

Tutorial:

Landing on the moon in Orbiter

using only standard MFDs, HUDs and autopilots

Introduction

In this tutorial I'll explain how you can land on the moon without special landing autopilots like Land MFD. Only standard HUD modes, MFDs and standard Orbiter autopilot modes (Prograde, Retrograde, KillRot etc.) will be used. If you are skilled enough (or if you have plenty of fuel), you'll even be able to land at an exact location, like the landing pad of a surface base.

This tutorial will focus on realistic spacecrafts, like NASSP's Apollo LM, and FrancisDrake's CEV LM. These only have one set of engines, which is pointed in the “hover” direction (downward from the pilot's point of view). More futuristic spacecrafts, like the Delta Glider, often have separate sets of engines for acceleration (pointing backwards) and for hovering (pointing downwards). While you could use this tutorial on these spacecrafts (using the hover engines only), it's probably easier to use both kinds of engines. Also, in this tutorial, no radio navigation is used: the only navigational aids are Map MFD and the base marker in Surface HUD. However, you can combine this tutorial with the use of radio beacons: they can make life a lot easier if you know how to use them.

Some stages of the landing require fast action, and sometimes you'll have to do a lot of things simultaneously. Therefore, it's probably best to first read the entire tutorial once before trying, so that you're always prepared for the next stage of the landing. Even then, you'll probably have to practice many times, before you manage to finish your first perfect landing. While practicing, you can always use Ctrl-P to pause the simulation, and re-read a part of this tutorial. Of course a real pilot wouldn't be able to do this, so if you want to simulate a realistic landing, you should know the procedures by heart.

Good luck!

Basic concepts

I assume you're already familiar with all basic spaceflight concepts, but some of these can be a bit confusing when flying a machine that has its engines pointing downwards instead of backwards. In this section I'll define these concepts.

- **Prograde / Retrograde** orientation: Point the “nose” of the machine (the direction you're looking at) parallel / anti-parallel to the orbital velocity-vector. This is exactly what the Prograde and Retrograde autopilots do.
- **Pitch**: Rotate the “nose” up/down. Can be done with keys 2 and 8 on the numpad.
- **Yaw**: Rotate the “nose” left/right. Can be done with keys 1 and 3 on the numpad.
- **Roll**: Rotate around the “nose” clockwise/anticlockwise. Can be done with keys 4 and 6 on the numpad.

Further, I assume you know exactly how to control the engine thrust in Orbiter. For making this tutorial, I used the CEV LM, and its engines can be controlled using the main engine controls. It is possible that on some spacecrafts you can only use the hover engine controls (numpad 0 and .); in that case, controlling the engine is a bit more difficult, but it's not impossible.

Initial situation

This tutorial starts with your spacecraft in a LLO (Low Lunar Orbit): an almost circular orbit with an altitude of not more than a few hundred kilometers. I'll not explain how to get there; you should use other tutorials for that purpose.

If you wish to land at a certain base, your orbit should go exactly through the location of the base in Map MFD. If it doesn't, then you can accelerate time and let the rotation of the moon bring the base under your orbit. However, this can take several weeks, so in a realistic scenario you'll probably want to avoid this. If you have plenty of fuel, you can also do some engine burns to change your orbital plane, but, again, in a realistic scenario you wouldn't have enough fuel for this. Therefore, the only realistic thing to do is to make sure your orbit is already above the target base as soon as when you enter it.

The screenshot below shows what the initial situation should look like. Orbit MFD shows a circular LLO with an altitude of 38km. The exact value isn't really important, as long as it's a low and almost circular orbit. Map MFD shows that we selected a target base, and that our orbit exactly passes over it.

