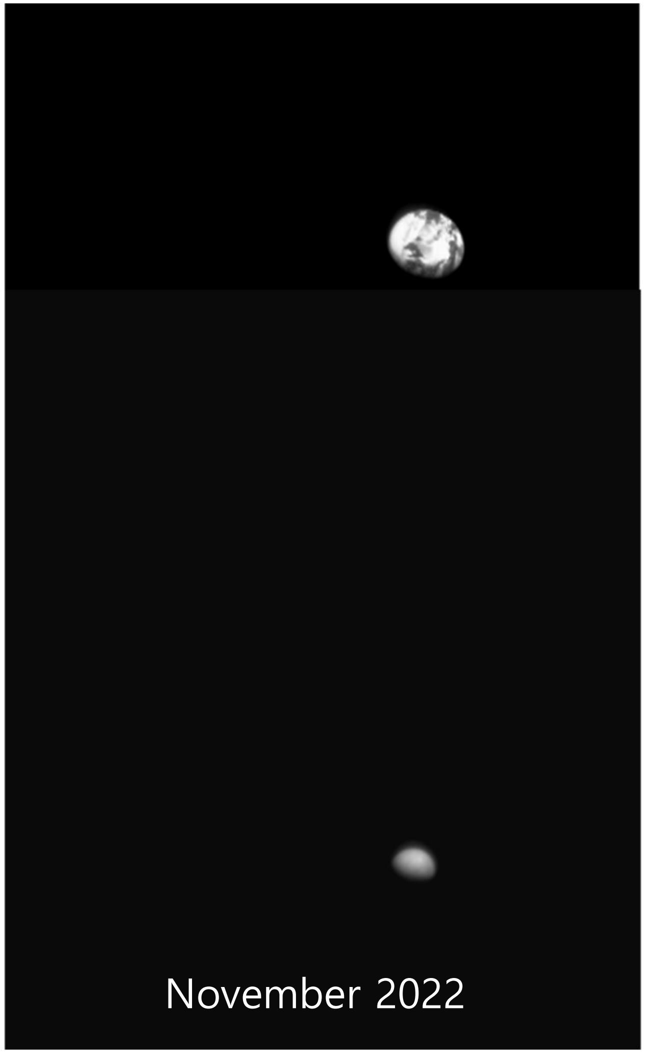
Physics of Launch Vehicles and Space Orbits

Sungsoo S. Kim
Kyung Hee University

- Danuri and PolCam
  - Danuri perfectly entered its mission orbit (100 km altitude) in late December (in fact, surprisingly well).
  - Danuri is currently in a month-long commissioning phase.

