Problems of motion control and navigation of small spacecraft in interplanetary missions

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Objectives

- What does it mean a Cubesat and what is it purposed for?
- Why interest to interplanetary Cubesat missions are growing on?
- The purpose is to present varieties of the ballistic mission design approaches to develop an interplanetary mission based on a Cubesat
- To pay attention to constrains and limitations inhering in interplanetary Cubesats which dictate implementation of advanced math techniques

What is a Cubesat?

Parents of a Cubesat (1998)

Bob Twiggs
Stanford Univ

1 litre x 1 kg

Klaus Schilling with 1U-Cubesat in hand

Jordi Puig-Saari
Cal Poly Univ

History, today state-of-art, variations of missions, missions launched and scheduled, designers, manufacturers etc

Today no chance to count small satellite and even Cubesats missions were already launched and scheduled to be launched.
However!

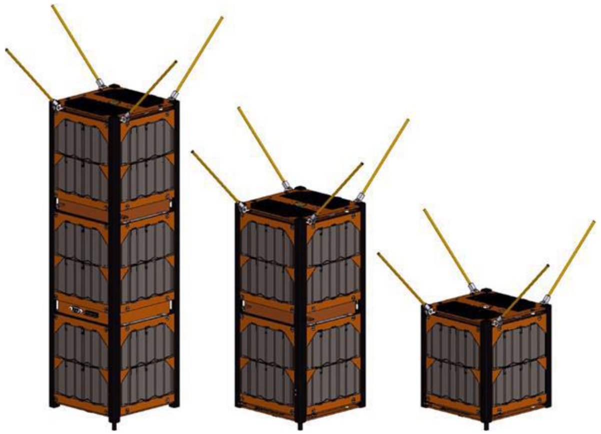
Internet ⟷ Cubesats

For those who are interested in history, ideology and lessons learned of Cubesats I quite recommend to watch a lecture “CubeSat: An Unlikely Success Story” by Jordi Puig-Saari (https://www.youtube.com/watch?v=uVbERsrAAJo)

Formal identification and classification

Mini	Small	Micro	Nano	Pico	Cubesat (1U) / Poketsat
1000–500 (kg)	500–100	100–10	10–1	1–0	1/0.25

1U-3U for near-Earth use

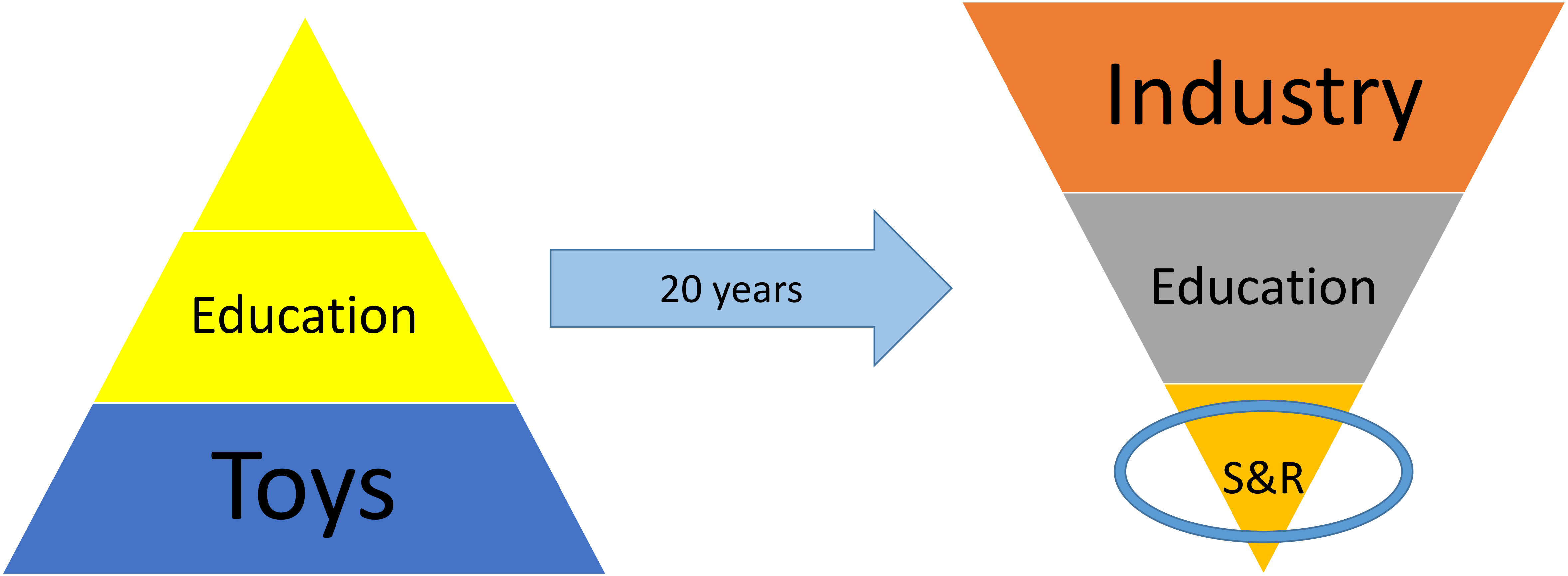


6U-12U for interplanetary use

Essentiality of small sats

- Alternative approach for development, testing and servicing wrt big SC
- Involvement of low-cost manpower for development and designing
- Components-Of-The-Shelf (no-space qualified) implementation
- Low-cost launch opportunities (conversion missiles, piggy-back style, dedicated light launchers)
- Lower reliability, lower cost and faster substitution in orbit by more modern satellite
- New spatial configuration of multi-agent satellite system
- Small size and low cost lead to benefit of private business

Cubesats implementation evolution



Science & Research

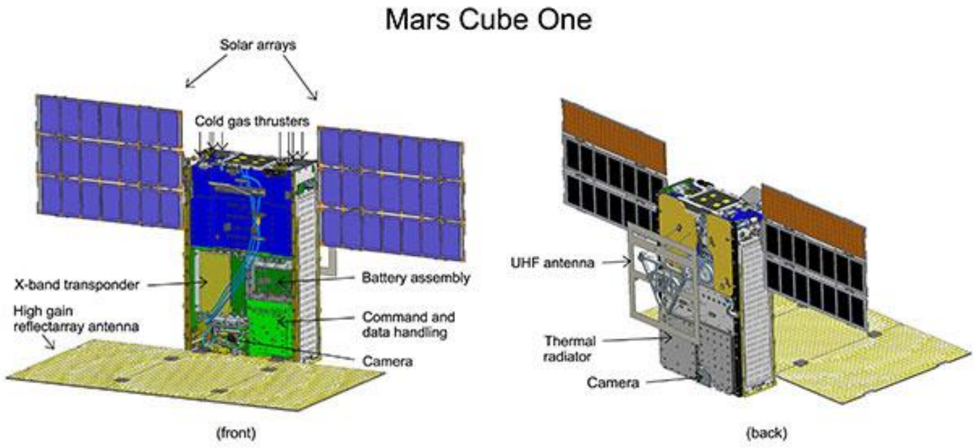
- Interplanetary missions require an extreme effort in various branches of science and technology due to unknown factors effecting the satellite

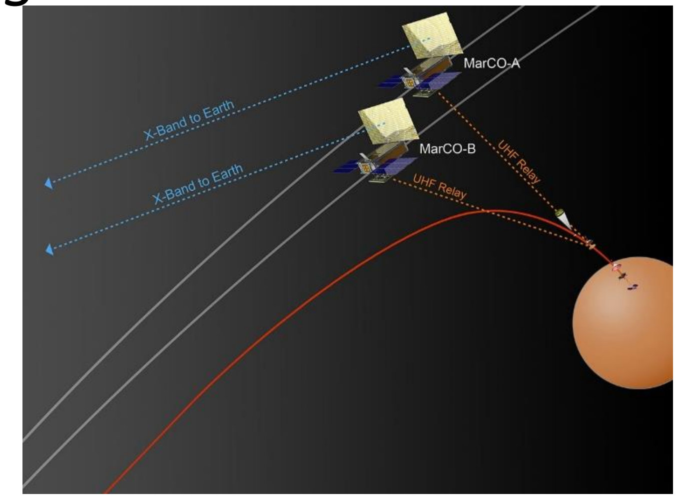
- Cubesats' small size, mass and other limitations and constrains aggravate the difficulty of mission design

- The interplanetary missions based on Cubesats is the guiding star for research and, consequently, for invention and new scientific and technological results

Interplanetary Cubesats have already flown

- MarCO-A & MarCO-B are **the first and upto now the last Cubesats** operated beyond the Earth orbit for a deep space mission, 13.5 kg each
- Launched in 2018, deployed from main SC InSight, during the cruise phase were kept about 10,000 km away from *InSight*, operated flyby over Mars in 2019 and transmitted data from the landing *InSight*

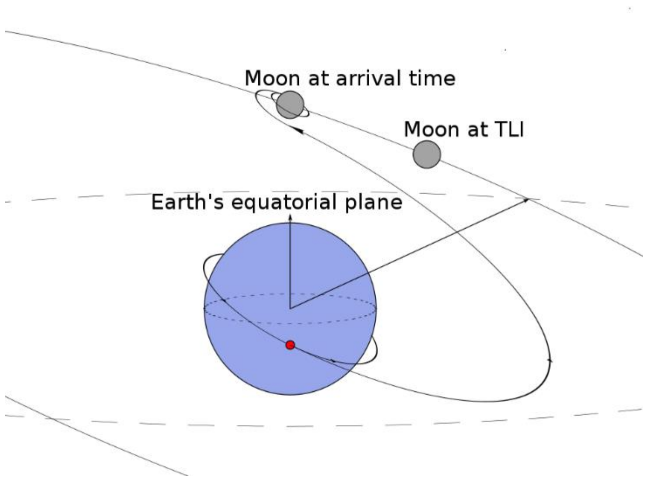




Credit: https://www.jpl.nasa.gov/news/press_kits/insight/launch/appendix/mars-cube-one/

Trajectory to the Moon

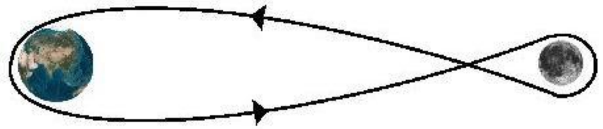
Direct flight (patched two-body approximation) with the trans-lunar injection (TLI) ~3.2 km/sec and insertion maneuver to approach an orbit around the Moon ~0.6÷0.9 km/sec



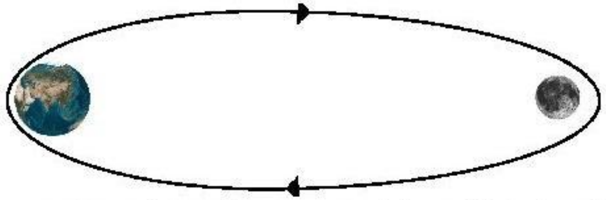
Credit: Aresv at English Wikipedia

Trajectories to the Moon

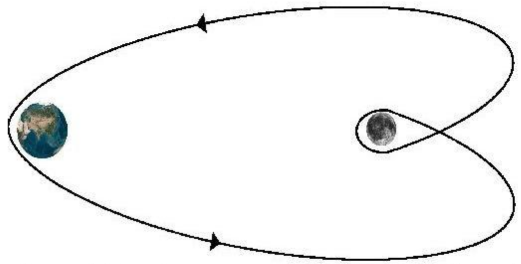
Free-return trajectory (patched two-body approximation) with the trans-lunar injection (TLI) ~3.2 km/sec



