are the procedures:

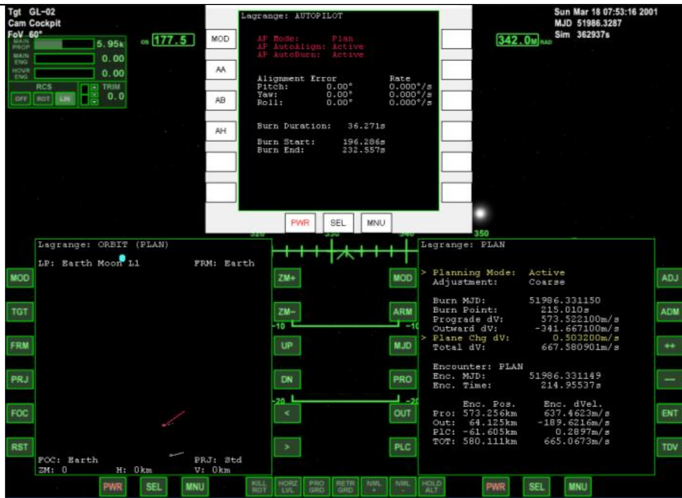
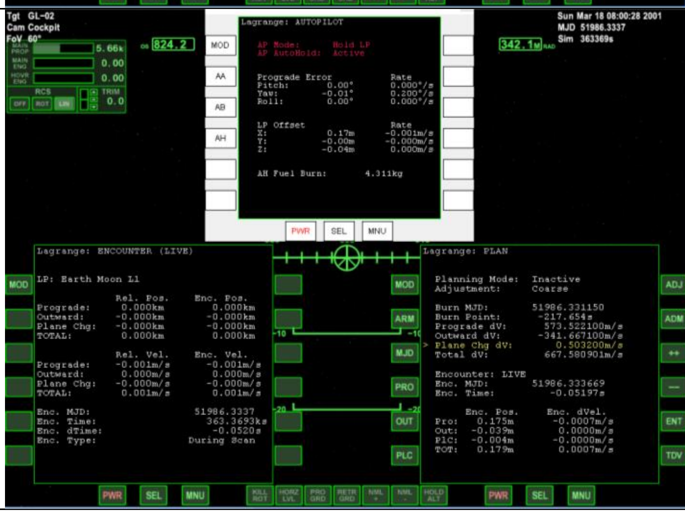
1.		Start with the Lunar-Coplanar LEO scenario and bring up Lagrange MFD on both sides.
2.		Cycle through the screens by pressing the MOD button and bring up the ORBIT screen on the left MFD and the PLAN screen on the right MFD.

3.		Arm the PLAN (click the ARM button) and start by putting in a reasonable prograde dV value of say, 3200 m/s. Notice that your planned orbit, the purplish dashed line shows that you are on an escape trans-EML1 trajectory, which is not a fuel efficient transfer. We want to conduct a Hohmann transfer if possible.
4.		Adjust the increment (Press ADJ) to Super or Ultra and advance the date by pressing the ++ button until the TOT Enc. Pos. value starts to drop. Then, fine-tune your closest approach with either Micro or Hyper increment until you get to some 10 km or so. Try to aim for a Hohmann transfer orbit by advancing or bring forward the eject date.
5.		Further fine-tune your orbit with the Prograde variable until you get to the minimum distance from EML1. Again, try to achieve a Hohmann transfer orbit by fine-tuning the prograde variable and the date variable. Now, you have the plan.

6.		Hit MOD on your left MFD (Or open an external MFD) to bring up the autopilot screen. Observe your maneuver date (eject date) and “Burn Point” value in the PLAN screen. Engage AutoBurn by hitting the AB button in the autopilot screen. Your vessel will be automatically rolled to the correct orientation (burn vector).
7.		Warp time as you prefer. The AuroBurn autopilot will automatically reduce time warp by steps as the burn time approaches. Keep an eye on the “Burn Start” value in the autopilot screen. PLAN mode will be “frozen” just before the burn commences and all display data will revert to the live vessel to allow users to monitor how their trajectory changes when the burn commences.
8.		When “Burn Time” counts down to 0, allow Lagrange MFD to commence the burn automatically. Monitor how the trajectory changes throughout the burn. You may time warp during the burn if you prefer, but only do this to 10x or the burn may become inaccurate.

9.		Fine-tune your final orbit with short bursts of main engine, retro engine and linear RCS thrusters.
10.		Use the Enc. Pos. value in the PLAN screen to gauge your final position with respect to EML1. You should obtain an encounter value close to your plan. Time warp for a few moments until you are halfway or nearer to EML1. Get ready for some mid-course corrections.
11.		When conducting mid-course correction, use linear thrusters to burn in either Prograde, Outward or Plane Change axes to fine-tune your final position relative to EML1. (Consider deoptimizing your approach by some 10-100 km, i.e. Enc. Pos. should be greater than 10/100 km to give space to adjust for final approach later.) You need to conduct more mid-course corrections as you get closer to EML1.

12.		Also, reduce the RNG value. Notice that the Enc. Pos. value should not change even though the S4I calculation range is reduced. If the value changes, increase the calculation range until it stops changing or just wait a little longer until the vessel is within the new calculation range again.
13.		As time to intercept EML1 drops below 10000 (10 k) seconds, it is time to plan the approach burn to cancel out your vessel's relative velocity with respect to EML1. Make some further fine-tune and deoptimization. Reduce RNG value in S4I screen. Then input the negation of all velocity components as the variables and (Enc. MJD-0.01) as the Maneuver time in the PLAN screen. The -0.01 is for deoptimization purposes.
14.		Keep the RNG value low. Arm the PLAN. (You can also arm the plan earlier to allow for more time for adjustment/ fine-tuning of your approach.) The component velocities and Enc. MJD values will fluctuate, so remember to change them as well.

15.		Then, engage AutoBurn in the autopilot screen. (You may also engage AutoBurn earlier.) Allow the burn to commence automatically when “Burn Time” reads 0.
16.		As the burn ends, fine-tune your position with respect to EML1 using linear thrusters to get even nearer to EML1 and presto! Welcome to Earth-Moon Lagrange point 1! Engage AutoHold when you are very near the Lagrange point.

Now, you can get to EML2/3/4/5 using the same method except from changing the maneuver date and prograde velocity. An ecliptic LEO trip (scenario provided) to SEL1/2 will just be the same, except that you target SEL1/2 in the ORBIT screen. Whereas from LLO to EML1/2, set the FRM from Moon while planning.

Perhaps you are wondering why trips to SEL3/4/5 are not discussed here. That is because we need another way to get there. This way, which applies orbital resonance, will be shown below.

Note: The approach used in the following tutorial is the TransX method. You can also use IMFD to get to SEL3/4/5 and EML3-5, but only one orbit is allowed before you intercept those SEL and EML points because IMFD is a single-period Lambert Problem Solver. Hence only the lowest possible resonance scheme is allowed if one uses IMFD to plan their trips to SEL/EML 3-5. Refer to the tutorial on page 41 on how to intercept SEL3-5 using IMFD.

Introduction to Orbital Resonance

Orbital resonance occurs when two orbiting bodies exert a regular, periodic gravitational influence on each other, usually because their orbital periods are related by a ratio of two small integers. In our case here, the 2 orbiting bodies correspond to the Earth and your vessel. Since SEL3 is collinear to the Earth-Sun line but it orbits the Sun in Earth's orbit exactly opposite to Earth, we need to escape Earth and enter a transfer orbit, such that after n orbits, we will be at SEL3 but Earth has only travelled $n - \frac{1}{2}$ orbits, hence, we will lead Earth and get to SEL3. So, how do we calculate the orbital parameters we want?

Rough Calculation

Let's suppose that we want to get to SEL3 using a 3:4 resonant orbit. Here, in escaping Earth, the spacecraft lowers the perihelion of its orbit so that it completes four orbits of the Sun in the same time it takes the Earth to complete three orbits around the Sun (i.e., three years). After two years, then, the spacecraft will have returned to its original position but the Earth will have only completed by 1.5 orbits, so that instead of encountering Earth, the spacecraft will have a close approach of SEL3 (and by 'close' we mean 'within a few million km').

If the spacecraft is in the 3:4 resonance, then it follows that having escaped Earth, its orbital period around the Sun will be 0.75 years. So, the question is what escape plan is needed to eject the spacecraft into an elliptical orbit with a period of 0.75 years?

To answer this question, we do some simple calculations. First, we ask what semi-major axis of our new orbit do we need. We can calculate this by considering the expression for the orbital period:

$$T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

Here, a is the semi-major axis of our orbit and μ is the gravitational constant, GM, for the Sun. To make life simple for ourselves, we are going to work with units such that the orbital radius of the Earth around is 1 unit, and the orbital speed of the Earth around the Sun is 1 unit. In these units, the orbital period of the Earth is exactly 2π and μ=1. So, if we want to have an orbital period of 0.75 years, we must have:

$$0.75 \times 2\pi = T = 2\pi\sqrt{a^3}$$

or, upon re-arranging:

$$a = 0.75^{\frac{2}{3}} = 0.825$$

In other words, we now know that after escaping Earth, we want to be in an elliptical orbit around the Sun with semi-major axis 0.825. This is a dimensionless quantity and we can convert back to real distances by simply multiplying by Earth's mean orbital radius which is, of course, 1 AU. So, we want an elliptical orbit around the Sun with semi-major axis of 0.825 AU.

