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

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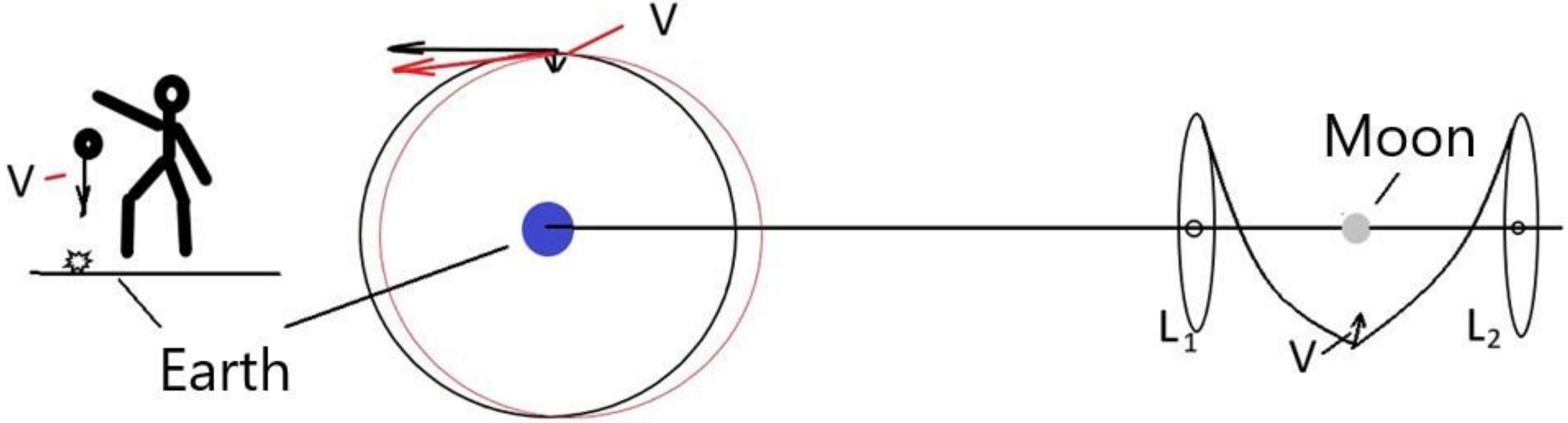
Instead of Objectives:
Worlds where we live and where SC fly



plane-parallel field

central Newtonian field

field of two attracting particles (Earth and Moon)

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 it is not possible to count small satellite and even Cubesat missions already launched and scheduled to be launched.

They compose a basis to create a network like Internet cables – even a satellite is broken a constellation or a formation flying are able to continue mission task performance