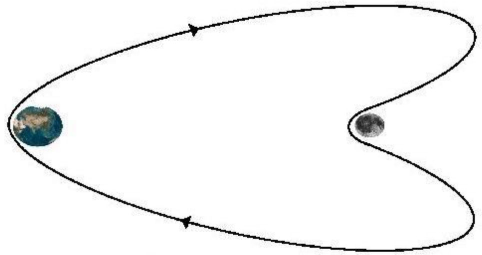
a) Coplanar circumlunar free-returns: Type Ai in inertial coordinate system (Apollo class)



b) Coplanar circumlunar free-returns: Type Aii in inertial coordinate system



c) Coplanar cislunar free-returns: Type Bi in inertial coordinate system (Egorov class)



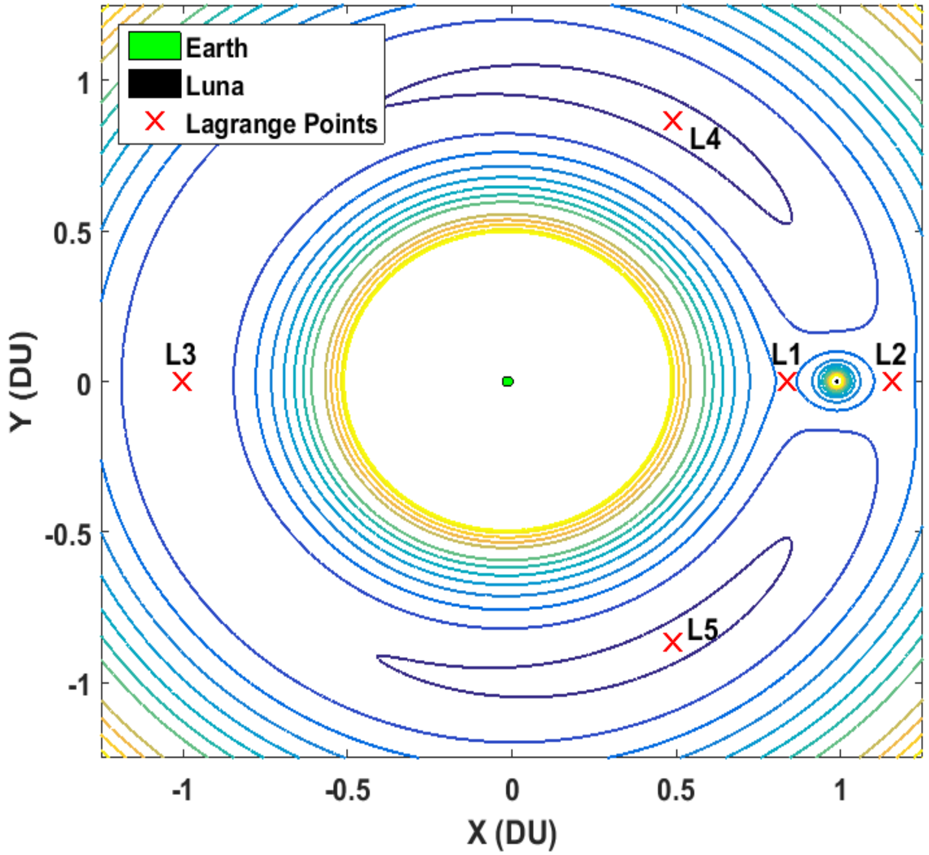
d) Coplanar cislunar free-returns: Type Bii in inertial coordinate system

Characteristic	Value	Definition
Lunar passage	A	circumlunar
	B	cislunar
Earth departure	i	posigrade
	ii	retrograde

CR3BP

Spiral unwinding from MEO-GTO via L1 “neck” and spiral winding to LLO (varying the Jacobi integral constant) – CR3BP approximation

First mission was ESA’s SMART-1 in 2003 – 2006, **370 kg:** dry-288 kg + xenon-82 kg)



https://core.ac.uk/download/pdf/77511224.pdf

Problems met for spiral flight with low-thrust

- Radiation doze absorbed during flight in the radiation belts that requests:
  - Choice of the starting orbit which should be proper by inclination to minimize the radiation doze and launch campaign available
- Available amount of fuel onboard should be enough to fly to the Moon and keep the orbit around the Moon

Bifrost: bridge to the Moon (Atlas Beyond+IRF+KIAM + …)*

The mission scenario is somewhat similar to the one of SMART-1, but important differences exist:

- Smaller tMicrospacecraft 35-37 kg, 10 times smaller than SMART-1 (closer to Cubesat)
- thrust acceleration (0.14 mm/s^2)
- Very challenging maneuvering in low lunar orbits (several working orbits required, at least some of them are not frozen)
- The total amount of fuel available for the transfer and LLO keeping is strictly limited to 5.2 kg

* M. Ovchinnikov, M.. Shirobokov, S. Trofimov, S. Barabash, Per-Erik Atterwall, Low-Thrust Microspacecraft Delivery to a Lunar Orbit after the Launch to GTO or MEO, 71st International Astronautical Congress 12-14 October 2020, IAC-20-C1.4.13, 8p.