OK, so how can we use this information? The first thing we want to do with this is to calculate the periapsis of our new orbit. Since:

$$a = \frac{1}{2}(r_a + r_p)$$

and

$$r_a = 1$$

where r_a is the aphelion radius of our orbit and r_p is the perihelion radius of our orbit.

So, we have then:

$$0.825 = \frac{1}{2}(1 + r_p)$$

$$r_p = 0.651$$

We now know that after escaping Earth, we will need to be in elliptical orbit around the Sun with period 0.75 years; with a semi-major axis of 0.825 AU; with an aphelion radius of 1.00 AU; and a perihelion radius of 0.651 AU. So, how do we calculate the escape plan from this information?

First, let's recall the expression for our orbital speed around the Sun at aphelion. This is given by:

$$v_a = \sqrt{\frac{r_p}{r_a}\frac{2\mu}{r_a + r_p}}$$

And since we are working in units where μ=1 and because we know that r_a=1, we have:

$$v_a = \sqrt{\frac{2\mu}{1 + r_p}}$$

Substituting r_p=0.651 into this gives:

$$v_a = 0.888$$

Again, this is a dimensionless quantity. To convert it back to more conventional units, we multiply by Earth's mean orbital velocity of 29.78 km/s. So, we calculate that upon escape from Earth, we need an aphelion velocity of 26.45 km/s.

And how does knowing this help us? Relative to the Earth, our velocity will be 26.45 - 29.78 km/s = -3.33 km/s. i.e., we need to escape Earth with a hyperbolic excess velocity of -3.33 km/s.

So, finally, we now have enough information to describe the TransX escape plan:

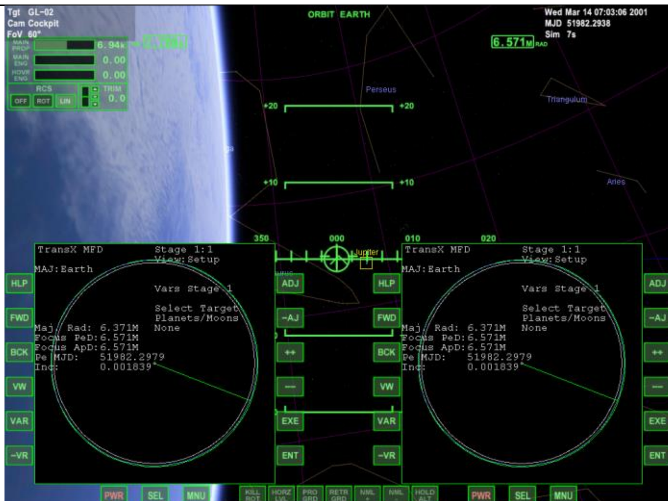
1. MJD: Any date
2. Prograde: -3.33 km/s
3. Outward: 0 km/s
4. Plane: 0 km/s

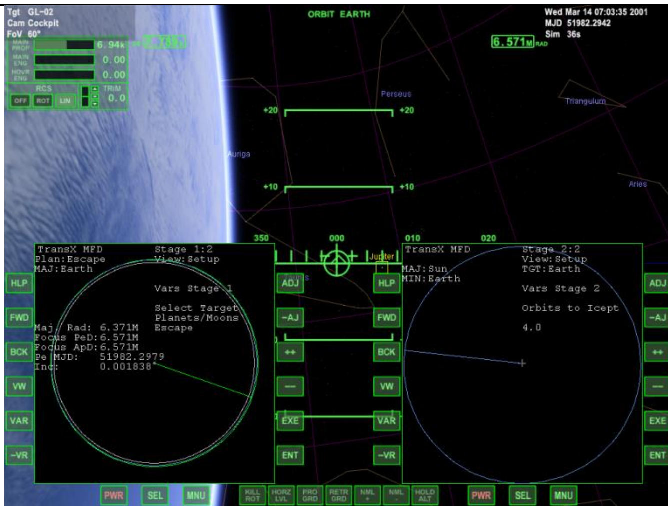
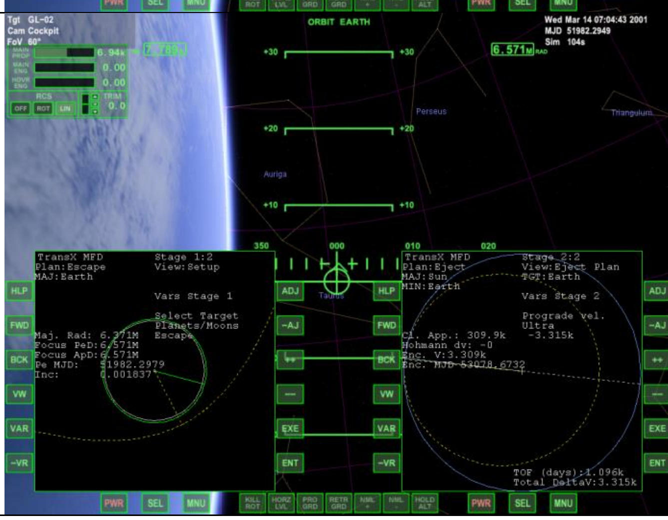
From Ecliptic LEO to SEL3

Using TransX to refine the escape plan

The above calculations have assumed that the Earth orbits the Sun in a perfect circular trajectory. It doesn't quite, so the numbers will need to be adjusted a little to take into account the eccentricity of the Earth's orbit around the Sun.

Since we have a rough idea of the escape plan we need, and because we know that we want to target a 3:4 orbital resonance, we can use TransX itself to refine the escape plan. Here is the procedure:

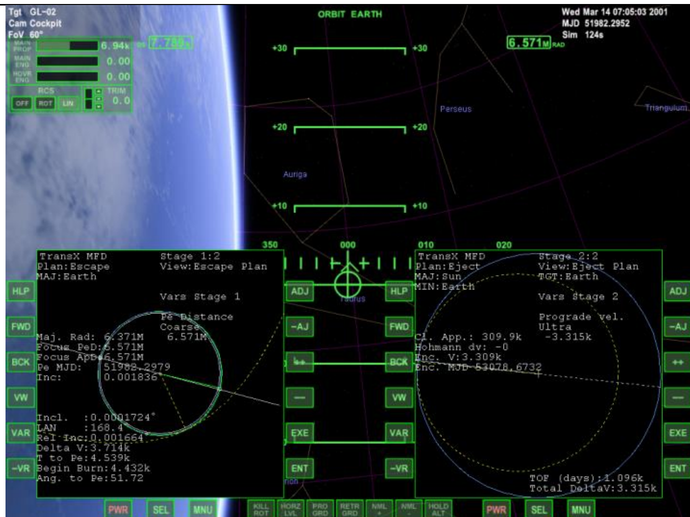
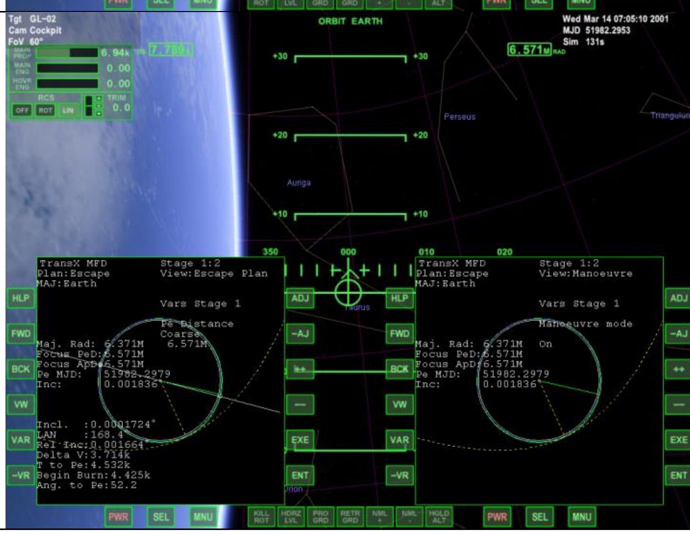
1.		Start with the Ecliptic LEO scenario and bring up TransX on both sides.
2.		On the left-hand side, set target to 'Escape' while on the right-hand side, hit the "FWD" button and select Earth as the target.

3.		On the right-hand side, scroll through the variables until you reach "Orbits to intercept". Increase this until it says 4.0.
4.		Then, hit the "VW" button to view the Eject Plan in the right MFD.
5.		Enter the prograde value -3330 m/s and adjust the increment setting to "Fine" or "Super" etc. Then, hit "++""or"–" until the closest approach is as low as you require it to be (Of the order of a few km, say)

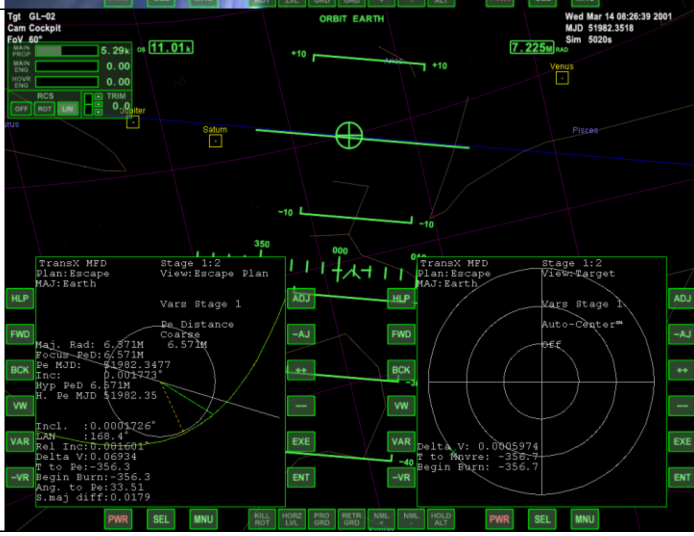
After having completed this exercise, you will have set up an escape plan in TransX that will have you escaping Earth with the correct orbital resonance (3:4) to get to SEL3.

