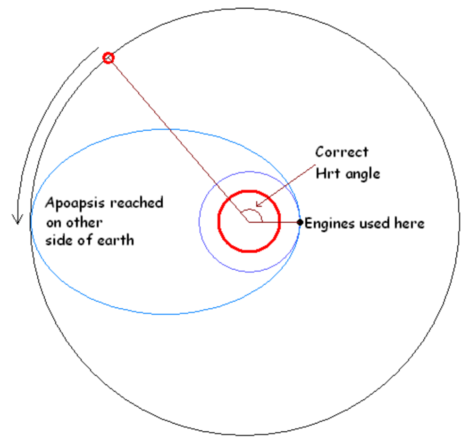
Training Assignment: Complete a transfer orbit to the moon
Departure from earth orbit and arrival in lunar orbit

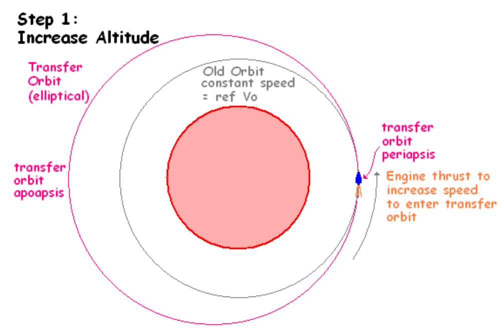
Low Energy Method

In this procedure, an engine burn is made while in orbit around the earth. Since we are transferring to a higher orbit around the earth, the engines are used to speed up the spacecraft. This engine burn puts the spacecraft into an elliptical transfer orbit with the apoapsis at the same distance from the earth as the moon's orbit. The spacecraft coasts along the transfer orbit to its apoapsis.



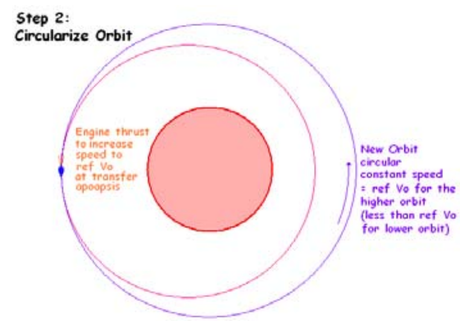
While coasting up to its apoapsis, the moon continues to orbit the earth, so you cannot aim your apoapsis directly at the moon when the engine's are fired, because the moon will have moved to a new position in it's orbit by the time you reach apoapsis. The engine burn must be timed so that the moon reaches your apoapsis point at the same time that you do. The best way to time the engine burn is with the Hrt angle. The TRANSORB program will give you this angle, or you can take a few trials to estimate it: try one angle, and see what Hrt angle you have with the moon when you reach your apoapsis. Adjust your departure Hrt angle by this amount and try again.

Your apoapsis will be displayed during your engine burn, so you need only cut off main engines once the desired apoapsis is displayed. All that you need to know is what distance the moon is from the earth. That is your desired apoapsis.



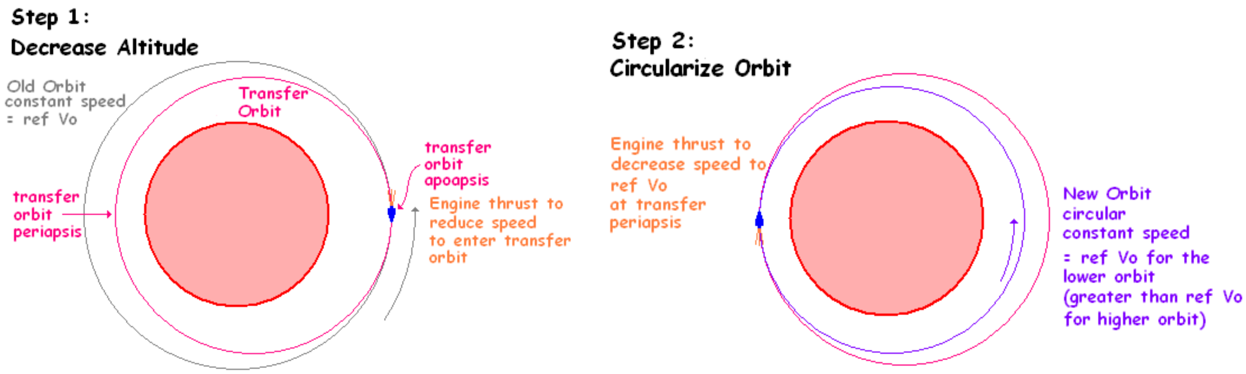
Keep in mind, however, that the moon's orbit is ***not*** circular. The earth-moon distance at the point you fire the engines may not be the earth-moon distance at the point of your apoapsis.