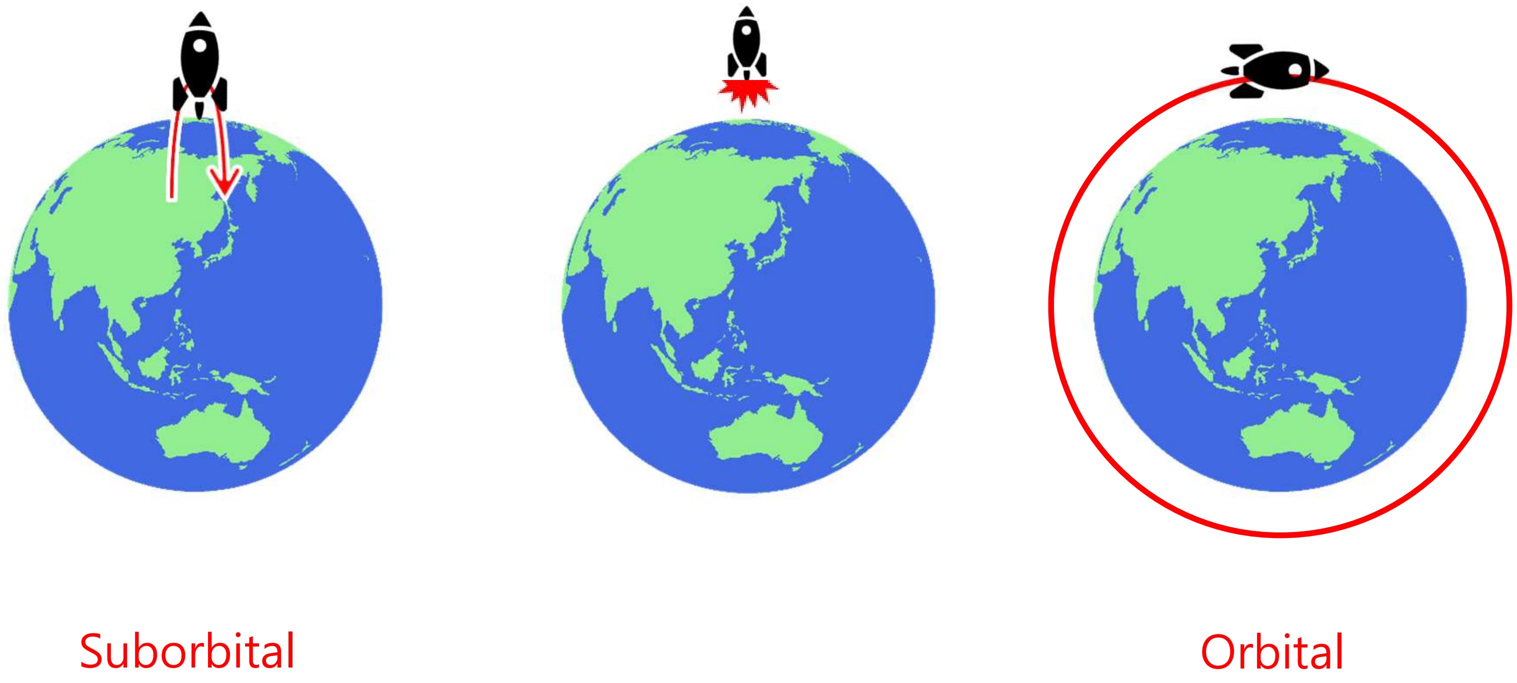

November 2022


December 2022

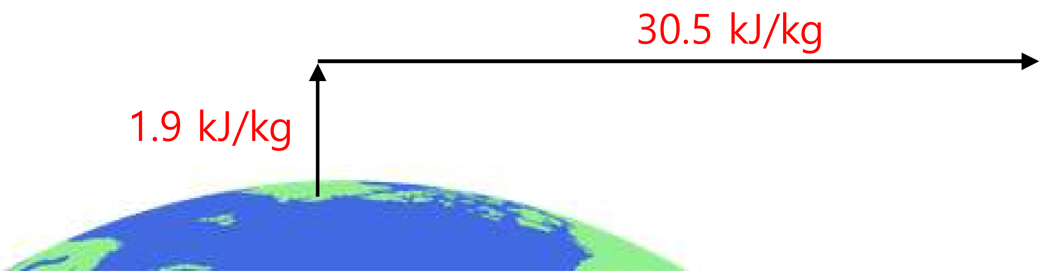
- Survey in the Solar System
  - Often takes place in target's orbit.
  - Need to understand difficulties and expenses of sending spacecraft to various solar system bodies.
  - Essential to understand space launches and orbits.

1. Getting to Low Earth Orbits (LEO)

- Suborbital vs. Orbital Motions

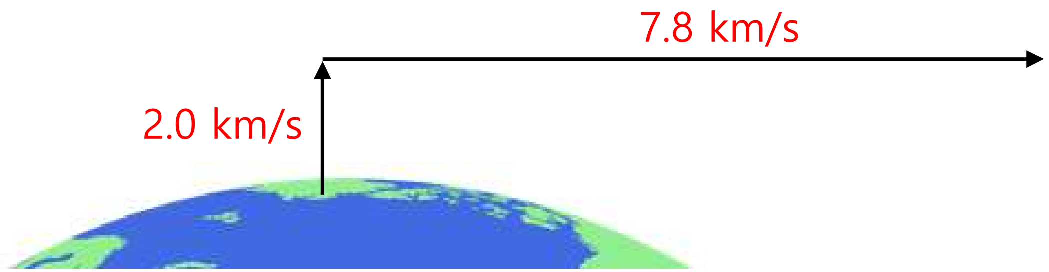


- Reaching a high altitude vs. staying in the altitude
  - One needs quite an amount of energy to reach a high altitude, but needs much more energy to stay in that altitude.
  - Specific energies to obtain a circular motion at an altitude of 200 km:
    - Potential energy difference between 0 km & 200 km altitudes = 1.9 kJ/kg
    - Circular velocity at 200 km altitude = 7.8 km/s
    - Kinetic energy corresponding to this velocity = 30.5 kJ/kg

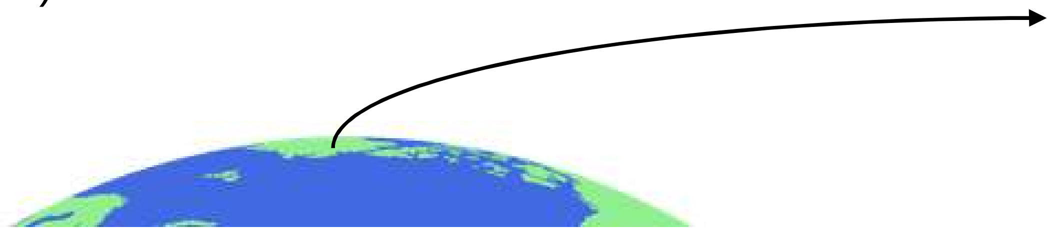


- Δv
  - Δv is more often used quantity for energy or thrust requirement.
    - $\Delta E = \frac{1}{2}(\Delta v)^2$
    - $\Delta v = \int a\, dt$

- Δv to obtain a circular motion at an altitude of 200 km:
  - Vertical motion to an altitude of 200 km: Δv = 2.0 km/s
  - Circular motion at an altitude of 200 km: Δv = 7.8 km/s



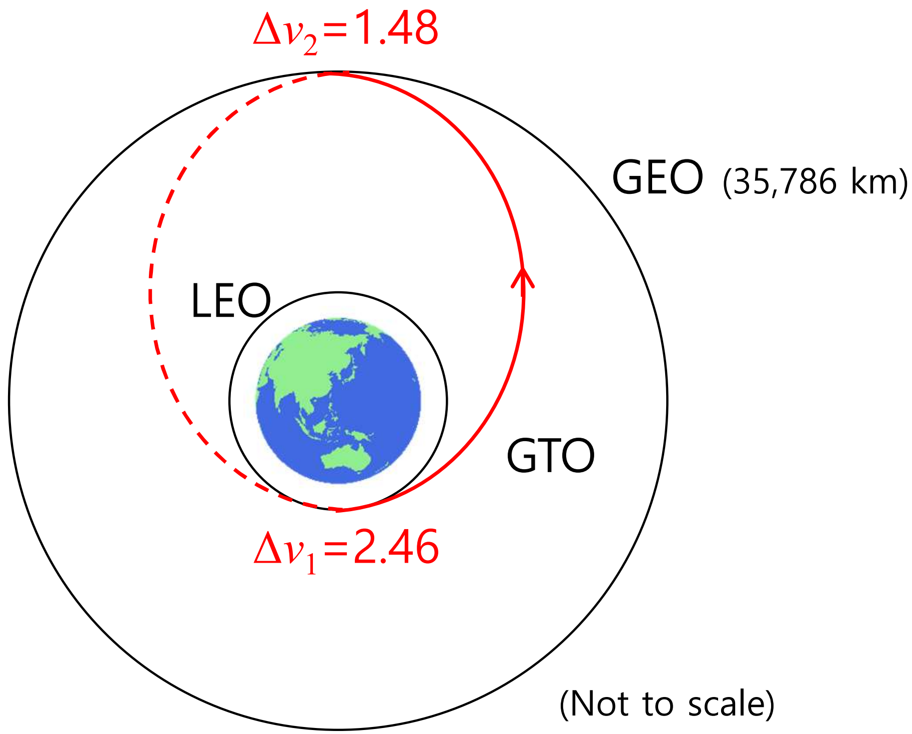
- In reality, instead of 1) getting to an altitude vertically, 2) and then obtaining a circular velocity, it is more efficient to gradually change from 1) to 2).



