InterplanetaryMFD

(IMFD)

Version 4.2

for Orbiter

Space Flight Simulator 2005

June 4, 2005

Copying / Warranty

Internet

Latest IMFD and tutorials is located in *http://koti.mbnet.fi/jarmonik/Orbiter.html*

Notes

1. Some of the screen shots are from olded version of IMFD and those not looking exactly the same as the current version. 2. You may need to press [MOD] button to bring up the surface launch data.

Requirements

Orbiter Patch 050126 is required.

Installation

Unpack the package in to the Orbiter installation folder. Unless you have all ready done. Config folder will contain IMFD.cfg for configuration options.

Special thanks

To Robert B. Denny for a great features he have coded and added to IMFD to improve its usability and make it easier to use. =) Also thanks for the great tutorials.

General information

Setting values from keyboard

You can setup values in a many form from the keyboard by pressing [Set] button. The exponent form can be used like "12.4e3" or "11.45e-2". Also the exponent can be replaced by a letter like "12.4k" or "33.2M" or "22.2G". Where k is equal to "e3" and so on. "d"=day and it will multiply the input value by 86400. "h" is equal to an hour and "a" is one astronomical unit. It is possible to enter MJDs in a date format like 02-Jun-2005 or 02.06.2005 (dd.mm.yyyy) Used names for the months are *Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov and Dec* (not case sensitive).

Color configuration

IMFD allows a colors to be configured by configuration file. The file is located in Config folder and the file is named as IMFD.cfg The same file will be used at least by BaseSyncMFD

Start Key Selection

You can define the key to be used to open this MFD by your self. `IMFDKey` variable can be edited in a IMFD.cfg Key codes are listed in a orbitersdk.h the default setting is "I"

Burns, Crosshairs and AutoBurn

Autoburn feature is originally developed by Robert B. Denny.

Most of the programs are capable to generate a burn data. The data will appear in a lower left corner and there is a Time to Burn (TtB) item and remaining Burn Time (BT) item. After the (BT) there may appear (PG) or (RG) flags. Those will indicate that the burn is a pro-grade (PG) or a retro-grade (RG). If the flag is not present the burn will use a burn vector and you must use a cross hair tool to setup the attitude of the space craft. The cross hairs will appear when pressing [BV] button. Also the autoburn will complete the burn automatically, no need to play with the cross hairs. The autoburn can be activated / deactivated by pressing [AB] button. When using slowly rotating space crafts you may want to decrease an attitude control speed from IMFD.cfg and that would be `AP_MAX_ANG_VEL` maximum angular velocity in attitude control (rad/sec).

Burn Integrations

In the IMFD a burn integrations are used to improve the accuracy of the burns. Typically in a transfer calculations is expected that the delta velocity is gained at once with no burn time at all. This is the initial burn executed in the initial position. However, In a reality the time required by the burn must be notified somehow. The most easiest way is to reduce a half of the estimated burn time from the initial burn position. So, that would be the actual position where the engines should be started. The ship will end up, almost but not exactly, in a right direction. The grey sector in a picture below is presenting this method.

In the burn integrations a numerical methods are used to calculate the burn position more accurately, so that the ship would end up in a trajectory that would match the initial target trajectory as well as possible. This technique is used with the Pro- and Retro-grade burns. The green sector is presenting this technique in a picture.

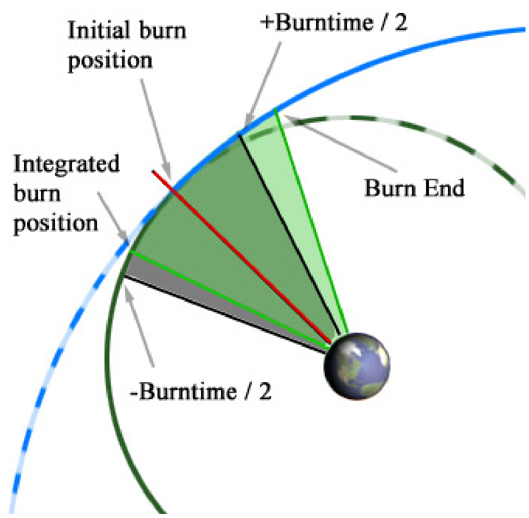

Figure 1: Idea of burn integrations

BurnTiming

If for some reason above integration fails, the burn position will start jumping all over the place. Due the experimental nature of this method it is possible to control it from the IMFD Menu by pressing [PRJ] button. Approximate mode is using "reduce half" - method and Precise mode is using burn integrations.

Information Flow

IMFD will contain a separate programs for transfer, sling-shot, orbit-eject, trajectory plotting and burn control. There is some information transfered form the program to an other, beginning from the transfer programs and ending in to the trajectory plotting and burn control. In this version of IMFD all the programs are not updated automatically only the programs those are visible. So, you need to configure the flight plan in right order and the flight plan must be configured just before the launch to ensure that the information is up to date.

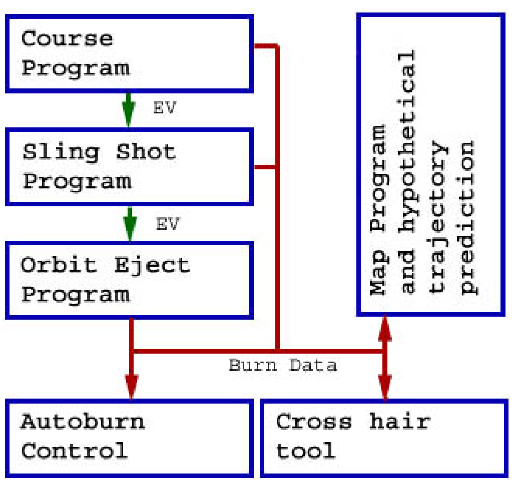

Figure 2: Information flow inside IMFD

...Flight plan from the Moon to Mars
At first, the course program (*transfer program*) will generate an escape vector for the Earth-Mars transfer. Using the Earth as an source object. Then, the sling-shot program will translate the escape vector in to a new escape vector for the Moon-Earth-Mars sling shot, using the Moon as an source object. After that, the orbit-eject program will read the escape vector and it generates a burn data for autoburn and map program for plotting purposes. The hypothetical orbit will be shown in a Flight Planing mode. *See Map program section.*

Sources, Targets and References

For correct operation the source, reference and target must be correctly defined. The reference and source objects are automatically set after setting the target. So, start the flight plans by setting the target first. If necessary the reference and source can be manually overridden. If for some reason the source of the target is incorrectly defined en error will be displayed.

To be able to generate an escape vector the source must be set to the planet being orbited. Setting the source to "x" a currently used ship will be selected. In the IMFD the target must be always defined otherwise the ecliptic is targeted automatically. There are some special targets available see Map program section for more details.

Space stations can be targeted and sometimes they can be used as a reference objects but a space station can not be a source object.

Target [TGT] and reference [REF] selection buttons are in a left edge of the MFD and the source [Src] button is in a second button page in a right edge. Change the page with [PG] button.

Orbits, Colors, Line of Nodes

The colors has a special meaning in a displays. The green orbit is presenting a current orbit of the source object. The Orange orbit is presenting the target orbit. The target orbit is not always visible for an example when ecliptic of local equator is targeted. The blue orbit is presenting hypothetical (*planned*) orbit. White line is presenting an intersection/interception positions and in the orbit-eject program it will show the escape direction. The orange dashed line will indicate the target position at the time of intersection. Sometimes blue dashed line is used to indicate a ship position at a time of interception. The green dashed line is the position for the burn. Finally, the dashed line between two square boxes is called a line of nodes. It is indicating an intersection of the orbital planes. Most often this is the intersection of target and hypothetical orbits. This is usually presented in a blue. Sometimes the line of nodes will be drawn to present the intersection of the Ship's orbit and the hypothetical transfer orbit (HTO). This is usually presented in a green. The plane change maneuvers will happen in a positions pointed by the nodes (*boxes*).

A Plane Change Maneuvers

The plane change maneuvers are often required. IMFD will provide a basic information required to execute the plane change maneuver. Time to Node (Tn) indicated how long it takes to reach the next node. (PlC) item is displaying the burn time required for the plane alignment also there is a flag (-) or (+) that is indicating the attitude that must be used with the burn.