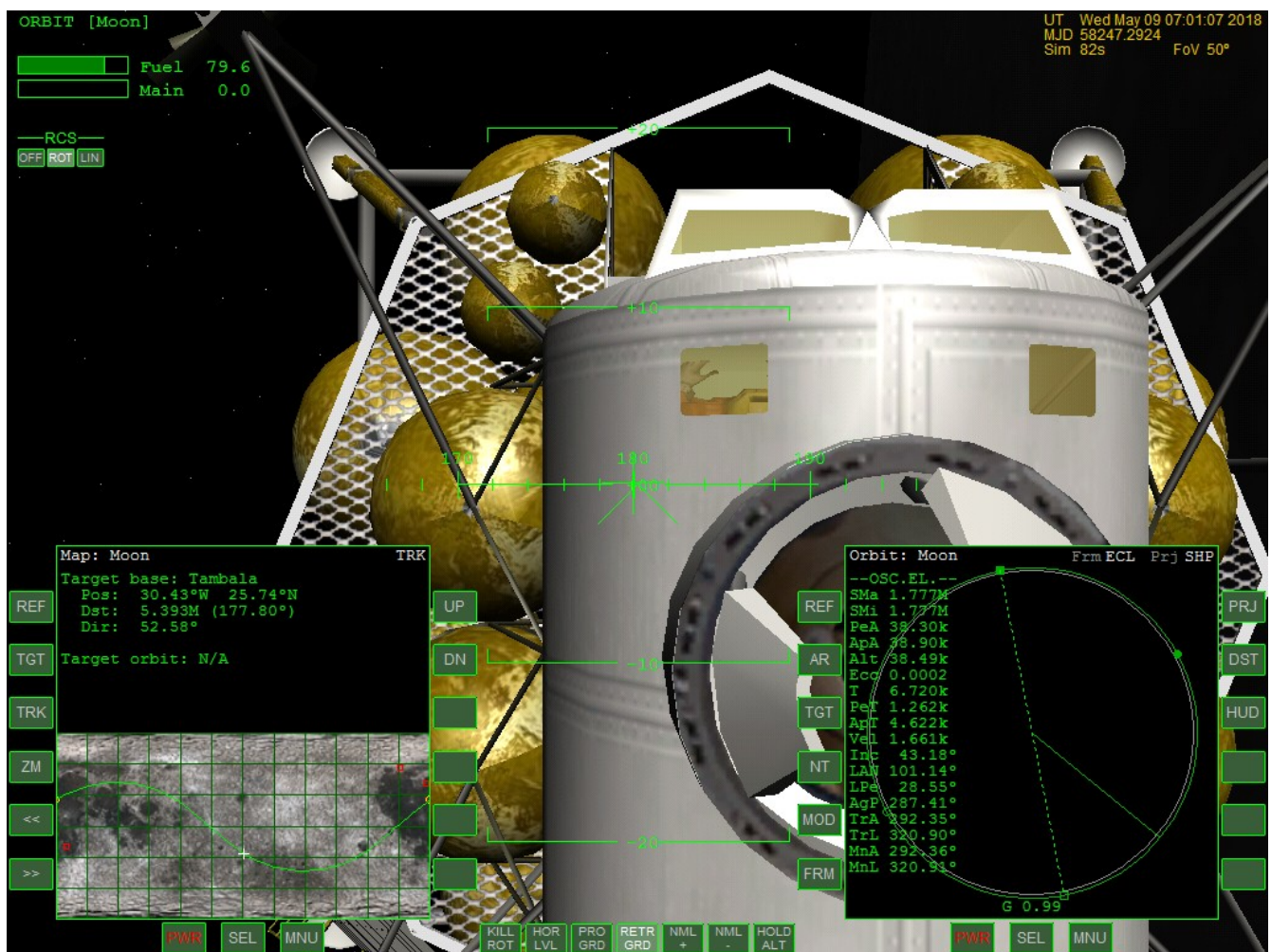


Figure 1: The situation just before the orbital lowering burn: a circular LLO passing exactly over the target base.

Stage 1: Lowering the orbit

The first step is to lower your PeA as much as possible. This will lower your altitude as much as possible while you're still in orbit, which is efficient: lowering your altitude in a later stage requires you to hover for a long time, which costs lots of fuel. Your new periapsis should be just above the target base, so the deceleration burn should take place exactly on the opposite side of the moon.

If you have an orbital spacecraft (like the Apollo CSM, or the CEV orbital spacecraft), you can use its engines for the deceleration burn. This will save fuel on the LM descend stage. Also, it's easier to align its engines retrograde, because you can simply use the Retrograde autopilot. But, the decision on which engines to use is up to you: you know the best where you need your fuel most.

This is what you should do if you decide to use the orbital module's engines:

- **Take control of the orbital spacecraft (F3)**
- **Use Orbit MFD, Map MFD and Orbit HUD**
- **Keep the orbital spacecraft in retrograde orientation (with the Retrograde autopilot)**
- **Wait until you are at the exact opposite side of the moon as your target base (then Map MFD looks like in Figure 1)**
- **Then, burn your engines until your PeA is approximately 1 km (say, between 900 m and 1.5 km)**
- **Undock from the LM**
- **Rotate the orbital spacecraft 180 degrees and enable Prograde autopilot**
- **Move it a bit sideways using linear RCS thrusters (this is to make sure our engine exhaust won't damage the LM)**
- **Burn your engines again to bring the orbital spacecraft back to a safe parking orbit. Make the orbit as circular as possible to make it easier to rendez-vous with the LM in the future.**
- **Disable all autopilots on the orbital spacecraft (for safer time acceleration)**
- **Take control of the LM spacecraft (F3)**

This is what you should do if you decide to use the lander's engines:

- **Take control of the LM spacecraft (F3)**
- **Use Orbit MFD, Map MFD and Orbit HUD**
- **Undock from the orbital spacecraft**
- **Wait until you are at the exact opposite side of the moon as your target base (then Map MFD looks like in Figure 1)**
- **Make sure your *engines* are in retrograde orientation. The Nml+ autopilot will do this.**
- **Then, burn your engines until your PeA is approximately 1 km (say, between 900 m and 1.5 km)**

The result is that you are in control of the LM spacecraft, and that after one half orbit it will fly very low (1 km altitude) over the target base. The exact PeA altitude is selected for safety reasons: if you are a better pilot, you can choose a lower altitude, but 1 km will give us some time to correct for errors, so that a small mistake won't immediately let us crash. If you use Orulex or another landscape generator, then you might want to use a higher value, so that you won't crash into mountains. A higher PeA value means you'll need to spend more fuel in the final descend.

