Transfer from Europa to Callisto

Destination

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Abstract— **The purpose of this paper is to introduce Orbiter[1] users to the use of the Interplanetary multi-function display[2] for transfers from one circular orbit to another between planets in a system. It details the procedures needed to transfer from a circular orbit around Jupiter's moon Europa to Jupiter's moon Callisto. The procedure attempts to optimize fuel. The scenario date was chosen to be August 30, 2002 at 04:43, an optimum launch time for this flight, and uses the standard Delta Glider spacecraft.**

Note: The included scenarios require the standard DeltaGlider, a Jupiter mass of 1.8986111e+27 Kg., and a Jupiter JCoeff of 0.01475. Double-check these in Jupiter.cfg. It also requires Interplanetary MFD Version 4.2 or later.

I. Introduction

This document introduces Orbiter Spaceflight Simulator users to the use of the Interplanetary multi-function display (IMFD) by detailing the procedures for achieving a transfer from Europa to Callisto. The scenario begins with an 80% fueled Delta Glider in a ~200 Km circular prograde orbit around Europa, with an ecliptic inclination of ~0 degrees (orbital plane was previously adjusted). In Figure 1 below, the Orbit MFD display shows (approximately) the initial conditions. **Set this display for Ecliptic projection.**

The objective is to get from this orbit into a circular 300 Km orbit around Callisto at a prescribed inclination with a minimum of fuel used. This will require multiple burns at points during the flight. All burns are done to the utmost accuracy, as is the initial course setup.

The overall flow of the procedure consists of the following stages:

1. Plan the transfer from Europa to Callisto
2. Set up for the ejection from Europa
3. Eject into the transfer orbit
4. Wait until exit from Europa's sphere of influence, change modes
5. Early mid-course correction to remove ejection errors
6. Mid-course plane change at node
7. Late mid-course correction to fine-tune intercept.
8. Approach burns for insertion into prescribed orbit
9. Orbital insertion burn at Callisto

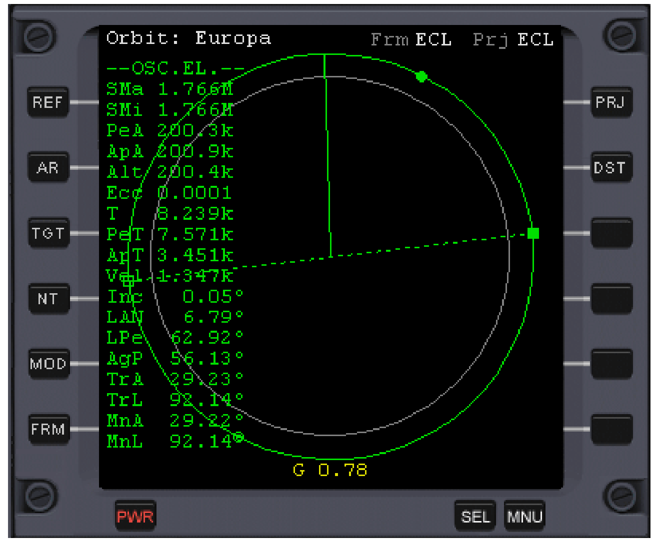


Figure 1. Initial Orbit

The objectives of the scenario are

- to use the minimum amount of fuel (both MPS and RCS), and
- to minimize the adjustments needed to achieve the final orbit of prograde, 150Km circular, 35 deg inclination, around Europa.

This will require a mid-course plane change, a precise MCC, several approach burns, and an insertion burn at Callisto. IMFD's capabilities will be exercised in this scenario, giving the student a solid base from which to expand his knowledge and capabilities.

II. Initial Preparation

A transfer from one Jupiter moon to another is analogous to transferring from one solar system planet to another. The advantage of doing these maneuvers in the Jovian system is that the time needed is much less than the equivalent needed for solar system transfers. The disadvantage is that Jupiter's strong gravity results in its inner moons moving fast and being subject to gravity gradients that cause significant orbit perturbations. We'll see that, even in this extreme environment, IMFD performs very well.

We will use IMFD's **Course/Planar Intercept** program to plan and execute the transfer. The objective is to create a transfer orbit that will take us from Europa to Callisto. The minimum-energy transfer is a Hohmann transfer across the Jovian system, with intercept near the opposite side of the starting point. Ejection should occur prograde from the outside of the origin body to make the most of the combined

[1] The Orbiter Spaceflight Simulator, Dr. Martin Schweiger, University College London

[2] The Interplanetary Multi-Function Display, Jarmo Nikkanen, Finland

velocities of the origin planet in its orbit and the spacecraft's orbit around the origin body. See Figure 2 below.

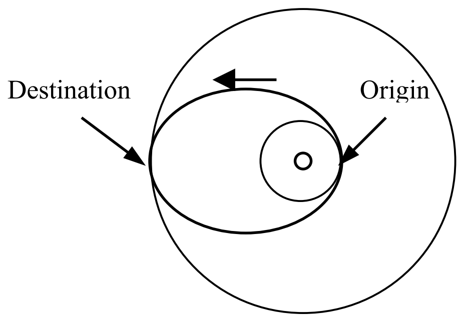


Figure 2. Minimum Energy Transfer

IMFD's Course program has several sub-modes, two of which can be used to plan and execute interplanetary transfers. As stated, we will use the Planar Intercept mode. This mode allows a transfer between bodies that have different inclinations by ejecting in the inclination of the source body's orbit, then doing a plane-change into the plane of the destination body at the intersection of the two bodies' orbital planes. Figure 3 below shows this conceptually.

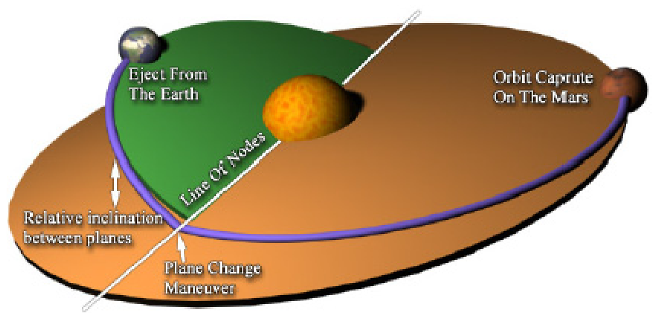


Figure 3. Planar (two-plane) transfer

In this scenario, the plane change is small (less than 1 deg.), This type of transfer can, however, be used to go between bodies whose orbits have large relative inclinations. The transfer should be planned so that the line of nodes is far away from either body, so as to minimize the plane-change burn. The plane change burn depends on the distance from the reference body. If the node is very close to the source, you'll have problems because the burns can't be combined with Planar Intercept.

Alternatively, if an ejection window can be found that places the line of nodes at the point of interception at the destination body, then the plane change can become part of the planet approach and orbit insertion.

A. Activate the MFD and Setup Initial Modes

1. Start Orbiter and load the **Fig-1** scenario supplied with this tutorial
2. Activate the right MFD and select **Interplanetary**
3. Select the main menu ([MNU])
4. Select the **Course** program ([Course])
5. Select **Planar Intercept** as the mode ([Set])
6. Select **Callisto** as the target ([TGT])
7. **Quicksave the scenario**

The right MFD display should now look like Figure 4. Due to our choice of scenario time (favorable ejection window), you will see a nearly perfect Hohmann transfer orbit in blue, and the intercept as a dashed line at the 4 o'clock position. The *reference* (Ref) is switched to Jupiter (the dominant source of gravity), the *target* (Tgt) of course shows Callisto, and the *source* (Src) shows Europa (we're in orbit around Europa).

The blue circle is the *hypothetical transfer orbit* (HTO), which we will tweak to produce the final transfer orbit. The blue line is the eject position, initialized to Europa's (and our) current position with respect to Jupiter. The outer yellow circle is our target Callisto's orbit and the yellow line extending to that outer circle is Callisto's current position. The inner green circle is Europa's orbit. Europa's current position is not shown.

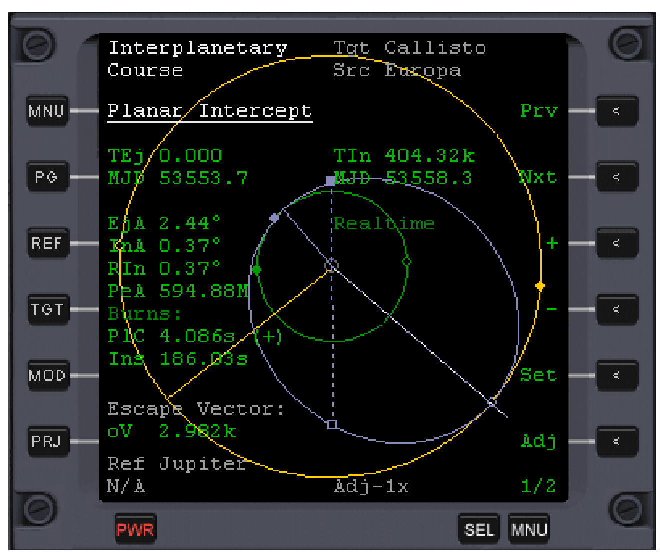


Figure 4. Initial Course Transfer Plan

The fact that the source (Src) is a planet (Europa) indicates that IMFD is in *escape* mode. Note that the Escape Vector item appears on the display. This provides the delta-V to the Orbit-Eject program, which we'll use shortly. After we eject, we'll switch the source back to our ship, putting IMFD into *enroute* mode for the remainder of the flight.

The various parameters that determine the transfer orbit are adjusted by first selecting the item with the [Prev] and

[Next] buttons, then using the [+] and [-] buttons to increase or decrease the value, respectively. [+] and [-] are also used to switch between discrete values or modes. The [Adj] button sets the step size for increasing or decreasing. Repeatedly clicking [Adj] will rotate the step size between 1x, 10x, and 100x (vernier, fine, and coarse, respectively).

Finally, the [Set] button may be used for direct entry of values. You can, use suffixes of m for milli (thousandths), K for kilo (thousands), M for mega (millions), and AU for astronomical units (149,597,871 Km/AU). So for example, to enter 12345.67, you can enter 1.234567K.

WARNING: If you click [+] or [-] while the program (Planar Intercept in this case) is selected, you'll be taken back to the mode selection page and all of your settings will be lost! This will probably be corrected in a future version (post-4.3)

III. Ejection Into Transfer Orbit

The next step in our flight is to set up the ejection from Europa orbit. The objective is to leave Europa orbit and establish ourselves as accurately as possible on the HTO. We use the Orbit-Eject program for this.

1. Left MFD to **Interplanetary** (IP)
2. Select the **main menu** ([MNU])
3. Switch OpMode to **shared**
4. Select **Orbit-Eject** program
5. Orbit-Eject mode to **Course** ([+])

You should now see a display as in Figure 5 below. The outbound velocity for the ejection orbit (oV) is taken from the Course program because we enabled OpMode shared. This mode causes the two MFDs to share data instead of operating independently.