- Other factors to consider: 1) the fact that rocket's thrust is not impulsive, 2) atmospheric drag, 3) attitude control, and 4) Earth rotation. Considering all of these, total Δv for obtaining a circular motion at 200 km becomes 9.0~9.3 km.

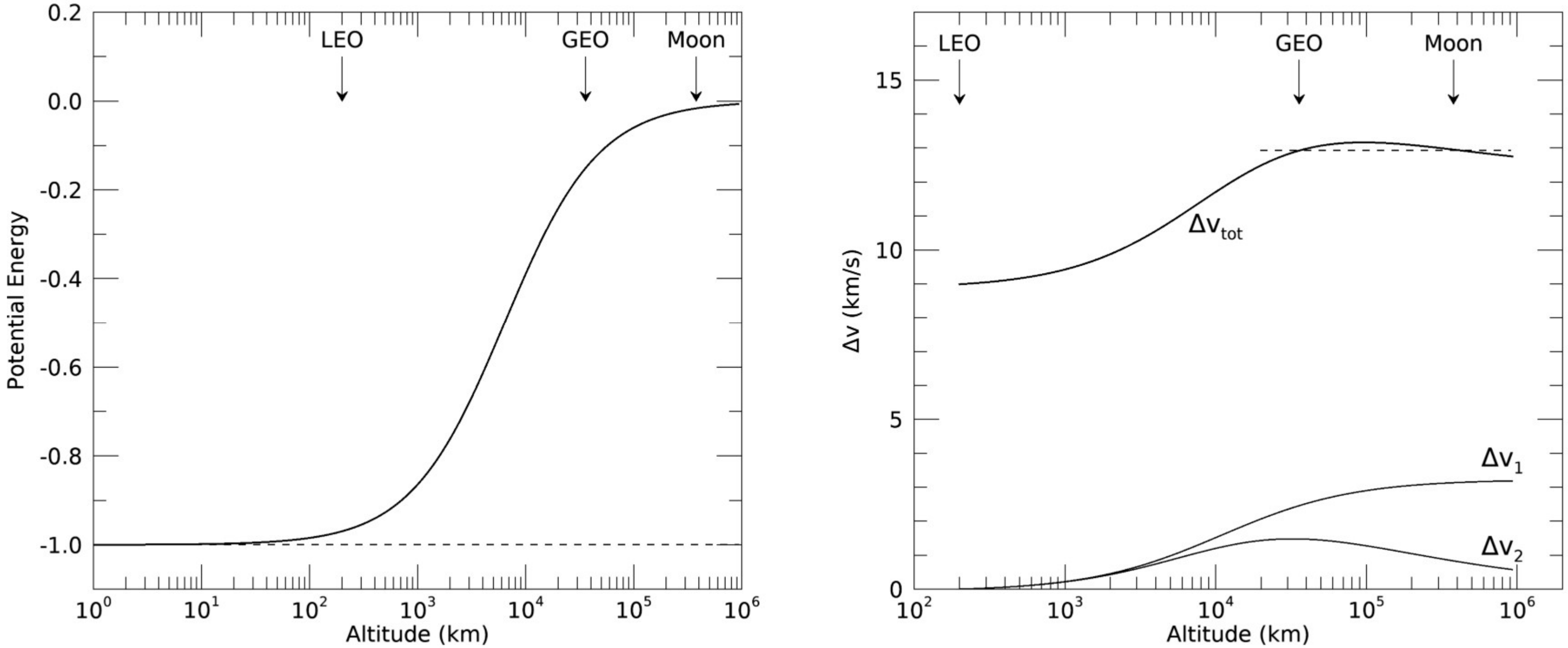
2. Getting to Higher Orbits

- Hohmann Transfer
  - Most efficient way to change orbits
  - One impulsive thrust when leaving the original orbit, plus another impulsive thrust when reaching the target orbit.



- Δv_{tot} (= $\Delta v_1 + \Delta v_2$) from LEO to a higher circular orbit initially increases with altitude, but decreases after ~98,000 km altitude.
- This is because while Δv_1 continuously increases with altitude, Δv_2 decreases after a certain altitude.