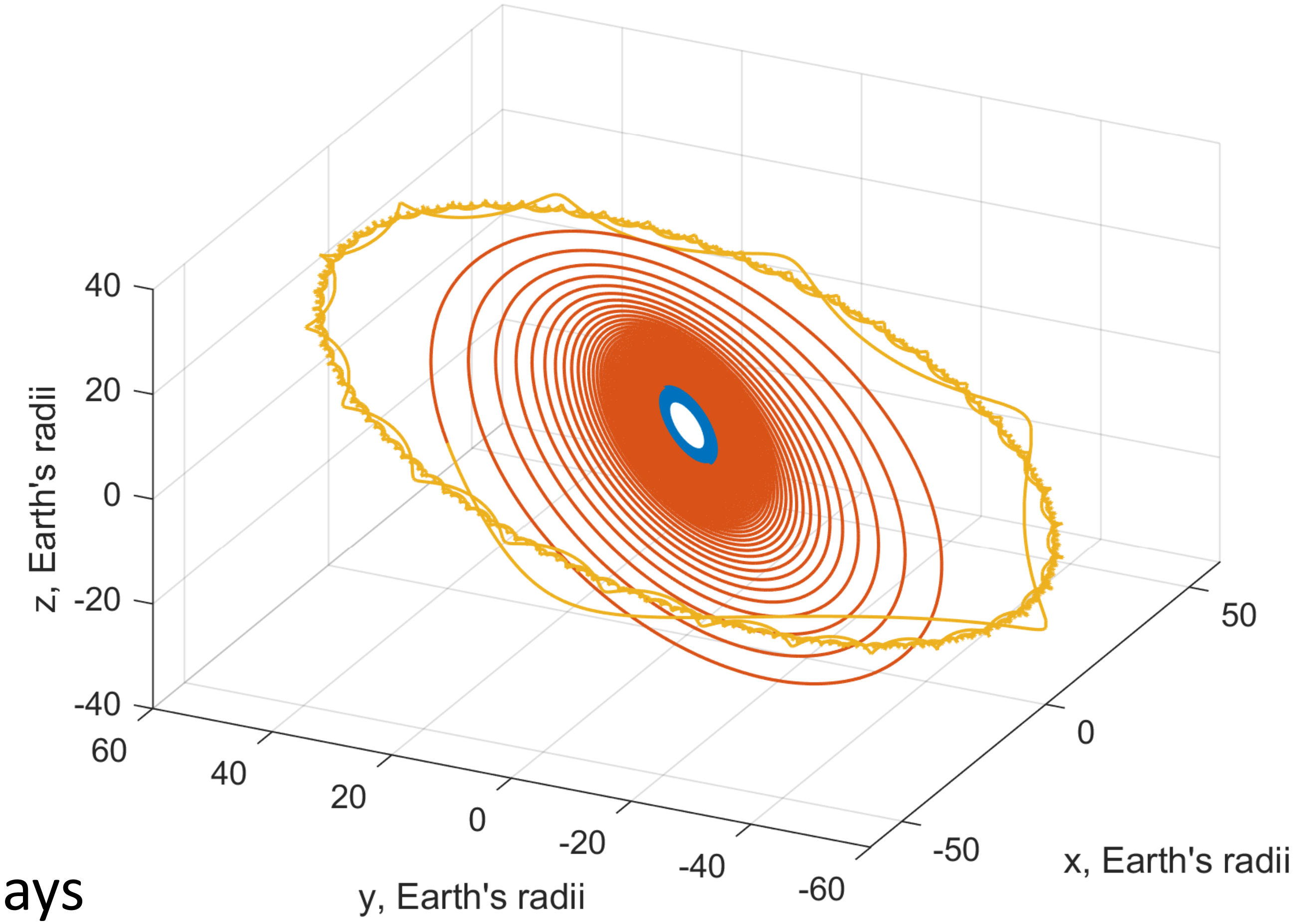
MEO-LLO transfer trajectory

MEO:
i=55 deg
h=23,200 km
e=0

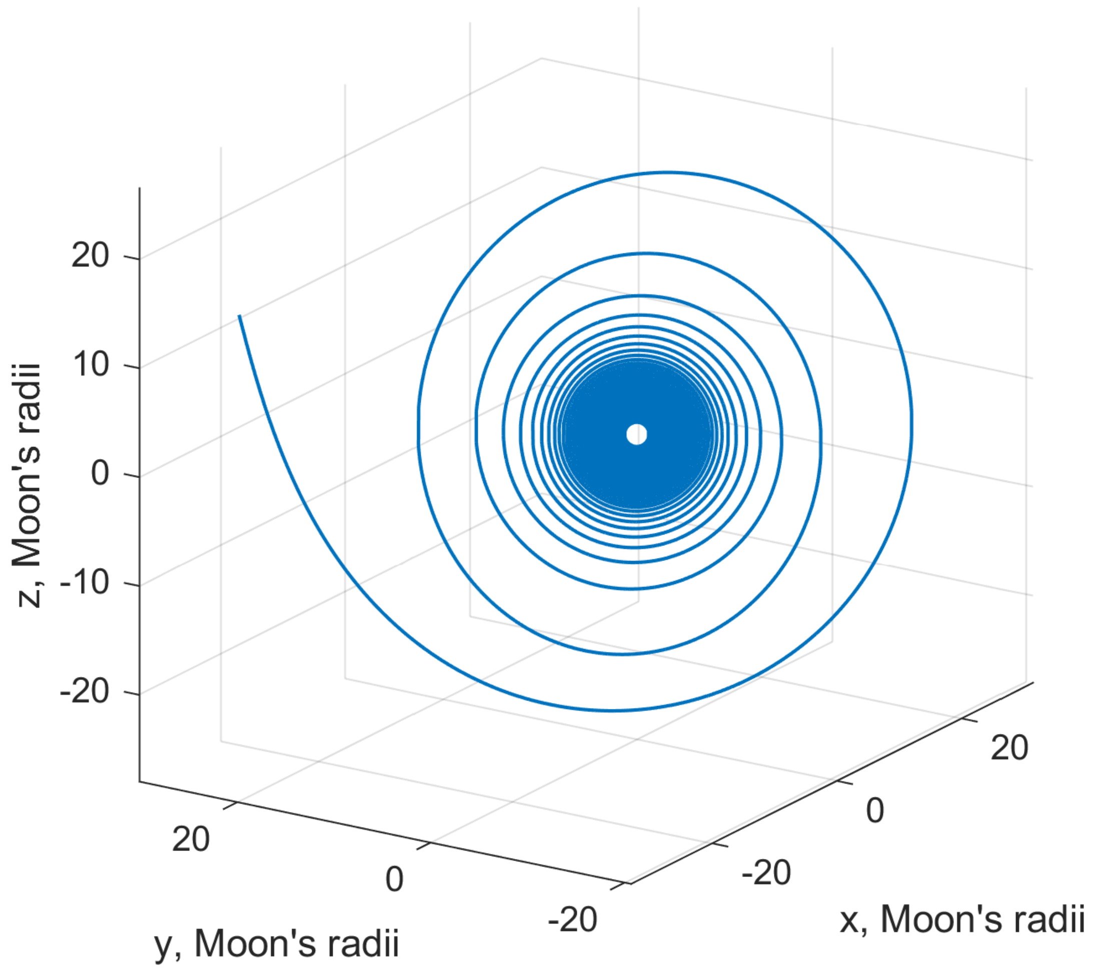
Target LLO:
polar, 100 km

Spacecraft:
m0 = 35 kg
mf = 30.6 kg

TOF (total): 443 days



Spiraling down to the 100 km LLO



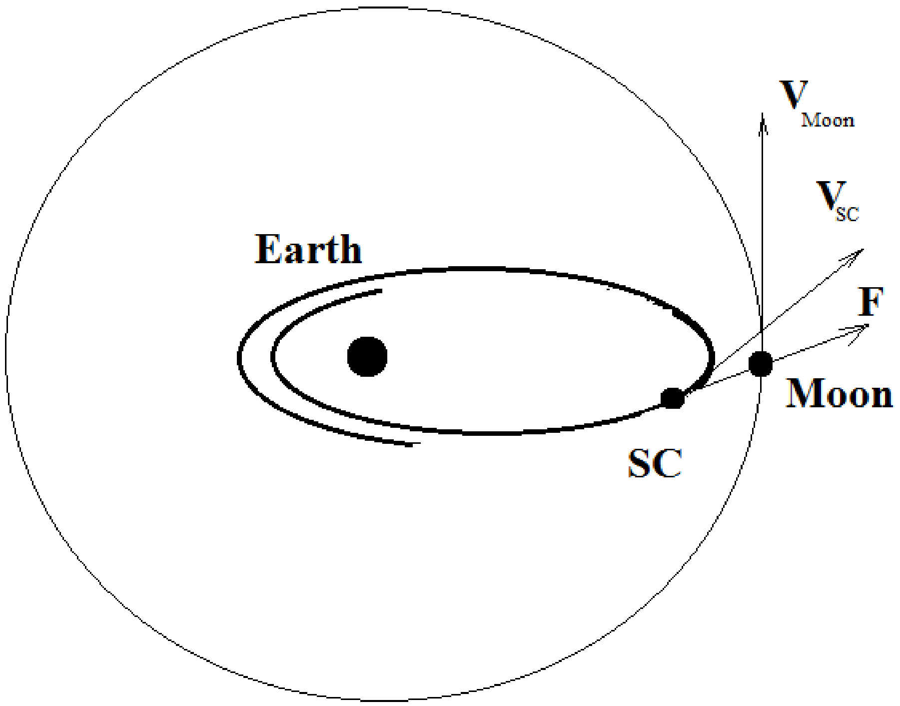
Antivelocity thrust
F = 4.9 mN

TOF since passing the L1 bottleneck: ≈100 days

First working LLO to start science: polar, 100 km

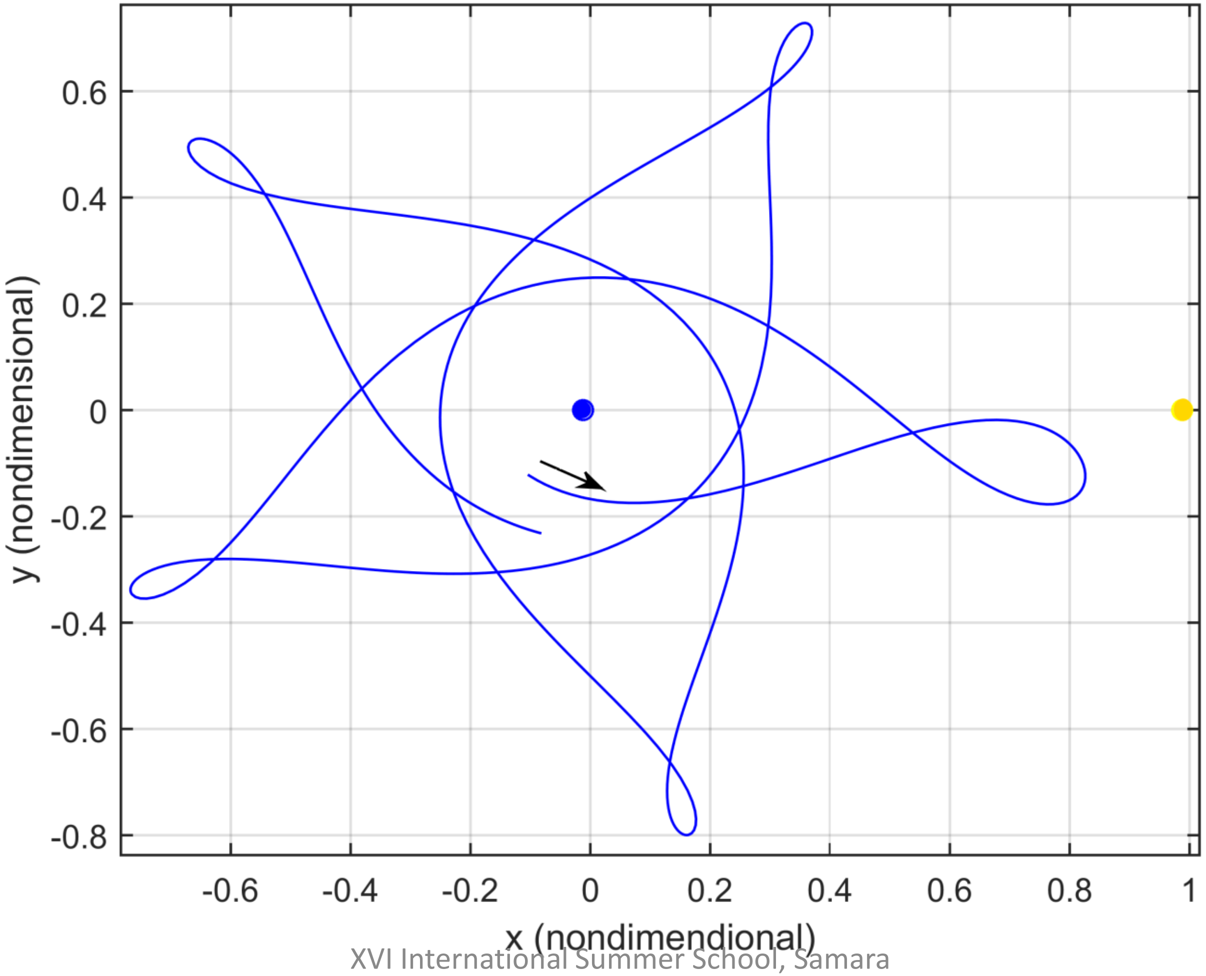
Everyday corrections seem to be required

Resonant encounters (just idea)