Setting up the escape maneuver in TransX

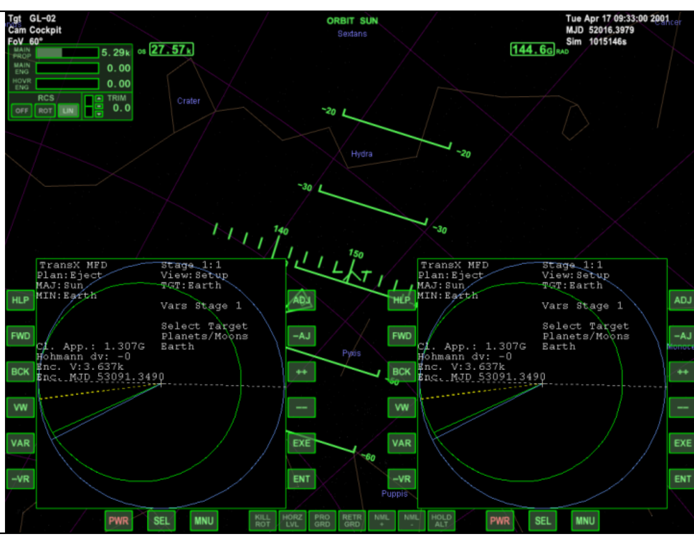
With the TransX MFDs open on both the left-hand side and the right-hand side, here is the procedure for executing the Earth escape maneuver. This procedure assumes that your vessel is already in LEO co-planar with the ecliptic and that you have just completed the preceding TransX procedure.

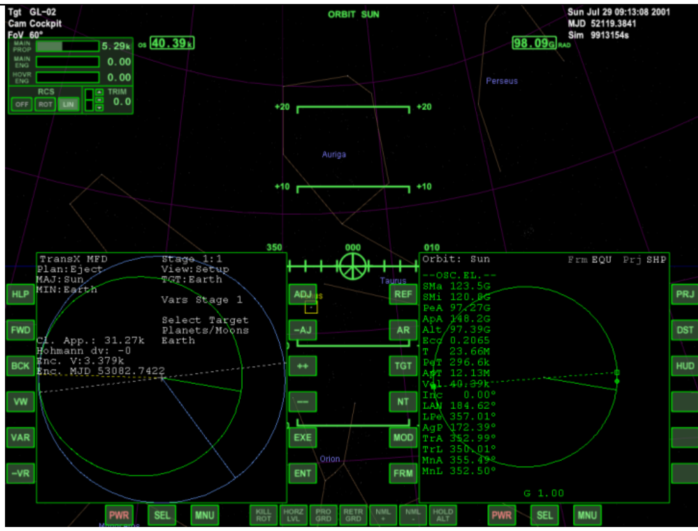
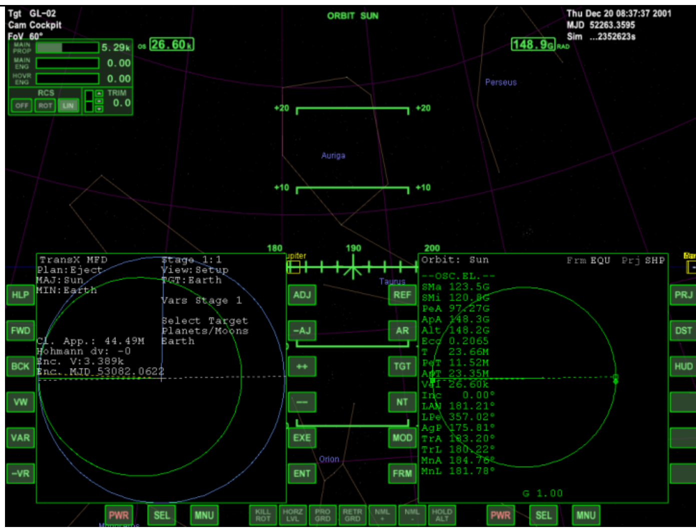
1.		Continue with the scenario above or start with the Escaped Plan Refined scenario. Then continue by clicking VW on the left MFD to bring up the "escape plan" view. Adjust the Pe distance to your current orbital radius, i.e. 200 km circular = 6371 km + 200 km = 6571 km = 6.571 Mm
2.		On the right MFD, hit the "BCK" button and then the "VW" button to bring up the Maneuver view. Turn maneuver mode ‘on’.

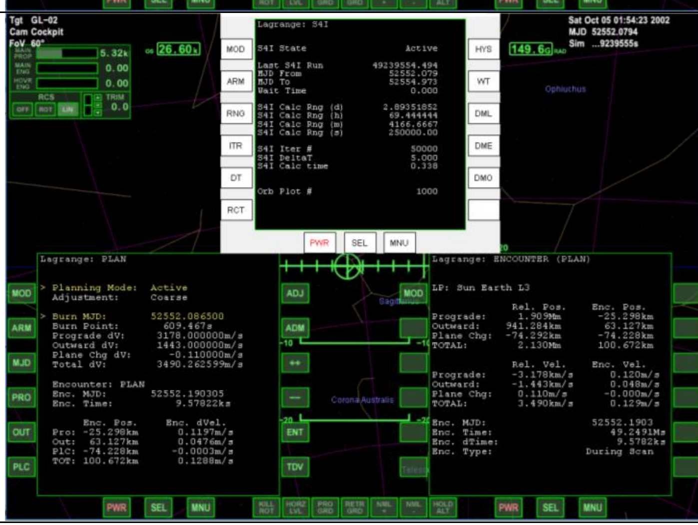
3.		Scroll through the variables until you see ‘Prograde vel.’ On the left MFD, you should see a Delta V quantity. Enter this Delta V value into the Prograde vel. Setting on the right MFD.
4.		On the right MFD, change variables to the ‘Man. date’ and adjust the increment until it says ‘Hyper’ or ‘Ultra’. Then hit "++" until the yellow dotted maneuver line lies on top of the escape plan line. You now have your escape maneuver set up.
5.		Open an external MFD, bring up BurnTime MFD. And click "GET" to import the TransX escape burn parameters. On the right MFD, hit VW to bring up the Target (Cross-hair) screen. Cycle through the variables until you see Auto-center. Wait until some 200-300 seconds before burn, engage the auto-center function. Now, you have the vessel oriented in the right direction to execute the escape maneuver.

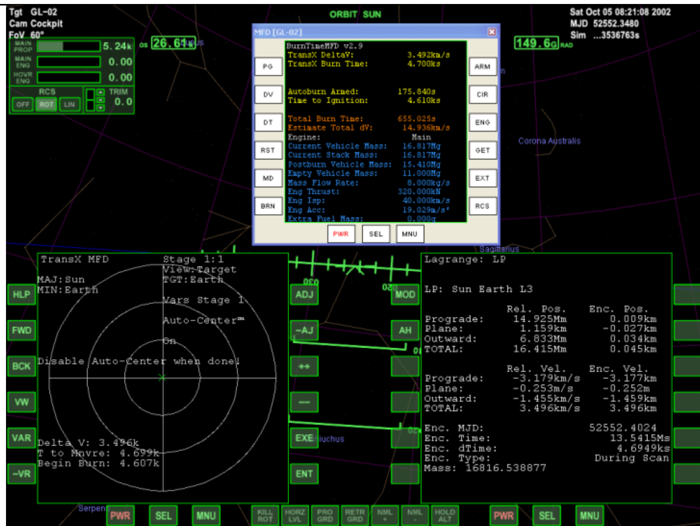
6.		Allow the flight computers to commence the burn automatically.
7.		Fine tune your orbit when the burn ends. Disable auto-center and Maneuver mode. You are now in your transfer orbit to SEL3.

In Heliocentric Transfer Orbit

1.		Continue with the scenario above or start with the Ecliptic LEO scenario and redo the procedure mentioned previously. Bring up TransX on both MFDs. Note that as you escape Earth, your closest approach value will drop as time passes by. It will then increase rapidly. So, a mid-course correction is required. Ideally, you want to do your fine tuning close to perihelion (because of the Oberth effect).

2.		As you approach your first perihelion (Bring up Orbit MFD on one side and keep an eye on your time to perihelion PeT), EITHER press VW in TransX and enable maneuver mode, then, adjust the prograde, outward, plane and maneuver date to fine tune your course OR simply align your vessel in the +Z axis (Prograde direction) and apply linear thrusters to fine tune your orbit. Bring your closest approach value down to some 10-100 km.
3.		Note that as you complete one orbit around the Sun, Earth is behind you (lags you) by 90 degree. This needs to happen as your orbital period is 0.75 years. By the time you completed 1 orbit around the Sun, 0.75 years has elapsed, but Earth completes 1 orbit around the Sun in 1 year, hence you are faster than Earth. And that is why we can intercept SEL3 in 2 orbits, since we leads Earth by 90°/orbit, we will lead it by 180 degree in 2 orbits.
4.		As we approach our second perihelion (0.5 orbits to SEL3), we want to fine tune our orbit to intercept SEL3. So, bring up Lagrange MFD on the Orbit-MFD-side MFD and bring up the S4I screen. Increase RNG value so that we can have a broader view range of our current orbit. Bring up LP screen and start to apply linear thrusters or short bursts of main engine to fine tune your closest approach with SEL3 (down to within 300-500 km or better).