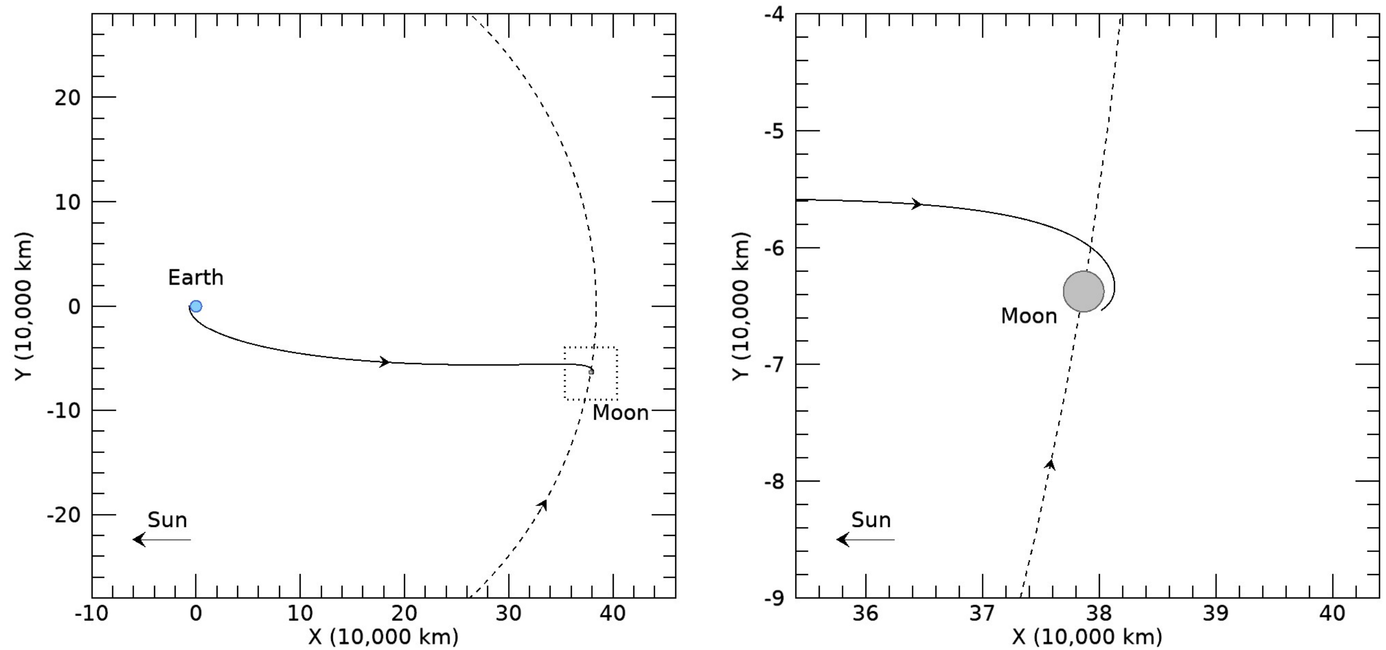
Circular velocity: $v = \sqrt{\frac{Gm}{r}}$



왼쪽: 지표면으로부터의 고도에 따른 퍼텐셜 에너지. (100km 고도에서 -1의 값을 가지도록 단위가 조정됨.)
오른쪽: 지표면에서 출발하여 주어진 고도의 원궤도에 이르는데 필요한 총 Δv. (200 km 고도에 먼저 오른 후 최종 고도로 전이하는 것을 가정함.)

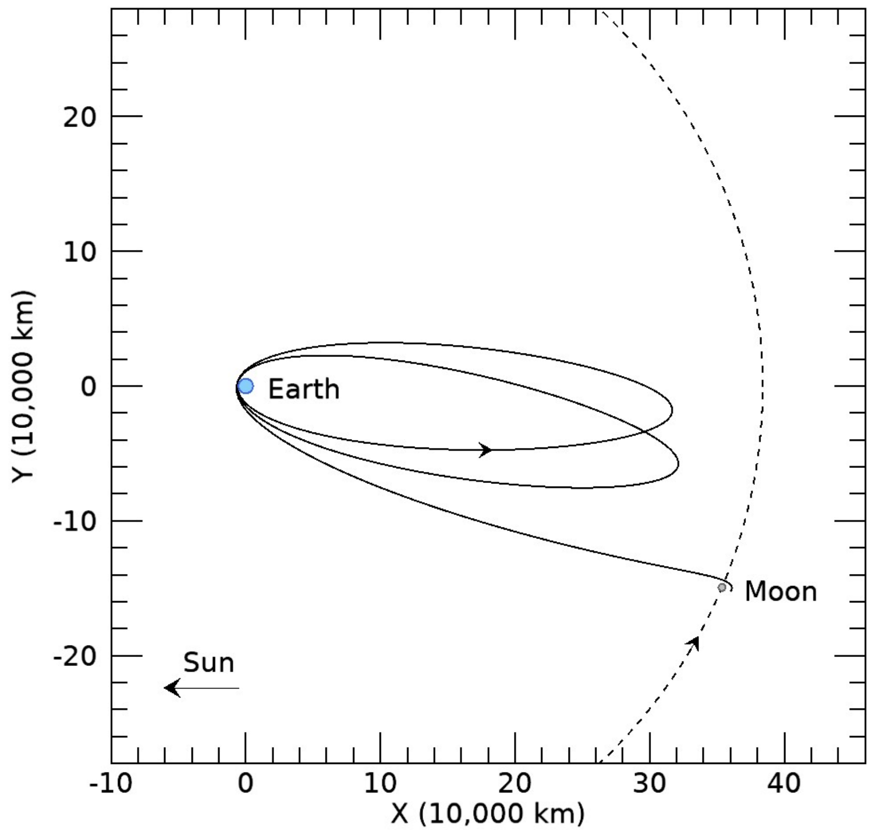
2. Getting to the Moon

- Direct transfer
  - Takes 3~4 days
  - Δv_{tot} to Moon's low orbit (100 km): 12.9~13.0 km
    - Almost same Δv as Δv to GEO (coincidence)