At the transfer orbit apoapsis, your spacecraft will be traveling slower than ref Vo for the earth and slower than the moon (which is orbiting at about the correct ref Vo for the earth). So, the moon will be coming towards you from behind. Its gravitational attraction will be slowing you down even more. So, you need to fire your engines to speed the spacecraft up to the proper speed to enter a stable orbit around the earth.

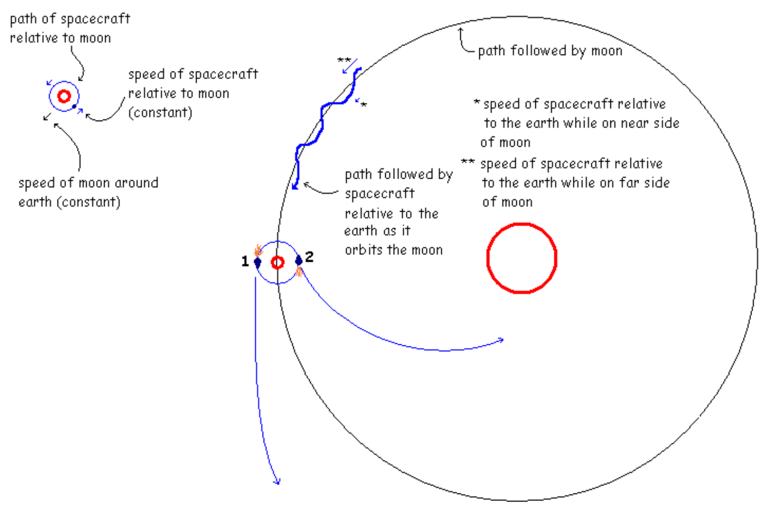


The best way to do this is to ignore the earth at this point, set your reference object to the moon. Your orbital velocities will show you falling towards the moon (or that it is racing towards a collision course with you depending on what point of view you want to take). Use your normal procedures to establish an approach to a stable orbit (step 9 in the low-energy transfer orbit procedures outlined below).

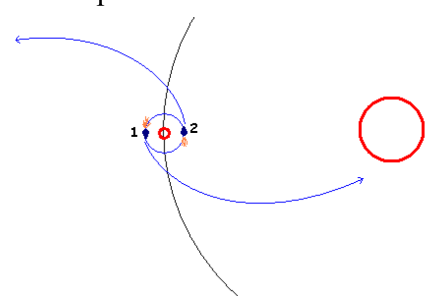
If we were trying to return to the earth from a higher orbit, we would use our engines to slow the spacecraft down relative to the earth.



However, we are leaving from an orbit around the moon and this complicates the issue. If we ignore the gravity of the moon, we might reason as follows. We would have our engine burn take place when we were on the same side of the moon as the earth, rather than the opposite side. This way, we would be speeding up relative to the moon, but slowing down relative to the moon's orbit around the earth, so that we would fall back down towards the earth (2). *Speeding up relative to the moon is important, because if we slow down relative to the moon, we will fall towards it and perhaps crash.*