5.		As you approach SEL3, periodically drop out of time warp and apply linear thrusts to refine your last approach. Note that you are now nearly 180 degree opposite Earth (The green radius vector is nearly opposite to the blue radius vector.)
6.		You should ignore TransX's Cl. App. (Closest approach) value and stick to Lagrange MFD's Enc. Pos. value. Also, hit MOD on Lagrange MFD to bring up S4I screen and decrease RNG setting as time to interception decreases. When the enc. dTime counts down to some 50 ks, you should plan your approach burn.
7.		Bring up the PLAN screen and input the negation of the approach burn parameters from the Encounter screen and enter enc. MJD. as the maneuver date. Note that fluctuation of component velocities will occur as we fine tune our approach periodically. In this case, reenter the new negation of velocities and maneuver date into the PLAN screen. Arm the PLAN.

8.		Alter the RNG setting if fluctuations occur. Proceed by engaging AutoBurn. Wait or warp time up to 10x until the burn point and let the burn commences automatically.
9.		When the burn ends, cancel out the residual velocity and apply linear thrusts to fine tune your approach to SEL3. Engage AutoHold when you arrive there. If you hit F1 and have an external look outside the vessel and hit F9 to enable the Planetarium Mode, you will notice that Earth is hidden behind the Sun. (Hence, your vessel, the Sun and Earth are collinear.) Welcome to Sun-Earth Lagrange point 3!

Note that your approach velocity of 3.496 km/s to SEL3 using the 3:4 resonance scheme is very high. You can reduce the total dV requirements by opting for a 2.5 year or even 3.5 year resonance rather than 1.5 year resonance but these plans will take considerably longer to implement.

Here is a summary of the resonance schemes available (assume starting from 300 km circular LEO):

a. With a 3:4 orbital resonance (Earth rotates around the Sun 1.5 times, for the spacecraft's 2 orbits - 1.5 years to insertion into SEL3), the dV cost of getting out to SEL3 is ~ 3650 m/s + 3300 m/s = 6950 m/s.

b. With a 5:6 orbital resonance (Earth rotates around the Sun 2.5 times, for the spacecraft's 3 orbits - 2.5 years to insertion into SEL3), the dV cost of getting out to SEL3 is ~ 3370 m/s + 1990 m/s = 5360 m/s (a saving of 1490 m/s).

c. With a 7:8 orbital resonance (Earth rotates around the Sun 3.5 times, for the spacecraft's 4 orbits - 3.5 years to insertion into SEL3), the dV cost of getting out to SEL3 is ~ 3280 m/s + 1150 m/s = 4430 m/s (a saving of 2520 m/s).

In other words, if you are prepared to wait, the dV cost of insertion into SEL3 need only be slightly higher than the cost of getting to, say, EML1/2.

Actually, there is another resonance scheme that can bring you to SEL3. Instead of having your vessel going faster than Earth, you can move slower than Earth and intercept SEL3 in one orbit. See if you can figure out that resonance scheme. Answer is available below this page.

Now that you have mastered the way to get to SEL3, trips to SEL4/5 wouldn't be hard for you.

Ans: 3:2 resonance scheme.

From Ecliptic LEO to SEL4/5

SEL4/5 are Lagrange points 60 degrees ahead and 60 degrees behind Earth. Let us start with SEL4. Now, you want to go around once and end up in front of the Earth by 60 degrees. So, the Earth will complete 5/6 ths of an orbit; whereas the spacecraft will have to complete one. So, the resonance scheme will be 5/6 :1 = 5:6. Perhaps you want to try out other resonance scheme.

So, instead of going 60 degrees in one orbit, you may want to try 30 degrees/orbit. After 2 orbits, your vessel will be revolving 720 degrees around the Sun, but Earth is 60 degrees behind you, i.e. 720-60 = 660 degrees. So, the resonance scheme is 660:720 = 11:12.

For SEL5, you want to go around once and end up 60 degrees behind the Earth. The Earth will have had to rotate by 360 + 60 degrees by the time that the spacecraft returns to aphelion. So, the resonance is (360+60)/360 = 7/6 or 7:6.

With this resonance, the spacecraft has to leave Earth with a longer orbital period than the Earth. Instead of lowering perihelion, the goal is to raise aphelion so that orbital period is 7/6 of a year.

So, instead of going 60 degrees in one orbit, you may want to try 30 degrees/orbit. After 2 orbits, your vessel will be revolving 720 degrees around the Sun, but Earth is 60 degrees in front of you, i.e. 720+60 = 780 degrees. So, the resonance scheme is 780:720 = 13:12.

In general, to find resonance schemes for SEL4 and SEL5, we can use the formula:

$$\frac{(n \times 360) \pm 60}{n \times 360}$$

or,

$$(n \times 360) \pm 60 : n \times 360$$

where n is the number of orbits around the Sun and we use +60 for SEL5 (Earth leads us by 60 degrees) and -60 for SEL4 (Earth lags behind us by 60 degrees).

Now that we know our resonance scheme for SEL4/5, we can calculate the orbital parameters that we need to know and feed into TransX for refining purposes. Then, we can execute TransX's plan and get to SEL4/5, just as what we do to get to SEL3 previously. (The procedures will not be repeated here, please review the Rough Calculation section of the previous SEL3 tutorial.)

From Coplanar LLO to EML 3/4/5

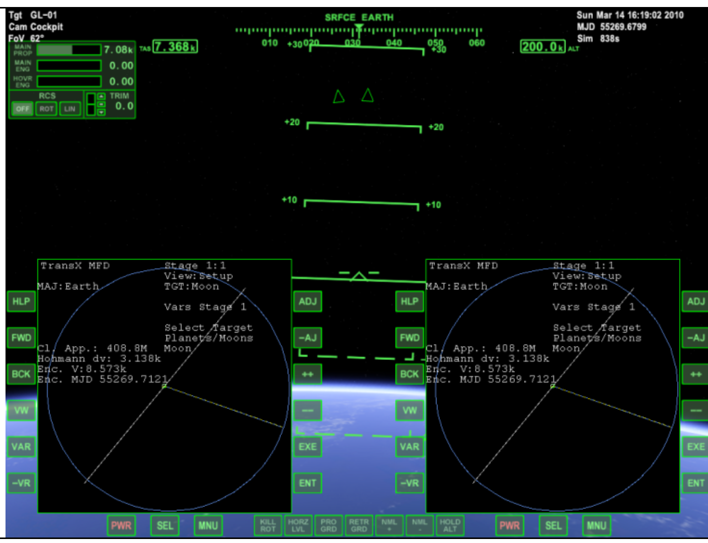
Using the same technique as mentioned above, one can calculate the required dV to escape Moon and enter a geocentric transfer orbit to intercept with EML3/4/5 with ease. A point to note is that the Moon's orbital speed is 1.022 km/s. So, one should multiply the dimensionless number of the final answer with 1022 m/s instead of 29.78 km/s which is Earth's orbital speed around the Sun.

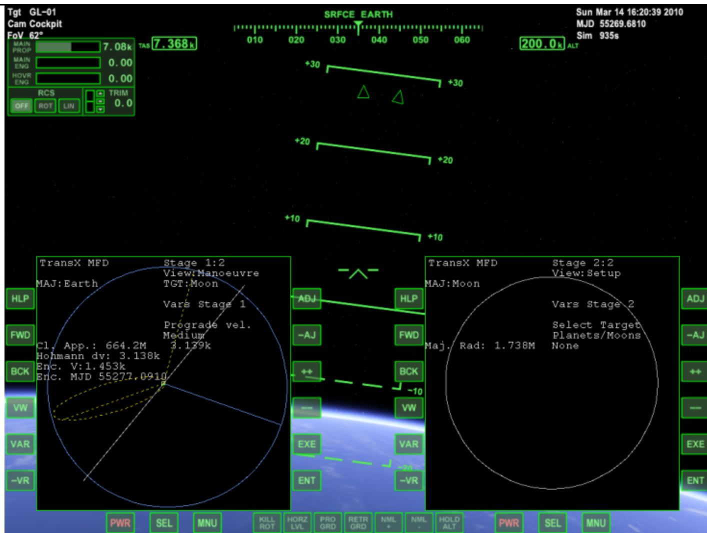
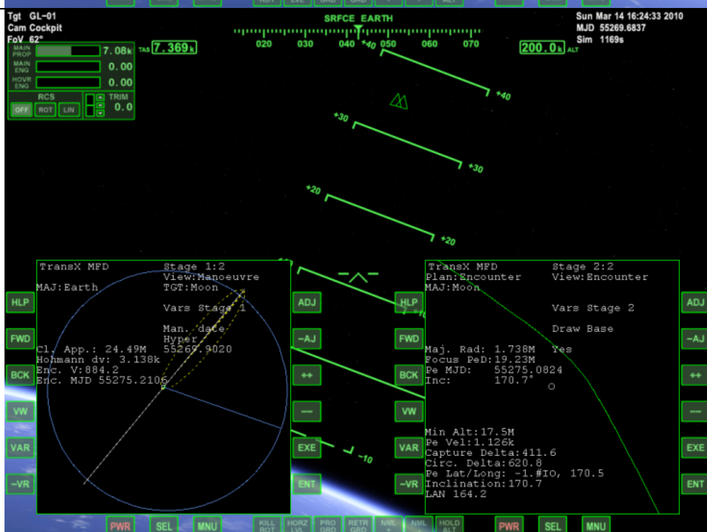
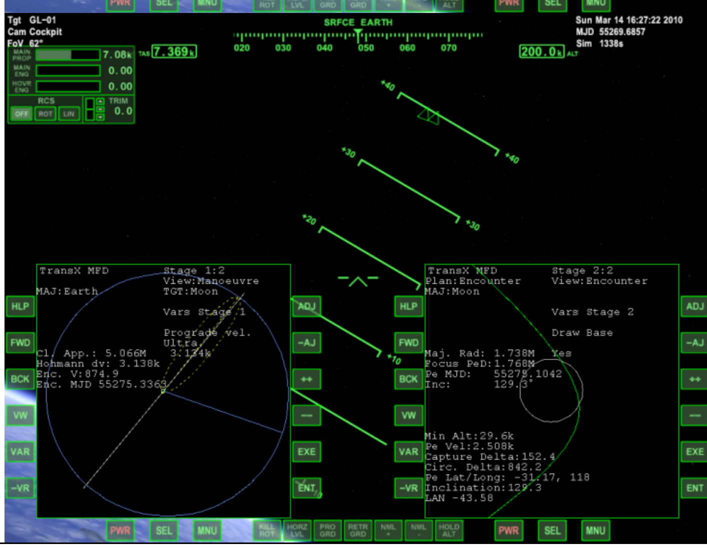
Off-plane Transfer