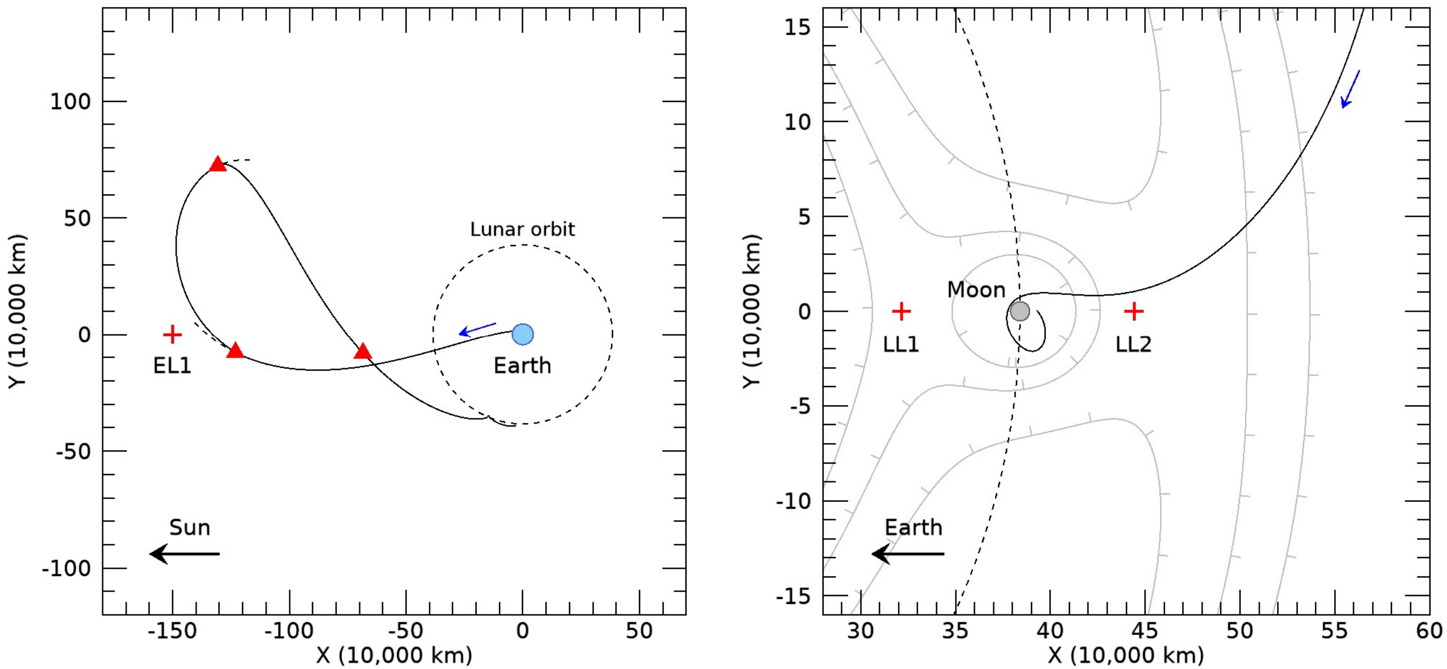
지구 저궤도에서 달 공전궤도로의 직접 전이 궤도(지구가 중심에 있는 태양–지구 회전 좌표계). 오른쪽 그림은 왼쪽 그림의 점선으로 된 상자 영역을 확대한 것이다. 달 궤도에 다다른 우주선의 속도보다 달의 공전 속도가 빠르기 때문에 달 중력장에 포획되기 위해선 달 근처에서 우주선에 두 번째 Δv 를 가해야 한다.

- Transfer using phasing orbits
  - Takes a few weeks
  - Gradually increases apogees.
  - Wider launch window and more time to stabilize instruments.



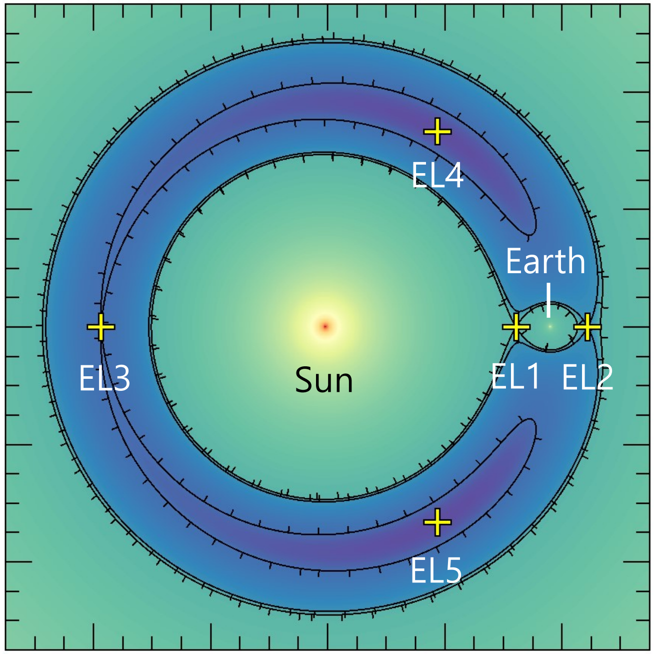
지구 저궤도에서 달 공전궤도로 의 위상 전이 (지구가 중심에 있는 태양–지구 회전 좌표계).