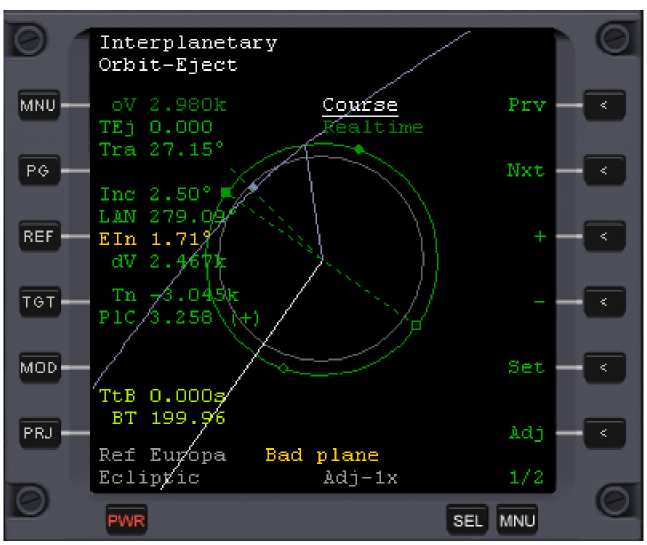


Figure 5. Initial Orbit-Ejection Display

The white line extending off-screen toward the 7 o'clock position shows the ejection direction. The blue hyperbola is our ejection orbit. The dark gray circle is the outline of Europa. The green circle is our current orbit around Europa, and the blue line is the current ejection position, which is the same as our position in orbit (which is a green line hidden beneath the blue line – more about this shortly). The green dotted line through the periapsis (blue dot) of the ejection orbit is the *optimum* ejection point. The time to ejection (TEj) is currently zero, indicating that the plan is to eject now. But now is not the best time.

A. Set Ejection Time

The position of the blue line (our current position) indicates that we're getting close to the optimum ejection time. We could eject at the upcoming time if our plane alignment was acceptable, however, it is not. Note the Bad Plane message at the bottom of the display. This indicates that our current orbit around Europa is out of plane with respect to the HTO. We must first align our current orbit's plane to that of the HTO. We need to do a pre-ejection plane alignment. So we'll give ourselves some time to do this by moving the ejection time (TEj) to the *next* optimum time, which is something over one complete revolution around Europa away.

1. Left MFD select **TEj** ([Nxt])
2. Increase TEj **one full revolution**
3. Further increase TEj to **optimum ejection point**
4. **Quicksave Scenario**

The result should look Figure 6 below.

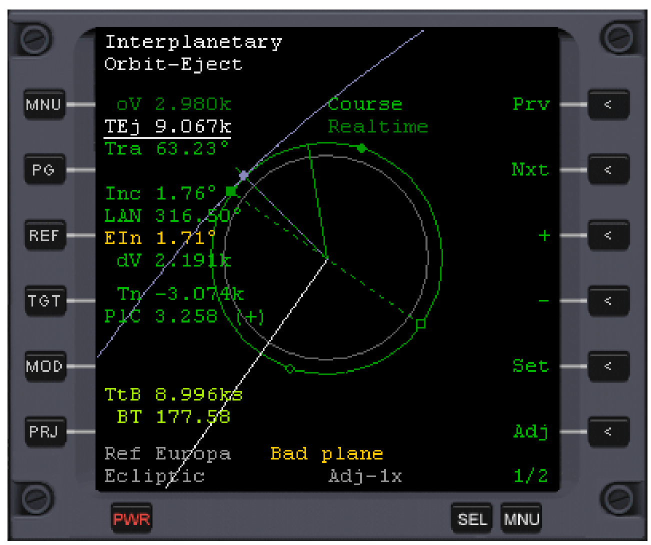


Figure 6. Initial Ejection Time Set Up

B. Pre-Ejection Plane Alignment

The **inclination between the ecliptic and the escape hyperbola** (Inc) shows 1.76 degrees. Since the flight computer calculates its HTOs in the most efficient manner, the HTO is not necessarily co-planar with the ecliptic. So how do we know what our inclination needs to be?

The **inclination between ships orbital plane and the escape vector** (EIn) shows the error in inclination of our current orbit with respect to the HTO. The **Time to Node** (Tn) and **Plane Change Burn Time** (PlC) items are our guide. As always, the most efficient time to change planes is at one of the nodes (ascending or descending) of our current orbit. We should wait until Tn (which now shows about –3000 sec.) is zero, then burn for PlC seconds in orbit-normal +/- as indicated by the sign following the PlC value. In our case we need Orbit-Normal (+). Note that the flight computer will always choose the node that comes before the optimum ejection point, not necessarily the next node we will pass. Just follow the guidance of the Tn and PlC displays for your plane change burn. In this case, the plane change will be done at the descending node (hollow square at 4 o'clock).

Ejection Plane Burn Checklist

1. Left MFD Orbit-Eject (OE)
2. OE verify eject time (TEj) and geometry
3. RCS auto-attitude **Orbit Normal + or –** per PlC item (+)
4. OE wait for **Tn = 0**
5. Main engines **100%**
6. OE wait for **PlC <= 1 sec**
7. Main Engines **0%**
8. RCS translate forward for **Ein = 0.00**
9. RCS Orbit Normal to **Off**
10. OE confirm Bad Plane is extinguished

The results should look like Figure 7 below. Note that the plane error EIn = 0.00.

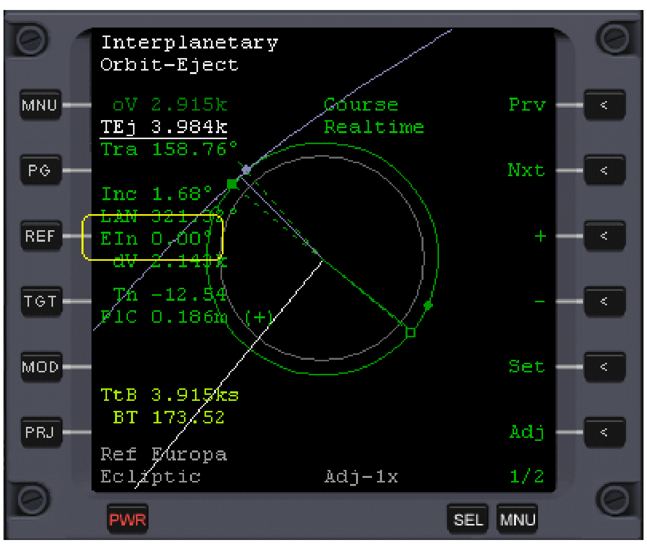


Figure 7. Ejection Plane Alignment Complete

Note: In the above case, EIn was relatively small. If there is a large plane error the simple plane change can be expensive, particularly with low orbits and/or massive planets with high gravity. In this case, you should consider other methods of plane change.

C. Final Ejection Mode

Note the "Realtime" mode annunciator below Course. This indicates that the Orbit-Eject computer is in a "free" mode where you can use it to do off-plane ejections at times other than the optimum. However, we have set things up so that there is no plane error between our orbit around Europa and the ejection hyperbola, and the time is set for the optimum (or at least close!).

It is most efficient to eject in a prograde direction. If the conditions are right, the Orbit-Eject computer can be placed into a "locked" prograde mode, where you cannot adjust the ejection time (TEj). It is locked to the optimum ejection point, and the ejection will be done prograde, without adjustments for any plane error (EIn). Since we have reduced EIn to zero, and we have set the ejection time to nearly the optimum point, we can switch modes and take advantage of the locked mode to make the most efficient ejection.

Ejection Plane Burn Checklist (cont.)

11. OE select **ejection mode** ([Nxt/Prv], below "Course")
12. OE select **Pro-grade**

At this point, the left MFD should look like Figure 8 below. Note that the TEj changed slightly; it is now the exact time for prograde ejection.

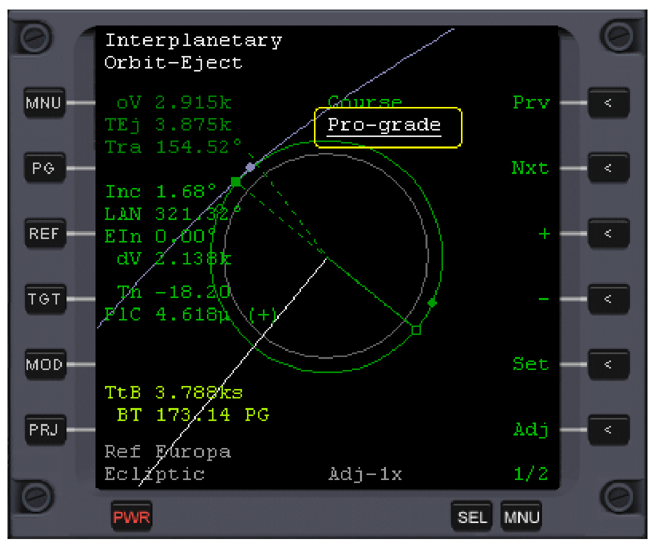


Figure 8. Orbit Eject Ready

D. Final Course Setup

At this point, we're almost ready. The Orbit-Eject setup resulted in an ejection time (TEj) of around 3800 seconds. But the TEj in the Course computer is still 0. In this version of IMFD (4.3) the TEj in the Course computer is *not* locked to that in Orbit-Eject, even when OpMode is shared. Therefore, we'll need to manually set that TEj into Course. In addition, we want to tweak the HTO by varying the arrival time (TIn) so that the arrival inclination (InA) is zero. This is possible because the plane-change in front of us will discard the error between planes. Within Planar Intercept, everything is made co-planar, even if the real situation involves different planes.

When we change TEj in Course to match that in Orbit-Eject, the Pro-grade lock in Orbit-Eject will cause the ejection point to change, reflecting the new ejection time set in Course. This will cause the TEj in Orbit-Eject to change, requiring us to again change the TEj in Course. Thus it is necessary to adjust TEj in Course repeatedly until it matches that in Orbit-Eject. This may change in future versions of IMFD. Note that TEj in Course is not critical on long transfers such as Earth to Mars, and may be left at 0. When in doubt, though, match them up!

Final Course Tweak Checklist

13. Verify Right MFD **Course**
14. Course select **TEj**
15. TEj set **equal to TEj in Left MFD** (Orbit Eject)
16. Repeat (3) until TEj in Course and Orbit-Eject match
17. Course select **TIn**
18. Adjust Tin for **InA = 0.00**
19. Course select **TEj**
20. TEj set **equal to TEj in Left MFD** (Orbit Eject)
21. **Quicksave scenario**

The results in the Orbit-Ejection display should look like Figure 9, and the Course display should look like Figure 10.

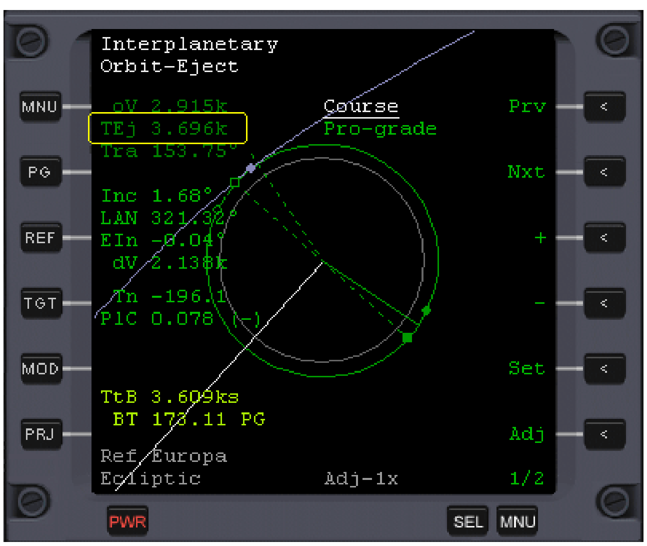


Figure 9. Ejection Setup Completed

E. Do the Ejection Burn

The Orbit-Eject program will guide us through the burn. It has a mode in which it displays a burn guidance crosshair, which assists the pilot in maintaining the (changing) spacecraft attitude during the burn. It also has its own burn-time (BT) and time to start of burn (TtB) displays to assist in starting and ending the burn on time.