Stage 2: De-orbiting

This stage will slow us down to sub-orbital velocities when we approach the target base. The first thing that needs to be done is to rotate the spacecraft to a convenient orientation:

- **Use Orbit MFD, Map MFD and Surface HUD**
- **While you fly your orbit, keep an eye on the PeA value in Orbit MFD. If you enabled non-spherical gravity sources, it could change and become dangerously low. My experience is however that when the initial PeA was 1 km, it won't become less than 800 m, which is acceptable.**
- **Zoom in on Map MFD, and wait until you are so close to the base that it becomes visible. As you can see in figure 2, this will happen when Map MFD reports a distance (Dst) to the base of approx. 1900 km.**
- **Orient the spacecraft such that it looks like figure 2. Enable the HorLvl autopilot to keep your spacecraft exactly horizontal, and use the yaw controls (and KillRot) to point the nose exactly in prograde direction.**

If you do this at approximately 2000 km away from the base, then you have plenty of time to do this. The result should look like this:

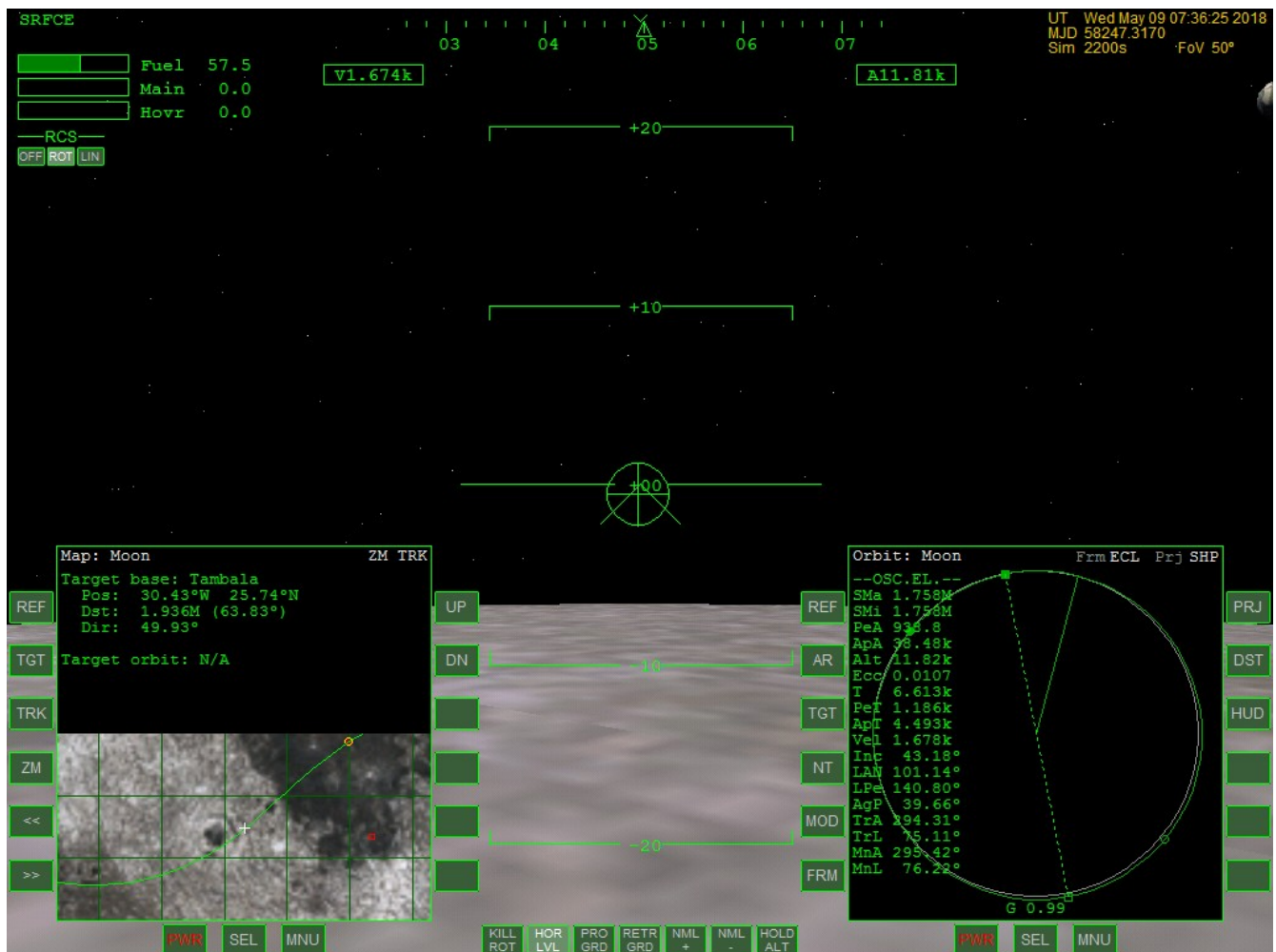


Figure 2: The first step in orienting the spacecraft: HorLvl and in prograde direction.