MFD Operation Mode

Operation mode of the MFD can be changed in a main menu by pressing [PG] button. The modes are Shared and Unshared, this will control how the information is shared between different MFD screens. When the mode is changed the existing flight plan will be corrupted but the programs will hold the configurations. When the unshared mode is in use all the MFD screen will contain an individual flight plan and flight data. When the shared mode is in use one flight plan will be shared between the MFD screens and a program can be used in one MFD screen at a time. So, you can not run Orbit-Eject in both screens at the same time.

Swing-By Calculator

This is the latest additions in the IMFD. Currently there is only a partial support for SBC. The dates of the planet fly-bys are important but there is no support for them. There is an auxiliary vector input button [Aux] located in some programs, that will open an dialog box for input parameters. And there are four of them. At first enter the V-departure in an order of appear and finally the C3-departure with the spaces between the values. *For an example: 13.234 12.002 -2.123 23.223*

This will setup your exit vector for a plant escape or a fly-by. These parameters can be used in Orbit-Eject and Sling-Shot programs. These programs may not provide required accuracy on a missions with a multiple fly-bys. In those cases you can use Off-plane intercept program to keep the mission in a schedule. That will take the time of fly-by as an input parameter. This will put your ship in a collision course, that's not good, but this should be fixed from the future versions. At right now, you need to use the Planet Approach program to raise the periapis distance to prevent the collision. This maneuver should take a place immediately after crossing the edge of the sphere of influence or well before that. Off-plane Intercept program should be used when you have exited the sphere of influence.

Known Problems

If you encounter a problems while loading old scenarios those are using IMFD try to remove the `BEGIN_MFD - END_MFD` sections from the scenario files.

Map Program

Map display is general display used for monitoring the ship's course and predict an approaches to the target planets. It allows to view entire solar system as well a single target. The map program is using a planet to planet perturbated trajectories. The trajectory is no longer limited in an ellipses and hyperbolas now, it can be displayed around a multiple references regardless the distance or influence the reference causes. The user have an ability to control the speed and accuracy of the trajectory engine. The modifications can be made from the configuration page. Even the fastest modes will provide a great accuracy for interplanetary missions. Update rates as high as over ten times per second can be archived with out a significant system load with an average home computer.

The Core

The core is using the Encke-Fehlberg methods those will allow a high speed trajectory prediction. In this version of the trajectory engine the graphical steps and the numerical integration steps will go a side by side. So, increasing a step size will lower the graphics quality. It would be possible to use a high order integration methods with a long time steps to compute the trajectory and a sub integrations for increasing the graphics quality. That would be more complicated and it would not significantly increase the overall performance. So, a lower order method with a lower step size have been chosen as an default option. However, The user can select the integration method from Third order RK3, RK4-Gill, Symplectic 4th Order and RK-Fehlberg methods. Also Adams-Multton method is under consideration. Of course, it is possible to create a much much more faster trajectory predictors but it is questionable that does it provide satisfied rewards/efforts ration. Surely, in the integrations where a graphical plotting is not required such a methods could be used more easily.

Core Configuration

Some of the core functions are configured through the IMFD.cfg file. The `LegSize` option will define the size factor for the leg. Higher number will make the legs longer therefore, amount of legs required to compute the trajectory will decrease. `LegsPerFrame` option will define how many legs are computed within every frame. If the frame rate is 80 frames per second and 20 legs are calculated in every frame that will make 1600 legs per a second. `Integrator` option will define the integration method to be used in a prediction.

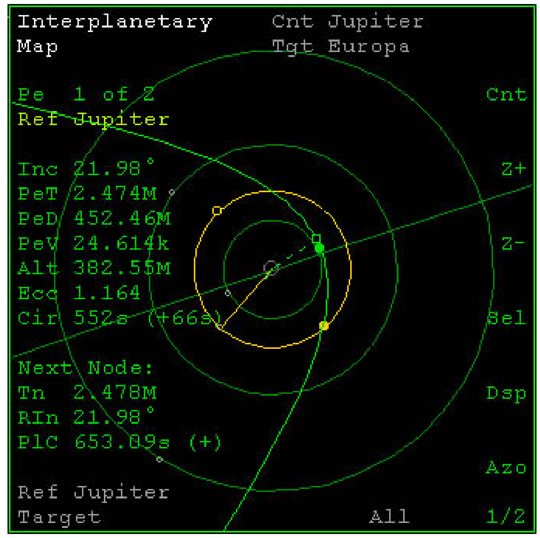

Figure 3: Typical view of the map

Centering the display

You can center the display in a specified position by pressing [Cnt] button. Then, you can type the name of the object you wish to center. The display will move in the object's present position. If you wish the center the display in a future position it can be done but only for the positions and times of the periapis passages. You can center the reference planet of the periapis by writing "r-" in a front of the name for an example "r-Mars". And command "p-" will move the display in the periapis location. Before using these commands the correct periapis must be selected with the [Sel] button.

About the Periapis

There can be multiple periapses on a trajectory. Number of available periapses and the currently selected periapis is shown in a top-left corner "Pe 1 of 2". "Ref Moon" is indicating that the Moon is the reference if this periapis. Only the selected periapis is shown on a display. Also there are two different kind of periapis points, strong and weak once. This is simply because,

Inc	Relative inclination in periapis
PeT	Time to periapis
PeD	Periapis distance from reference
PeV	Velocity at periapis
PeA	Periapis altitude
Ecc	Orbit eccentricity at periapis
Cir	Burn time for orbit circularization
RIn	Relative inclination in a node
Tn	Time to next node
PlC	Plane change burn and attitude
Lon	Longitude of periapis on planet's surface
Lat	Latitude of periapis on planet's surface
EqI	Equatorial inclination of orbit in periapis
GeR	Radius of geostationary orbit

Table 1: Items shown in a display

the strong periapis is located inside the SOI (*Sphere of influence*). The weak periapis is located outside the SOI and most likely there aren't a stable orbit in that position. So, that could be considered to be the position where the ship will by pass the planet at minimum range. The periapis strong or weak one will be displayed for a reference and target planets only. If the trajectory goes several orbit periods around the reference planet up to six periapies/apoapies can be displayed. But only if "One Pe/Ref" option is disabled from the configuration page.

The Display Screen

The projected course of the space craft will appear in green by a default and it will appear in blue when using flight planning mode. The flight planning mode will generate hypothetical trajectory based on the information created by some other program. The white spot is the space craft it self. The green/blue spot on the trajectory is a periapis, the closest position to some object. Orange circle is the target orbit. Sometimes the target is not visible on a screen. The boxes on a trajectory line are the nodes. The line nodes will be drawn between the node and the reference planet. That is the position where ship's orbital plane and target orbit intersects. This is also the position for the plane change maneuver. Due the numerical computations, the perturbations may cause some weird effects to the node positions. Usual they are located at the opposite sides of the reference planet.

The information on a screen is displayed for the periapis positions not for the current position of the ship. However, There is one exception when no single periapis is available the current position of the ship is used.

Include Plane Change

The Map program will automatically include the plane change in a first node if the (IPC) is activated.

Warning: Sometimes the plane change is required in a prediction but it may cause failures in a prediction if used in wrong place.

What is included in Map

All planets having the following conditions are included in computions: a mass greater than 1e20 kilograms *(depends from configuration)* and orbiting same reference planet as the ship or orbiting the Sun. In addition, planet, ship or station that is selected as an reference or a target is also included. The moons those have a different reference than the space craft are not notified in trajectory calculations.

Trajectory Limiters

Due the nature of numerically computed trajectory. The generation of the trajectory must be limited somehow. Because, there is no end point in a trajectory. There are two automatical limiters for the trajectory such as a Period- and a Hyperbolic-limiters. These limiters will cut the trajectory other vice there would be a plenty of trajectory on the screen and that would look chaotic. You can manage these limiters from the configuration page. The period will limit the trajectory in one orbital period around the reference planet. The hyperbolic will limit the trajectory in one hyperbolic periapis relative to reference planet. The automatical limiters can be overridden manually by setting the time limit and it will limit the trajectory in a specified amount of seconds. That is the most usable if the others fails. So, If the trajectory looks a little strange or short it may have been limited incorrectly by automatic and you should make some manual configurations.