Switch the Orbit-Eject program (in the left MFD) to the burn vector display by clicking [PG] to show page 2, then clicking [BV] to show the burn vector display. Center the crosshairs precisely. The crosshairs will turn white when the attitude is within limits. You should try to keep them within one pixel of dead center. You should see a display similar to Figure 11.

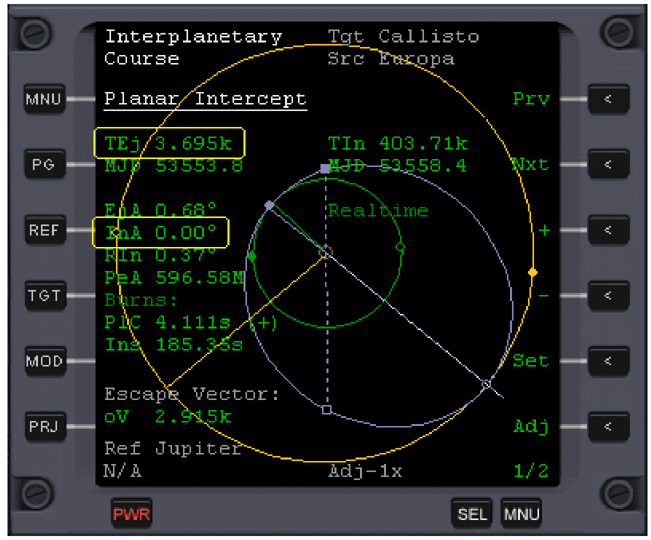


Figure 10. Transfer Orbit Ready for Ejection

Figure 11. Ready for Eject burn

Now we're ready to do the ejection burn. Wait until TtB gets to 0 then engage the main engines. During the burn, the indicated attitude will slowly change until BT gets below a few seconds. As BT nears zero, the indicated attitude may vary wildly. Don't worry; just burn down a small dV (< 1 M/s) by throttling down during the last seconds of the burn so that BT (and dV) change slowly. If you overshoot, you can use RCS linear back, or retro engines, to bring the dV back down to near 0.

Ejection Burn Checklist

1. Right MFD verify **Course**
2. Left MFD verify **Orbit-Eject** (OE)
3. OE verify ejection is set up per flight plan
4. OE verify that Bad Plane light is off
5. OE to **burn guidance** mode ([PG]/[BV])
6. RCS to **rotation mode**
7. RCS **center crosshairs**
8. HUD to **Orbit**
9. RCS **level roll**
10. OE wait until **TtB = 0**
11. Main engines **100%**
12. OE wait for **BT = 5** with crosshairs centered
13. Main engines **throttle down to 25%**
14. OE wait for **BT = 0** with crosshairs centered
15. Main engines **0%**
16. RCS **kill rotation**
17. OE to **eject orbit display** ([BV])
18. OE confirm successful ejection
19. **Quicksave scenario**

The Orbit-Ejection display should now look like Figure 12.

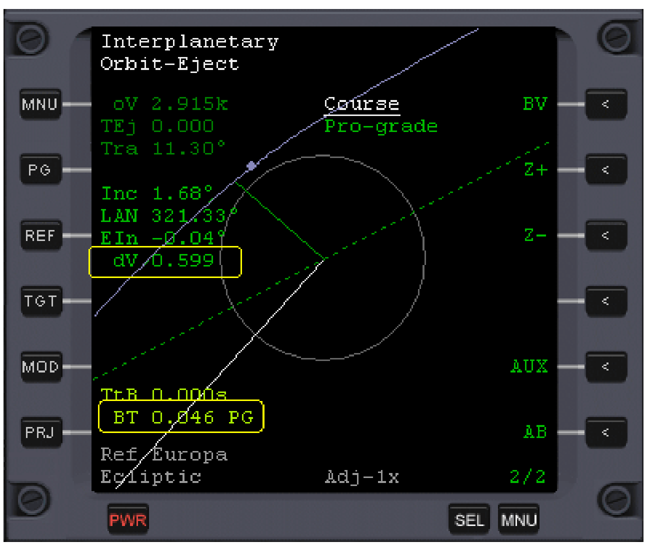


Figure 12. Orbit-Ejection Display After Eject Burn

F. Post-Ejection Housekeeping

You may have noticed that the Course display did not change during and after the ejection. This is due to it's having Europa as the Source (Src) of the plan. Until we leave Europa's sphere-of-influence (SOI), we cannot change Course's source. Trying to do so will result in an error message.

So how can we find out when we have left Europa's SOI? One way would be to watch Orbit-Eject and wait until it tells you. But this is a tutorial; so let's watch a picture. The next section covers the Map program in IMFD. After ejection, the IMFD Map program can be used to watch the spacecraft exit from Europa's SOI. After you learn how to use Map, you can do this quickly and easily. We're done with the Orbit-Eject program in the left MFD now, and we *must* leave the Course program in the right MFD alone, or we risk losing our plan (remember the warning?).

If you want to try this now (instead of simply waiting for Orbit-Eject to indicate leaving SOI), switch the left MFD to the Map program ([MNU], Map). Then select Callisto as the target ([TGT]), turn off auto-zoom ([Azo]), turn on other orbits and bodies ([Dsp]), center on Europa ([Cnt], Europa), zoom in till you see Europa's outline ([Z+]), and enable SOI display ([PG], [SOI]). You should see a display like Figure 13 below.

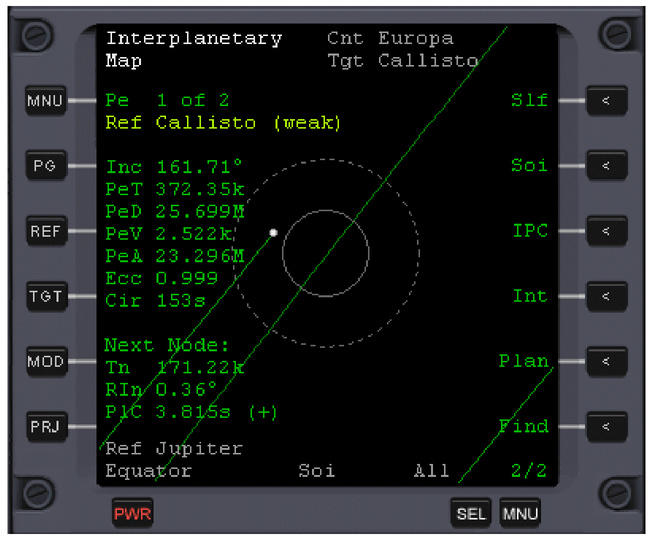


Figure 13. Map With SOI After Eject

Now wait until the spacecraft (the white dot) leaves Europa's SOI (the white dotted circle) as shown in Figure 14 below. Alternatively, wait until at least 18:50 UTC and you'll be outside the SOI.

Hint: To make precise burns, use the keypad + key to instantly engage the main propulsion system (MPS) and wait until the remaining burn time *nears* zero, and release the + key. Use short bursts of MPS (keypad + key) until the burn time is less than a few tenths of a second. Then use bursts of the RCS translation forward thrusters to tweak the burn to the goal of near-zero burn time.

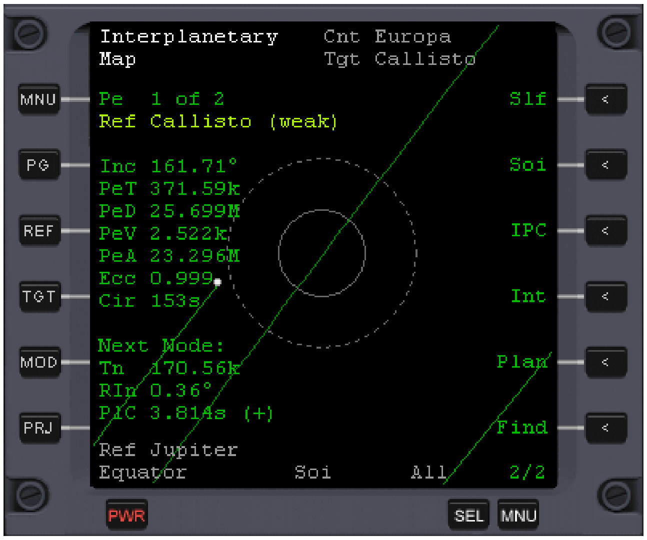


Figure 14. Exited SOI (Map)

Once outside Europa's SOI we can change the source in Course from Europa to our spacecraft. This will switch Course from *escape* mode to *enroute* mode.

Exiting SOI Course Checklist

1. Verify Right MFD **Course**
2. Course switch to **Page 2** ([PG])
3. Course set Src to **spacecraft** ([Src], x)
4. **Quicksave scenario**

The right MFD (Course) should now look like Figure 15 below.

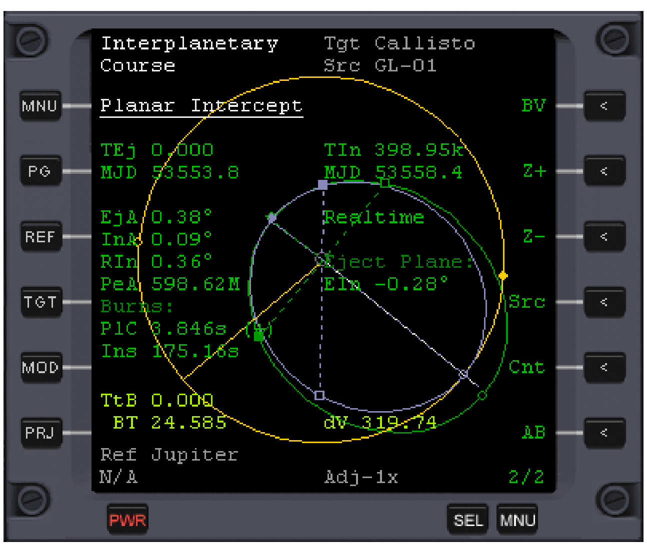


Figure 15. Course in Enroute Mode After Eject

In the Course display note that the green line (our conic-based real orbit) is not aligned with the HTO, and we see an 0.28 degree ejection plane error. But watch the BT and you will see that it is *decreasing*. We just ejected and just left Europa's SOI. The Course computer calculates orbits based on simple conic sections, and actually we're in a strong gravita-tional field resulting from the masses of both Jupiter and Europa. As we get further away from Europa this calculation will get better, Once we get a "long way out" from Europa, the BT will start to increase again. Don't worry for now.