- Low-Energy Transfer
  - Takes a few months
  - Weak Stability Boundary/Ballistic Lunar Transfer (WSB/BLT)

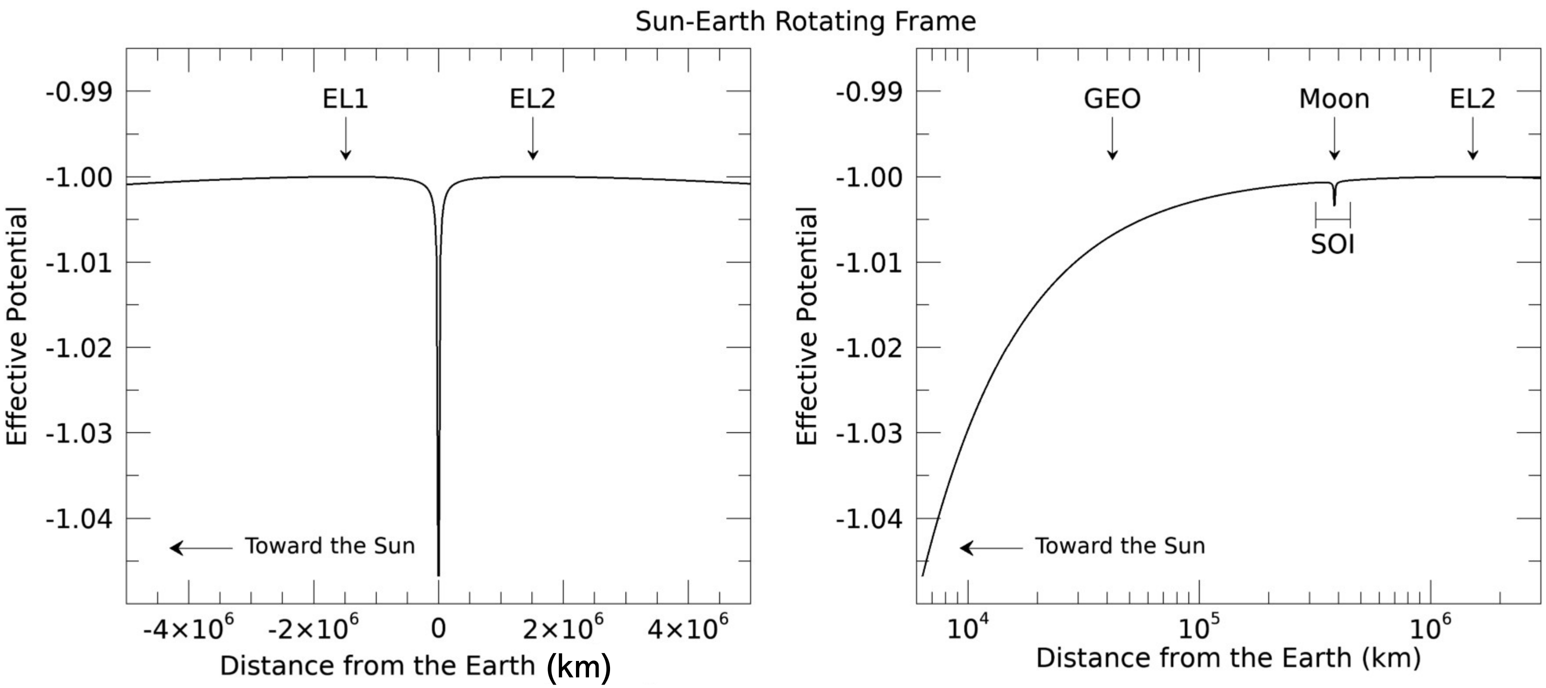


지구 저궤도에서 달 공전궤도로의 위상 전이 궤도(왼쪽은 지구가 중심에 있는 태양–지구 회전 좌표계, 오른쪽은 지구가 중심에 있는 지구–달 회전 좌표계). EL1은 태양–지구 계의 라그랑지 점, LL1/LL2는 지구–달 계의 라그랑지 점이며, 빨간 세모는 추력이 가해진 지점이다.

- Why Low-Energy Transfer is efficient:
  1. Δv to Moon's altitude (380,000 km) is similar to Δv to EL1/EL2 (1.5 million km).
  2. Around EL1/EL2, effective potential is nearly flat, thus small Δv can significantly change the perigee.
  3. When S/C approaches the Moon through LL2, S/C can be captured by the Moon with very small Δv (nearly ballistic).