Special orbits

You can also target one of the special orbit like the ecliptic, equatorial orbit, and the geostationary orbit

(GEO). Also the orbital plane of the reference planet can be targeted. This is good especially when transferring between planets or returning from the Moon. Special orbits can be used with all programs. Type the corresponding letter when asking the name of the target.

e	Ecliptic plane (not visible)
g	Geostationary orbit
l	Equatorial orbit (not visible)
r	Orbit of the reference planet (not visible)

Table 2: Special Orbits

Flight Planning mode

In a earlier versions of InterplanetaryMFD this mode was called "external mode".

This mode allows to use a numerical multibody predictor to generate the hypothetical transfer orbit based on the information generated by other programs. When this mode is activated the "Plan" text and the name of the program, generating the plan, will appear in a title. Also the trajectory will be displayed in blue. (*in a default configuration, of course*). When ever the burn information is present a hypothetical trajectory can be generated. This mode is especially great when planning a free-return trajectories and returning from the Moon.

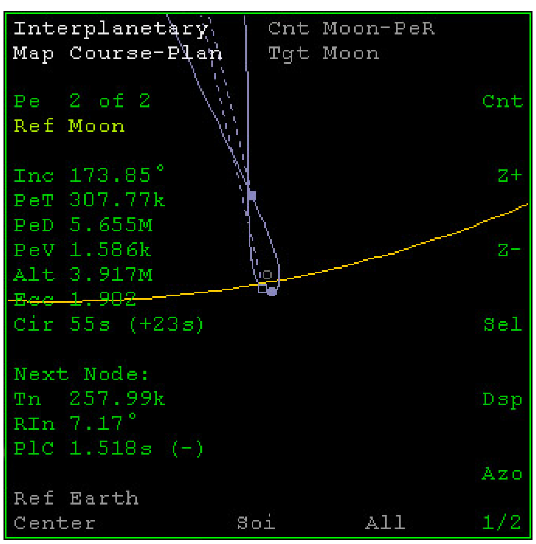

Figure 4: Free-Return trajectory in flight planning mode

Projections

You can select the projection plane by pressing [Prj] button. Because the space is a three dimensional, displaying it in a two dimensional display will cause some graphical problems. Therefore, choose the proper projection.

Ecliptic	Ecliptic plane
Target	Use the target orbit for projection
Self	Use current orbit of the ship
Center	Automatically use the orbit of centered object
Periapis	Ship's orbit in a periapis around Pe. reference

Table 3: List of projections. Available projections will depend on program being used

Nonspherical Gravity

The Map program can include a non-spherical gravity in a predictions. Currently only J2 coefficients are notified and this will be included only when the ship is within the sphere of influence. This feature is controlled by automatic. However, it can be manually overridden from the IMFD.cfg by setting the option `NonSpherical 0` it can be forced to be always active with `NonSpherical 2`

Configuration Page

Some basic configurations, required by multi-body predictor, can be made from the configuration page. In a top edge there is an indicator telling an amount of integration steps used in the prediction. Also it will tell how many planets are currently included in the computations "3+5 of 62" indicates that there is three objects fully perturbated and five objects using an analytical update.

Legs/Frame	How many integration steps are made in time step
Leg Size	Step size multiplier. Large value = Longer steps
MassLimit	Include bodies with higher mass than this
Period	Limit trajectory in one orbit period
Hyperbolic	Limit trajectory in one hyperbolic periapis
TimeLimit	Limit the trajectory in amount of seconds
One Pe/Ref	Show only one periapis per reference
Rectific.	A rectification constant for trajectory engine
Integration	Active integration method

Table 4: Configuration options

Orbit Eject

Orbit eject is probably the most easiest program to use. It is used for escaping from the current reference planet. That is required when travelling between planets or moons. However, it is not required when travelling from the Earth to the Moon because you never leave the influence of the Earth. In a program, there is five items those can be modified. (oV) is presenting the outward delta velocity, that's the velocity added in a velocity of the planet. (TEj) is the time to the ejection and (Trl) is the true longitude of the ejection position. These items are presenting the same thing in a different forms. "Escape mode" item is the one in a top-right corner, it will choose the source of the escape information. Finally, the "Burn mode" item is used to select the burn mode, that would be a pro-grade or a realtime.

Warning: If the blue trajectory on a screen will go through the planet being orbited. So will you if you engage your engines right now. Wait a position pointed be green dashed line before the main engine start. When using the autoburn feature in a realtime mode the burn timer must be used by increasing the (TEj) or (Trl) so that the eject position (*blue line*) is in a location pointed by the green dashed line.

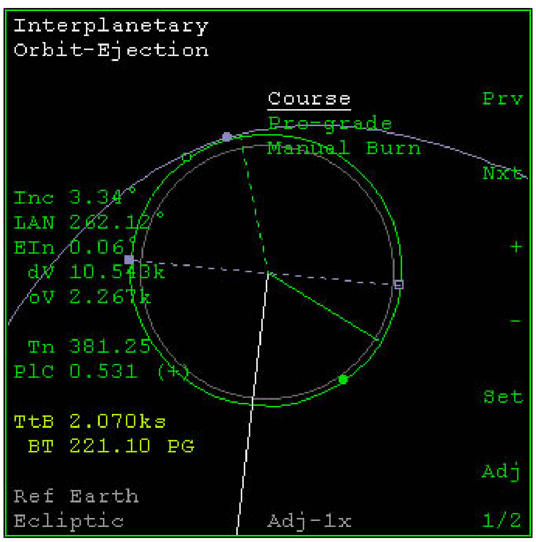

Figure 5: Orbit-Eject program

Green dashed line is the position for the burn recommended by the flight computer. Time to Burn (TtB) will tell how long it takes to reach this position.

Escape Mode

The top right item is used to select a source of the escape information. If the source is selected incorrectly the data on a screen is meaningless or it doest appear at all. This is because there are multiple programs those are capable to generate the escape information. Lower/Higher-Orbit modes are internally generated by orbit eject program.

Lower-Orbit	Eject to lower orbit.
Higher-Orbit	Eject to higher orbit.
Course	An Escape vector created by Course
BaseAppr	An Escape vector created by BaseApproach
Sling-Shot	An Escape vector created by Sling-Shot
SBCalc	Use an auxiliary vector.(See SBC)

Table 5: Escape information sources

oV	Setup Outward velocity for Lower/Higher-Modes
Lnc	Setup Orbit-Eject countdown (Optional)
Trl	Setup Orbit-Eject position (Optional)
Inc	Inclination of current orbit relative to ecliptic
LAN	Longitude of ascending node relative to ecliptic
EIn	Escape inclination (Important)
dV	Delta velocity for the burn
oV	Outward velocity
TtB	Time to main engine start
BT	Remaining burn time
Tn	Time to node
PlC	Magnitude of plane change burn

Table 6: Items used in Orbit-Eject

Lower-Orbit can be used for an easy return to the Earth from the Moon. Setup oV to 700.

Burn Mode

There are also a two different burn modes available and those are a Realtime and a Pro-Grade. Realtime mode is a good one for escaping from the low gravity bodies. This mode is using a burn vector to eject the ship in a correct heading. However, this mode in highly inefficient in a long burns. The Pro-grade mode is created for a long burns and it is using a Pro-grade burn. So, use a PG autopilot or the autoburn feature to complete the burn. Pro-grade mode is not available if (EIn) is greater than 1.0 degrees. Neither it is available during the liftoff. On a highly elliptical orbits the integration of the exact burn position may take a few seconds. The position is integrated with high accuracy and you should end up exactly in a correct heading after the burn. For the last few seconds you can use the Realtime mode to improve the accuracy but that's usually not necessary. (Tra) and (TEj) items are not available in the Pro-grade mode.

When ever possible use Pro-Grade mode

Surface Launch

Orbit-Eject program can be used for a surface launch. Press [MOD] button to activate this mode. The launch heading (Hed) is indicating the launch direction from the current position at the current time. This information can be used to launch in the Orbit around the planet. The target is more like a point rather than a plane. So, a later course corrections are possible and the flight data is updated all the time. Escape inclination (EIn) is presenting deviation from the target point. That should be as close to zero as possible but not during the first few minutes when launching some other direction than "090". You should be able to control the liftoff so that the (EIn) is zero before the orbit insertion. You can effect in the value by changing your heading to the left or the right about 1 to 5 degrees.