Meanwhile, can you form a mental picture that connects your instruments with what you see out the window? You should train yourself to maintain this *situational-awareness* (SA), as you become a more proficient astronaut. Solid SA can save your bacon in a tough situation.

Tip: To view a planet or moon, use the IMFD Orbital program ([MNU], Orbital, Find ([Fnd]). Select the target ([TGT], try Europa and Jupiter now) and use the crosshairs to point the spacecraft directly at the selected target. You might have to pitch down a bit if you have the panel displayed. You can currently see the dark side of Europa and a crescent Jupiter.

IV. Interlude – Using the Map Program

Now is a great time to become familiar with the Map program of IMFD[3]. It is a very powerful tool for visualizing what's *actually* happening and *predicting* what *will* happen in the future, based on the real gravitational field throughout the path. It allows viewing of an entire planetary or solar system as well as the region around a single body (as we just saw!).

A. Background

Our HTO was calculated by the Course program, which used a simple two-body method. The actual orbit will not precisely follow this path. The Map program contains a very fast *numerical orbit integrator* that calculates *perturbed trajectories* that are very accurate. It is capable of rapidly calculating and displaying the precise path that will be followed based on the present position and velocity vectors.

In the Map program, the trajectory is not limited to ellipses and hyperbolae. Instead, the trajectory is computed and displayed using the possible multiple gravitational influences of stars, planets, moons, etc.

There are limitations to which bodies are included in the perturbation calculations. Bodies that will be used are:

- Bodies with masses in excess of 1.0E+20 Kg.
- All bodies orbiting the reference body (Jupiter in our case)
- The body, spacecraft, or station that is selected as the target (Europa in our case)

These parameters (as well as others) can be changed in the Map program's configuration page.

The *sphere of influence* (SOI) of a body is the region within which the gravitational field of the body is the

[3] Parts of this section were adapted from the Interplanetary User's Manual, written by the program's author, Jarmo Nikkonen.

dominant gravitational force. The greater the mass of a body, the larger its SOI.

The Map program distinguishes between *strong* versus *weak* orbit periapses and nodes (ascending and descending). A strong periapsis or node is one located within the SOI of the reference body. A weak periapsis or node is one located outside the SOI of the reference body.

Note: Moons of a planet are not included in perturbation calculations unless the spacecraft enters the reference planet's SOI. For example, if we are orbiting the Sun near Jupiter, its moons will not be included in calculations unless our spacecraft's position is within Jupiter's SOI.

B. *The Map Display*

We have no more need for the Orbit-Ejection program running in the left MFD, so let's switch it to the Map program and set up the display:

1. Left MFD to **Interplanetary** (IP)
2. IP to **Map** program ([MNU], [Map])
3. Map to **center Jupiter** ([Cnt], enter "Jupiter"))
4. Map target to **Callisto** ([TGT], enter "Callisto"))
5. Map to display orbits ([Dsp])
6. Map Auto-Zoom to **Off** ([Azo])
7. Map [+] and [-] to fill display with yellow circle
8. Map mode to **Show Data Items** ([MOD])
9. Map to **Page 2** ([PG])
10. Map to **display numerical orbit** ([Slf]), see transfer orbit
11. Map SOI to **On** ([Soi])
12. Map **Intercept mode** ([Int] to show intercept lines and Ref Callisto (weak))
13. Map to **Page 1** ([PG])

0 shows the Map display as we just configured it. The yellow circle is the orbit of the selected target (Callisto). The second green circle inside the yellow circle is the orbit of Europa, from which we just ejected (the first inner green circle is the orbit of Io). The small gray circle in the center is the outline of Jupiter. The bright white dot is our current position, still very near Europa's orbit. The white dashed line is the intercept position.

NOTE: If the intercept is not visible, switch to page 1 and click [Sel] to select the target's periapsis (Ref Callisto here). During burns, the selected periapsis may change by itself.

The green ellipse is the "real" transfer orbit. It looks much better than the one currently calculated by Course! IMFD did a great job ejecting us.

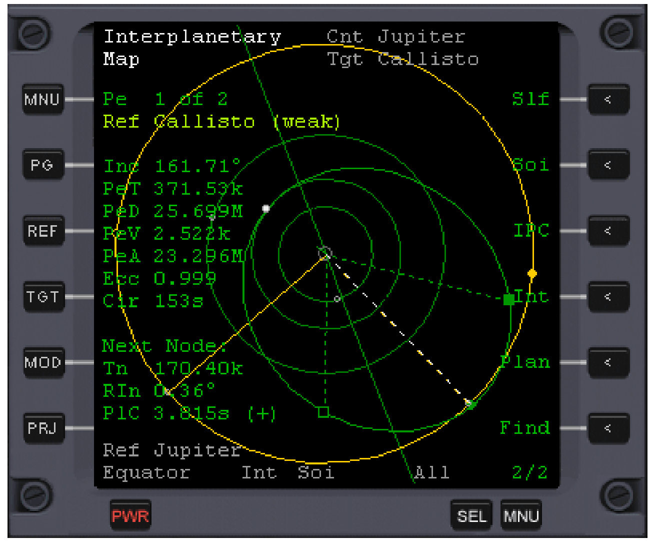


Figure 16. Map Program Display Mode 1

Figure 17 below shows the data items that appear upon clicking [MOD] to get to the second page of periapsis data items.

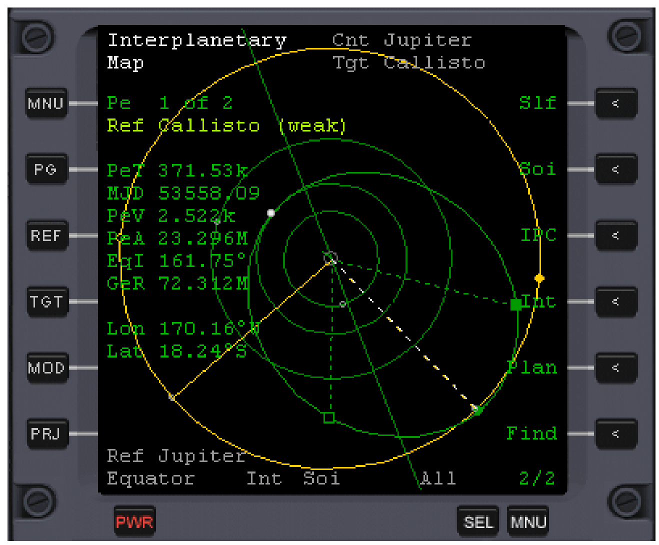


Figure 17. Map Program Display Mode 2

Inside and outside Europa's orbit, the small open gray circles show the positions of other inner moons of Jupiter. These will move with time according to their orbits. You can zoom out using the [-] button to see the orbits, or at least the small open gray position dots, of other moons. If you have installed the Outer Planets add-on you will be able to see all 40+ of Jupiter's moons displayed! If you played with this, zoom back in [+] until Europa's orbit fills the display as shown.

The green spot is the selected periapsis. The white dashed line shows the position of intercept. Note that there are two available periapses (the display says Pe 1 of 2). You can cycle between the periapses by clicking [Sel]. One periapsis is the strong one created by Jupiter's gravity. The other (visible in Figs 16 and 17 at the 4 o'clock position) is the one created by

Callisto *at the point of intercept*. It is selectable, even though it may be weak, because we have Callisto selected as the target. Again, by repeatedly clicking the [Sel] button, you can cycle through the periapses.

Green boxes are the nodes (plane intersections). A line of nodes is drawn from the reference body to a *strong* node only. Both nodes are strong because we're inside *Jupiter's* SOI! The two nodes are not opposite each other because Callisto will change our course if we pass it by without entering orbit. Note that perturbations may cause strange-appearing effects to lines of nodes, especially if RIn is small. They are accurate, though.

There are two pages of data items for the selected periapsis, selectable by repeatedly clicking [MOD]. Some data items appear on both pages. These items are described in Table 1.

Table 1 – Data Items for Selected Periapsis

`Inc`	Relative inclination at periapsis
`PeT`	Time to periapsis (sec.)
`PeD`	Periapsis distance from reference body
`PeV`	Reference-relative velocity of periapsis
`PeA`	Periapsis altitude above reference body
`Ecc`	Orbit eccentricity at periapsis
`Cir`	Burn time for circular orbit at periapsis
`MJD`	Modified Julian date/time at periapsis
`EqI`	Equatorial inclination of orbit at periapsis
`GeR`	Radius of stationary orbit ("geostationary")
`Lon`	Longitude of periapsis on planet's surface
`Lat`	Latitude of periapsis on planet's surface

The node data items in the Map display page 1 labeled "Next Node" are for the upcoming node in the trajectory, and are shown in Table 2:

Table 2 – Data Items for Upcoming Node

`Tn`	Time to node
`RIn`	Relative inclination between orbital planes at node
`PlC`	Plane-change burn time and orientation

The [PRJ] button cycles between planar projections of the orbit display. The gravitational reference body and the selected projection are shown in the lower left corner. The available projection types are shown in Table 3.

Table 3 – Map Display Projection Types

`Ecliptic`	Ecliptic plane
`Target`	Orbital plane of the target body
`Periapsis`	Ship's orbit in the periapsis around Pe. reference
`Equator`	Equatorial plane of the target body
`Self`	Current spacecraft orbit

C. Flight Planning Mode

When IMFD is in OpMode *shared*, the Map program in one MFD can project forward using the spacecraft position and the burn data from the Course program in the other MFD instead of the current spacecraft velocity. This allows you to see where a burn will *really* take you, versus the simple conic-section calculation done by Course. If you are planning a transfer that involves passing near strongly attracting bodies, Map can help you tweak your plan to get you where you want. All of the power of its numerical integrator is available to you during transfer planning. *The canonical example is planning a free-return trajectory to the Moon!* The integrator is super-fast, and can be configured for trajectory limits, integration algorithm, and more.

To switch Map to its flight-planning mode, click [PG] until you see the [Plan] selector along the right edge, and then click it. If the other MFD has valid Course (or other planning) info, you'll see "Map" in the upper left corner change to "Map Course-Plan" (or some other name if another planning program is running in the other MFD). At this point, the transfer orbit will change from green to blue (hypothetical). As you adjust the burn in the other program and see the real-world effect in Map.

D. Intercept Display Mode

When the [Int] button has been toggled to show information on a periapsis, the Map program is in the intercept mode. Currently, this mode is enabled and the periapsis at our destination (Callisto) is selected for intercept. Map program calculates the actual transfer orbit using perturbed trajectories, and the Course program uses the simpler and faster 2-body theory (which is not as accurate).

The flight computer's intercept system uses the concept of *target-relative periapsis*. This is the position where the spacecraft on its trajectory passes closest to the target planet. We already have Callisto selected as our target.