Now, the nose is pointed prograde. The next step in orienting the spacecraft is to give the engines a retrograde orientation:

- **Disable all autopilots**
- **Pitch up 90 degrees**
- **Stop the rotation with KillRot**
- **Change to Orbit HUD**

You can check in the external view that your ship's engines are oriented correctly for a retrograde burn. Your HUD should look like this:

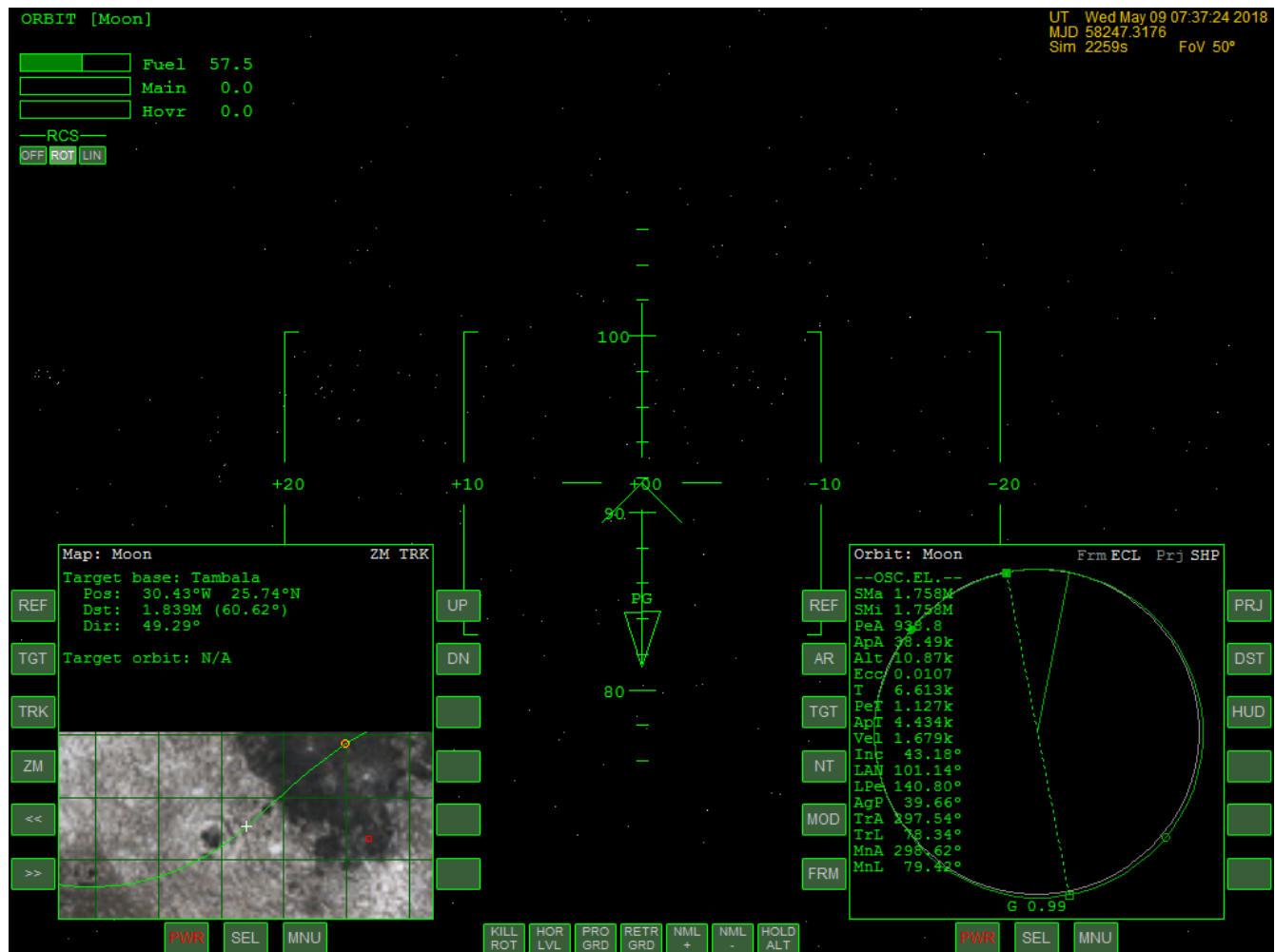


Illustration 3: The final orientation for the de-orbiting.

Now, you should wait for the right moment to start your engines. Timing is very important here, but unfortunately it's different for different spacecrafts. The value to watch here is the distance to the base (in Map MFD). My experience is that with the CEV LM, the deceleration burn should be started 150 km before the base, but for other vehicles you'll have to find the optimal distance with some trial and error (or maybe with some simple calculations).