The (Time) item under the optimal launch conditions is presenting the time that it takes to reach the recommended launch position. With in 24 hours there are two launch opportunities those are better than the others. You can launch any time you want in a heading (Hed). The launch will be a little more difficult because of the planet rotation and it will consume more fuel.

The best launch heading is "090" because the launch would be in a rotation direction of the planet and you can use the rotation velocity to assist.

Launch in the best heading "090" is not possible when the escape angle is greater than the latitude of the launch location. However, the launch latitude should be as close to equator as possible. (OLat) is presenting optimal launch latitude but you don't have to launch from there. (OHed) is presenting a recommended launch heading from the current location. This launch should take a place when the (Time) is zero.

During the liftoff you should note that your ship must be moving in the direction guided by (Hed). It is not enough that your nose is pointing it that direction.

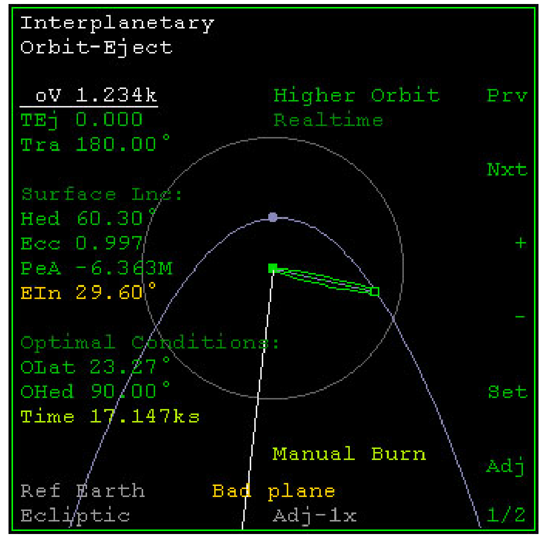

Figure 6: Surface launch mode

Ejection Plane

Ejection plane can be adjusted by making the plane change burn in a node pointed by the green dashed line with the boxes. Time to Node item (Tn) is showing the time how long it takes to reach the node. (PlC) item is showing the attitude mode that must be used with the burn, that would be Orbit Normal (+) or Orbit Normal (-), and it will show the burn time required for the plane alignment. On a low orbit around a planet the plane maneuvering is highly expensive in a terms of fuel. So, It is highly recommended the you make sure that the plane alignment is correct from the first place.

Course programs

This is entirely new program in the IMFD. It contains many different programs for interplanetary transfer, course correction and approach.

Planar Transfer Orbit

Planar transfer orbit follows the orbital planes of the source and the target planets. The plane change maneuver must be executed in a node. That is the intersection location of the orbital planes. The amount of fuel required in a plane change depends from the relative inclination and the distance from the reference body. So, If possible the mission should be planned so that the plane change would happen as far from the reference as possible. If possible, the target could be intercepted in a node.

The delta velocity required in a plane change maneuver is defined as:

$$\Delta_v = \frac{2h\sin(i/2)}{r}, \quad h = |\overrightarrow{\mathbf{r}} \times \overrightarrow{\mathbf{v}}|$$

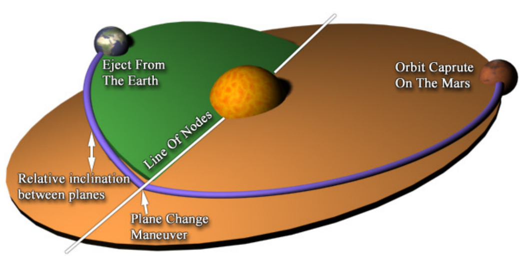

Figure 7: Planar Transfer Orbit

Off-plane Transfer Orbit

Off-plane transfer orbit will transfer the ship directly from the source planet to the target planet. No plane change maneuver required. It is included in the ejection and the capture burns. If the target planet is on the opposite side to the source planet, the inclination of the transfer orbit may become very high. That would be also very fuel expensive. In such a cases it is recommended to use a planar transfer. In the off-plane transfer the transfer plane is defined by two vectors $\overrightarrow{r_{earth}} \times \overrightarrow{r_{mars}}$

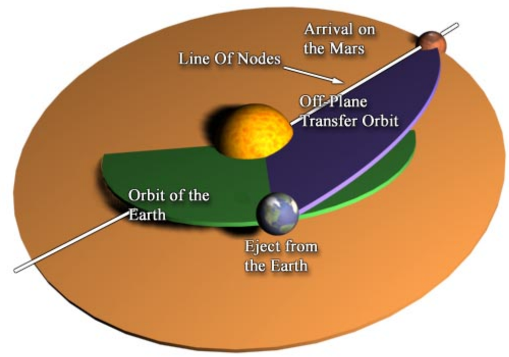

Figure 8: Off-plane Transfer Orbit

Program Menu

You can select the program by pressing [Prv] and [Nxt] buttons from the right edge of the screen. *(That would be Shift-1 and Shift-2)* When you have selected the program you wish to use press [Set] button to activate it. Pressing the set button on a program title will always reset the program to it's default condition.

Important: Press [+] or [-] on a title to return to the program menu. Unfortunately the program configuration will be lost. This problem should be fixed from the future releases. However, you can return to main menu with (MNU) button without losing the configuration

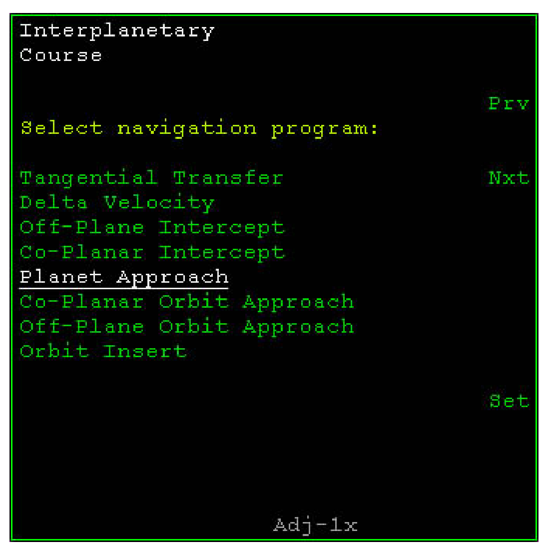

Figure 9: Navigation program menu

Target Intercept - Program

From technical point of view this program will calculate a solution for the Lambert's problem sometimes known as Gauss problem.

This is the primary navigation program and there are two versions available. One for Planar Intercept and the other for Off-Plane Intercept. This program will set your course to intercept the target after a time or date you have specified. This program can create an escape vectors for interplanetary transfers. The program can be also used in a mid course corrections and later interception maneuvers after that. If you are using a planar transfer to your destination. After executing the plane change maneuver in a node you should continue with the off-plane version of the program to target directly towards the planet.

In some cases the program may generate highly inefficient transfer orbits. To optimize your transfer choose the time to intercept (TIn) that will give a lowest burn time or escape vector. The target can be a planet, mood or a station. Equator and Ecliptic can not be targeted an "Invalid Target" message will be displayed.

The burns generated by the program are usual not a pro- or a retro-grade burns. However, in some special cases a pro-grade burn can be used for an example when intercepting the moon from the low earth orbit. Pro-/Retro-grade burns are more efficient than non pro-/retro-grade burns.

Important: When adjusting the setup the burn mode should be set to Realtime because the Pro-grade mode will make some adjustments on it's own.

Above is a screen shot about a takeoff from the Earth. The blue/white dashed line is the position of interception. This position can be freely selected with the Intercept Timing items. But be aware of the transfer efficiency. The line of nodes (*blue dashed line*) is the position where hypothetical transfer orbit and the target orbit intersects. This vector is the cross product $\vec{\mathbf{l}} = \vec{\mathbf{n_h}} \times \vec{\mathbf{n_t}}$ of the normal vectors $\vec{\mathbf{n_h}}$ and $\vec{\mathbf{n_t}}$ of the hypothetical orbit and target orbits. (RIn) is the relative inclination measured in this node.