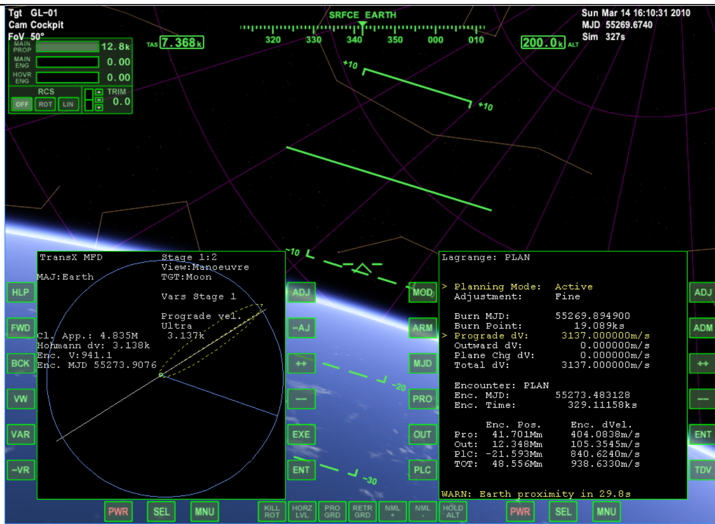
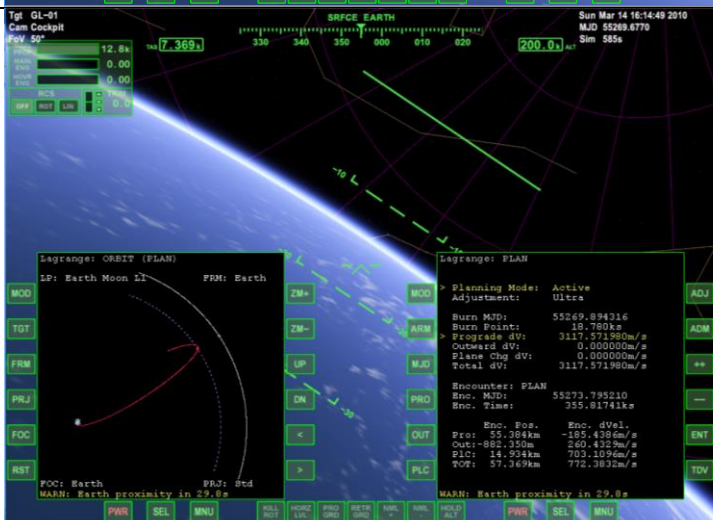
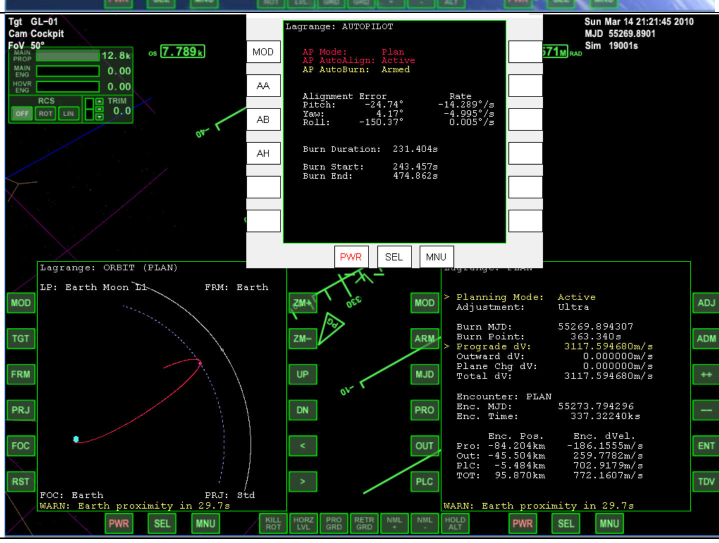
So far, we already know how to get to all Earth-Moon and Sun-Earth Lagrange points. But we only restrict ourselves to coplanar transfer. What happens if we need to conduct off-plane transfers from the ISS or from spaceports on Earth that are not coplanar with the Moon's orbit and the ecliptic? Now, we will learn how to conduct off-plane transfer to Lagrange points.

From LEO (arbitrary orbit, or from ISS).

*The following tutorial only covers trips to EML1-5. For trips from LEO to SEL1/2/3/4/5, the steps are the same like the steps mentioned before in the coplanar transfer tutorial "From Ecliptic LEO to SEL1/2/3/4/5".

<table>
<tr>
<td>1.</td>
<td>
</td>
<td>Start with any scenario which has a vessel that is not coplanar with the Moon or launch in 90 degree heading to enter LEO. Bring up TransX on both sides. Select Moon as the Target.</td>
</tr>
</table>

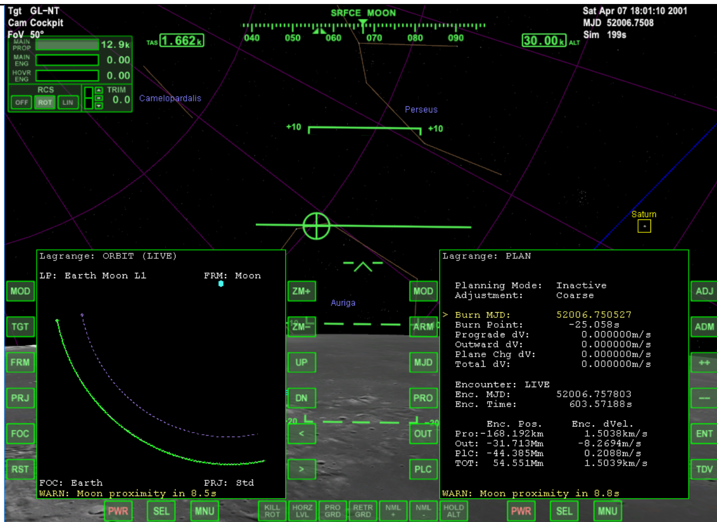
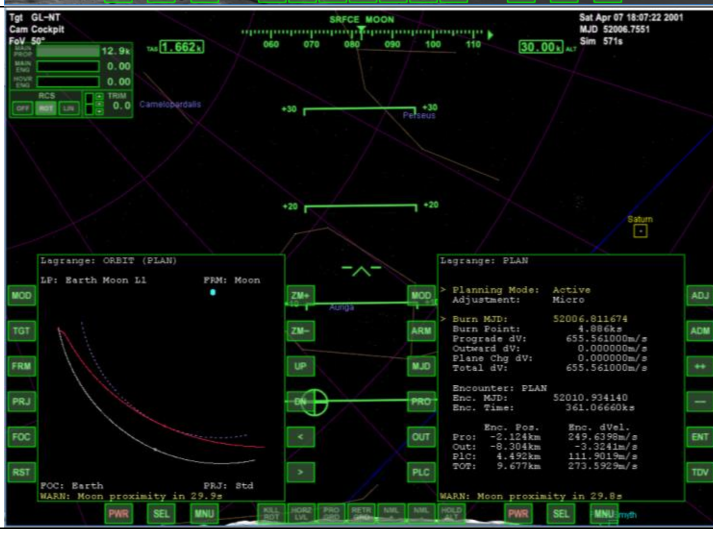
2.		Plan a transfer to the Moon. Enable Maneuver mode, click VAR a few times and add in prograde velocity until your transfer orbit intercepts the lunar orbit (blue).
3.	 	Now you want to intercept the Moon off-plane, which can only be done at the nodes, i.e. the white line. So adjust your time of maneuver such that your transfer orbit will bring you intercept with the Moon at the line of nodes (the white line). Note that you can find a better solution by advancing your orbit (or reduce your maneuver date, depending on which works for you) by trial and error. Also, fine-tune your approach distance to the Moon by adjusting prograde vel. component as well.

4.		Now, copy the variables from TransX to Lagrange MFD (The date and prograde vel.) Notice how close TransX's plan approximates the trip to EML1.
5.		Fine tune the variables. (This takes a longer time, but you will get an even accurate solution in a few minutes.) Bring up the ORBIT screen to assist you in planning your trip.
6.		Now that you have the plan, bring up the Autopilot screen in another MFD and you can burn at the right time and get to EML points using the procedure taught before.