As you are waiting for the right moment, you'll notice that the HUD changes. You have to pitch down the ship to correct for this, to keep the 90 degree mark in the Orbit HUD centered. Some 150 km before the planned start of the burn (for the CEV, that is at a distance of 300 km from the base), you do the final preparations:

- **Use Surface MFD, Map MFD and Orbit HUD**
- **Just seconds before the start of the burn, do a final correction of your orientation**
- **Switch to Surface HUD**

Finally, when Map MFD shows exactly the correct distance to the base (150 km in the case of the CEV LM), start your engines. Go immediately to full throttle, because that is the most efficient way to de-orbit. Now you have to monitor multiple things at the same time:

- **Keep your spacecraft at a constant altitude (my suggestion is an altitude of 1 km). You'll have to look at altitude (in the HUD or ALT in Surface MFD), the vertical velocity (VS in Surface MFD) and vertical acceleration (VACC in surface MFD). By changing the pitch, you can change the vertical acceleration: pitching down will increase the vertical acceleration, and pitching up will decrease vertical acceleration. If your altitude is above 1 km, you should aim for a negative VS, and if your altitude is below 1 km, you should aim for a positive VS. Keeping the VS low (not more than several meters per second up or down) will make it easier for you. Once you're happy with a certain VS, you should make the VACC as small as possible by using the pitch controls and KillRot. You'll have to adjust your pitch continuously, because there are also other factors that change VACC (such as your decreasing velocity, and the decreasing amount of fuel)**
- **Watch the velocity of your spacecraft (in the HUD or in Surface MFD). During de-orbiting, it will decrease, until it becomes almost zero. At that point, the de-orbiting burn should stop, or otherwise you'll start accelerating in the opposite direction. Watch how fast your velocity drops, and continue with the next stage when**
 - **it will only take seconds to reach zero**
 - **it starts to stabilize to a certain value**
 - **it has started to increase (actually, that's already a bit too late)**

Once your velocity is as small as possible, you should continue to the next stage. But first let me give you a table that could help you with maintaining your altitude:

<i>ALT</i>	<i>VS</i>	<i>VACC</i>
> 1 km	< -5 m/s	aim for positive VACC
	-5 m/s ... 0 m/s	OK; aim for very small positive VACC
	> 0 m/s	aim for negative VACC
< 1 km	< 0 m/s	aim for positive VACC
	0 m/s ... 5 m/s	OK; aim for very small negative VACC
	> 5 m/s	aim for negative VACC

After some practice you should no longer need this table. There is no need for panic as long as ALT is between 500 m and 1.5 km, and VS is between -5 m/s and 5 m/s. VS closer to zero is better, because the situation changes less rapidly, and it will be easier to control the situation. The same is true for VACC: you should only use large vertical acceleration in emergency situations (e.g. when you're about to crash). Generally speaking, you should only need minor pitch changes to change from negative to positive VACC and vice versa.

Stage 3: Hovering

As soon as you finish the de-orbiting, you quickly have to do the following:

- **Shut down your engines**
- **Immediately pitch down to a horizontal orientation, and enable HorLvl autopilot**
- **You've started to fall down: give some small full-throttle engine burns to throw you up again (make sure your vertical speed (VS) becomes positive: +5 m/s would be a nice value)**
- **Throttle up your engine until your vertical acceleration (VACC) is only a very small negative value**

Now it's time to stabilize your altitude again. You can use the same table as in the previous stage, but this time you use the engine throttle to change your vertical acceleration: more thrust = higher VACC, and less thrust = lower VACC.

The view should now look like the picture below. You can also yaw the spacecraft to let the nose point towards the base indicator in the HUD, like in the screenshot. In the screenshot, the base is already visible, but if you're further away, that might not be the case. (This is no reason for panic. The only reason for panic would be an empty fuel tank.) You can see the distance to the base in the Map MFD. If you're really too far away, then you can learn from this: next time, choose a different distance for starting the de-orbiting. For instance, I ended up approx. 30 km before the base, so next time I'll try to start de-orbiting at 120 km before the base instead of 150 km.



Illustration 4: Hovering horizontally, just after the de-orbiting stage

Now, what you should do next depends on two things: the distance to the base, and, more importantly, on the amount of fuel in your tanks. In the last stage, you'll need some fuel to descend the last kilometer, typically between 5 and 10 percent of your fuel. In any case, you'll want to avoid to empty your tanks before you touch the ground. You could do the following:

1. If you think you don't have enough fuel, you can decide now to abort the landing, and use the descend stage to return to orbit.
2. If you think you might have just enough fuel for a landing, you can ignore the distance to the base, and land right at the spot where you are hovering now. The Apollo LM, for instance, has just enough fuel to land, so you can't use the remaining fuel to reach a base if you're hundreds of kilometers away from it.
3. If you still have plenty of fuel, you can start to accelerate towards the base and try to land there.