When using Off-plane version, Ejection angle (EjA) and the Intercept Angle (InA) will also contain the error in inclination. The outward/inward delta velocity is defined as:

$$\Delta_v = \sqrt{v_s^2 + v_t^2 - 2v_s v_t \cos(\varphi)} = |\vec{\mathbf{v_t}} - \vec{\mathbf{v_s}}|$$

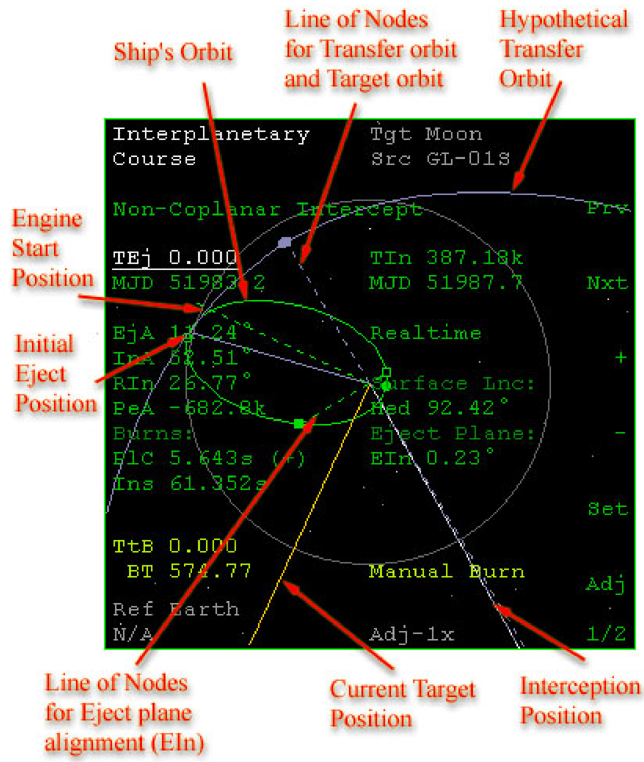

Figure 10: Takeoff from the Earth

EjA	Angle between tangents in ejection
InA	Angle between tangents in a planet intercept
RIn	Relative inclination
PeA	Periapis altitude
PlC	Plane change in a node (blue one)
Ins	Target orbit insertion burn

Table 7: General information

Where v_t is the target velocity, v_s is the source velocity and φ is (EjA) or (InA). Therefore, lower the angle the better the transfer.

Plane Align (*planar transfer only*)

When using planar transfer and the ship is the source object a Plane Align information is displayed and the line of nodes will appear (*greed dashed line*). Ejection Inclination (EIn) is the inclination measured in the node. Technically this is the same as the escape inclination in the Orbit Eject program but you are not about to escape at this time. When the (EIn) is zero,

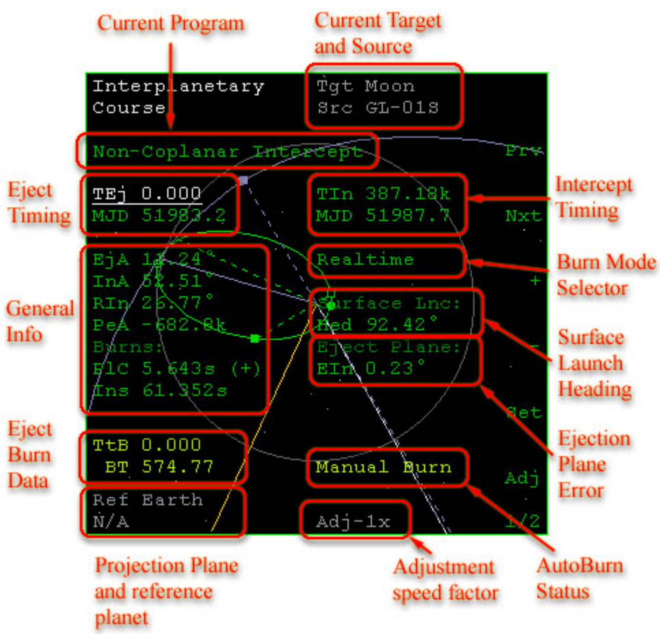

Figure 11: Takeoff from the Earth

the target is located in the orbital plane of the ship at the time of interception. In such a case the node of the transfer orbit (*blue dashed line*) is located in the interception position. So, the transfer would be similar to the off-plane transfer. But it have one advantage to the off-plane transfer, it doesn't suffer the rotation problem when the ship is located on the opposite side to the interception position.

The error in inclination (EIn) can be reduced with normal/anti-normal burns in any position but it is most efficient in the node (*green dashed line*). However, this doesn't notify that the plane change is cheaper far from the planet.

The vector pointing to this node is the cross product $\overrightarrow{\mathbf{p}} = \overrightarrow{\mathbf{n_s}} \times \overrightarrow{\mathbf{r_t}}$ where $\overrightarrow{\mathbf{n_s}}$ is the normal vector of the ship's orbit and $\overrightarrow{\mathbf{r_t}}$ is the position vector of the target at the time of interception. The eject inclination (EIn) is defined as $\phi = \pi/2 - \angle(\overrightarrow{\mathbf{n_s}}, \overrightarrow{\mathbf{r_t}})$

Burn Mode (*planar only*)

The default burn mode is the realtime mode. That might not be the best name for it but it is used now. The realtime mode alloys the user to define the time of ejection manually. Most often the ejection burn is executed in the current position of the ship where ever the ship is. This will cause that the burn is not a prograde burn and it is not as efficient as it could be. So the pro-grade mode is created to improve the performance, this is especially vital in a long burns. The pro-grade mode will place the ejection position in a proper location where the ejection angle (EjA) is zero. In that case the position for main engine start can be calculated with the burn integrations. The position would be the green dashed line and the Time to Burn item (TtB) is displaying how long it takes to reach that position. Of course, the burn information (TtB) is also valid in the realtime mode.

Surface Launch (*planar only*)

It is possible the launch from the surface with the planar Intercept program for an example on the Earth to the Moon missions. As in all surface launches, the launch in the heading "090" is the most efficient but you can make the ejection burn at any time you want, in the direction guided by (Hed), Of course. You have to make the orbit insertion at first. After raising the periapis above the surface, the surface launch mode will be disabled. It is important that you will define the target interception time (TIn) before the launch. Note, that you can not change interception time after orbit insertion. That would cause the plane alignment to fail (*EIn to change*). (TEj) should be set to zero, there is no point to set it in anything else.

In a surface launch, at first, you don't have to worry about anything else than a launch heading and ejection inclination (EIn). That should be zero. Make a successful orbit insertion in anyway you like. Then start worrying about how to continue the mission. **See More details from Orbit-Eject chapter.**

Space Station Intercept (*off-plane only*)

The Off-plane intercept program can be used to intercept the space stations as well. The graphics may not be shown well but the numbers are correct. It is recommended to intercept the station in a periapis or apoapis of the hypothetical transfer orbit. A station can be intercepted with an accuracy of few meters. The ability to intercept a space station is limited because there is very little of space for maneuvering in orbit. When intercepting a space station you must align the planes at first. Also the difference between the positions of the ship and the station should be no more than 10-15 degrees. Setup (TEj) to zero and Adjust (TIn) So that the intercept line is in opposite side to the ship or it is in a periapis (*blue spot*). Also (TIn) must be less than a one orbit period. Watch the periapis altitude (PeA) to prevent entering in atmosphere.

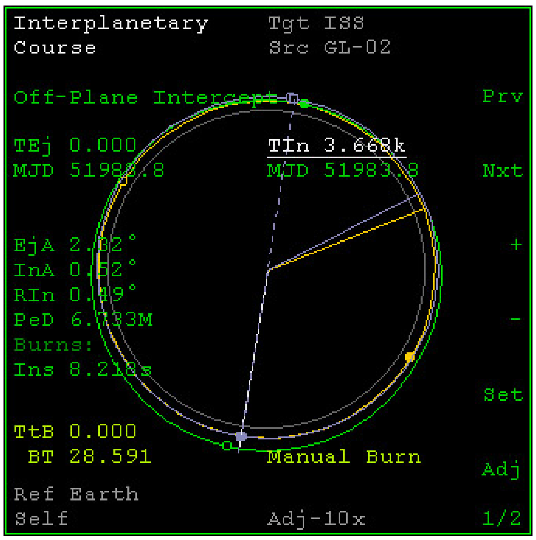

Figure 12: Space station intercept

Tangential transfer - Program

This program will take only a one input parameter from the user and that will be expressed in a two forms, a time to ejection (TEj) and a MJD of ejection. This program generates a transfer orbit that will have a matching tangents with the source orbit and the target orbit. The program uses a planar transfer and a plane change burn is required in a node. The ejection burn will be a pro- or retro-grade burn.