From Brighton Beach to EML1/2/3/4/5

From Brighton Beach to EML1/2

1.		The default Brighton Beach.scn under the Delta Glider folder is used in this case. Sitting on the Brighton Beach base, bring up TransX on both sides.
2.		Select "Escape" as Target and hit FWD to enter the 2nd stage. Hit VW to bring up the "eject plan" view. Then enter a negative prograde dV of some 850-900 m/s (-850 to -900).
3.		On the left MFD, click VAR/-VAR a few times and change the Graph Projection to Plan, then hit VW to view the escape plan and enter your Pe distance and swing the Ej. Orientation course just before it intercepts the green line, your current position.

4.		Launch into the correct heading to enter LLO or use the scenario editor to bring you to orbit. (If Launch MFD is used, please read [this](#) carefully) Then bring up Lagrange MFD on both sides. Bring up the ORBIT screen and the PLAN screen on both MFDs. Change FRM to Moon.
5.		Enter a reasonable dV of some 650-700 m/s and adjust the burn MJD to obtain a rough plan and fine tune it further to obtain an even accurate plan. It is possible to get down to some 10 km from EML1. Then, bring up an external MFD to show the Autopilot screen and engage AutoAlign and AutoBurn to bring you out to EML1. Finally, conduct your approach burn when you arrive there. Engage AutoHold when you are near EML1.

For trips to EML3/4/5, while in LLO, bring up TransX on both sides and simply conduct an escape transfer to a resonant geocentric orbit to intercept with EML3/4/5 using the method taught previously in the “From Coplanar LLO to EML3/4/5”.

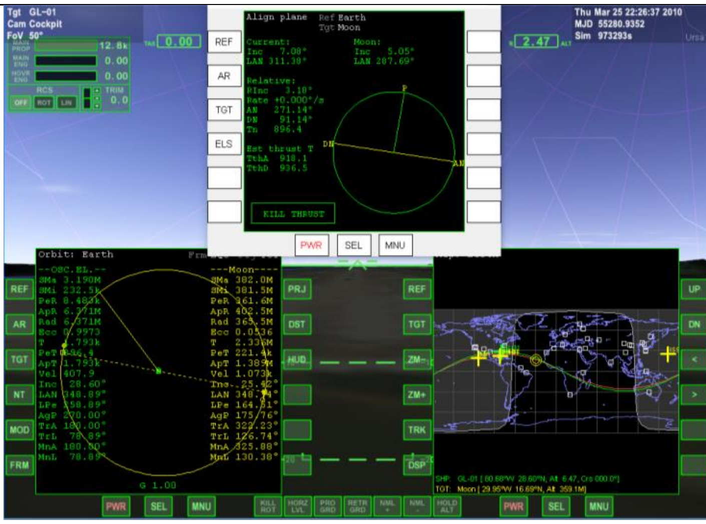
Surface Launch from KSC to EML1/2/3/4/5

However, for surface launches to EML1/2/3/4/5, take note that because TransX doesn't accept moons as valid escape targets, the above plan will not work if you start planning on Earth's surface. You have to get into a low RInc (Relative Inclination) orbit with respect to the moon and target it from maneuver mode. There are a few ways of doing this and all of them rely on the fact that EML points are coplanar to the lunar orbit.

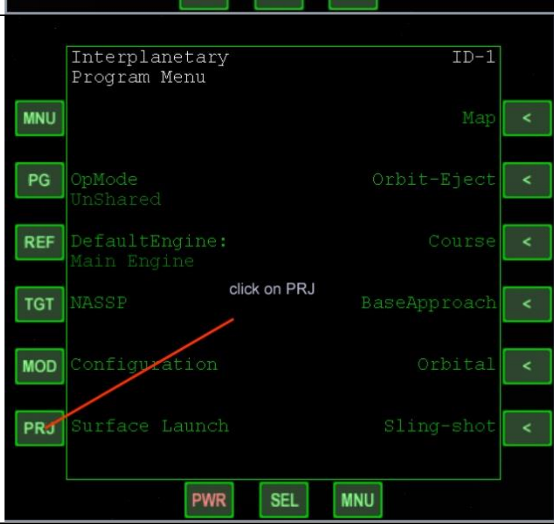
From Surface (Using Orbit MFD + Align Plane MFD + Map MFD with Launch MFD)

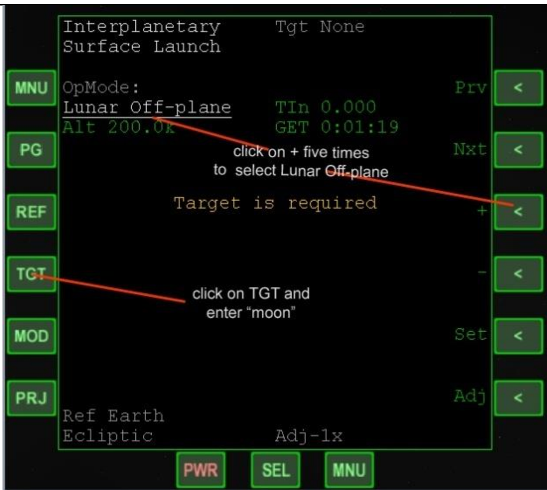
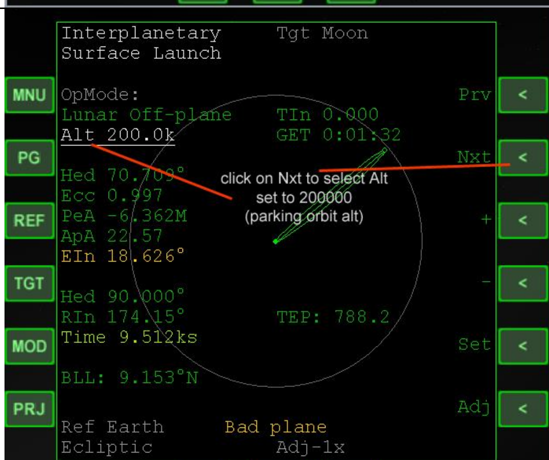
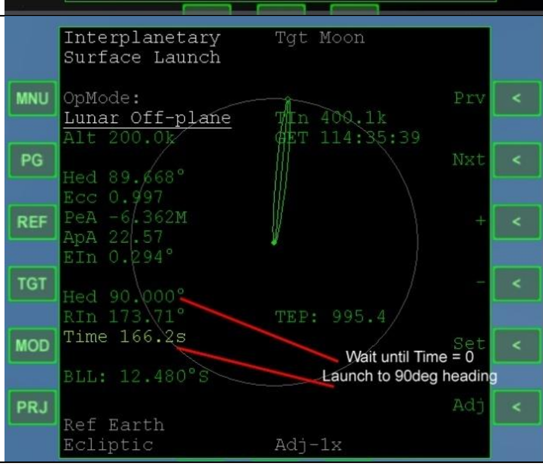
*Refer to dgatsoulis and blixel's video tutorial here.

1.		The quickstart.scn under the Checklist folder is used in this case. While still on Earth, bring up Orbit MFD and Map MFD on both sides. Target the Moon in the Orbit MFD, set Frm as EQU and Prj as TGT. On the Map MFD, target the Moon as well, change "orbit lines" setting to Orbit plane. Referring to the Orbit MFD, check if the current Moon's position is at least some 45 degrees behind the ascending node or descending node.
2.		If it isn't, warp time until the Moon is at least some 45 degrees behind AN or DN. Notice that in the Map MFD, the Moon's orbit (red line), is nearly coincident with our projected orbit (green line).

3.		Then, bring up Align Plane MFD and target the Moon. Watch the RInc value reduces. Refer to the Rate value as well. If it is positive, RInc will increase and vice versa. Use the scenario editor to advance or reverse time depending on your RInc and Rate value. Launch into 90 degree heading when RInc value is at its minimum. Or simply bring up Launch MFD and target the Moon. Launch when Time to Intersection = Half of Orbital Velocity Time. Proceed with the previous tutorial to conduct an off-plane transfer to EML points.

From Surface (Using IMFD)

1.		While on Earth's surface, bring up IMFD on one side and click MNU to bring up the Program Menu.
2.		Click PRJ to bring up the Surface Launch page.

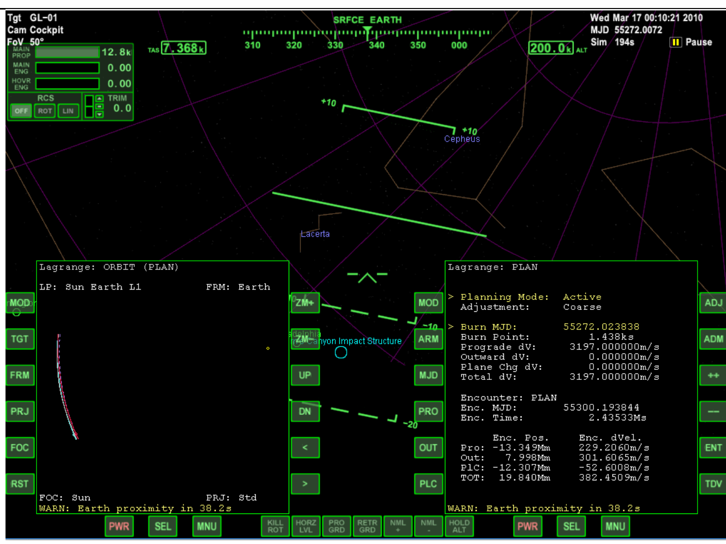
3.		Click the + button a few times to select Lunar Off-Plane. Then, target the Moon by entering Moon after clicking the TGT button.
4.		Click Nxt to select Alt and set the parking orbit altitude to 200 km or 200000 m. (Type in 200k.)
5.		Click NXt to select TIn and enter the Earth-L1 flight time, 400000 seconds. Then, note the time to launch and add it to the flight time (In this case, it is 400000+12250.)
6.		Now, wait until Time = 0 and launch to 90 degree heading (Using Launch MFD.) You will get into a parking orbit that will bring you to intercept EML points. For EML3, the transfer burn occurs at the opposite node to EML1/2. Whereas for EML4/5, add or subtract 1/6 Moon-orbit-time to the IMFD "Surface Launch / Lunar Off-Plane" Time-to-insertion parameter (TIn).