This is what you should do in each of these scenarios:

Abort to orbit:

- **Set the descend engine to maximum thrust. We use the descend stage and its remaining fuel as a first stage in the ascend.**
- **Make sure you have the right heading to get back to the right orbit**
- **Pitch down to make your horizontal acceleration as high as possible. Keep your vertical acceleration as low as possible, but there is no need to stay at a constant altitude.**
- **Once the descend stage is empty, make sure you start the ascend stage as soon as possible, and continue your ascend to orbit.**

Immediate landing:

- **Reduce your sideward (left/right) velocity as much as possible (see below)**
- **Reduce your forward (front/back) velocity as much as possible (see below)**
- **Maintain a (not too large) negative vertical speed to reduce your altitude**
- **The final landing is described in the last stage.**

Accelerate towards target base:

- **Point your nose towards the target base (marked in Surface HUD)**
- **Reduce your sideward (left/right) velocity as much as possible (see below)**
- **Accelerate towards the base by pitching down (e.g. 40 degrees), while increasing the thrust a bit for maintaining altitude. Remember the initial distance to the base and amount of fuel, because you'll need these values later.**
- **Continue with the next stage**

Reducing your sideward velocity is done by rolling the spacecraft (of course you need to disable the HorLvl autopilot). If you move to the right, you should roll a bit counterclockwise, so that your engines will point a bit to the right. If you move to the left, you should roll a bit clockwise. Rolling away from the vertical orientation will reduce your vertical thrust, and you should compensate this by increasing your engine thrust a bit.

During this manoeuvre, you should keep your vertical speed constant (vertical acceleration = 0), so that you can see on the velocity indicator when the sideward velocity has reached a minimum. The safest situation is when you keep the vertical speed at 0 m/s, but if you are brave enough, and you want to save

fuel in an immediate landing situation, you can choose to use a constant negative vertical speed. This will bring you closer to the ground while executing the manoeuvre. Once your velocity has reached a minimum, you should roll back to vertical, enable the HorLvl autopilot again, and check your thrust and vertical acceleration.

Sometimes, when you are landing in the middle of nowhere, you don't have enough visual clues to find out whether you move to the left or to the right. In such situations, you can simply try one side. If it causes an increasing velocity, you should do the other side.

Reducing forward velocity is done in exactly the same way, but with using pitch instead of roll. If you move forward, you should pitch up, and if you move backward, you should pitch down.



Figure 5: Hovering towards a base. The LM is pitched down to cause a forward acceleration.

Stage 4: Approaching the base

Now, if everything went alright so far, you find yourself accelerating towards your base, while maintaining a constant altitude. The next question is of course: when to stop accelerating and start slowing down? This is why you had to remember the distance and fuel percentage before you started accelerating.

During your approach, you should watch both the distance value in Map MFD and the amount of fuel. You should stop accelerating and start decelerating as soon as you reach one of these points:

- If your distance to the base becomes half of the original distance. You'll spend the second half of the approach decelerating, and it will bring you to a halt exactly above the base.
- If you've spent half of your fuel. You'll spend the other half of the fuel on decelerating, and you'll run out of fuel exactly when your spacecraft comes to a halt. This won't bring you to the base, but it will bring you as close as possible. Remember to keep some fuel for the last descend and landing manoeuvres, typically 5 to 10 percent. For instance, if you start accelerating with 25% fuel, and 5% of it is reserved for the final manoeuvres, then you can use 20% for acceleration and deceleration. After spending 10% on acceleration you should start decelerating, so you should start decelerating when there is still 15% fuel in the tank.

You should do the deceleration at the same angle as the acceleration, or otherwise the numbers won't match. So, if you accelerated by pitching down 40 degrees, then the deceleration should be done by pitching up 40 degrees. Actually, acceleration and deceleration will never match exactly, because your vehicle is a bit lighter during deceleration (as it carries less fuel). But, it is a very good approximation, and it will get you *a lot* closer to your base. You should be able to see the base below you after you finished decelerating.

Of course, you should still keep a safe altitude during accelerating and decelerating. The number of things you have to do simultaneously keeps increasing, so at this point you should be able to maintain altitude without thinking, or otherwise you'll probably get into trouble.

At a certain moment, the base should become visible. Also, your velocity indicator should be visible in Surface HUD. Now, while you are probably still decelerating, you can try to point the velocity indicator to the base, and to the landing pad. You can modify thrust to move it up or down, and you can roll a bit to move it to the left or to the right. The vertical correction will probably take you away from your "safe hovering altitude", but at this stage, this is OK. You can point a bit above your landing pad if you want to make sure you won't hit any buildings. After applying a left/right correction, you should always roll back to neutral, or otherwise the velocity indicator will continue to drift away from your target. As an alternative, you can also apply small corrections with the linear RCS thrusters. While this is easier, it will only give small corrections. If you are still decelerating during a left/right correction, you should also yaw the ship a bit, to make sure that the engines point exactly into the velocity direction.