The white line in a display indicates an orbit intersection position and the orange dashed line indicates the position of the target planet at the time of intersection. If these two lines are over each other, you will intercept the target in that position. Source orbit can be a hyperbolic one but the target must be elliptical or circular.

When the local equator or ecliptic is targeted the radius of the target orbit can be defined. There are no

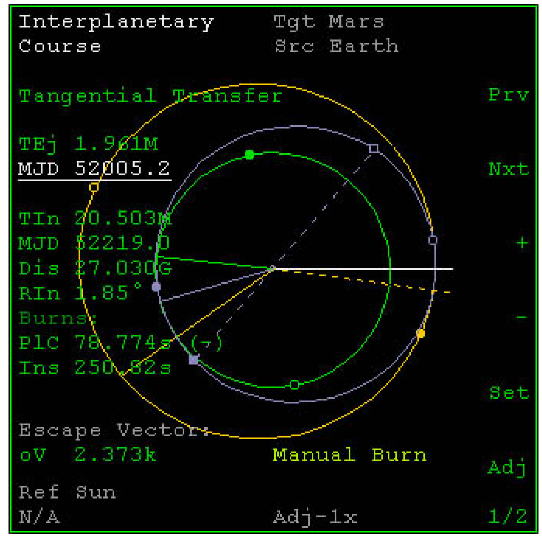

Figure 13: Tangential transfer program

orbiting bodies so the target position is not displayed.

TEj	Time to ejection
MJD	MJD of ejection
Rad	Radius of target orbit (when available)
TIn	Time to intersect the target orbit
MJD	MJD of orbit intersect
Dis	Distance between positions
RIn	Relative inclination between orbits
PlC	Magnitude and AP mode for plane change
Ins	Burn time for orbit insertion (capture)

Table 8: Items shown in a display

Orbit Insert - Program

This program requires not much explanations. But it is used to make an orbit insertion from hyperbolic approach orbit to a low orbit around the reference planet. You can define the eccentricity or the apoapis distance of the target orbit. The burn integration technique is used for the burn position calculations. The orbit insertion should be very accurate and efficient.

Delta velocity - Program

Delta velocity is an old fashion transfer program using a date of ejection and delta velocity values. Also a true longitude of the eject position can be used. Program will display the intersection locations with the target orbit. The intersection positions can be choused with the intercept-1, -2 items.

Planet Approach - Program

You can easily change the orbit altitude with the planet approach program. Expecting that you are in an approach stage. *(Close to the sphere of influence and on hyperbolic orbit)* Also the equatorial inclination can be adjusted. This is good when planning to approach a high inclination orbit. However, you can not choose the inclination lower than your current inclination to the equator. To reach a lower inclinations, normal plane change maneuver must be used and executed in the ascending or descending node of the equator. "Min EqI" and "Max EqI" is displaying the limits where the inclination can be adjusted. Inclinations higher than -90 and lower than 90 degrees are presenting a pro-grade orbits and inclinations higher than 90 and lower than -90 degrees are presenting a retro-grade orbits. When the inclination is negative you will approach the planet from the south pole other vice from the north pole.

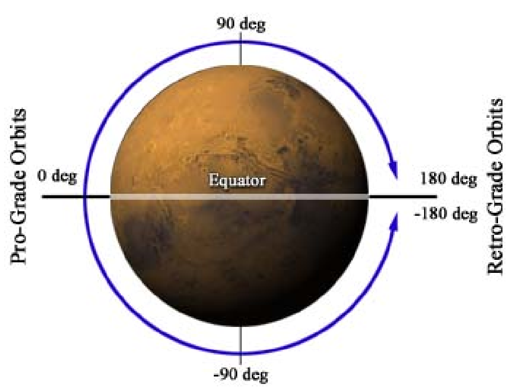

Figure 14: Equatorial Inclination

The burn created by this program should be executed as far from the planet as possible. Sometimes it is possible to execute the burn as far as three times the sphere of influence. This will minimize the fuel usage. Smaller correction burn can be executed later if required.

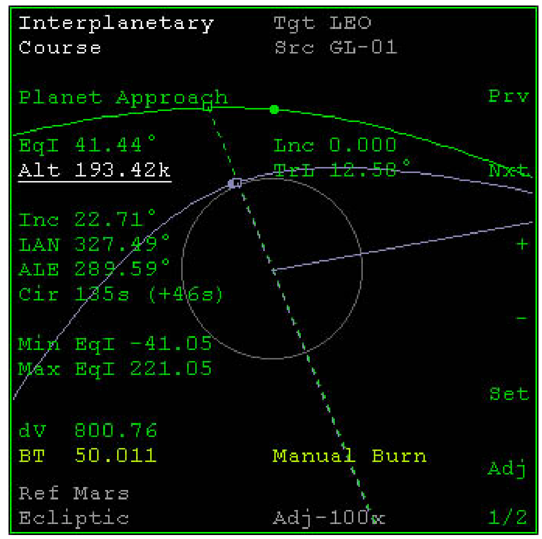

Figure 15: Planet approach program

PeA	Altitude of the periapis
EqI	Equatorial inclination of the orbit
TEj	Time to ejection
Trl	True longitude of ejection
Inc	Inclination relative to ecliptic
LAN	Longitude of AN relative to ecliptic
ALE	Longitude of AN of local equator
Cir	Orbit circularization time in periapis

Table 9: Items in Planet Approach

Sling Shot

Technically the sling shot program is very much like the orbit-eject program. User interface is similar and the mathematics in a program are equal to orbit-eject. This program is used to change your course to the next target and it can be used for powered or unpowered fly-bys. The program will create a burn data for the correction burn to make sure that your exit vector will be exactly the same as defined by the transfer program containing a course to the next stage.

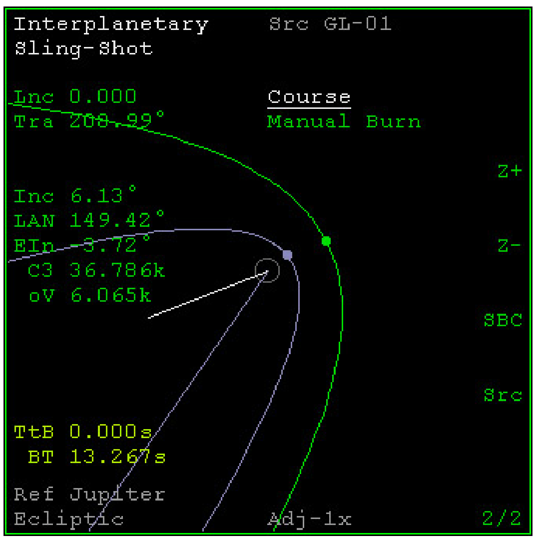

Figure 16: Sling-shot program

The source of navigation information can be selected with the right-top item. Available sources are described in the Orbit-Eject section. Items in a left edge allows you to define the position of the burn but usual this is not required since the burn should be executed as early as possible.

This program doesn't contain any functions to optimize sling-shots neither it contain any sling-shot planning functions.

The program is capable to generate an escape vector for a minor body. This will happen when you setup the source to a moon. So, you can eject the ship from the Moon to the Mars if you want to. When ejecting from the Moon, the most recommended time for the ejection is when the Moon is moving in the escape direction.

Pro/Retro-grade

You can choose wheter launch in a pro- or retro-grade directions over the reference planet. Choose the mode carefully so that you won't collide to the reference planet. Watch the periapis altitude item (PeA)

EIn	Angle between ship's orbit and escape vector
Inc	Inclination relative to ecliptic
LAN	Longitude of AN relative to ecliptic
PeA	Periapis Altitude
C3	Orbital energy of escape asymptote
oV	Outward delta velocity
Lnc	Time to burn position
Trl	Longitude of the burn position

Table 10: Items used in Sling-shot program

Math

Orbit-Eject and Sling-Shot equation used in IMFD. ρ is the angle between current position and escape vector. r is current distance of the ship. a is the semi-major axis and that's only depended from outward velocity.

$$\rho = \angle(\vec{\mathbf{r}}, \vec{\mathbf{e}}), \qquad \rho \in [0, 2\pi] \tag{1}$$
$$a = -\mu / v_o^2 \tag{2}$$
$$x = r^2 \sin^2 \rho \tag{3}$$
$$y = 2ar(\cos\rho - 1) \tag{4}$$
$$e = \sqrt{\frac{x - r\sin\rho\sqrt{x + 2y} + y}{2a^2} + 1} \tag{5}$$

BaseApproach

BaseApproach program is improved version from old TEI program. It does have a similiar functionality. With this program it is possible to design a flight that will allow to land directly on a base located on a planet without an orbit insertion before landing. This program must be used far from the planet like from the edge of the SOI. That will allow better syncronization with the base.