Surface Launch from KSC to SEL1/2/3/4/5

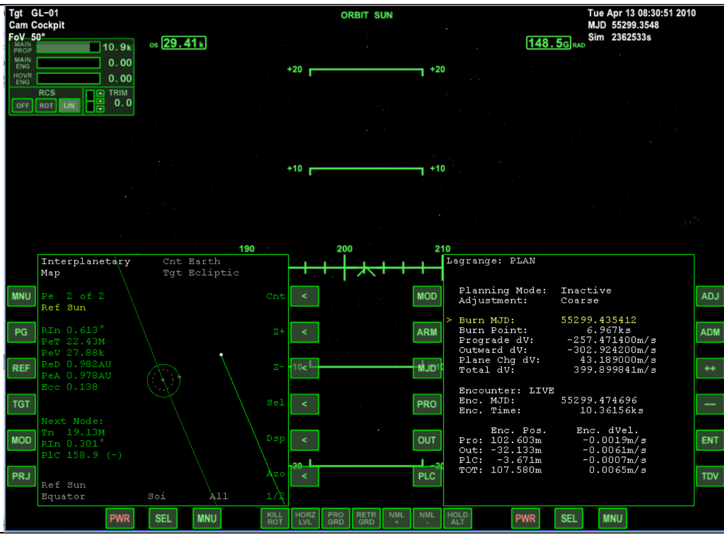
For SEL1/2, we will use Orbit MFD to determine the time to launch, then proceed with the normal way we do with a coplanar transfer from Ecliptic LEO to SEL1-2.

There are 2 methods for SEL3-5's surface launches. They will be explored in the SEL3-5 tutorials. The Align Plane MFD + Launch MFD method and the TransX method will be used with trips to SEL3/4/5.

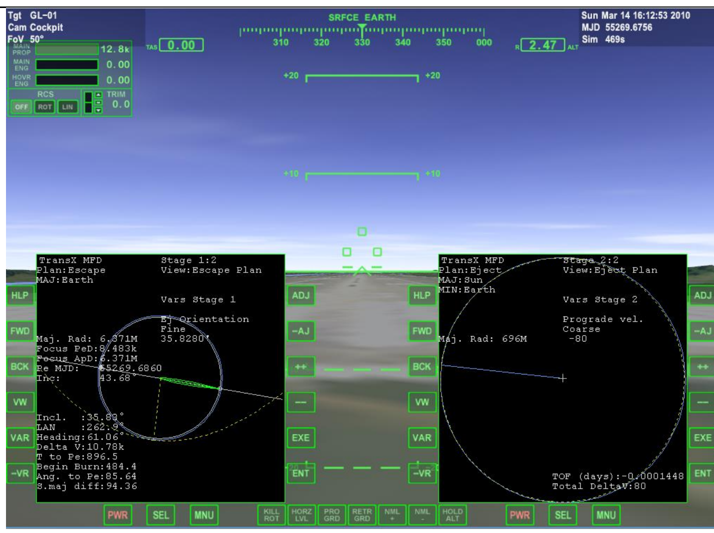
Surface Launch from KSC to SEL1/2

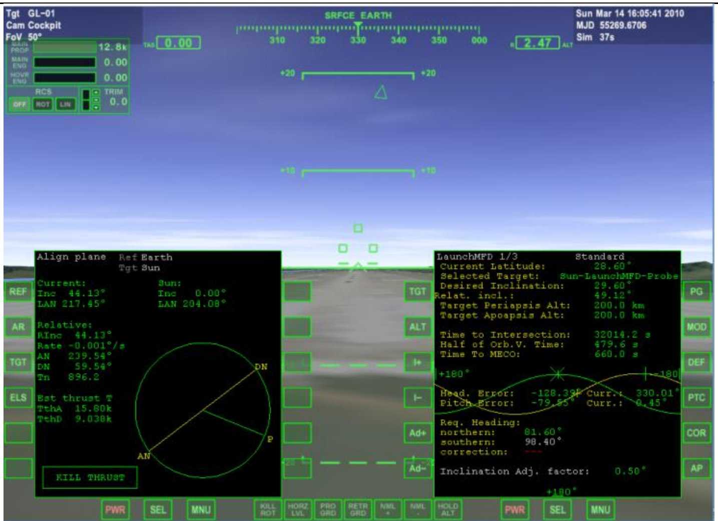
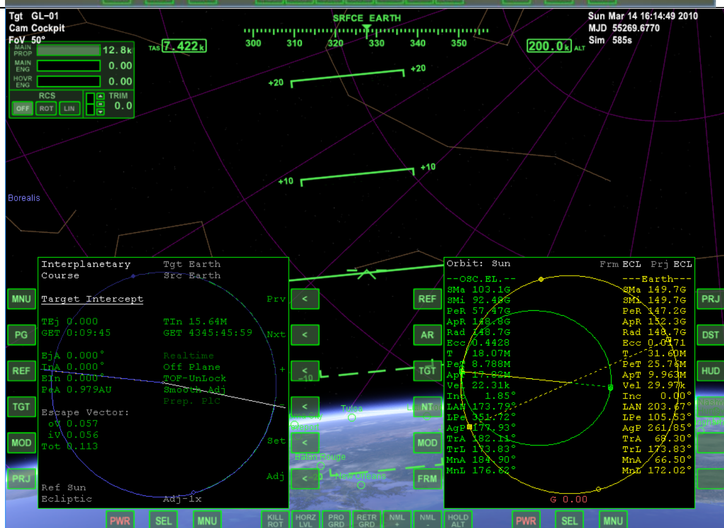
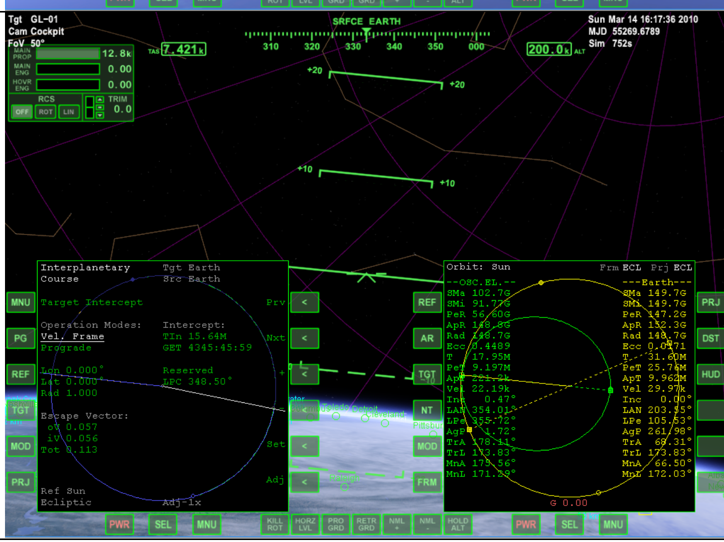
1.		The quickstart.scn under the Checklist folder is used in this case. Open OrbitMFD on both sides. On the right reference the Sun and target the Earth. Make a note of Earth's "TrL". Wait until the LAN on the left side is the same as Earth's TrL + 30° or + 210°. (whichever gives you the lowest Inc.). For SEL2, LAN = TrL + 35° or + 215° . Wait for 2-3 days for the Moon to clear its way out of our orbit, then launch into 90 degree heading and enter a parking orbit with the correct LAN value. Beware of the Moon's position. Passing through the Moon's SOI will distort your trajectory, resulting in high Enc. Pos. and Enc. Vel.
2.		While in orbit, bring up the ORBIT screen and PLAN screen in both MFDs. Target SEL1 in Orbit screen and increase RNG in S4I screen to 20-50 days to allow a wider orbit view of Earth around the Sun. Put in a reasonable prograde value of 3200 m/s. Then, ARM the plan and observe how the Enc. Pos. changes. Adjust the Burn MJD and the Prograde dV until you arrive at a minimum Enc. Pos, value. Take note that Enc. Vel. must not be too high. Enc. Vel. should be around 400-600 m/s for pure prograde transfer.