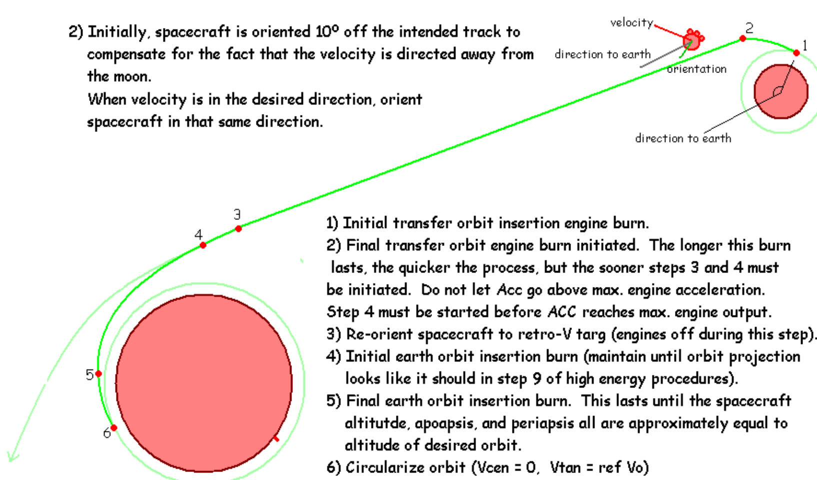


If the engine burn takes place on the far side of the moon relative to the earth, the direction of thrust is such that the spacecraft speeds up both relative to the moon and the earth. The spacecraft would then rise up away from the earth to a higher apoapsis (1).



However, the moon's gravity ***does*** affect our transfer orbit! In fact, any engine burn will produce an elliptical orbit around the moon just like the transfer orbit we produced when we left earth. So, we can see that firing the engines to increase speed on the far side of the moon (1) from the earth is the correct procedure after all.

There is one complication, though. The earth's gravity is much stronger than the moon's. The earth will start affecting this transfer orbit and bending it towards the earth much more and much sooner than the moon did in our transfer orbit from the earth to the moon. Because of this, a lot more trial and error will be needed to work out the correct timing and duration of the engine burn.



As a result of this complication, it is probably easier to conduct a high-energy transfer orbit to the earth. A sustained engine burn would be used to accelerate towards the earth

Low Energy Transfer Orbit Procedure
Start Orbit5tm; press “r” to load the file “TLI”

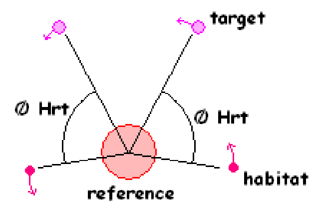
Step 1: a) Estimate the Hrt angle between moon-earth-spacecraft at which to initial engine burn.
- guess
- use TRANSORB software

b) Determine the altitude of the moon “above” the earth.

Step 2: a) Select NAV mode ccw prog (assuming that you have a prograde orbit).
b) Select target = moon, reference = earth
c) Press “l” (“L” key) if the target information box does not display ‘r’ after Vcen, Vtan, etc.
d) The reference angle (below Vtan) should read Vtr (angle between velocity vector and angle to target vector) rather than Pch (pitch angle) since Vtr is more useful to us later in this procedure. Press “p” if this is not the case.

Step 3: Verify that the current orbit is circular
(apoapsis = periapsis, Vcen =0, Vtan=ref Vo, press “o” to display projected orbital path).
Verify that fuel supply is adequate (10 to 20 thousand kg) and that RCS pressure is nominal.

Step 4: Wait until desired Hrt angle is reached with the spacecraft traveling towards (not away from) the moon. Remember that the desired Hrt angle will happen twice each orbit, once going towards the target and once traveling away from the target.



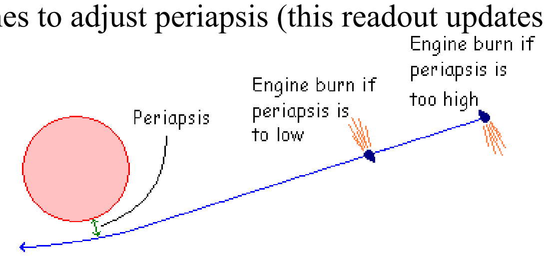
Step 5: Initiate engine burn at near maximum thrust.

Step 6: a) Monitor apoapsis during the engine burn. It updates continuously.
b) Main engine cut off (MECO) should occur when apoapsis equals the moon’s distance from the earth (determined back in step 1).