14. Left MFD per procedure in Section 0 above.
15. Verify Ref Europa (weak) is displayed
16. Center on Callisto. Switch to page 1, click [Cnt] and enter **p-Callisto**
17. Click [Z+] to zoom into region of Callisto

The display should look like Figure 18:

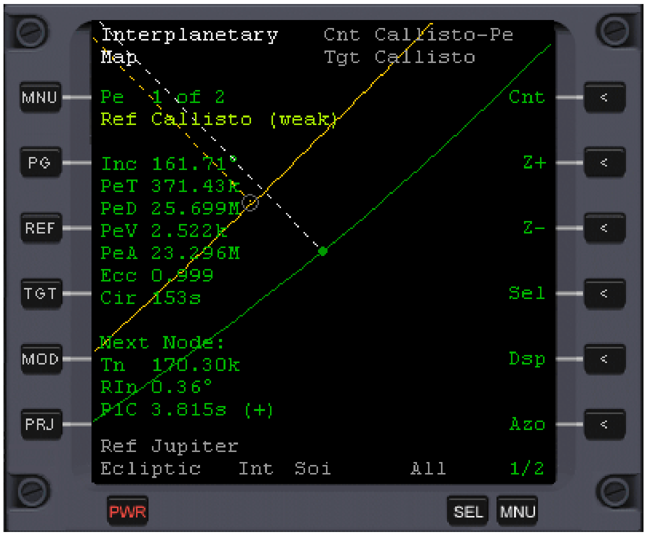


Figure 18. Map Display Initial Intercept at Callisto

The green dot is the target-relative periapsis. The white dashed line points to the target-relative periapsis. The green dashed line leads to the position of Europa at the moment we reach the target relative periapsis. You can see the (tiny) outline of Europa at the end of the dashed green line.

Try to visualize this (SA again!). The target-relative periapsis and the current position of Europa are pretty close, given that we just ejected within a few hours! The objective is to get both lines in Figure 12 to converge to Europa's center before arrival, with minimum fuel of course! As we'll see, our mid-course plane change and correction burns will be quite small. Leave the left MFD (Map) set up per Figure 18!

E. Trajectory Limits and Other Map Settings

The numerical calculations for the trajectory must be given some sort of limits as to how far ahead of the current spacecraft position the trajectory will be calculated. There are three different limiters:

- Maximum of one orbital period around the reference planet (elliptical orbits, "period limit")
- Maximum of one periapsis (hyperbolic orbits, "hyper. limit")
- Maximum time ahead. Setting this to non-zero will override the other limiters.

These parameters (as well as others) can be changed in the Map program's configuration page. Adjustment of the time limit is the most useful.

> **Note**: If the trajectory looks strange or short, it may have been incorrectly time-limited. Try making manual adjustments to the time limit.

There are other settings available in the Map program's configuration page. If you can't figure out what they do by their descriptions, then leave them alone!

F. Non-Spherical Gravity

By default, Map considers only the gravitational J2 terms, and only if the trajectory passes within the SOI of the corresponding body. You can enable J2 terms at all times by editing IMFD.cfg and changing **NonSpherical** from 0 to 2.

V. Mid-Course Corrections

The objective of the mid-course corrections will be to refine our intercept with Callisto. We first need to make a mid-course trajectory correction to remove errors during ejection. Then we need to make a mid-course plane change to get from the orbital plane of Europa (into which we ejected) to the plane of Callisto (in which we will arrive). This is the basis of the Planar (two-plane) transfer that IMFD's flight computer calculates. Finally, late in the transfer, we'll do one more "tweak" burn to refine the intercept.

The Course display should still be up on the right MFD. You should still see something similar to the display in Figure 15 above. As time passes from ejection, you'll see that the burn time (BT) will *decrease* and then slowly start increasing. At the same time, the green computed transfer orbit will shrink down to match the blue HTO. This is a result of the imperfect 2-body conic-section calculations done by Course. Remember that Map's calculated//integrated transfer orbit already looks good.

A. First Mid-Course Correction

Warp ahead watching BT in Course decrease, until it starts to increase. Warp until BT decreases, then increases by a few seconds, or until the time is 03-Jul-2005 @ 12:30. You should be somewhere near (but before) the line of nodes (at which we'll do the mid-course plane change in the next section).

Mid-Course Correction Checklist

1. **Quicksave Scenario**
2. Left MFD to **Map**
3. Map to **display intercept region** (per Figure 18)
4. Right MFD to **Course**
5. Course mode to **orbit display ([MOD])**
6. HUD to **Orbit**
7. RCS HUD level
8. Course mode to **burn vector** ([PG]/[BV])
9. RCS **center crosshairs**
10. Main engines **100%**
11. Wait for **BT < 0.5** with crosshairs centered
12. Main engines **0%**
13. RCS **kill rotation**
14. RCS mode to **translate**
15. RCS translate forward for **BT < 0.01** sec
16. Course mode to **orbit display ([BV])**
17. Course **confirm successful maneuver**
18. Map **zoom in** to see detail
19. **Quicksave scenario**

In Course, the green (computed) and blue (HTO) orbits should now coincide. In addition, the Map display (left MFD) should now show a much closer intercept. In fact, the intercept in Map may have gotten closer then spread apart a bit again during the burn. That's fine, we still need to do a plane change and later a tweak burn. You could have stopped this mid-course when the Map intercept was at its closest, though. The results in the Map and Course displays should look like Figure 19 and Figure 20 below, respectively (Map has been zoomed in to show detail).

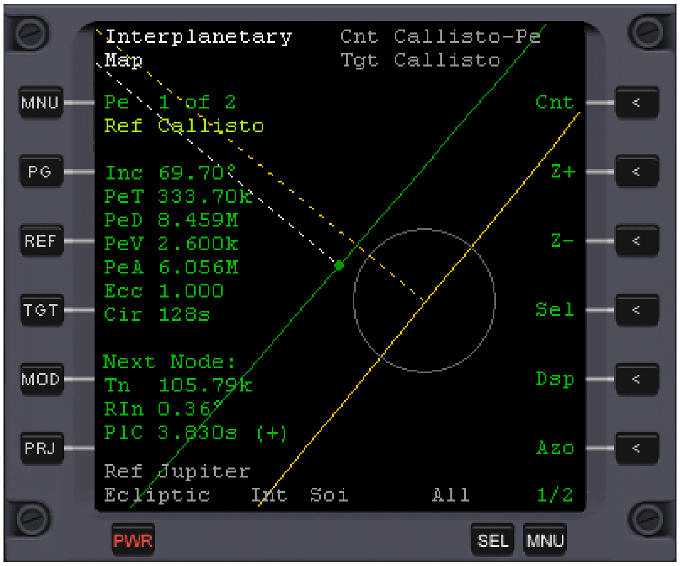


Figure 19. Map After 1st Mid-Course

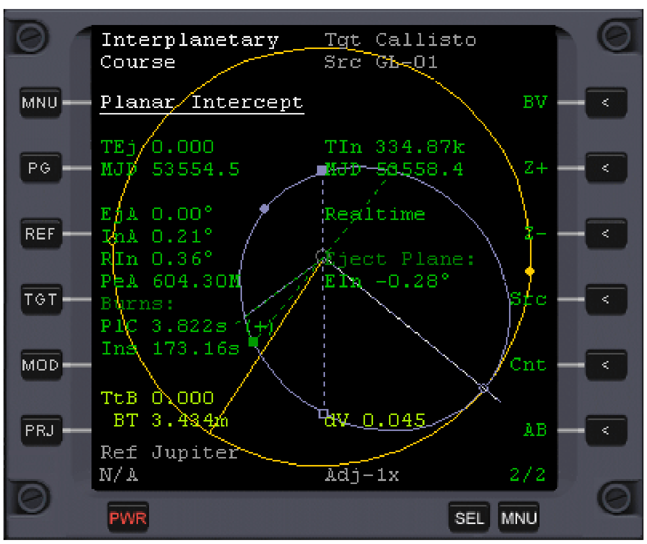


Figure 20. Course After 1st Mid-Course

Note: The earlier we can apply a course correction, the less fuel it will require. But since we just ejected, we're far away from Europa, small changes on our current velocity will cause large changes in our *projected* orbit at Europa. The tradeoff is that our *actual* orbit will vary as we progress, and thus early corrections may actually hurt our fuel consumption with needless delta-Vs.

B. Mid-Course Plane Change Burn

The next thing we need to do is the mid-course plane change. This is best done at the blue line of nodes at the 6 o'clock position in Course (right MFD).

Wait or warp ahead until the blue line (and the green one beneath it) move to a position on the blue dotted line of nodes. This should be around 04-Jun-2005 @16:50. **Pause**.

At this point, we have some choices. We could just do the indicated plane change as shown in Course under Burns: (a 3.8 sec. burn in orbit-normal (+)) and continue toward Callisto. Instead, we'll use another IMFD course program, so you can become familiar with it.

IMFD's Course computer has another mode called **Off-Plane Intercept**. This mode computes transfer and intercept HTO in a plane that intersects the spacecraft's orbit and the target's orbit. A complete discussion of this mode is beyond the scope of this paper (it will be covered in another tutorial). For now, just understand that the Off-Plane Intercept computer can handle combined trajectory and plane adjustments while it is in enroute mode (source (Src) is a spacecraft).

We'll now switch the Course computer in the right MFD to Off-Plane Intercept mode and adjust it for our enroute state, then use it to make the plane change (and any other adjustments that may remain!). The IMFD documentation recommends doing this – finishing up a Planar Intercept in Off-Plane Intercept mode.

1. Right MFD verify **Course**
2. Course select **Planar Intercept** ([Nxt/Prv])
3. Course to **course mode list** ([+/-])
4. Course menu select **Off-Plane Intercept** mode ([Nxt/Prv], [Sel])
5. Course set target to **Callisto ([TGT])**
6. Course select **TIn** ([Nxt/Prv])
7. Course **adjust TIn for minimum BT** ([+/-/Adj])
8. **Quicksave Scenario**

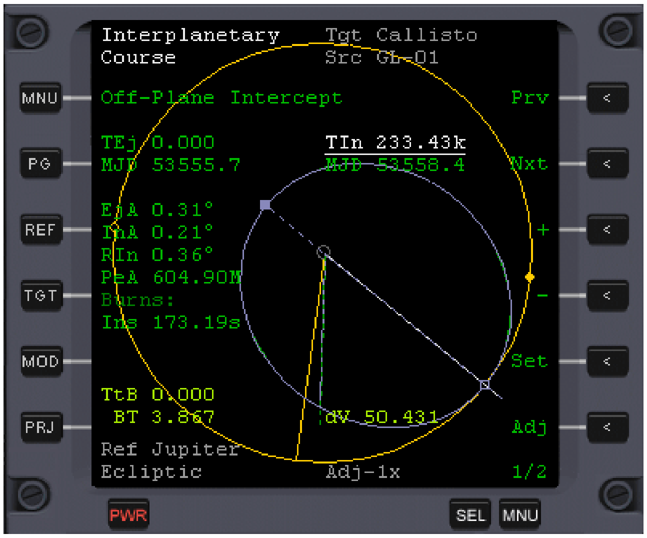


Figure 21. Course Changed to Off-Plane and Adjusted

The display should now look like Figure 21. Note that the burn time (BT) is 3.8 seconds, virtually identical to the plane-change burn time showing in Figure 20. This indicates that virtually all of the burn calculated by Off-Plane Intercept is the plane change needed to get into Callisto's orbit. If there were any other corrections needed at this time, the BT would be greater and the burn attitude would depart from orbit normal. In our case, though, we're so close that additional corrections aren't needed! The fact that Map isn't showing an intercept yet (Figure 19) is almost completely due to our plane error, which we're about to burn off.