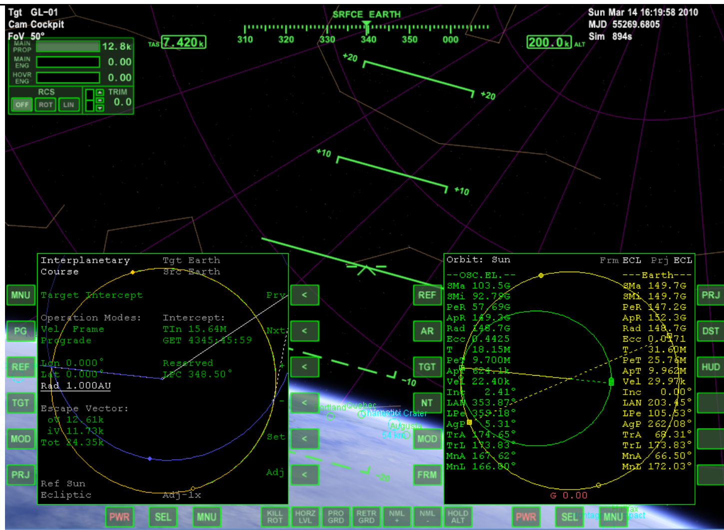
3.		Bring up an external MFD to display the Autopilot screen. Engage AutoBurn once you armed the plan. Allow the burn to commence automatically. Fine tune your Enc. Pos. with some main thrusts and linear thrusters.
4.		Conduct mid-course corrections whenever possible to fine-tune your approach to SEL1. Decrease your RNG setting as you get closer to SEL1. Your approach velocity shouldn't change much.
5.		As you get closer to SEL1, start entering the negation of the component velocities and the Enc. MJD as the Burn MJD. Arm the burn, bring up an external MFD, and get ready to engage AutoAlign and AutoBurn as you get closer to the burn point. Let the burn commences automatically.

6.		Welcome to SEL1. Engage AutoHold when you are very near there.

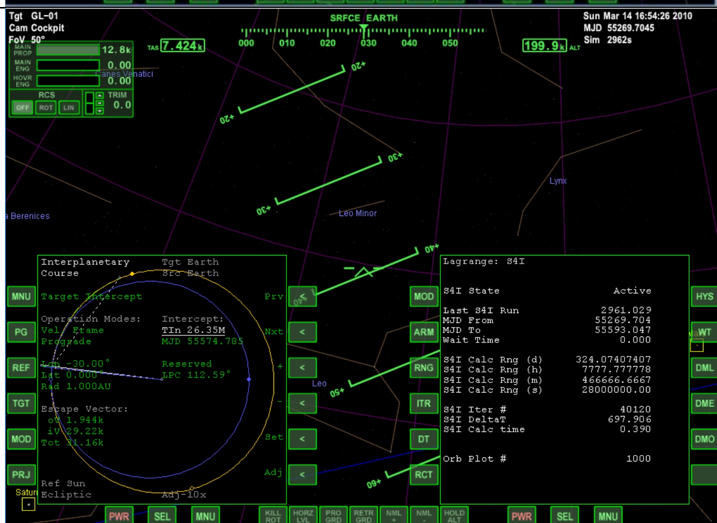
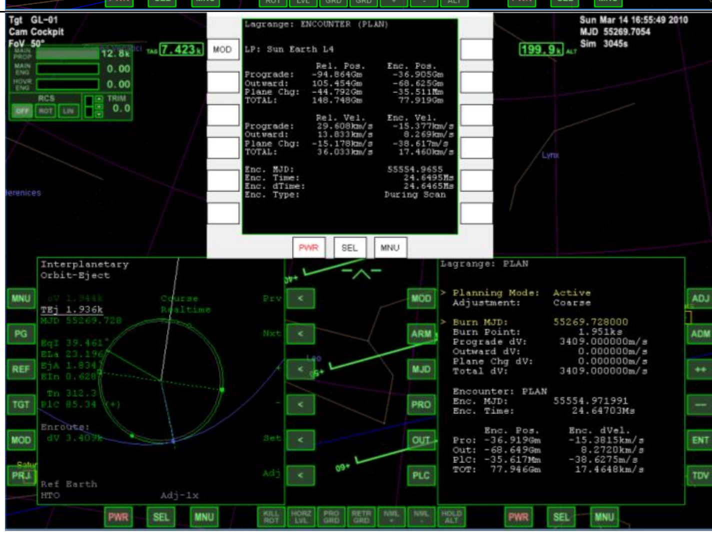
Surface Launch from KSC to SEL3/4/5

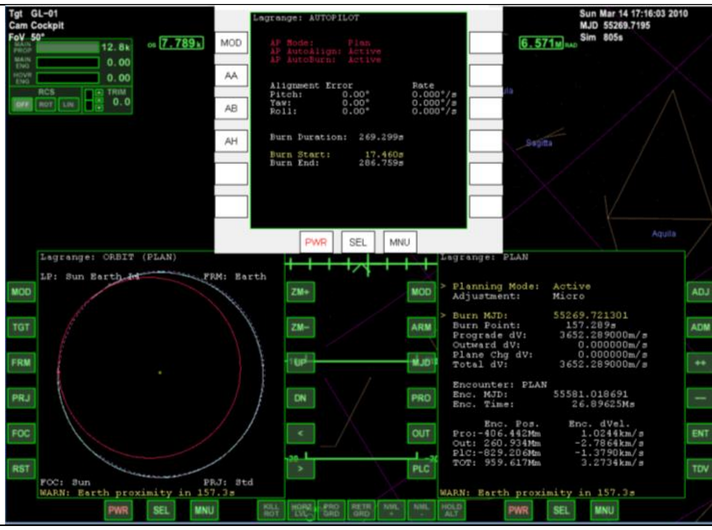
1.a		The quickstart.scn under the Checklist folder is used in this case. Bring up TransX on both sides of MFD. Target “escape” in left MFD and hit FWD to enter the 2nd stage in right MFD. Then, hit VW to bring up Eject plan screen. Put in just a little amount of prograde dV, be it positive or negative. Then, adjust graph projection to PLAN and adjust Pe Distance and swing Ej. Orientation Course line over your current vessel location. Launch into the heading as stated in TransX or use scenario editor to get into parking orbit.

1.b		Or, another way of doing this is: bring up Align Plane MFD or Launch MFD. Target the Sun in the MFDs and set your launch altitude in Launch MFD. Warp time until Align Plane MFD displays a minimum RInc value. Alternately, wait for Launch MFD displays Time to Intersection = Half of Orbital Velocity Time. Then, launch into orbit with a low RInc value.
2.		While in orbit, bring up IMFD on both sides and enable shared mode. On the left MFD, select MNU, Course, and then Target Intercept program. Target Earth. We will use the offset program in IMFD to plan our trip. On the right MFD, bring up Orbit MFD, set REF as Sun and target Earth. Note down the SMa of Earth around Sun, in the screenshot on the left it is 149.7G. Remember this number.
3.		Hit MOD twice in IMFD. Click Nxt and change “Operations Mode” to velocity frame by hitting the +/- button. (Make sure that IMFD date is set to MJD and nodal regression is set to off if nonspherical sources is disabled in Orbiter’s Launchpad.)

4.		Click Nxt a few times until “Rad 1.000” is highlighted. Click Set and enter the SMa value that you have noted from the orbit screen for trips to SEL4/5 and twice the SMa value for trips to SEL3. In our tutorial, we will go to SEL4. But I will show you how to tweak our plan to go to SEL3/5 as well. Click PG and click Z- or Z+ to zoom in and out to view our planned heliocentric transfer orbit.
5.		For SEL4, we will lead Earth by 60 degrees. So, alter the value of Lon to achieve this. Usually, it will be -30 degrees. Notice that we lead Earth upon arrival. Earth will be at the interception point between the dashed white line and the yellow circle while we will be at the interception point between the solid white line, the blue orbit and the yellow orbit upon arrival.
6.a		Notice that the oV displayed is still quite high in the above screenshot if we just change the Lon value, to minimize it, we alter the Tln value, which is our interception time. Click Nxt a few times until it is highlighted and adjust the Tln time until oV is at its minimum value. After that, bring up the Orbit Eject program on the right MFD. Click Nxt to select Course.

6.b		For SEL5, we will lag Earth by 60 degree. So, alter the value of Lon to achieve this. Usually, it will be -150 degrees. Compare the screenshot on the left with the previous one. Notice that we are behind Earth now.
6.c		For SEL3, we will be opposite to Earth, hence our offset distance is 2 Earth-Sun distance, or 2 times the SMa value. Set Rad to 2AU (or 2 times the SMa value) and adjust Tln like before to obtain out planned trip. Usually, Lon value is set to -90 degree and notice that we are directly opposite to Earth (solid white line is opposite to dashed white line).
7.		Back to our SEL4 trip, notice that my Eln value is not close to 0 degree, i.e. my planed heliocentric transfer orbit is not coplanar with my current parking orbit. To nullify the Eln value, adjust the Tln on the left MFD by advancing or reducing the interception time to allow Eln value reduces to nearly 0.

8.		Also, notice that EjA is not close to zero. Nullify it by altering the TEj value, either by increasing it or reducing it so that EjA is close to 0.
9.		Bring up Lagrange MFD at the right MFD as you are close to the burn point. In ORBIT screen, set FRM as Earth, target SEL4. In S4I screen, set RCT to something preferable, say 0.333 seconds and set RNG to the Tln value, somewhere near 28Ms or 28e6 in our example. Click the MOD button to bring up the PLAN screen.
10.		Bring up another external MFD and bring up the Lagrange MFD's Encounter screen. Bring up the Orbit-Eject program in the left MFD. Copy IMFD's prograde dV value into the PLAN screen and set MJD as displayed in IMFD as Burn MJD in PLAN screen. Arm the plan. Then, start to adjust the Enc. Pos. by advancing or reducing the Burn MJD and prograde dV. You may also want to put in some plane change dV if your Enc. Pos. is quite far from SEL4.

11.		Once you have got the plan, bring up Lagrange MFD's Autopilot screen and engage AutoBurn when you are near the burn point. After the burn, you can approach SEL4 like what we have done before in a coplanar transfer to SEL3, except that MCCs will be of larger dV due to greater plane offset. So, conduct MCCs wisely.

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THE END

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