There exists a few trajectories those will allow to land on a base. To find a proper trajectory or flight plan you must increase the suggested flight time (Hint). If the flight computer is unable to find a solution "No Solution" text is displayed. When the solution is found the flight data will appear. You can still increase the Hint to find an other flight plan. Before this you must setup the target with [TGT] and the atmosphere depended flight configuration.

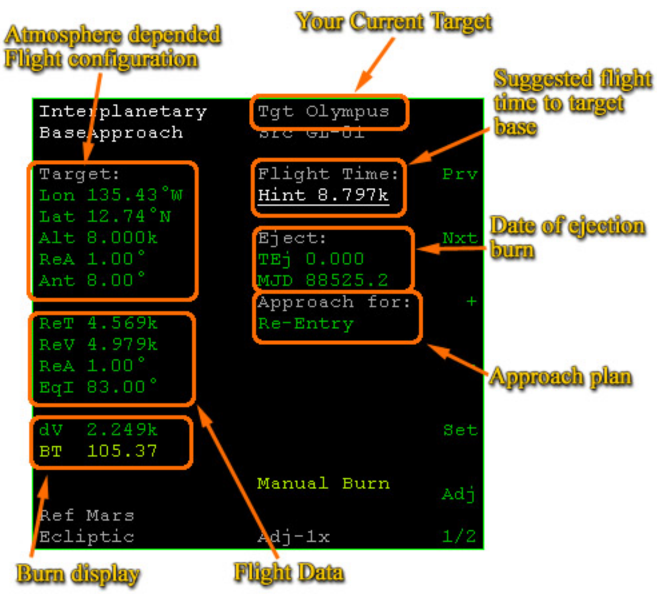

Figure 17: BaseApproach program

In a flight configuration you can define the re-entry angle, reference altitude and anticipation, that will choose the amount of space you will spare for the actual re-entry phase. *(see the picture for more details)*. The reference altitude must be set correctly, that is the level where the re-entry angle is measured and the anticipation beging. Good values might be 80km for the Earth and 8km for the Mars. Anticipation is measured in degrees from the center of the planet. When landing on a planets those have very thin atmosphere the anticipation should be increased because braking will take longer.

Lon	Longitude of the target base
Lat	Latitude of the target base
Alt	Reference altitude
ReA	Re-Entry Angle
Ant	Re-Entry anticipation
ReT	Time to re-entry
ReV	Re-entry velocity
EqI	Equatorial inclination
Sol	Select first or second solution
Num	Number of periods to spend on orbit

Table 11: Items in BaseApproach

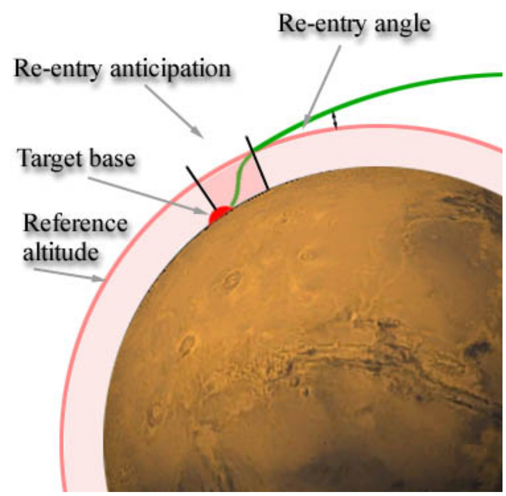

Figure 18: ReEntry Anticipation

Moon to the Earth return

When returning from Moon to the Earth, like Apollos used to, the landing zone is located on a far side of the Earth as seen from the moon. *(See fig. Elliptical)* Since, the re-entry angle is only 5.5 to 7.5 degrees the zone is located very close to the periapis. Latitude of the periapis will depend on the position of the Moon and the size of the landing zone will depend on the re-entry angle.

The inclination of the Moon is about 23 degrees relative to Earth's equator. Therefore, the area that can be targeted from the moon lies between 23deg North and 23deg South but only a small part of that area can be target at a time. So, if the base is located outside the 23 degree area it is highly difficult to land there by using elliptical orbit. When the rotation of the planet is notified the landing zone will cover all longitudes between the latitudes.

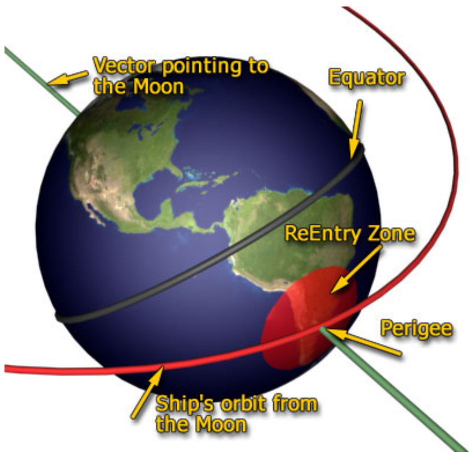

Figure 19: Elliptical

Hyperbolic approach

When approaching a planet, let's say Mars, the orbit will be hyperbolic. That will allow to rotate the periapis all over the planet. Therefore, the landing zone will be like a ring shaped area. *(See fig. Hyperbolic)* And that will cover most of the planet. So, there shouldn't be difficulties to land on the Mars. Diameter of the ring is depending from eccentricity of the orbit. When the eccentricity is very close to one the area will be more like in a picture "Elliptical". When the eccentricity increases the diameter of the ring will also increase.

It is nessecary to execute the first syncronization and plane orientation burn far from the planet. Something like 500000 seconds before the periapis passage. That would be far before crossing the sphere of influence. Making a burns that far is highly inaccurate and the trajectory will change a lot after the burn but it will reduce the magnitudes of the yet coming burns. So, two more syncronization burns will follow when the time to periapis is about 100000 and 15000 seconds.

Orbit Insert

Orbit insert mode can be used when you wish to establish an orbit over the base. (Alt) item defines the altitude of the periapis. The orbit must be circularized in a periapis. If the orbit is not circular the syncronization with the target base wont work as well as it could.

Figure 20: Hyperbolic

The rotation of the planet is notified in syncronization during the approach and circular orbit phase. (Num) item is used to define the number of full orbit periods to spend on orbit before landing. Zero means that there is only a fraction of orbit before landing, not nessesarily enough for de-orbit burn but should work fine with moon landings. There are two orbits, opposite to each other, those will lead to the target base. One will lead to pro-grade orbit and the other to retro-grade orbit.

Orbit insert mode doesn't suffer problems of critical timings and zones. Therefore, It is much more easier to use. It is possible to use orbit insert mode to return from the Moon to the Earth and land on a specific base but the orbit insertion to low earth orbit is required.

Reference Section

Key commands

To be able to access the commands in a second column you must change the page with [PG] Shift-I command. Open InterplanetaryMFD with the Shift-I command.