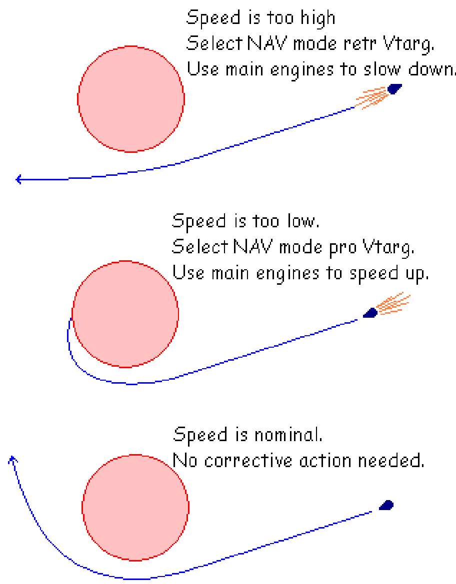
Step 7: The spacecraft will coast up to its apoapsis. It will get slower and slower as the earth’s gravity pulls on it. The moon will continue to follow its orbit to meet the spacecraft at the apoapsis point.

Step 8: When the transfer orbit is 80% to 90% complete, the moon becomes a significant gravitational force governing the spacecraft’s path around the moon.
a) Press “l” to change target data box to display information relative to target instead of reference.
All the little ‘r’ notations disappear.
Alternatively, you can select reference = moon.

Step 9: a) Note the periapsis of your orbit around the moon.
Ideally, we want this to be between 100 km and 200 km.
To adjust periapsis:
i) press “o” to display orbital path; you want a clear picture of the situation.
ii) use main engines to adjust periapsis (this readout updates continuously).



b) Press “o” to display orbital path.
We will use this to assess our speed at periapsis.



Step 10: Coast down to the periapsis point.
Monitor the periapsis readout continuously.
- it will drift up or down.
- adjust as needed using the procedure in step 9a.

Monitor periapsis speed periodically and adjust if needed using the procedure in step 9b.

Step 11: When the spacecraft is almost at the periapsis point, the orbit must be circularized.
If this is not done, the spacecraft will follow the hyperbolic orbit out into deep space.
This is because our tangential velocity is too large (it had to be to carry us to this point in a reasonable span of time.

Near the periapsis point: Vcen will be negative, but nearly zero.
- if Vcen is positive, you overshot the periapsis point

Distance to target will be decreasing, but close to periapsis distance

a) Select one of the following NAV modes: i) retro Vtarg (easiest to use)
ii) ccw prog (if in a clockwise orbit)
iii) ccw retro (if in a counter-clockwise orbit)

b) Initiate a high-thrust engine burn.
c) Monitor Vtan.
When Vtan = ref Vo, cut off main engines.

Step 12: a) Follow steps in training document 1 to adjust orbit so that it is circular.
b) Select target = target to identify intended landing site.

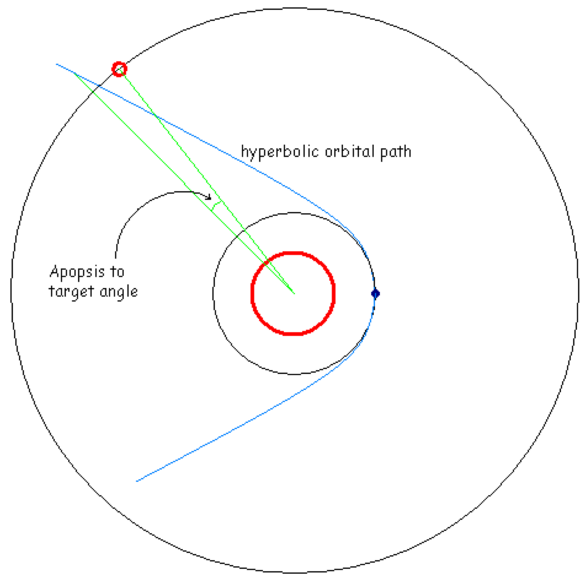
Step 13: Follow the steps in the landing training document: section 4 (landing from orbit).

High Energy Method

In this procedure, engines are used almost continuously during the transfer orbit. They are used to speed up the spacecraft until the half-way point and then to slow it down again during the second half of the transfer.

This procedure has the advantages of taking very little time and, as a result, we can aim more or less directly at the moon rather than calculate an Hrt angle to aim with.

The disadvantages of this procedure are the much greater fuel use and the dangers involved with the high speeds that are attained. High speeds make it difficult to process and act on information at critical phases of the transfer orbit. They also make the consequences of engine failure much more serious.