Also note that the blue line of nodes is now aligned with our intercept. Off-Plane Intercept always calculates a transfer orbit that intersects the target orbit at the point of intercept. Right? We're still at the line of nodes of our *current* transfer orbit, and the next "leg" that takes us to Callisto. Make sure you understand this before continuing.

We could do this burn away from the dotted blue line of nodes (Figure 20. If we did, the burn time would be higher and the remainder of our trajectory would not be in-plane with Callisto. The Off-Plane Intercept computer always computes a "direct" path and chooses its own orbital plane for that path. Since we're at the intersection of our transfer orbit and Callisto's orbit, though, Off-Plane Intercept will of course choose a path in Callisto's plane. Give this some thought until you have it clearly understood. **Perform the Mid-Course Plane Change checklist now**.

NOTE: If at any time you lose the intercept lines in Map, click [Sel] to re-select the periapsis at Callisto. For some reason, Map sometimes switches periapses during burns or when warping.

Mid-Course Plane-Change Checklist

1. Course verify current position at blue line-of nodes
2. Course verify **Off-Plane Intercept** mode
3. HUD to **Orbit**
4. RCS **HUD level**
5. Course mode to **burn vector** ([PG]/[BV])
6. RCS **center crosshairs**
7. Main engines **20%**
8. Wait for **BT < 0.5** with crosshairs centered
9. Main engines **0%**
10. RCS **kill rotation**
11. RCS mode to **translate**
12. RCS translate forward for **BT < 0.01** sec
13. Course mode to **orbit display ([BV])**
14. Course **confirm maneuver** (BT < 0.01)
15. Map **increase zoom** ([Z+])
16. **Quicksave scenario**

The results should look like in Figure 22 and Figure 23. Note that in Figure 22 (Map) the perturbed orbit goes right through the center of Callisto, and is twisted from its gravitational influence. We're still a *long* way out, but our current trajectory is already a perfect intercept! Map is telling us that we need no more mid-course changes.

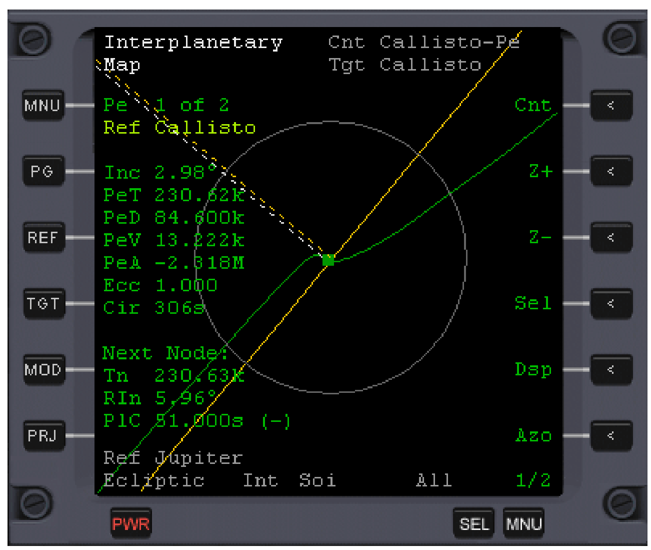


Figure 22. Map After Mid-Course Plane Change

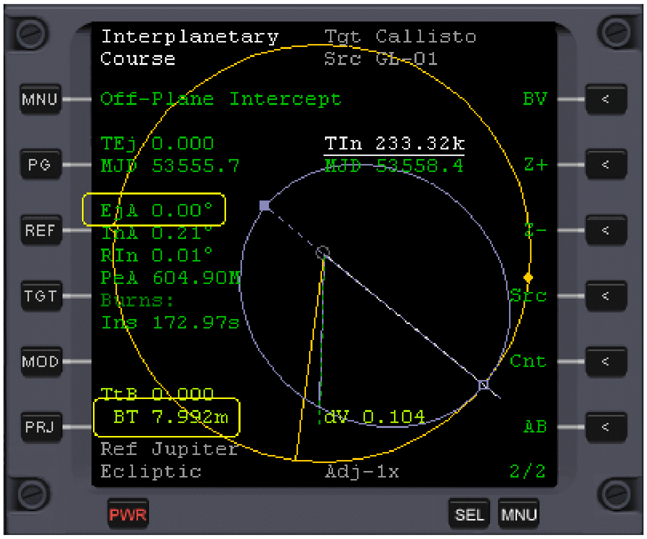


Figure 23. Course After Mid-Course Plane Change

VI. Final Approach Maneuvers

Right now, we're headed directly toward the center of Callisto. We'll crash into Callisto unless we do something. How can we get into a prescribed orbit around Callisto? We will do a series three of small burns to alter trajectory so that its periapsis is over a point from which we can decelerate into the desired orbit around Callisto.

The reason we do two small burns, rather than one burn close in, is to minimize fuel. The closer we are to Europa, the more expensive a given course-change is. So we make the *coarse* adjustment about ten hours out, and a final *vernier* burn about 90 minutes out. After that, all that is needed is a retro-burn to enter into the prescribed orbit. In summary:

1. Approach coarse burn at arrival – 10 hours (outside SOI)
2. Approach vernier burn at arrival – 90 minutes (just inside SOI)

How are these times chosen, particularly the time of the first (coarse) burn? We will be using the Planet Approach mode of IMFD's Course program. Its accuracy is best when close in, especially when inside the SOI of the destination. Outside the SOI, its accuracy degrades. The effect of this degradation with distance is that the indicated burn time becomes higher and higher (assuming that we are on a nearly perfect intercept trajectory, which we are in this case!).

So to find the best point at which to do the coarse burn, we set it up and simply wait until the burn time decreases to a minimum, then wait until it increases a few percent from the minimum. For our scenario, this point occurs about 10 hours out. But we'll go through this process on the way in so you can see it.

Again, for these approach maneuvers, we'll use IMFD's Planet Approach program. It's one of the simplest of IMFD's modes. It is a descendent of earlier IMFD versions' *TEI* programs. The author discovered that the older TEI programs could be tricked into being used for planet approach maneuvers, albeit somewhat tricky and non-intuitive. The developer of IMFD took this info and created a proper planet approach mode for IMFD4, and it is a beneficial addition!

Planet Approach will allow us to place our final approach trajectory over Callisto at a selected orbital altitude such that we can achieve either a prograde or retrograde orbit at almost any inclination. The available final inclinations are limited by the inclination of our transfer orbit, similar to the limits on inclinations that can be reached given the latitude of a ground launch location. The Planet Approach program displays the available range of final orbit inclinations, helping us to choose one that we can reach.

The inclination you choose in Planet Approach not only determines your final orbit's inclination, but also whether it is prograde or retrograde. The display will be set for ecliptic projection, so prograde rotation is counter-clockwise. Here's where your SA will be valuable again. From the display, determine the direction from which you are approaching. The white line extending from the planet's center indicates this. Now visualize passage of the planet on the prograde and retrograde sides. Figure 24 below shows this relationship.

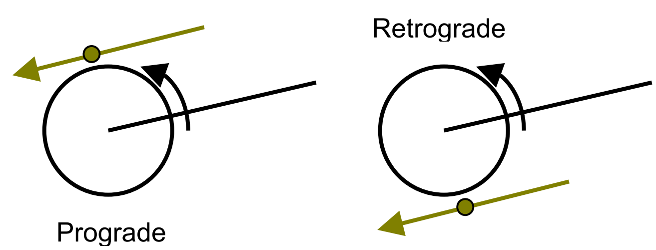


Figure 24. Prograde vs. Retrograde Approach

Inclinations ranging from –90 to 0 to +90 degrees represent *prograde* orbits. If you give an inclination between 90 and 180 or between –90 and –180, it represents a *retrograde* orbit. This is the usual astrodynamics definition of inclination, so get used to it. Appendix B gives an exercise using Planet Approach that can help you get used to this. For now, **we'll target a 10-degree prograde orbit at 300Km altitude**.

A. Preparation

With this background, we'll set up for the first approach burn and then do it when we're about an 10 hours out.

Wait or warp until PeT in Map is 100k seconds or the scenario time is about 06-Jul-2005 @ 04:55.

This is about 38 hours out, and will allow us to see the burn time decrease as Planet Approach comes into its operating range.

Perform the Planet Approach Startup checklist to switch the right MFD to the Course/Planet Approach mode. Leave the left MFD running the Map program.

Planet Approach Startup Checklist

1. Quicksave scenario
2. Left MFD verify **Map**
3. Map **zoom out to see spacecraft** ([Z-])
4. Map display to **orbit only** ([MOD] repeatedly])
5. Right MFD verify **Course**
6. Course select **Off-Plane Intercept** ([Nxt/Prv])
7. Course to **course mode list** ([+/-])
8. Course menu select **Planet Approach** mode ([Nxt/Prv], [Sel])
9. Course set **Reference to Callisto** ([REF])
10. Course select **EqI** ([Nxt/Prv])
11. Course set **EqI=10.00** ([Set]) *desired inclination*
12. Course select **PeA** ([Nxt/Prv])
13. Course set **PeA=300k** ([Set]) *desired orbit altitude*
14. **Quicksave scenario**

Figure 25 shows the resulting Planet Approach display and Figure 26 shows the Map display zoomed out to see our spacecraft (the white dot) and with the data items turned off for clarity.

In Figure 25 note the green orbit line, which is our current orbit. It is shown way off due to the loss of accuracy in Planet Approach at this distance from the destination. Also the high burn time (BT) reflects this loss of accuracy. The Low Influence annunciator indicates that we are still outside Callisto's SOI.

1. Wait or warp ahead, watching BT in the Planet Approach display (right MFD) until BT decreases to a minimum, then increases a few seconds.

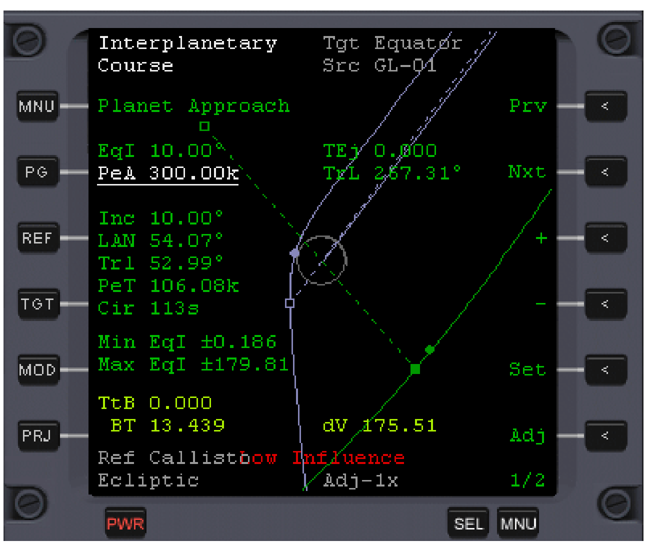


Figure 25. Initial Planet Approach Setup

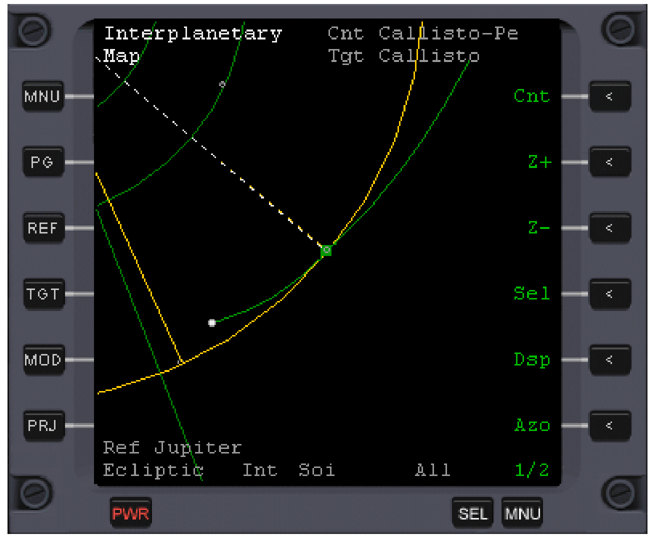


Figure 26. Map Zoomed Out and No Data Items

After warping ahead as described, the time to periapsis (PeT in Planet Approach) should be somewhere near 33k seconds. See Figure 27. The Planet Approach display should look much more reasonable, with the outline of Callisto filling much of the display and the blue HTO showing our desired approach orbit. Also note that the green line representing our actual orbit is now passing right through the center of Callisto, reflecting the real situation. Planet approach is now within it's operating limits.