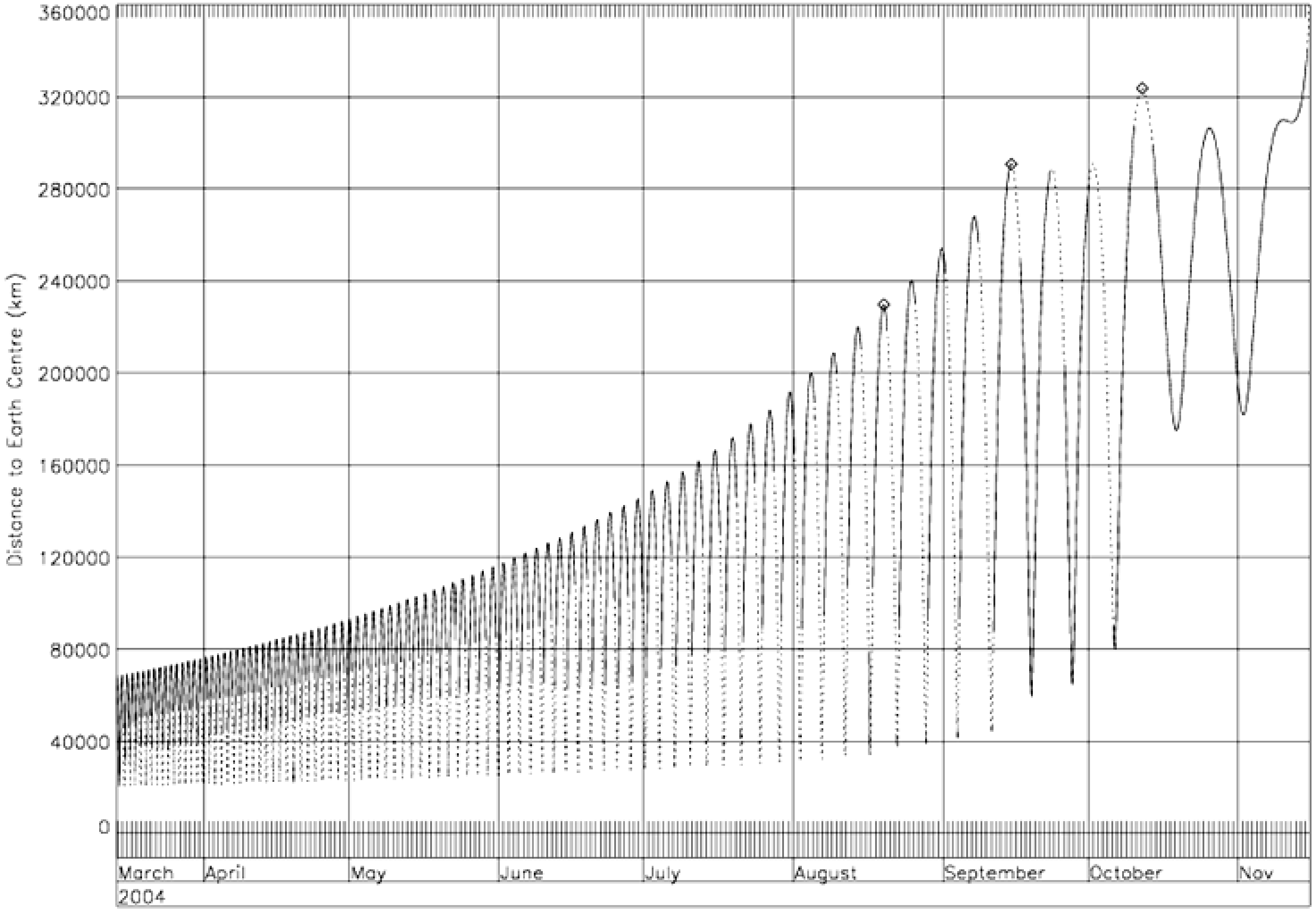


Perigee raising by using the high-altitude fly-by

Δr_π = 34,000 km

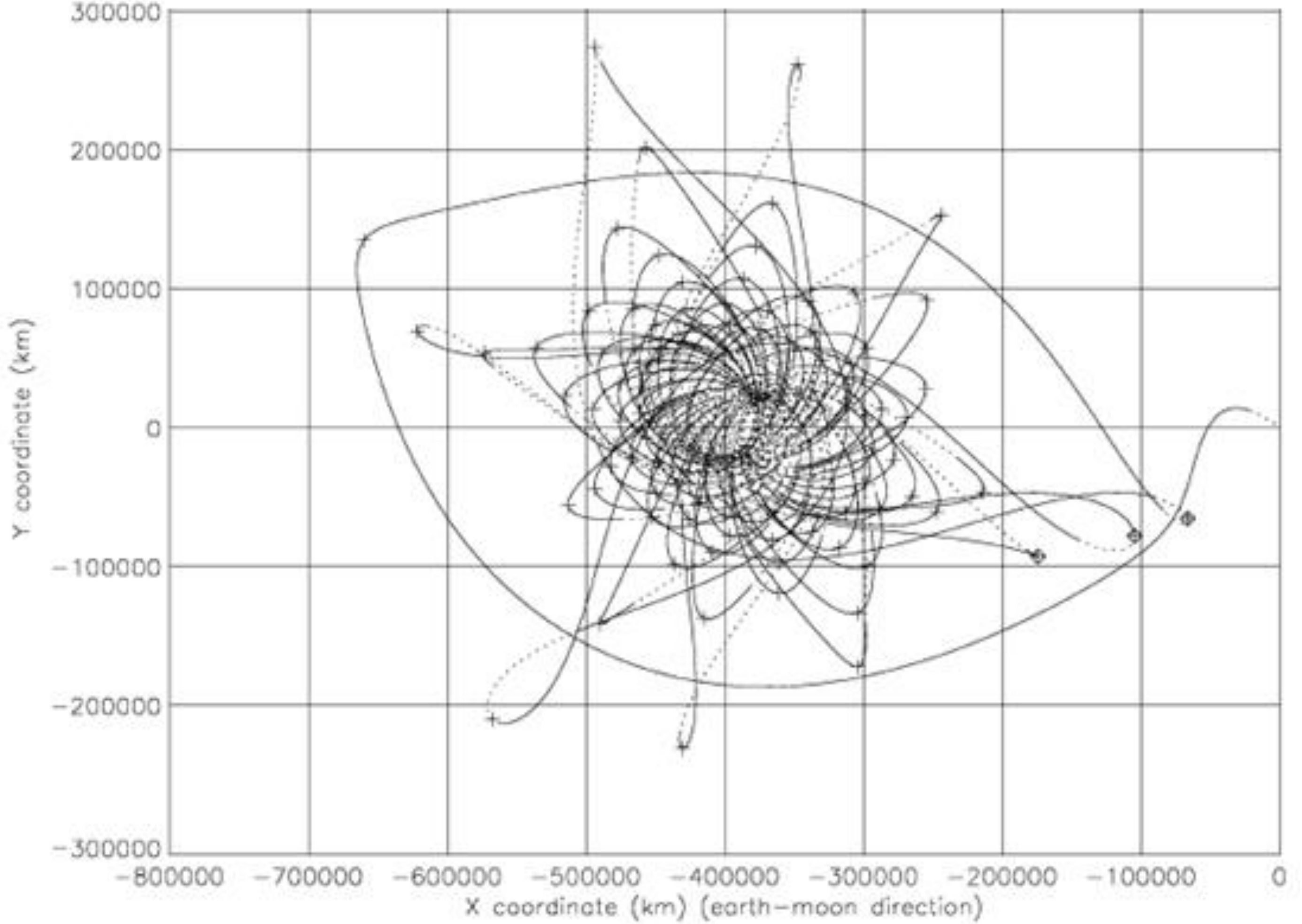


SMART-1 hopping



J. Schoenmaekers, ``Post-launch Optimisation of the SMART-1 Low-thrust Trajectory to the Moon,'' 18th International Symposium on Space Flight Dynamics, October 2004, Munich, Germany.

SMART-1 trajectory, capture by the Moon

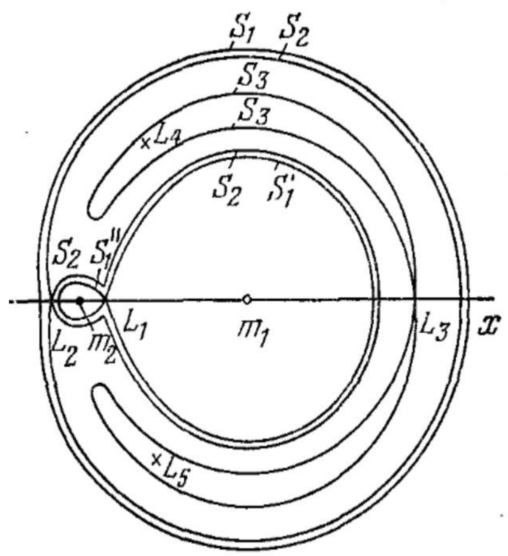


J. Schoenmaekers, ``Post-launch Optimisation of the SMART-1 Low-thrust Trajectory to the Moon,'' 18th International Symposium on Space Flight Dynamics, October 2004, Munich, Germany.

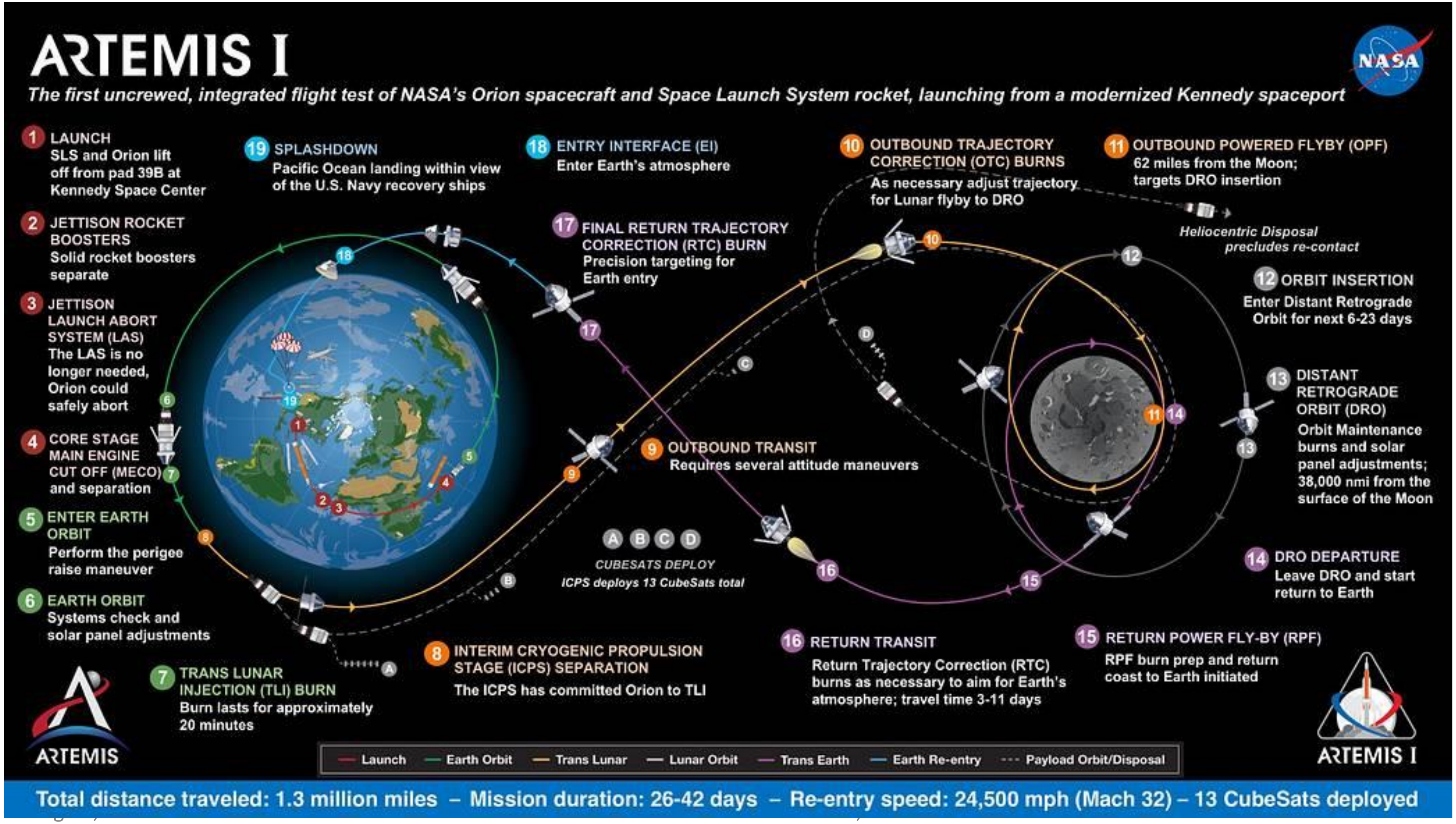
13 Cubesats to the Moon by SLS under NASA support

After being deployed from the second stage of the NASA heavy lift launch vehicle (SLS) in 2021 13 Cubesats would approach the Moon with various mission goals

The critical aspect of the campaign is a required 1.5 km/s Delta-V in order Cubesats to be captured by the Moon