Once the decelerating has made you slow down to only a few meters per second, you should turn the ship back to horizontal orientation, keep it horizontal with the HorLvl autopilot, and stabilize its altitude by adjusting the thrust (if you are still very high, a small negative vertical speed is acceptable). Yaw the ship to point its nose towards the landing pad. Now you should move slowly towards the landing pad. Large velocity changes can be made by pitching and rolling the ship a bit (don't forget to

pitch and roll back using the HorLvl autopilot), and small changes can be made with the linear RCS thrusters. Once you are happy with your horizontal velocity, you can adjust your vertical velocity (by changing engine thrust) to point the velocity indicator to the landing pad. Always make sure your velocity is not too high: as long as you have enough fuel, it's better to do things very slowly, because you need to get rid of all your velocity just before the final touch-down.

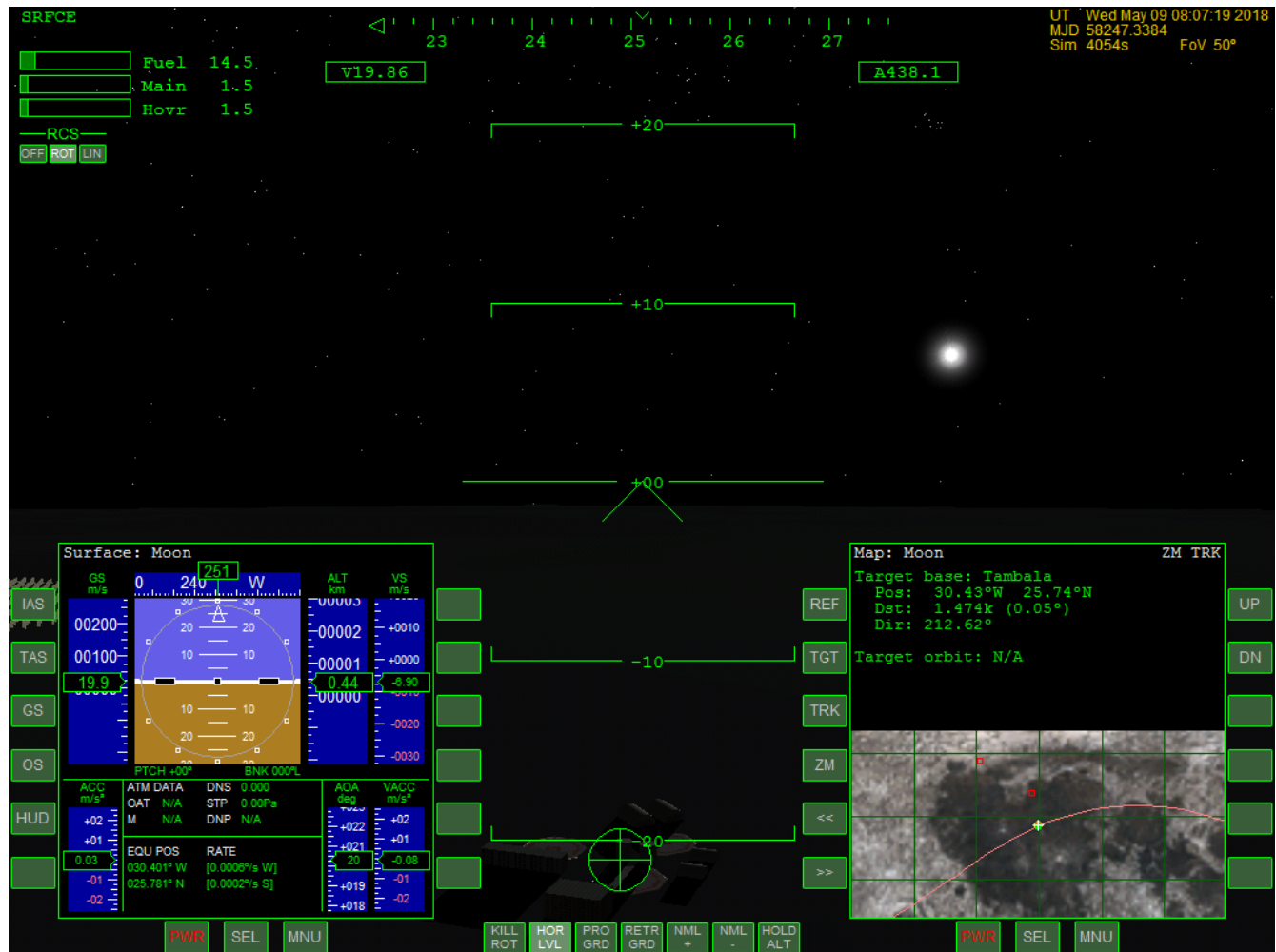


Figure 6: Approaching the landing pad. The velocity indicator is targeted correctly, but the velocity is a bit too high.