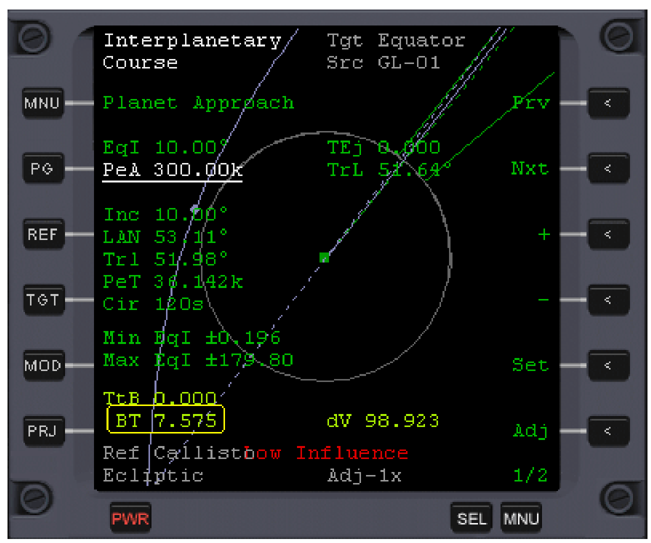


Figure 27. Planet Approach Ready for Coarse Burn

Center on the spacecraft in the Map display ([Cnt], "X") and zoom in to see more detail, while keeping Callisto's SOI in view (lower left). See Figure 28. You should see Callisto approaching the intercept position, with our spacecraft moving out ahead of it, also towards the intercept position (off screen upper right). To get rid of that "tail" of the projected orbit whipping around on the display, switch to the Map-Config page ([MOD] repeatedly) and set the Time Limit to double or triple PeT. 100K will do nicely. This will limit the orbit calculation to the next 100000 seconds and eliminate that long tail which extends all the way around the Jovian system! The rest of the Map screen shots reflect this (the time limit has been set).

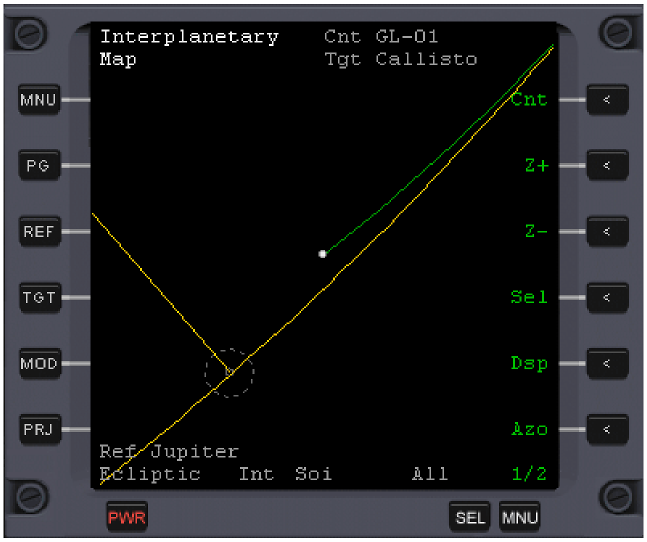


Figure 28. Map Zoom Set for Coarse Burn

During these burns, the attitude direction given by the crosshairs will change towards the end. If things get out of control, shut down the engines, re-center the crosshairs, then resume the burn. It's OK to do the burn at less than 100% main engine thrust, and it will make attitude changes more gradual. As you get close to the end of the burn (BT = 0), you may want to switch to RCS linear to trim out any remaining burn time. Try to get below 0.01 seconds BT.

B. Coarse Approach Burn (10 hours before periapsis)

With IMFD set up as shown in Figure 27 we're ready to do the coarse approach burn. This is a 7.5 second burn, as can be seen in Figure 27.

Approach Burn Checklist

1. **Quicksave scenario**
2. Left MFD verify Map
3. Right MFD **verify Course/Planet Approach**
4. Course **verify EqI and PeA**
5. Course display to **burn vector** ([PG]/[BV])
6. RCS **level**
7. RCS **center crosshairs**
8. Burn for BT < 0.01 sec (use main and RCS lin.)
9. Engines and RCS to 0%
10. RCS Kill Rotation
11. Course mode to Orbit Display ([BV])
12. Course verify BT < 0.01

The results should look like Figure 29 below. Our orbit coincides with the desired approach orbit.

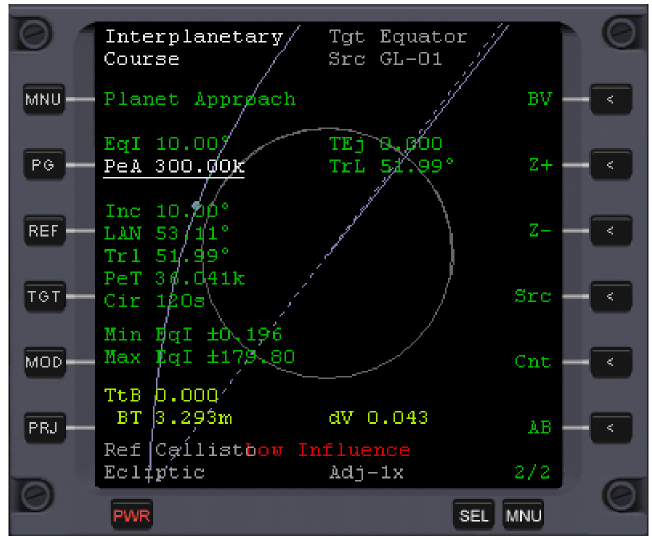


Figure 29. Coarse Approach Burn Complete

C. Vernier Approach Burn (90 minutes before periapsis)

Continue to use Map to monitor progress during the approach phase and note when the spacecraft enters Callisto's SOI. This is the time for the vernier burn. If you centered Map on the spacecraft, you will see Callisto's SOI approaching from the lower left. Keep zooming in with Map for better detail. At a PeT of around 1.5 hours you should enter Callisto's SOI. Figure 30 shows the Map display just after entering the SOI. PeT was 4667 seconds.

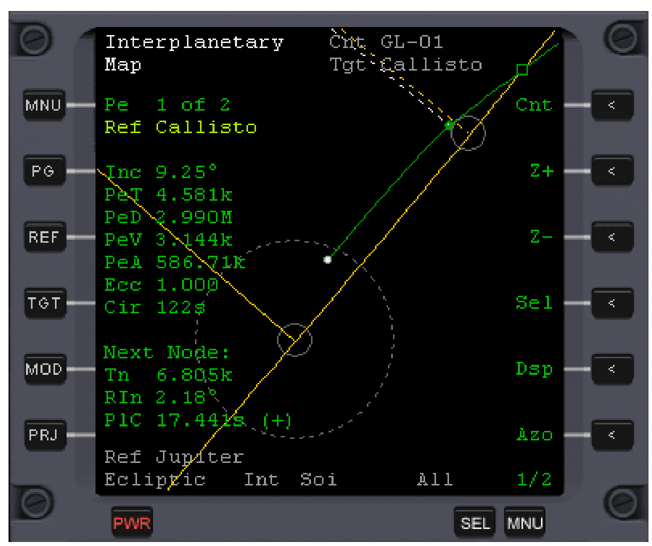


Figure 30. Map at Entrance to SOI

Now do the vernier approach burn. This should be less than 5 seconds, nominally 3.5 seconds. Use the Approach Burn Checklist again. The results should look like Figure 31:

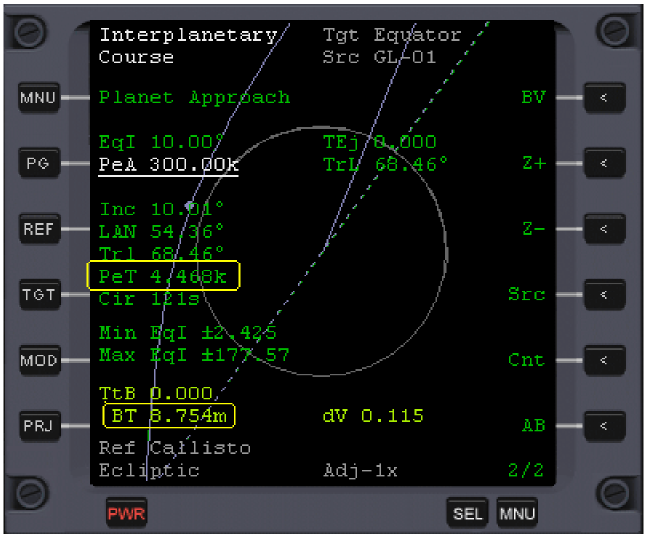


Figure 31. Vernier Approach Burn Complete

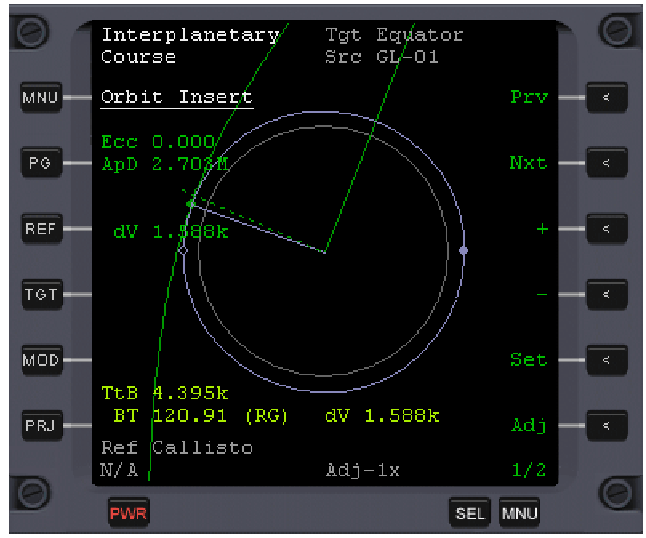


Figure 32. Pre-Insertion Display

VII. ORBITAL INSERTION

The last maneuver we will do is a retrograde burn to place us into the desired 300Km circular prograde orbit with inclination of 10 degrees that we set up during planet approach. Our current hyperbolic orbit has a periapsis at 300Km and 10 degrees north latitude. Thus, by burning this down into a circular orbit right at that periapsis, we'll be right where we want to be. For this maneuver, we'll use the Orbit Insert program.