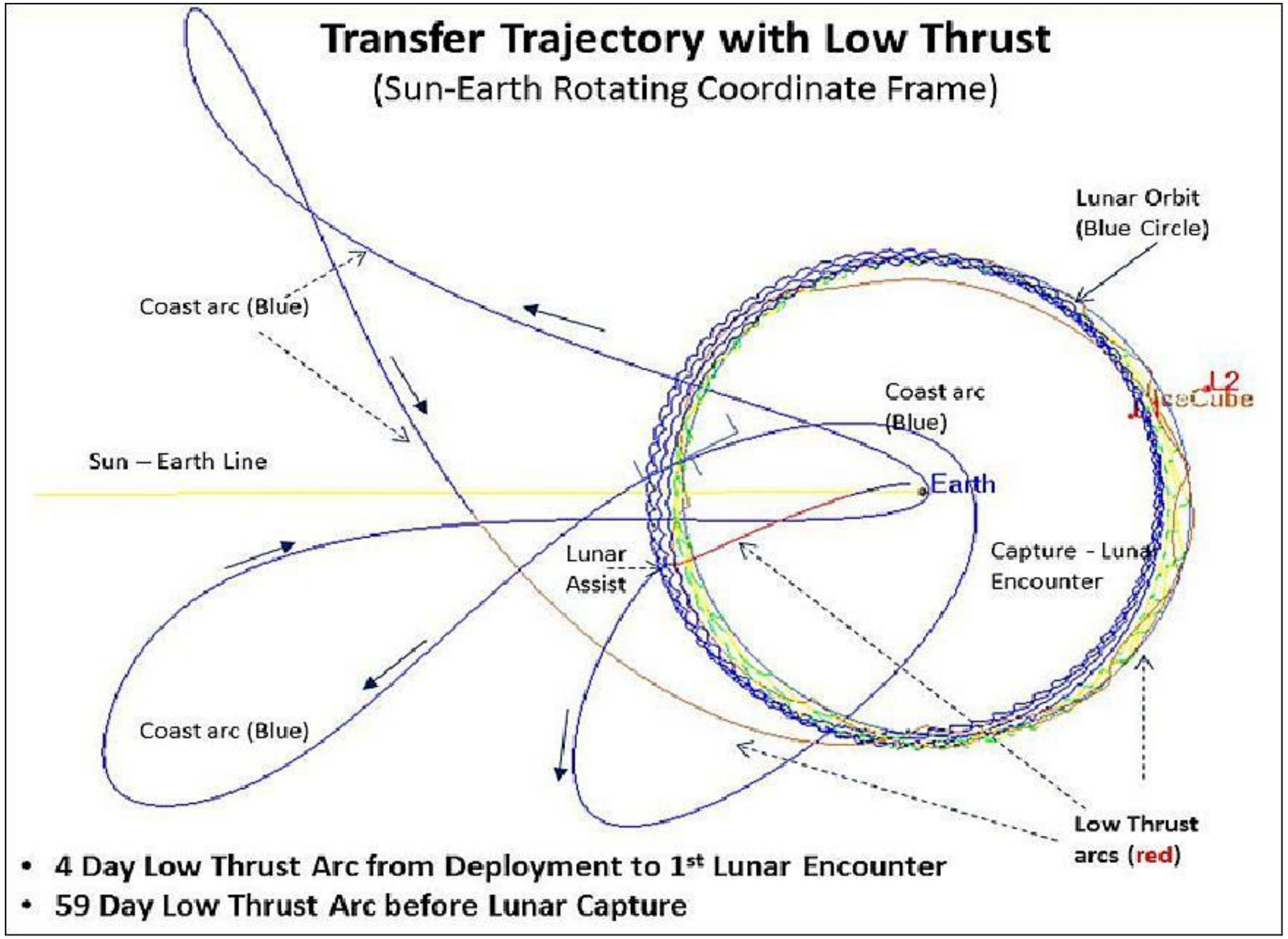
13 Cubesats deployment during Artemis 1 mission



Weak stability boundary (WSB) trajectories

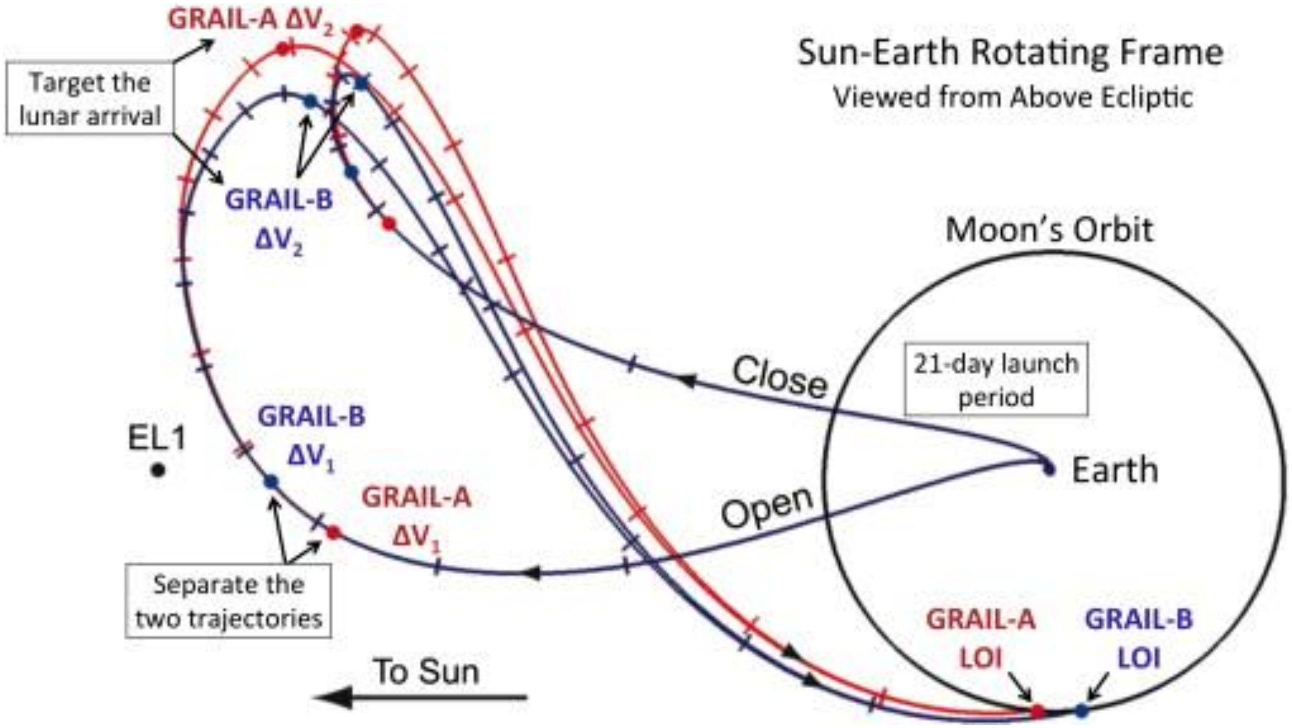
Four-body problem is considered. Instead of the Jacobi constant changing in CR3BP by low-thrust the gravity field of the Sun is used

6U IceCube (Morehead State University)



D.C. Folta, N. Bosanac, A. Cox, K.C. Howell. The lunar IceCube mission design: construction of feasible transfer trajectories with a constrained departure, 26th AAS/AIAA Space Flight Mechanics Meeting, February 2016, AAS 16-285, 19p.

The GRAIL trajectory



Advantages over the direct transfers to the Moon:

1) Lower LOI delta-v;
2) Low delta-v cost for LOI separation;
3) Longer launch period (at least 21 days)
4) Longer flight time

- Launch period: 8 Sep 2011 – 19 Oct 2011
- TOF to the Moon: 3—4 month
- Lunar orbit insertion (LOI): 190 m/s

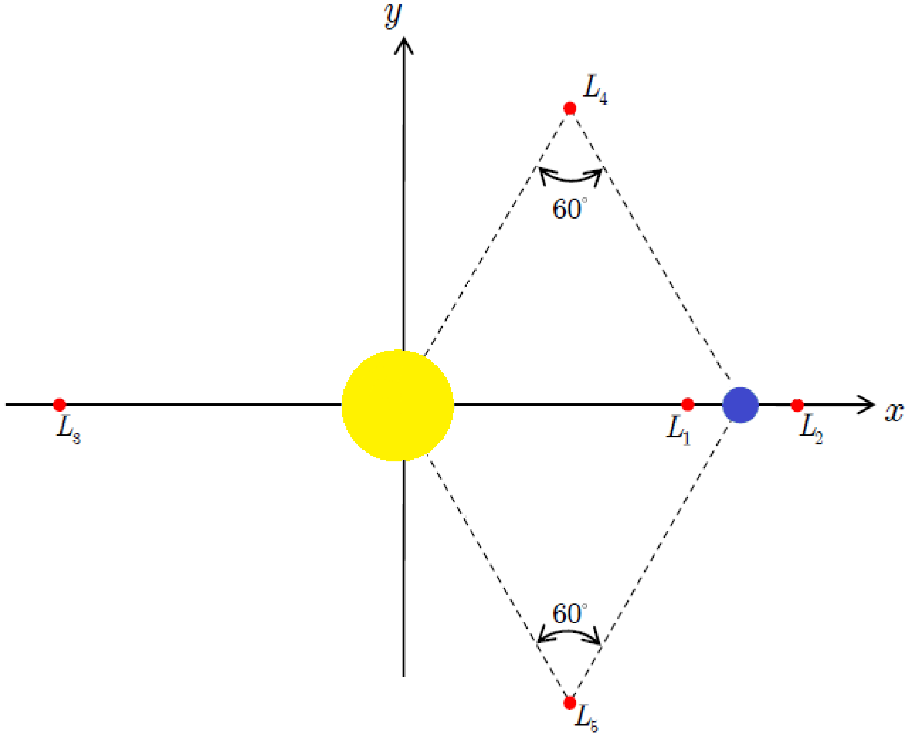
Parker, J.S., Anderson R.L., “Targeting Low-Energy Transfers to Low Lunar Orbit,” Acta Astronautica, 2013, Vol. 84, pp. 1-14.

M.-K. Chung, et al., “Trans-Lunar Cruise Trajectory Design of GRAIL (Gravity Recovery and Interior Laboratory) Mission,” AIAA/AAS Astrodynamics Specialist Conference, 2010, Paper AIAA 2010-8384

Stable/unstable invariant manifolds. Libration Points (LP) in CR3BP

Relative equilibria in the rotating reference system are to be obtained from

$$U_x = U_y = U_z = 0$$



	Sun-Earth	Earth-Moon
x_{L1}	0.989987	0.836914
x_{L2}	1.010074	1.155682
x_{L3}	−1.000001	−1.005062
x_{L4}	$1/2$	$\sqrt{3}/2$
x_{L5}	$1/2$	$-\sqrt{3}/2$