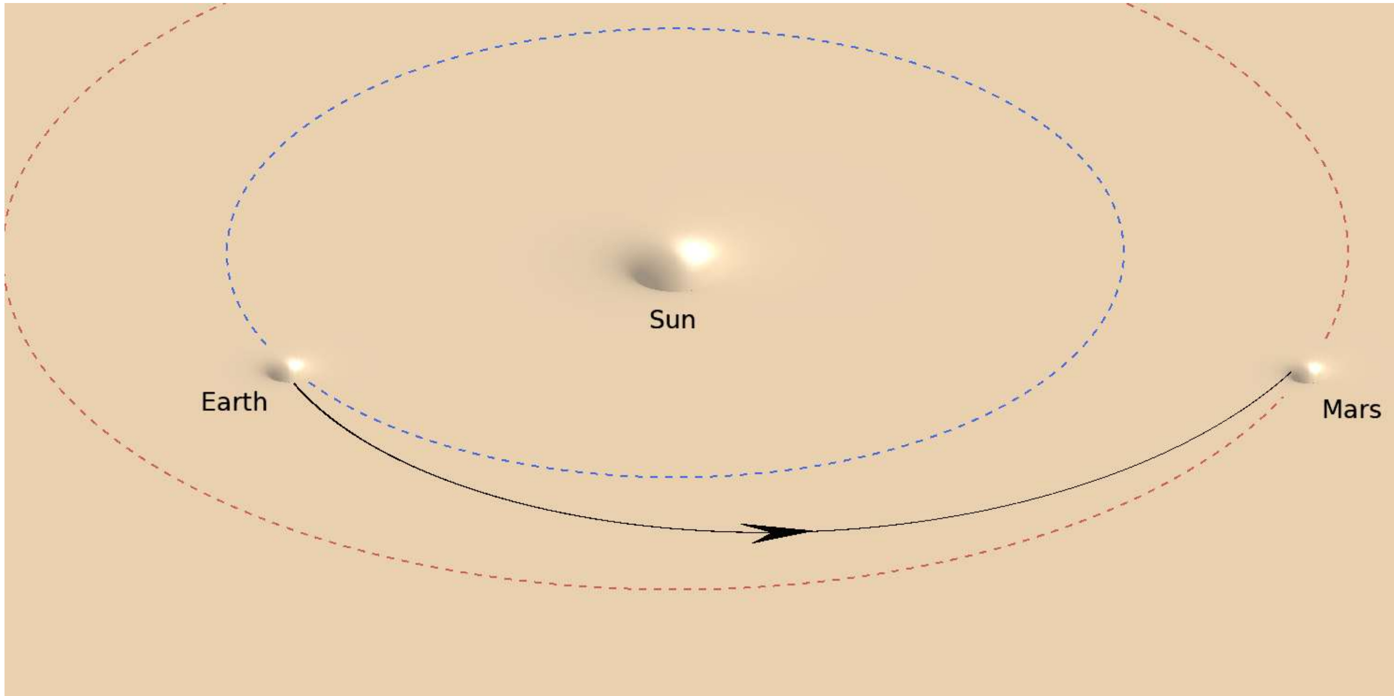
태양–지구에 의해 만들어지는 유효 퍼텐셜
(태양–지구 회전 좌표계). (Not to scale)



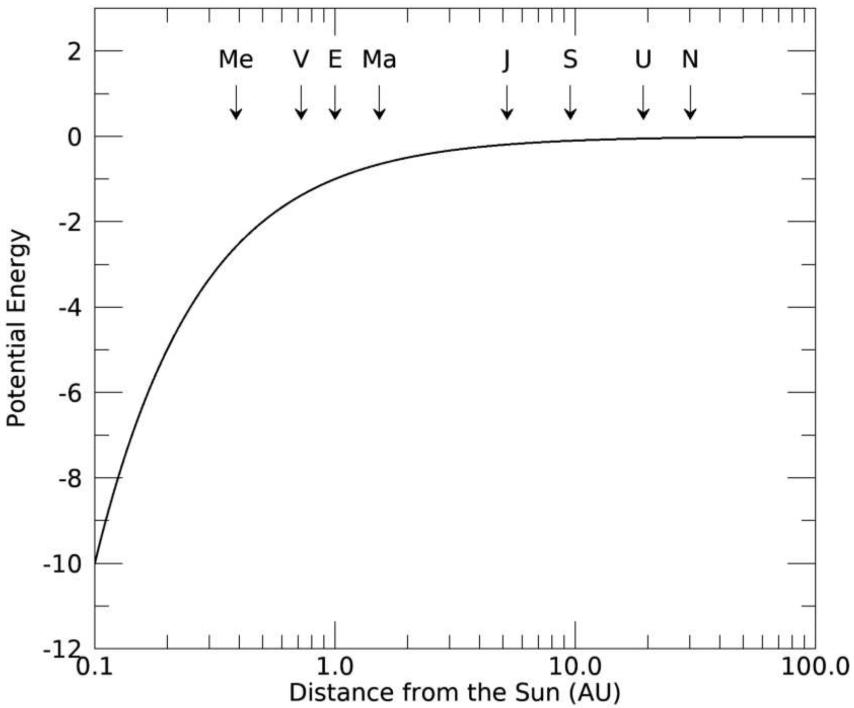
4. Getting to other planets

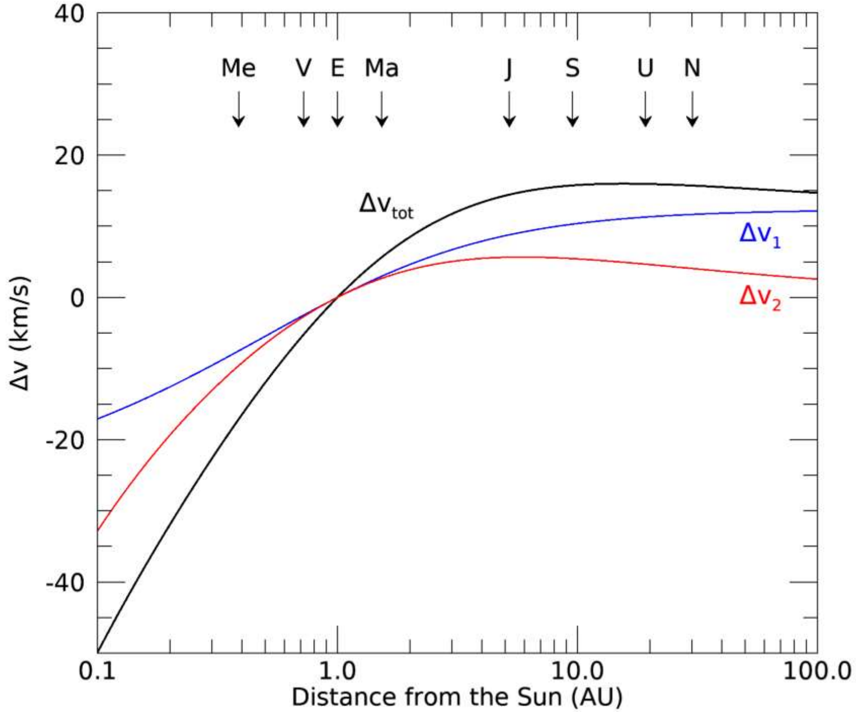
Bodies	r_{SOI}
Mercury	112,000 km
Venus	616,000 km
Earth + Moon	929,000 km
Mars	578,000 km
Moon	66,100 km

- Patched Conic Approximation
  - You only need to consider
    - Earth' gravity inside Earth's sphere of influence (SoI)
    - Sun's gravity in between (Hohmann transfer)
    - Target planet's gravity inside its sphere of influence



– Need acceleration to get to the outer planets, and deceleration to get to the inner planets.
– Need more Δv_{tot} to get to Mercury than to Jovian planets.