The aiming process involves use of the apoapsis-reference-target angle. This is displayed in the bottom-left corner of the screen when the orbital path is displayed. This is the angle between the apoapsis point and the target with the reference object as the vertex. This is just like the Hrt angle.

When the orbit is hyperbolic or parabolic, there are two apoapsis points, since the spacecraft is traveling at or above its escape velocity. Both of these points are at infinity. Thus, there will be two apoapsis to target angles displayed. You will be able to figure out which is which by looking at the path that is displayed. The actual angle is calculated from a point along the path that is closer than infinity, but the value will be approximately the same.
A periapsis to target angle also is displayed.

<u>High Energy Transfer Orbit Procedure</u>

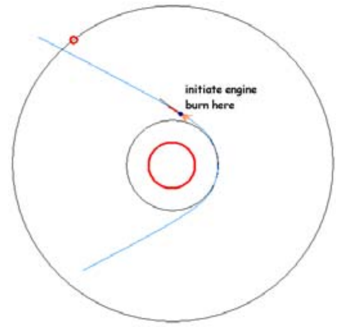
Start Orbit5tm; press “r” to load the file “TLI”

Step 1: a) Select NAV mode ccw prog (assuming that you have a prograde orbit).
b) Select target = moon, reference = earth
c) Press “l” (“L” key) if the target information box does not display ‘r’ after Vcen, Vtan, etc.
d) The reference angle (below Vtan) should read Vtr (angle between velocity vector and angle to target vector) rather than Pch (pitch angle) since Vtr is more useful to us later in this procedure. Press “p” if this is not the case.

Step 2: Verify that the current orbit is circular
(apoapsis = periapsis, Vcen =0, Vtan=ref Vo, press “o” to display projected orbital path).
Verify that fuel supply is adequate (10 to 20 thousand kg) and that RCS pressure is nominal.

Step 3: Wait until the moon is just over the horizon from the spacecraft (as in the diagram above).

Step 4: Insert spacecraft into a lunar transfer orbit.
a) initiate a high thrust engine burn
b) monitor orbital path (press "o") until the projected orbit becomes a hyperbola
- apoapsis display will be show ------ since apoapsis is at infinity
c) continue to fire engines while pressing 'o' until the angle until the apoapsis to target angle is close to zero. We want the orbital path to pass just a couple of degrees in front of the moon as is shown in the diagram on the previous page.



Step 5: Cut off main engines and coast until the velocity vector and vector to target are in about the same direction.

Step 6: a) Select NAV mode app targ
b) Engage main engines at approx. 90% thrust.

Step 7: Monitor ACC readout.
When ACC approaches the maximum engine acceleration:
a) Cut off main engines,
b) Select reference = moon
c) Select NAV mode Depart ref
d) Wait for reorientation of spacecraft to be completed (Pitch angle should be near 180^o)
e) Engage main engines at a thrust level that produces an acceleration as close as possible to ACC.

Step 8: a) Monitor ACC and Vtan as the spacecraft falls towards the moon.
ACC should stay fairly constant.
The target value is approximately the what the engine acceleration would be at 90% thrust
i) if ACC rises, you are going too fast
- increase thrust to maximum or (higher than ACC even if this means > 100%)
- when ACC drops to target value reduce thrust to match engine acceleration to ACC
ii) if ACC decreases, you are going too slow; not dangerous, but wastes time
- reduce thrust to less than ACC
- when ACC rises to target value increase thrust to match engine acceleration to ACC
iii) if ACC gets too high, it cannot be corrected without overheating the engines or reactor.
- select NAV mode ccw prog or ccw retro depending on which side of the moon you are on.
- use full thrust until the orbit projection shows a periapsis of at leas 1000 km
- select NAV mode retro Vtarg and use max sustainable thrust until your V hab-ref is nearly zero (you will have passed the moon, but not crashed into it)
- set NAV mode app targ and use high thrust until Vcen is -500 m/s or more negative
- follow steps 9 to 13 in the low energy transfer orbit procedure

Step 9: When the transfer orbit is about 80% to 90% complete:
a) Increase thrust until ACC drops to 50% of maximum engine acceleration,
b) Follow steps 9 to 13 in the low energy transfer orbit procedure.