Eigenvalues and solutions near L2

For planar motion eigenvalues are $\pm\lambda$ and $\pm i v$

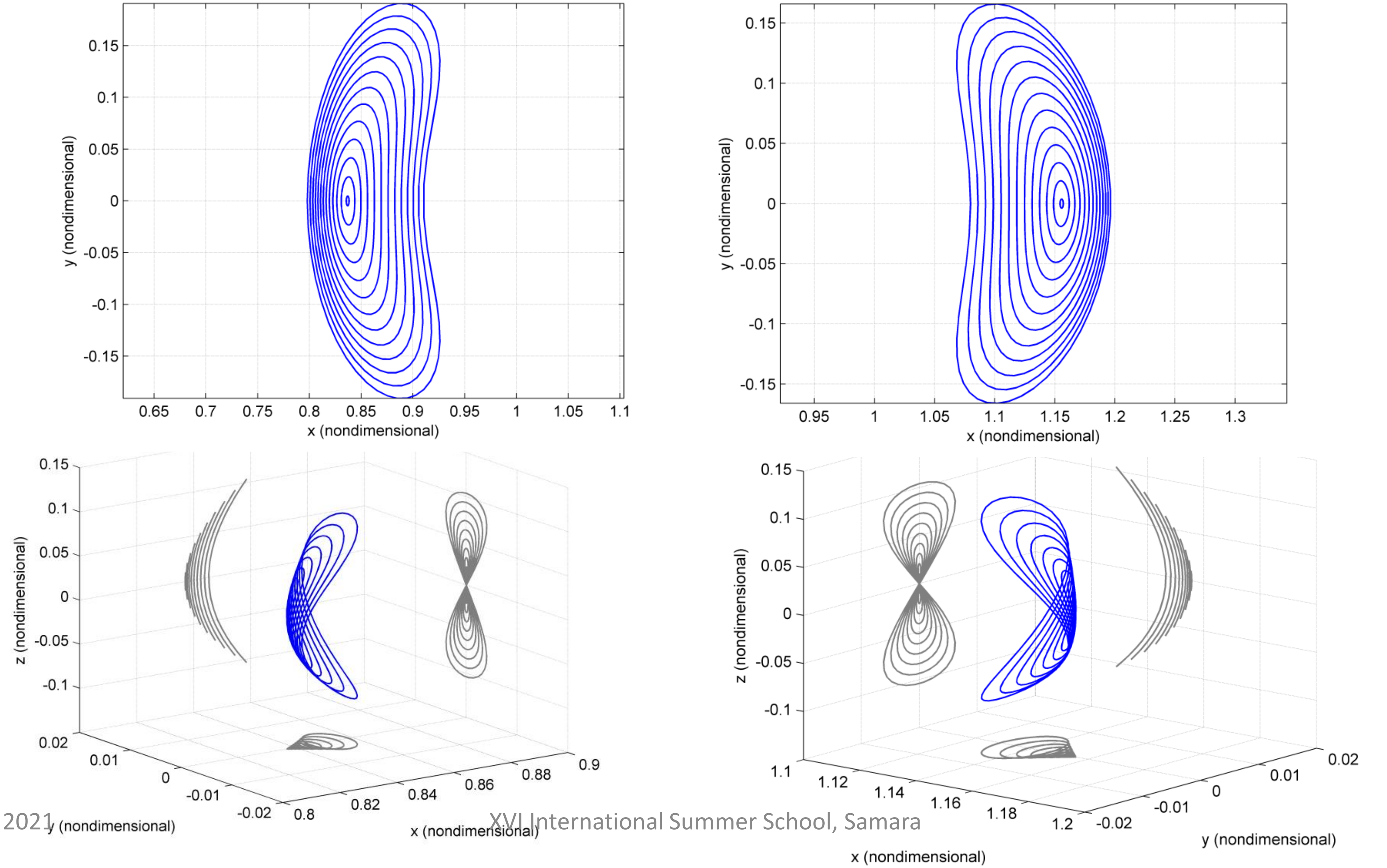
For spatial motion they are $\pm i w$

x = A cos (vt +φ1) +Cexp(λt) + Dexp(−λt) ,

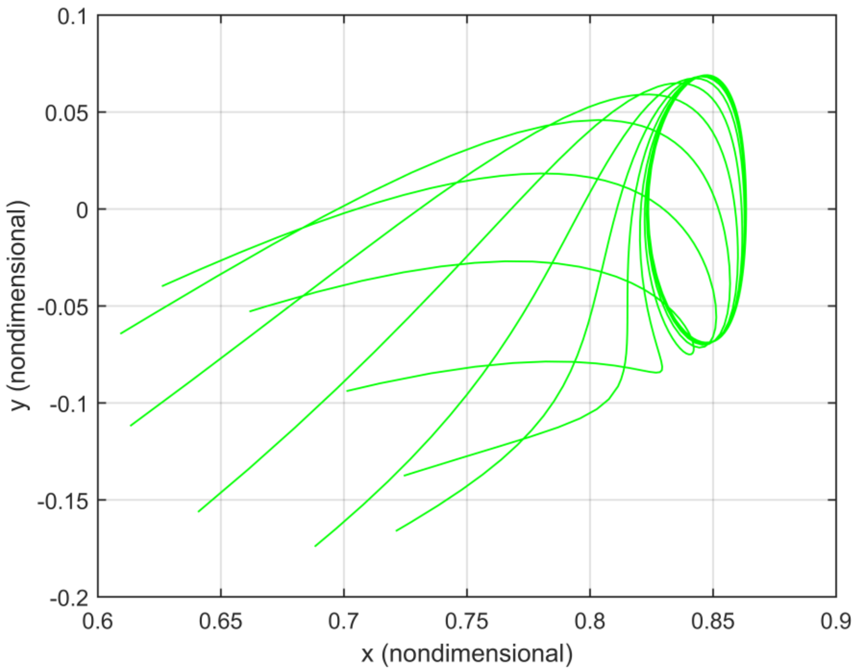
y= −k2 A sin (vt +φ1) + k1[Cexp(λt) −Dexp(−λt)],

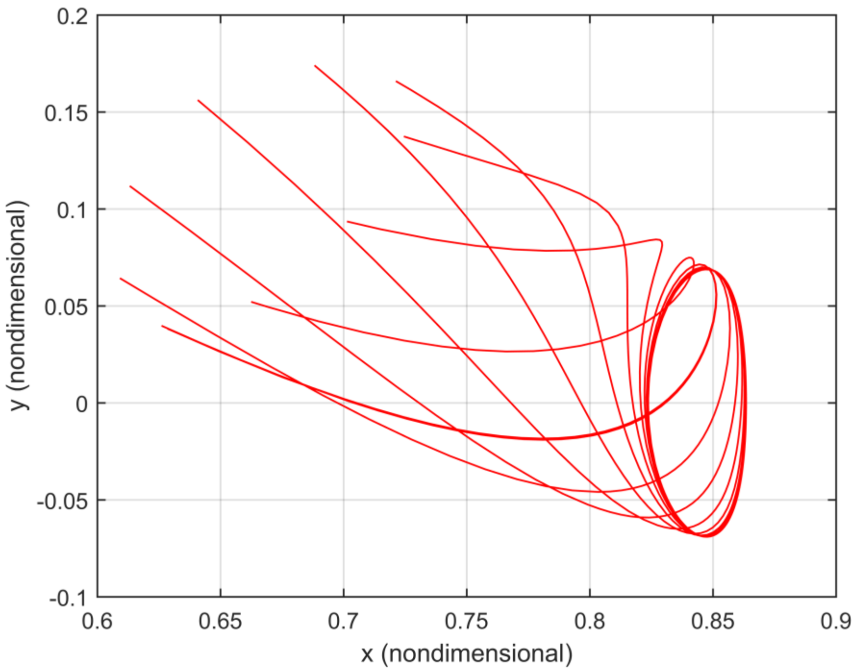
z = Bcos (wt +φ2)

Planar and vertical Lyapunov orbits in the EM system

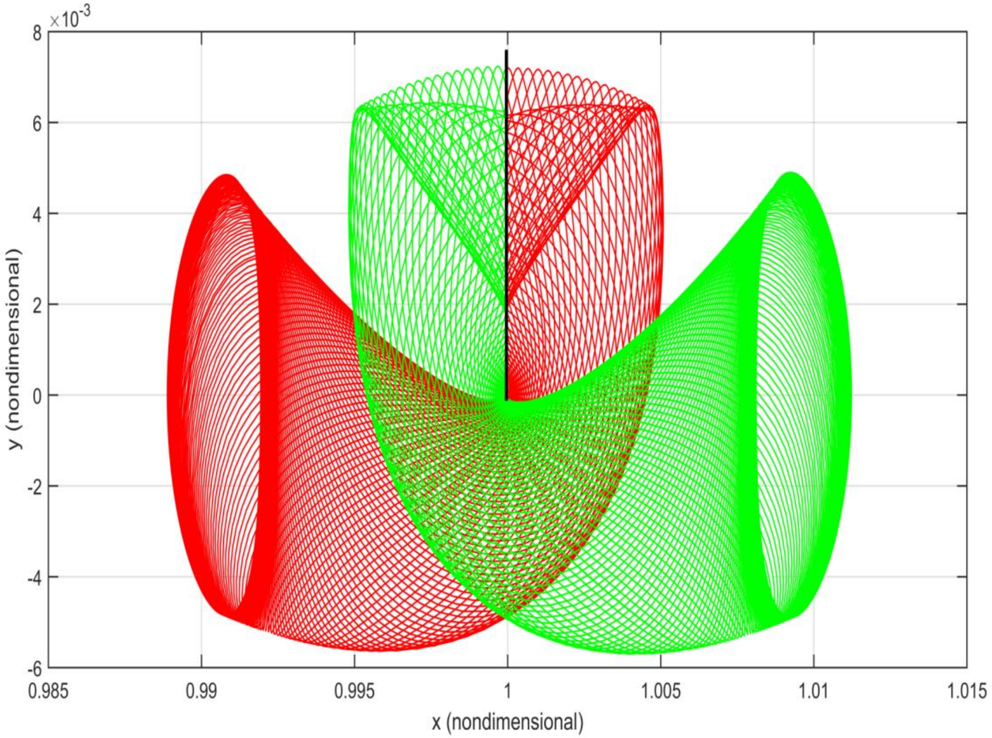


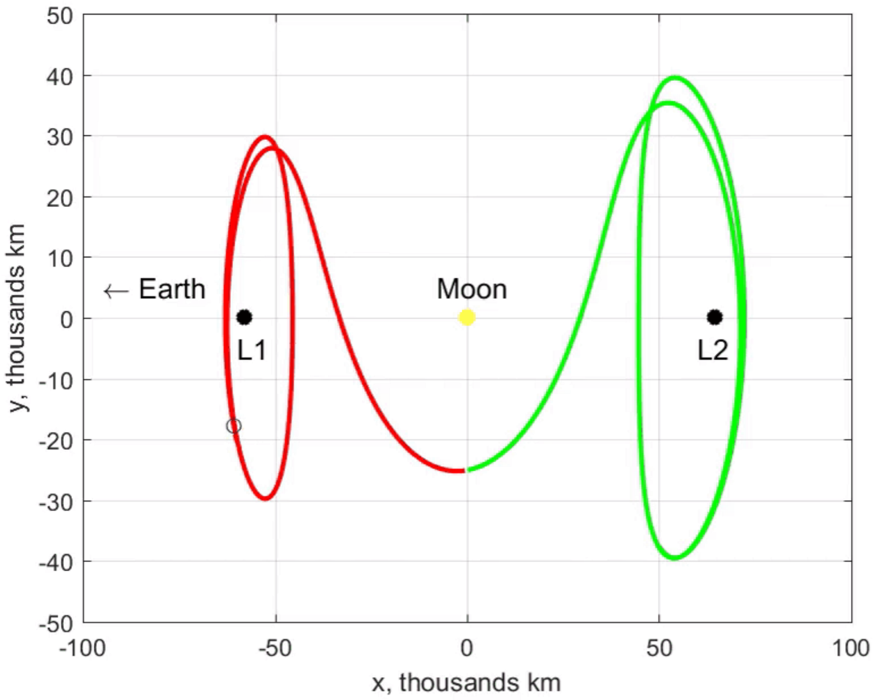
Stable (green) and unstable (red) manifolds near EM L1 halo orbit