We need to slow down at the right time to fall into the desired orbit. IMFD 4.0 and later have a *burn integrator* which does a rigorous calculation of the lead time at which to start the burn. This is more accurate than simply burning symmetrically about the periapsis. The burn time is given by the **burn time** (BT) in the Orbit Insert program. **Timing is everything!** This is the most time-critical maneuver of the flight, and the burn integrator will guide us toward a precise insertion.

Use the Pre-Insertion checklist to get set up. The results should look like Figure 32.

Pre-Insertion Checklist

1. Quicksave scenario
2. Left MFD verify **Map**
3. Map **zoom and center to see SOI, spacecraft and intercept**
4. Map display to **orbit only** ([MOD] repeatedly])
5. Right MFD verify **Course**
6. Course select **Planet Approach** ([Nxt/Prv])
7. Course to **course mode list** ([+/-])
8. Course menu select **Orbit Insert** mode ([Nxt/Prv], [Sel])
9. HUD to **Orbit**
10. RCS HUD level

Note the green dashed line slightly angled toward our direction of approach. This is the start-of-burn point calculated by the burn integrator. TtB indicates the time until we should start the burn, and BT (as usual) indicates the burn time at 100% main engine thrust. The blue circular orbit is our final orbit around Callisto. Note that there are no settings to make unless we want a non-circular final orbit (in which case we could set eccentricity (Ecc) or apoapsis altitude (ApD)). Our insertion point was completely determined by the set-up we did using Planet Approach. Orbit Insert simply burns to achieve the final orbit.

Now perform the Orbital Insertion Checklist to get into orbit. Again, **timing is everything**. This is the most time-critical maneuver of the flight.

Orbital Insertion Checklist

1. Course verify **Orbit Insert**
2. Orbit Insert to **burn vector** ([PG]/[BV])
3. RCS **center crosshairs**
4. Orbit Insert wait for **TtB = 0**
5. Main engines **100%**
6. Orbit Insert wait for **BT < 1.0** with crosshairs centered
7. Main engines **0%**
8. RCS **kill rotation**
9. RCS mode to **translate**
10. RCS translate forward for **BT < 0.01** sec
11. Orbit Insert confirm **dV < 0.01**
12. Orbit Insert mode to **orbit display ([MOD])**
13. Orbit Insert **confirm successful maneuver**
14. **Quicksave scenario**
15. Left MFD to **Orbit**
16. Orbit **confirm orbit achieved**

Figure 33 shows the results of a precise burn (BT = 0.005 sec.). Figure 34 shows the Orbit MFD display after insertion. The inclination is off by only 0.6 degrees, and the orbit altitude is off by ~2Km. Right on our goal! And we did this with much less fuel than would have been needed for seat-of-the-pants flying (well for all but the most skilled pilots!).

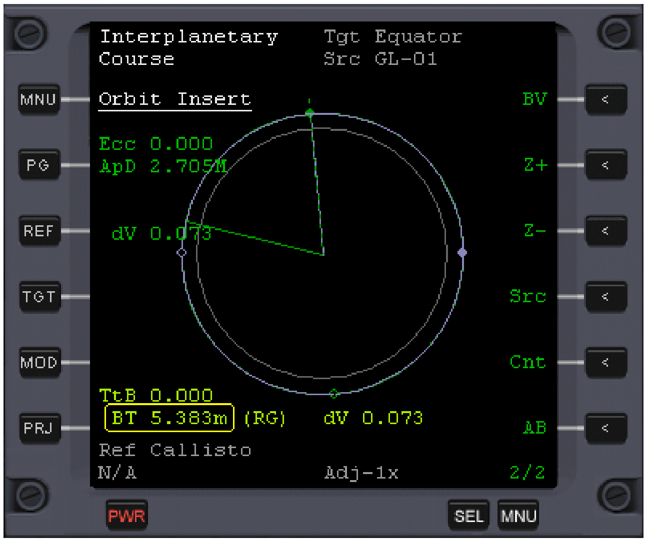


Figure 33. Orbital Insertion Complete

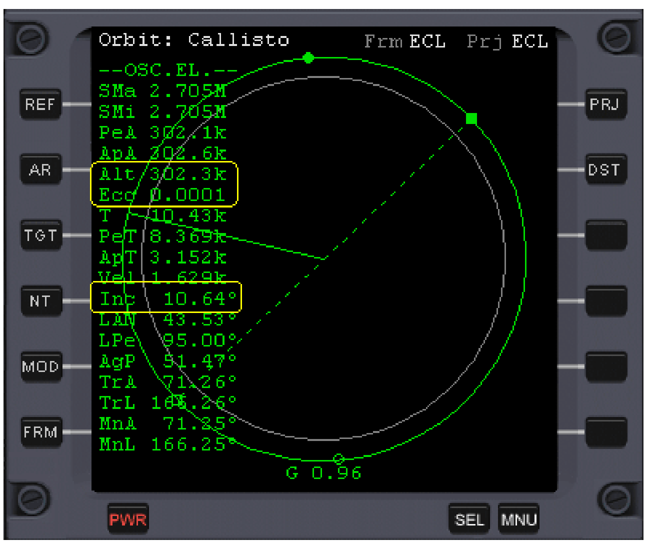


Figure 34. Orbital Insertion Complete

VIII. Conclusions

This tutorial paper demonstrates the use of the Interplanetary MFD (IMFD) for precise minimum-fuel transfers between bodies orbiting a central dominant body. The same procedures may be used for transfers between major planets orbiting the Sun. See Appendix A for additional exercises. For information on the optional **Auto-Burn features** of IMFD, see Appendix C.

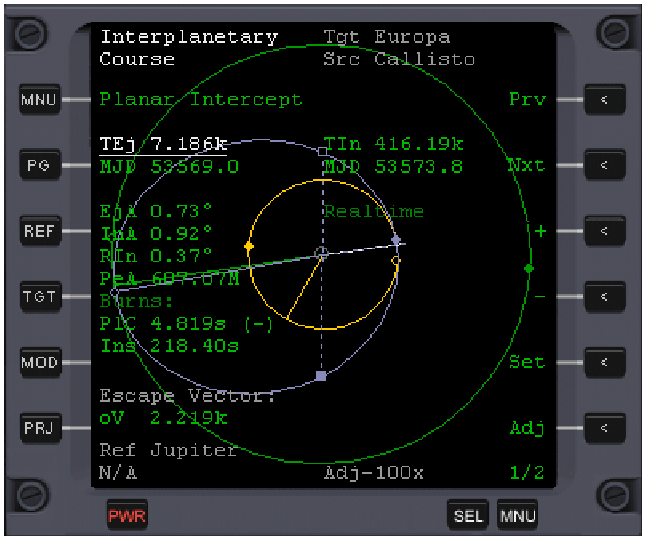
I. APPENDIX A

The following exercises are left to the reader:

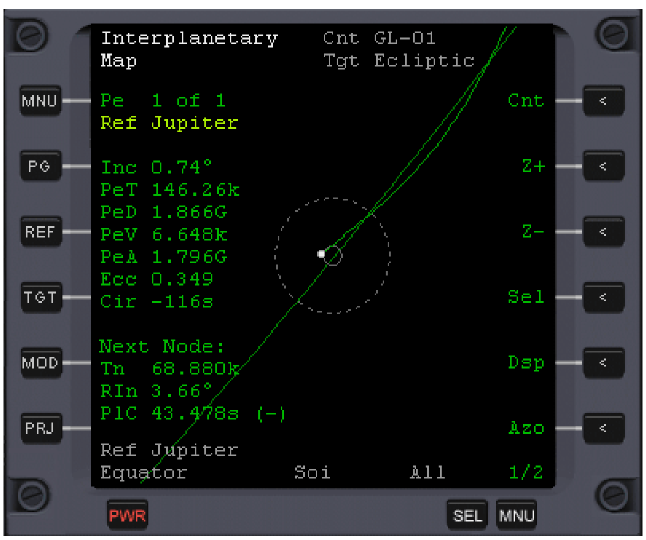
1. Adjust the inclination of the new orbit to exactly 10 degrees. There are no tools in Interplanetary MFD to allow arbitrary plane alignments. So use the method of your choice. It is a tiny burn, best be done with RCS translate.

2. Re-do this transfer, but this time use the **Off-Plane Intercept** mode from the beginning. Compare fuel usage and total time.

3. Return to Europa from Callisto. Hint: Create a starting scenario by editing the **Fig-35-36.scn** scenario and change the MJD to 53568.94 for an ejection window and saving it as a new scenario. Use Planar Intercept. A possible setup is shown below:



4. What's going on here?



II. Appendix B

Visualizing the inclination to set for a given desired orbit around the destination planet can be confusing at first. This section provides an exercise that may help. You will need the **Fig-33** scenario provided with this tutorial. Refer to Figure 24 for help visualizing.

1. Launch Orbiter and load the **Fig-29** scenario
2. In the right MFD (Planet Approach) select the **PeA** item
3. Reduce the periapsis altitude to 1 meter to better visualize low-inclination orbits
4. Ignore the green line
5. Select the **EqI** item (inclination)
6. Using the [Set] button, change the inclination to various values from –170 to +170 and note the change in the blue HTO.

Which EqI values result in prograde versus retrograde orbits? What's the difference between a –10 and +10 degree inclination? Remember, these inclinations are relative to the ecliptic plane, not the equatorial plane of Callisto.

III. Appendix C – Auto Burn

IMFD has an **auto-burn** (AB) feature. The AB computer has been tested with the original DeltaGlider, and should work well with most vessels. However, the attitude controller is somewhat crude, and may be insufficient or unstable with some vessels. The AB computer makes all burns except the initial pre-ejection plane alignment completely automatic. Burn lead times for ejection and orbit insertion are calculated by the burn integrator.

Virtually all of IMFD's displays have an **AB button**. Pressing this button will engage **Auto Burn**. Once you have a burn set up, *and at least 2 minutes before the burn should start*, switch to Auto Burn. The attitude alignment and burn will be performed automatically with a high degree of precision.

Attitude alignment begins 180 seconds before ignition. After attitude alignment is complete, the AB computer waits until it's time for the burn to start. At that time, the main engine is used unless the delta-V (dV) is less than 1.0 m/s. The main engine is throttled up to 100% unless the burn time (BT) is less than 10 seconds. When the burn time reaches 5 seconds, the main engine is throttled down gradually to 0%. At this point (which should be a dV of about 1.0 m/s), the RCS linear thrusters are used at 25% to trim the burn time to less than 0.01 second. During these burn operations the attitude controller holds the correct attitude per the IMFD burn vector computations. For burns less than 5 seconds, the main engines start partially throttled down and reduce to 0%. For burns of less than 1.0 m/s, only RCS linear is used. Once the burn has been completed, auto-burn is disengaged automatically.

END