Translunar injection

FizziQ activity · High school · 45-60 min

Scan to open in FizziQ

Vary a probe's injection speed in the Earth-Moon three-body system until it swings around the Moon and returns, with the FizziQ Web orbit simulation in a browser.

Learning objectives

- Identify the relevant parameters (position, speed, mass) of a three-body gravitational problem
- Measure the effect of initial speed on a probe's trajectory in the Earth-Moon system
- Verify that a free return trajectory exists in a narrow speed window
- Compare the experimental speed to the theoretical Hohmann transfer value
- Understand the principle of translunar injection used by Apollo and Artemis

Instruments and sensors

FizziQ Web Orbits and Gravitation simulation

Materials

- Computer, tablet or smartphone with FizziQ Web
- FizziQ experiment notebook
- Note: the protocol remains adaptable to any comparable orbital-mechanics simulation tool.

Protocol

1. Open the Orbits and gravitation simulation in FizziQ Web (Experiment → Simulations → Orbits and gravitation).
2. Set the distance scale to about 1,000 km/pixel to visualize the entire Earth-Moon system, and the time scale to 5 minutes per frame.
3. Configure body 1 — Earth: mass = 1 M⊕ (Earth), speed = 0 km/s, angle = 0°. Leave it at the centre of the screen.
4. Add body 2 — Probe (click the + tab): mass = space probe, initial speed = 4.3 km/s, angle = 0° (rightward). Drag the probe 40,000 km to the right of Earth.
5. Add body 3 — Moon: mass = 0.012 M⊕ (Moon), speed = 1 km/s, angle = -90° (upward). Drag the Moon 385,000 km to the right of Earth with the three bodies aligned.
6. Verify the distances in the upper-right panel: probe-Earth ≈ 40,000 km and Moon-Earth ≈ 385,000 km.
7. Centre the view on Earth (button 1 in the Centering area) to track the probe in the Earth reference frame.
8. Click Start and observe the probe's trajectory. What does the probe do?
9. By varying the angle and then the speed, create a trajectory that allows the probe to pass near the Moon and return to Earth without firing the engine.
10. For each attempt, click IMG to archive a trajectory snapshot in the experiment notebook, noting the speed tested.
11. Once a free return trajectory is identified (the probe swings around the Moon and returns to Earth), click REC to record the probe's x and y positions over time.
12. Let the simulation run until the probe returns near Earth, then click REC again to export the data to the experiment notebook.
13. In the experiment notebook, create a computed quantity: probe-Earth distance = $\sqrt{x_{probe}^2 + y_{probe}^2}$. Plot this distance versus time.

14. Compare to the Hohmann transfer speed and conclude.

Expected results

The student finds that the probe's initial speed must lie within a narrow window, of order 3.7 to 3.8 km/s, for it to reach the Moon's vicinity. Below this value, the probe traces an elliptical orbit that falls back towards Earth. Above it, it moves away from the system permanently. For a precise speed (around 3.75 km/s, to be adjusted according to the Moon's starting position), the probe swings around the Moon and returns near Earth, drawing a characteristic figure-of-eight or wide loop. The required precision on speed is typically a few tens of metres per second, less than 1% error. Total trip duration is about 6 to 8 simulated days. The result is sensitive to the Moon's initial position at launch, which illustrates the need for a precise launch window in real missions. The simulator's symplectic Euler numerical integration introduces a slight energy drift that can be visible over long durations.

Questions

- Why is the speed window allowing free return so narrow?
- What happens if the probe is launched at the wrong moment (Moon at top, bottom, left)?
- How does the Moon's mass influence the return trajectory? What would an "Earth without Moon" yield?
- Why was the free return trajectory essential for saving Apollo 13?
- How does the experimental speed deviate from the theoretical Hohmann transfer value, and why?
- In practice, what would propulsion of a spacecraft be useful for if the free return trajectory is free?
- When launching the probe at angle 180° (retrograde), why does the Moon no longer manage to deflect the trajectory? Compare the relative speed at flyby in both cases (prograde and retrograde) to explain.
- If the retrograde probe eventually returns near Earth, can it be called a free return in the Apollo and Artemis sense? What is the Moon's expected role in a real mission?

Going further

- Compare prograde and retrograde: take the speed found for prograde free return, then relaunch at angle 180° (retrograde) with the same speed. Observe the large reverse loop, the rapid Moon flyby with no deflection, and the probe's return to Earth solely via its natural ellipse. Show that in this case the Moon no longer plays its deflector role.
- Modify the Moon's mass (double it, divide by ten) and observe how the speed window for free return changes
- Reproduce the blog article configuration (fixed Moon, satellite at 36,000 km) and compare the speed found to that of the animated configuration
- Add the Sun as a fourth body to observe a gravitational perturbation on the trajectory
- Test the effect of a delay or advance of a few hours on launch (change the Moon's initial angle) to make the launch window concrete