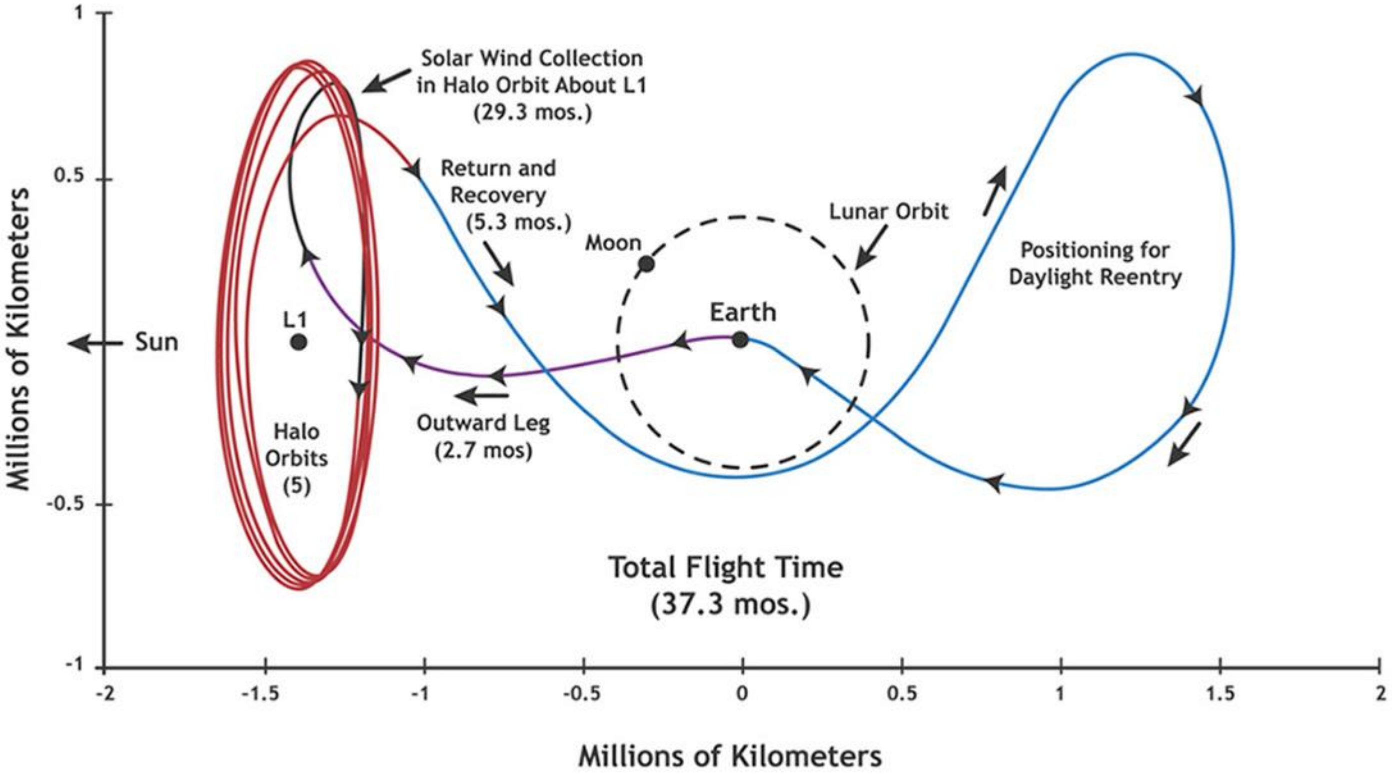


Transfers between halo orbits near EM L1 and L2 along unstable (red) and stable (green) invariant manifolds





The Genesis trajectory



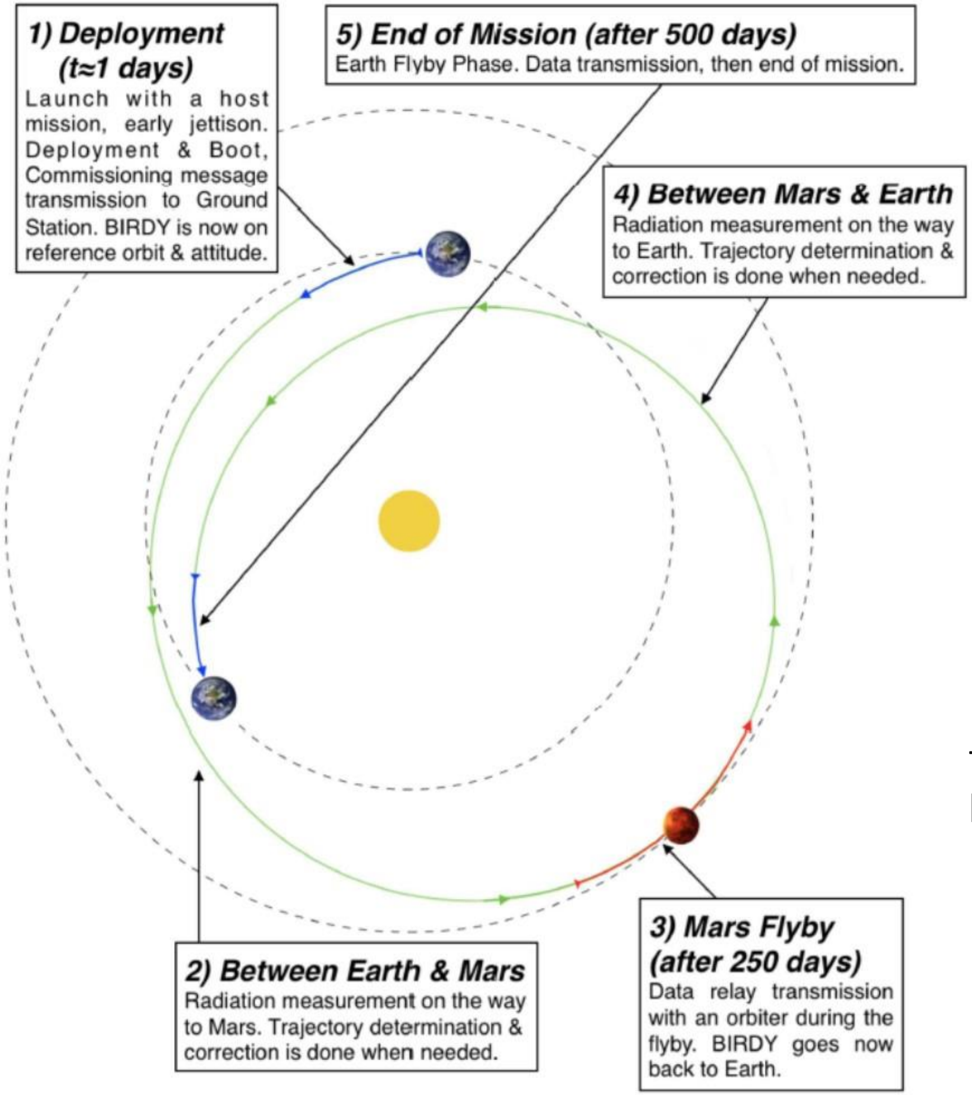
- LOI: 6-36 m/s
- SK: 9 m/s/year
- s/c mass: 636 kg
- Az = 450,000 km

Credit: NASA, http://genesismission.jpl.nasa.gov/gm2/mission/history.htm

Next step beyond the Moon: Flight to Mars

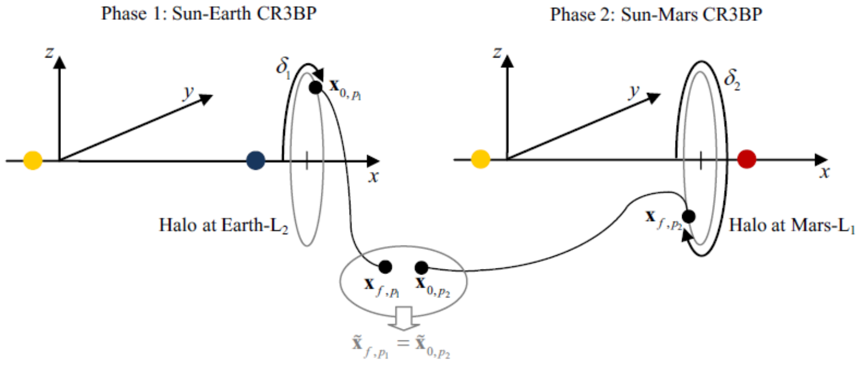
- No intersection of the invariant manifold of the Sun-Earth and the Sun-Mars systems but flight results of *GENESIS*, *MAP* and WIND increased the trust to dynamical systems theory:
  - To link the manifolds a pulse is demanded [F. Topputo, E. Belbruno, Earth–Mars transfers with ballistic capture, Celest. Mech. Dyn. Astr., V.121, 2015, pp.329–346]
  - Transfer from the Earth-Moon L2 to the Sun-EarthL1/L2 Halo orbit and next direct flight to Mars [M. Kakoi, K.C. Howell, D. Folta, Access to Mars from Earth–Moon libration point orbits: Manifold and direct options, Acta Astronautica, V.102, 2014, pp.269-286]

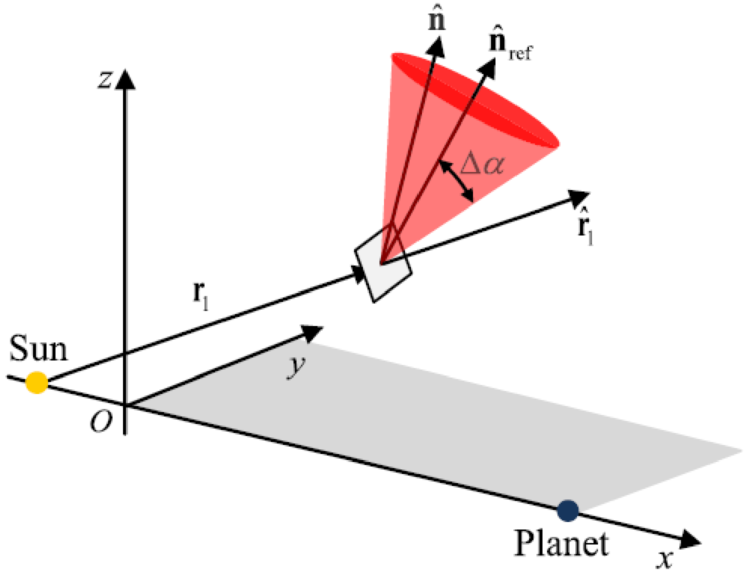
Free-return trajectory for BIRDY



B. Segret et al, BIRDY: An interplanetary CubeSat to collect radiation data on the way to Mars and back to prepare the future manned missions, Proceedings of SPIE , August 2014, VI(9150)

SE L2 – SM L1 optimal solar sail transfers for different steering capabilities





$$\cos^{-1}(\hat{\mathbf{n}}_{\text{ref}} \cdot \hat{\mathbf{n}}) \leqslant \Delta\alpha$$

Description	Departure date	Arrival date	Time of flight, days
$\Delta\alpha$ inactive	01/02/2022	01/08/2024	912
$\Delta\alpha = 20$ deg	05/02/2022	06/08/2024	914
$\Delta\alpha = 15$ deg	11/02/2022	23/08/2024	924
$\Delta\alpha = 12.5$ deg	06/02/2022	27/08/2024	932
$\Delta\alpha = 10$ deg	24/01/2022	05/09/2024	955
$\Delta\alpha = 7.5$ deg	21/01/2022	03/11/2024	1017

J. Heiligers, M. Giorgio, and C.R. McInnes, ``Optimal solar sail transfers between Halo orbits of different Sun-planet systems,'' Advances in Space Research, 2015, Vol. 55, Is. 5, pp. 1405--1421.