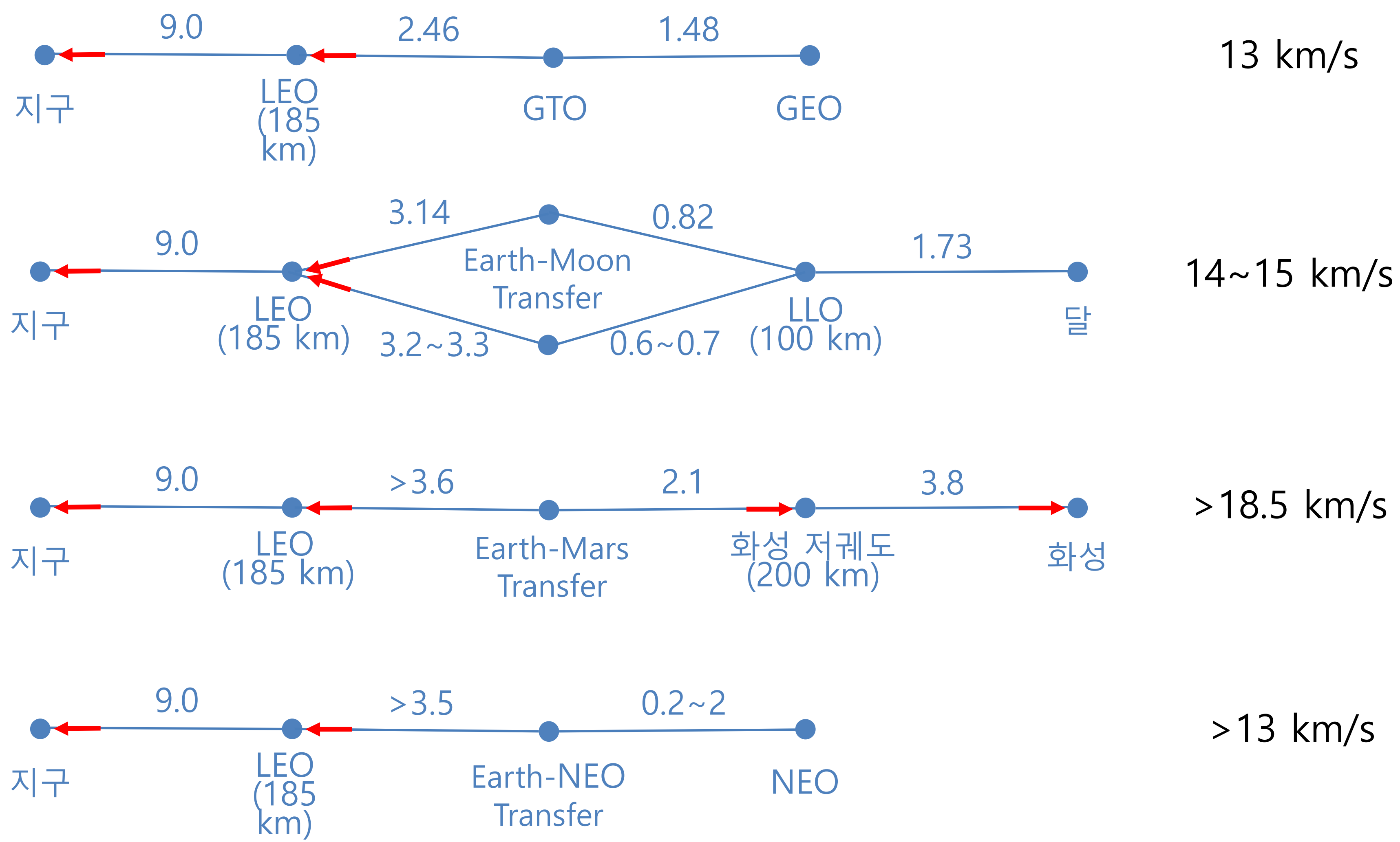




오른쪽 그림의 Δv_1은 지구 영향권을 벗어난 이후에 필요한 속도 증분이며, Δv_2는 목표 행성의 영향권에 들어가기 전 그 행성의 궤도에서 원궤도 운동을 하기 위해 필요한 속도 증분이다.

5. Delta-v Budget

Red arrows indicate that aerobreaking is possible.



Selling Moon's water in Earth orbits

- Water ice found on the Moon can be electrolyzed to H_2 and O_2 using solar energy, RTG or SMR.
- Liquid H_2 and O_2 brought back to GTO can be much cheaper depending on its mining cost.

	From Earth	From Moon
Earth Surface	$ 1/kg	-
LEO	$ 4,000/kg	$3,000/kg
GTO	$ 8,000/kg	$1,500/kg
GEO	$16,000/kg	$1,500/kg
LL_1	$12,000/kg	$1,000/kg
Lunar Surface	$36,000/kg	$ 500/kg