Stage 5: Landing

Just meters away from the landing pad, you should aim for a position just 1 or 2 meters above the landing pad. While you approach that position, make sure you get rid of all your velocity:

- **Eliminate the last bits of approach speed (by pitching up a bit if necessary, or with RCS thrusters otherwise)**
- **Stabilize your altitude. You can set the vertical acceleration to a small negative value, and compensate it now and then with the vertical linear RCS if you drop down too much.**

Then, you can fine-tune your position with the linear RCS, to take you exactly to the middle of the landing pad. Finally, you can do the landing by stopping to compensate the negative vertical acceleration with the RCS. You will accelerate slowly towards the ground, until you touch down. If your vertical speed becomes uncomfortable high, you can still compensate it a bit with vertical linear RCS. You can use the other linear RCS thrusters if you are drifting away from the landing pad.

When you finally touch down, shut down your engine, and turn off the HorLvl autopilot. Congratulations: you made it!!

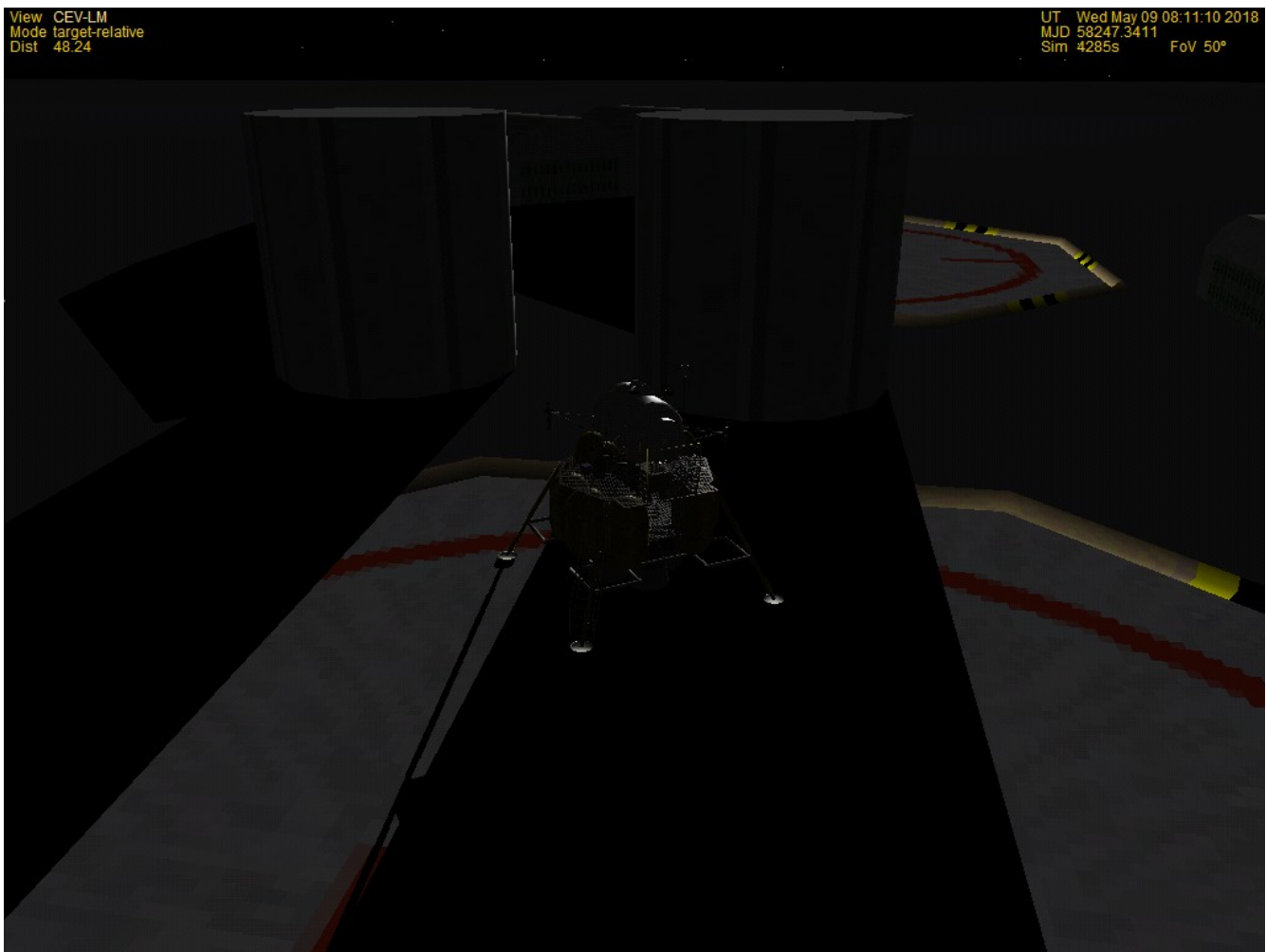


Figure 7: The position of the CEV LM at my landing attempt. It is a bit off-center, because the linear RCS didn't work properly.

Credits

- Martin Schweiger, for [Orbiter](#)
- FrancisDrake, for his [CEV add-on](#)