Transfers to the interstellar space

The purpose is to approach SGLF at 600-800 AE in 25-30 years to explore exoplanets to search life beyond our Solar system

- Gravity-assist maneuvers near Jupiter or solar sail drive to the Sun
- Powered flyby of the Sun (the Oberth effect)
- Sail-assisted trajectory to attain 20 AE/year (Voyagers achieved 3.6 AE/year)

6 **So much gain at 550 AU** [Ch. 1

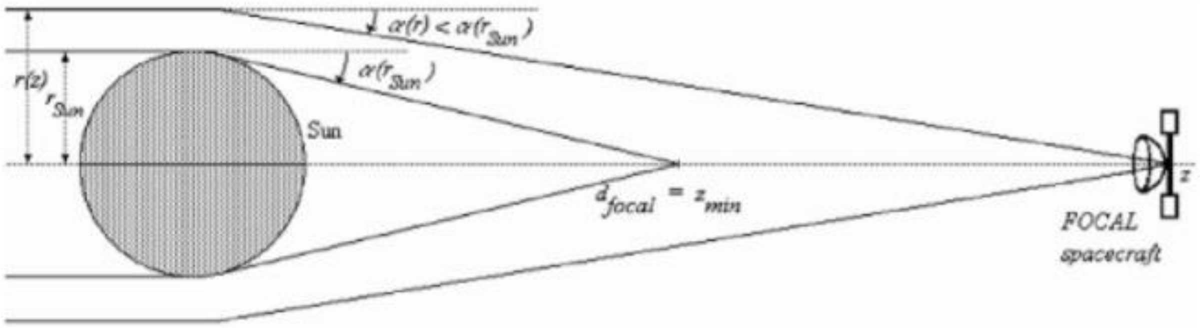


Figure 1.2. Basic geometry of the gravitational lens of the Sun, showing the minimal focal length and the FOCAL spacecraft position.

Credit: Slava Turyshev

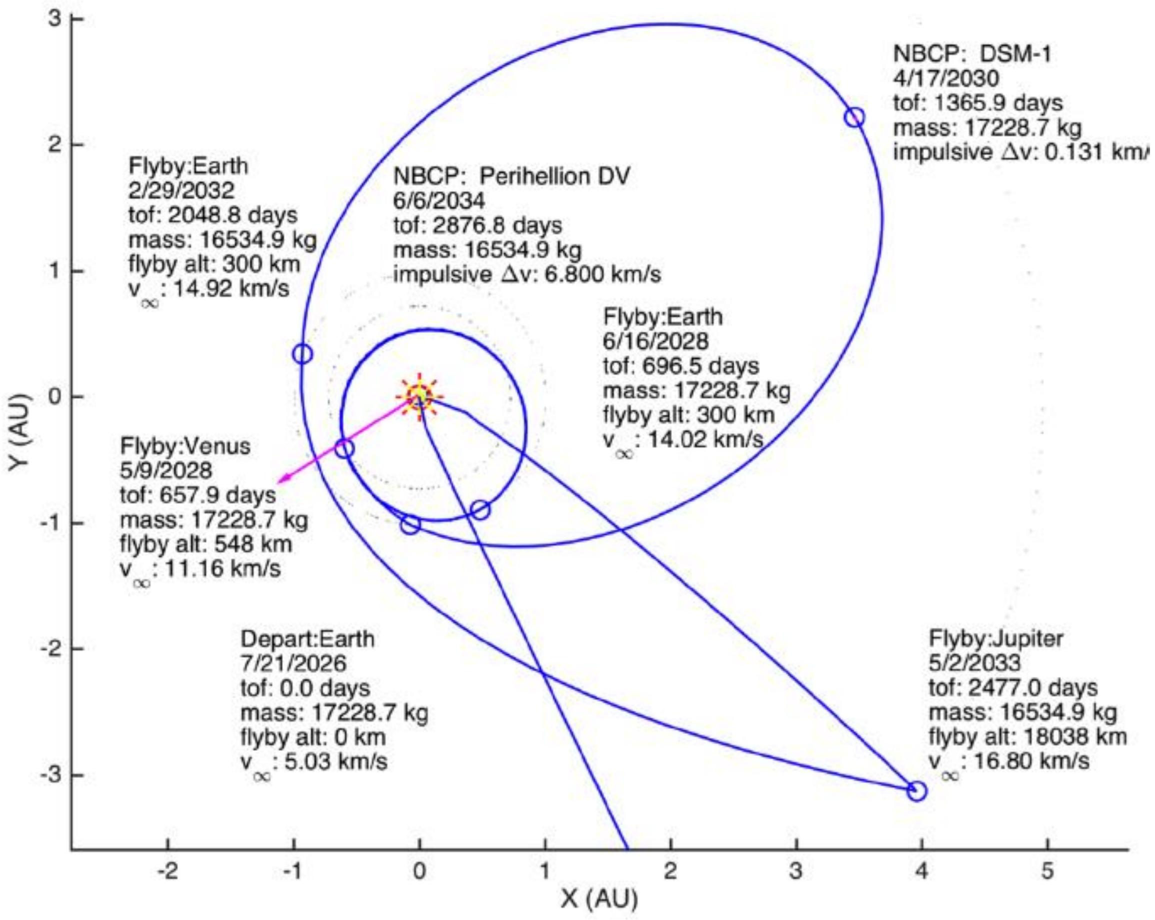
The Oberth effect is to be used

While one needs to increase the kinetic energy of a SC, it is more effective to execute a pulse maneuver at the pericenter

$$\Delta E = \frac{1}{2}[(V + \Delta V)^2 - V^2] \approx V \cdot \Delta V, \quad |\Delta V| << V$$

Trajectory to the Interstellar Space. Var 1

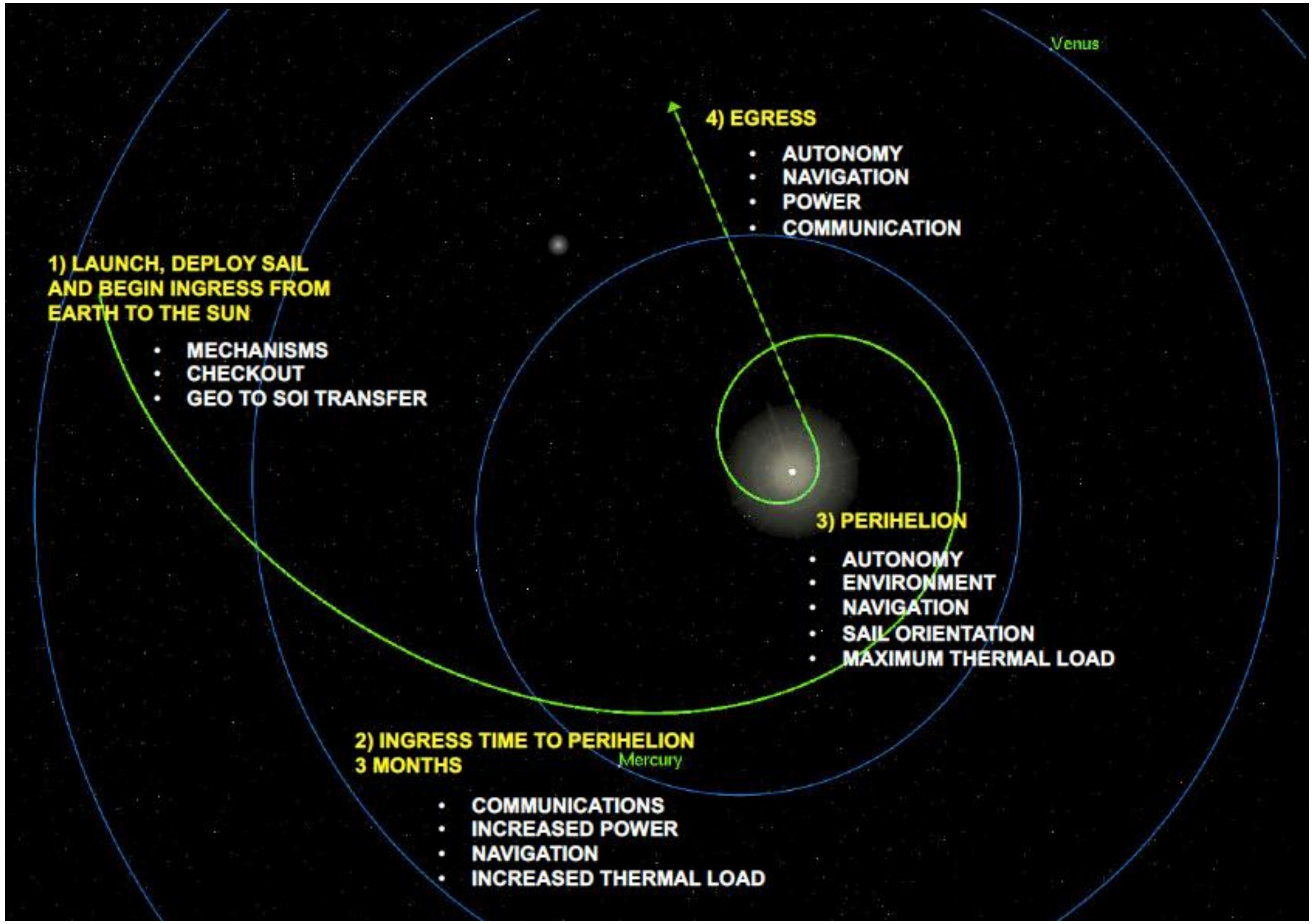
- passive Jupiter GA maneuver
- active perihelion fly-by



N. Arora, N. Strange, and L. Alkalai, ``Trajectories for a near term mission to the interstellar medium,'' AAS/AIAA Astrodynamics Specialist Conference, August 2015, Vail, CO, USA. Paper AAS 758

Trajectory to the Interstellar Space. Var 2

- Solar sail drive from the Earth
- active perihelion fly-by



Credit: Slava Turyshev

Navigation of Cubesats

- Conventional techniques:
  - Navigation by triangulation from on-ground stations
  - Navigation by the distance and Doppler shift of the frequency on the weakened signal measuring from on-ground station
- Pulsar-based triangulation use with either radio pulsars or X-ray pulsars is not currently feasible for nanosatellites due to large-sized sensors and high pointing requirements
- Autonomous techniques are preferable:
  - Italian Lumio Cubesat is to use a full Moon imaging technique to maintain a 14-day periodic halo orbit EM L2 (distance to the Moon 35 000 km). Accuracy of the orbit determination is about 10 km
  - Asynchronous triangulation of foreground celestial body (ESA's Gaia catalog contains 350 000 Solar system objects) with sufficient background stars [B.Segret, B.Mosser, Autonomous Orbit Determination for a CubeSat Cruising in Deep Space, https://arxiv.org/pdf/2104.09989]
- Many other questions about navigation approaches and techniques exist and are to be solved!

Thank you for your attention!