MNU	Shift-F	Prv	BV	Shift-1
PG	Shift-I	Nxt	Z+	Shift-2
REF	Shift-R	(+)	Z-	Shift-3
TGT	Shift-T	(-)	Src	Shift-4
MOD	Shift-M	Set	Cnt/Aux	Shift-5
PRJ	Shift-P	Adj	AB	Shift-6

Key commands for programs other than Map

MNU	Shift-F	Cnt	Slf	Shift-1
PG	Shift-I	Z+	SOI	Shift-2
REF	Shift-R	Z-	IPC	Shift-3
TGT	Shift-T	Sel		Shift-4
MOD	Shift-M	Dsp	Plan	Shift-5
PRJ	Shift-P	Azo	Find	Shift-6

Key commands for Map program

Prv	Shift-1	Select previous variable
Nxt	Shift-2	Select next variable
+,-	Shift-3,4	Adjust variable
Set	Shift-5	Set variable manually
Adj	Shift-6	Change adjustment speed
Z+-	Shift-2,3	Change a zoom factor
Src	Shift-4	Setup source object
Cnt	Shift-5	Center the display in other position
AB	Shift-6	Enable/Disable autoburn
BV	Shift-1	Open/Close burn vector display
Aux	Shift-5	Auxiliary vector input for SBC

Key commands for programs other than Map

PG	Shift-I	Change a button list in right edge
MNU	Shift-F	Open program menu
TGT	Shift-T	Select target orbit
REF	Shift-R	Select the reference planet
MOD	Shift-M	Change a display mode Text/Graphics
PRJ	Shift-P	Change the projection plane

Buttons available in a left edge

Sel	Shift-4	Select the periapis to use
Dsp	Shift-5	Display additional graphics in map
Azo	Shift-6	Enable or Disable autozoom feature
Slf	Shift-1	Display or Hide ship's trajectory
Soi	Shift-2	Display the Sphere of influence
IPC	Shift-3	Include plane change in prediction
Plan	Shift-5	Switch flight planning mode on and off
Find	Shift-6	Find targets from the reference

Key commands for Map program

Items in a displays

PeT Time to Periapis

PeD Periapis distance from the center of the reference planet

PeV Relative velocity to the reference planet in a periapis

PeA Periapis altitude from the surface of the reference planet

ReT Time to re-entry, time to landing

ReV Re-entry velocity

ReA Re-entry angle

Inc This is the inclination of current orbit relative to the ecliptic plane.

RIn This is the relative inclination to the target orbit. $\angle(\vec{\mathbf{n_s}}, \vec{\mathbf{n_s}})$

EqI Equatorial inclination of orbit

EIn Escape/Ejection Inclination. An angle between escape vector and the orbital plane of the ship, it is defined as: $\pi/2 - \angle(\vec{\mathbf{n_s}}, \vec{\mathbf{E}})$. In a transfer programs, It is also the angle between the orbital plane of the ship and the target position at the time of interception.

Tn Time to next node. When negative it is presenting the time after the node.

TEj Time to ejection. Time to launch window. (MJD) below this item is presenting the modified julian date of ejection.

TIn Time to intercept the target. (MJD) below this item is presenting the modified julian date of intercept.

TtB Time To Burn. Time to main engine start

EjA Angle between the velocity vectors (tangents) of the ship's orbit and the transfer orbit at the time of ejection

InA Angle between the velocity vectors of ship's orbit and transfer orbit at the time of interception

BT Remaining burn time in seconds at full thrust

Cir Burn time for orbit circularization in periapis

PlC Burn time for plane change burn and the attitude mode to be used with the maneuver.

Ins Burn time for target orbit insertion.

Lon Longitude on the planet's surface. In a Map program this is the periapis location and in a BaseApproach program this is the target location.

Lat Latitude on the planet's surface

Ecc Orbit eccentricity

LAN Longitude of ascending node relative to ecliptic

GeR Radius of geostationary orbit. Used in Map program only

Rad This item presents the radius of the orbit being targeted

Dis Distance between positions

Trl True longitude of ejection position

ALE Longitude of ascending node relative to the equator

C3 Orbital energy of escape asymptote. $C_3 = o_V^2/1000$

dV Delta velocity for the burn

oV Outward delta velocity

Tutorials and Checklists

Surface Launch From Earth To Moon

1. Load a scenario where a ship is located on the Earth's surface.
2. Open the **Planar Intercept** program, that's in a course program collection.
3. The program will ask you to setup the target. Press [TGT] (Shift-T) to setup the target to the "Moon".
4. The flight from the Earth to the Moon will take approximately three days. Select (TIn) item with [Prv],[Nxt] buttons and press [Set] button after that. When the dialog box opens write "3d". That would mean three days.
5. In a same way setup TEj to zero.
6. Look at the (Hed) item and wait until it is approximately 90 degrees. That may take 24 hours.
7. Engage the engines and turn the ship in a heading as guided by the (Hed) item. That should be approximately 90 degrees now.
8. Make the orbit insertion to almost a circular orbit as required by the ship. During the liftoff look at the (EIn) item. That will tell how much your ship is miss aligned from the optimal ejection plane. You can effect to that value by turning your ship in to the left or right from the heading displayed by (Hed). 2 to 8 degrees should be enough. The goal is to get the (EIn) as close to zero as possible.
9. After reaching the orbit. What ever the plain alignment is. Select the burn mode item that is currently labelled as "Realtime" and change it to "Pro-grade".
10. Press [PG] button to change the button labels in a right edge of the screen and press [AB] button to activate the autoburn. Note that you can change the zoom factor with the [Z+] and [Z-] buttons.
11. If the plane alignment was a great you will now intercept the moon. However, if the plane alignment was not so good you may need to do a mid-course correction with the Off-plane intercept program.

A mid-course correction

1. Open the **Off-plane intercept** program located in a course program collection.
2. Setup your target by pressing [TGT] button.
3. Verify that the source is the ship. That would be the (Src) item in a top edge and middle. If not, press [PG] and [Src] buttons and write "x" in a dialog. If you are about to do a course correction on interplanetary mission too early it may display that you need to wait until the ship leaves the minor SOI.
4. Select [TEj] item and set it to zero. By pressing [Set] button and writing the "0".
5. Then select the (TIn) item and adjust it with the [+] and [-] buttons. You can choose the speed of adjustment by pressing the [Adj] button. The current adjustment factor is shown in a bottom edge and middle of the screen. The goal is to adjust (TIn) so that the burn time (BT) in a bottom-left corner is as low as possible.
6. Engage the autoburn by pressing [AB] button.

Planet Approach

1. Open the **Planet Approach** program from course program collection.
2. Setup the reference to the planet being approached by pressing [REF] button. It is most likely chosen incorrectly by the automatics.
3. Wait until the "Low Influence" text goes a way if it is displayed.
4. Setup the periapis altitude by selecting the (Alt) item. Press [Set] and setup the value you want.
5. Select (EqI) item that would be equatorial inclination. Press [Set] and setup the value you want. Note that you can not reach low inclination orbits with this way. The limits will depend on your current approach angles. To reach low inclination orbit execute the standard plane change maneuver in a node.
6. Setup (TEj) to zero.

7. Engage autoburn with [AB] button. However, the burn executed far from the planet may not be accurate enough so you probably need to do another burn closer to the planet.

From ISS to the Moon

Of course, this small tutorial can be used to launch from any orbit around the Earth. This tutorial is using a technique that will have two launch windows in every month.

1. Open IMFD and the Planar Intercept program from the Course program collection.
2. At First, the program will ask you to setup the target. Press [TGT] button and write "Moon" in a dialog box. Source and reference will be configured automatically.
3. Then you need to setup the time of arrival to the Moon. Select the Time to Intercept item (TIn) with the [Prv] and [Nxt] buttons. Start Increasing it until the Ejection inclination (EIn) is zero. When it is zero it will mean that the Moon is located in the orbital plane of the Ship and the ISS at the time when the interception will occur. (*if you use the default scenario "Docked At ISS" a good value for Intercept MJD is 51992.2*)
4. Now you know when to be on the Moon but still need to figure out the launch date. The flight from earth to moon will take approximately four days. So, Let's reduce four days from the intercept time. Select Time to Ejection item (TEj) or the ejection MJD below it and set it to 51988.2
5. You can zoom in/out the display by pressing [Z+] and [Z-] buttons from the right edge. If you can't see the buttons press [PG]. When you see the orbit of the moon you can fine adjust the (TEj) so that the trajectory is what you want.
6. Then Choose the "realtime" item and switch it the pro-grade. The program will find a suitable position for the burn.
7. Then you need to wait the launch window. That will happen most easily by writing the ejection MJD on a paper and exiting the orbiter. Open the scenario file and edit the MJD but remember to reduce at least a few hours from it.
8. Due the long wait and the non-spherical gravity and the other perturbations. The (EIn) has changed a bit, that's not a problem since it can be fixed by fine adjusting the interception time (TIn).
9. Re-activate the pro-grade mode by switching the realtime/pro-grade selector. And the actual burn position is recalculated.
10. Enable the autoburn with the [AB] button.