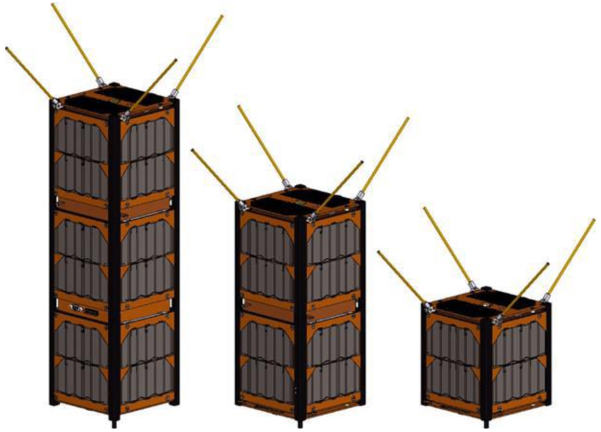
Internet ↔ Cubesats

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

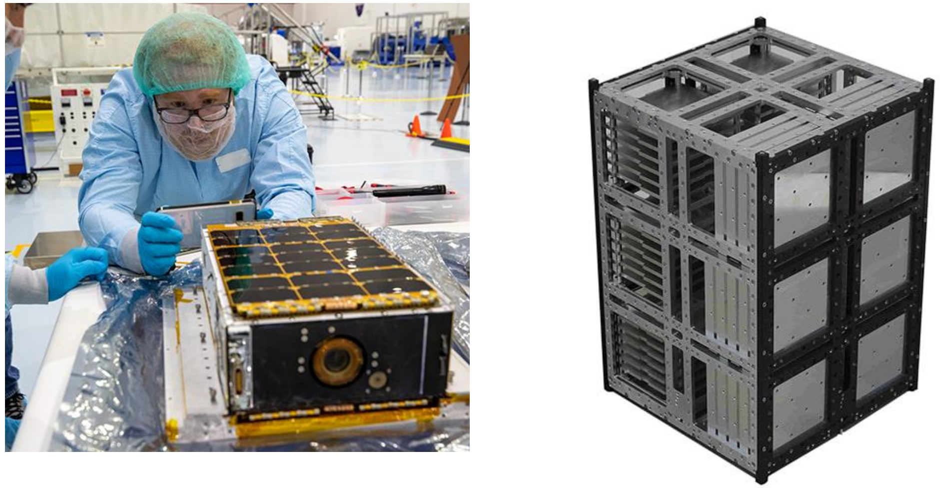
Formal classification (title vs. kg)

Mini	Small	Micro	Nano	Pico	Femto
1000–500	500–100	100–10	10–1	1–0.1	0.1-0.0

segment of our interest, generally will be called small SC or Cubesat



1U-3U for near-Earth use



6U-12U for interplanetary use

Small sats (including Cubesats) peculiarities

- Alternative approach for development, testing and servicing wrt big SC
- Involvement of low-cost manpower for development and design
- Components-Of-The-Shelf (no-space qualified) implementation
- Low-cost launch opportunities (piggy-back style, dedicated light launchers)
- Lower reliability, lower cost but faster substitution in orbit by more modern satellite
- New spatial configuration of multi-agent satellite system
- Fast development and well adapted to various applications lead to benefit of private business due to working capital turnover

Way for research business

- The previous slide demonstrates that near-Earth Cubesats have already become the object of engineering, production and even selling
- Difficultness is a thruster of progress
- Progress is a responsibility of research
- Interplanetary missions compose difficultness essentially for lean spacecraft, i.e. Cubesats
- Consequently, Cubesats for interplanetary missions are an object for deep research and implementation of new math techniques

Why interplanetary missions is a privilege for Cubesats?

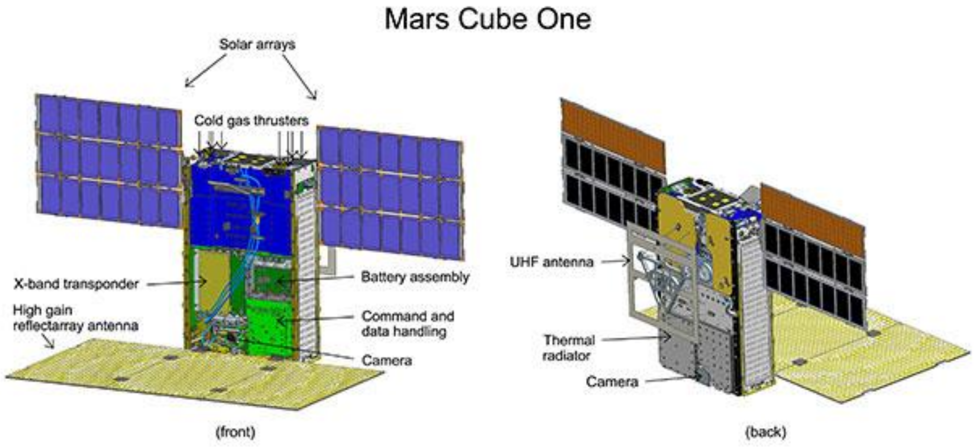
- Interplanetary missions require an extreme efforts in various branches of science and technology due to unknown factors effecting satellites
- Cubesats’ small size, mass and other limitations and constrains aggravate the difficulty of mission design
- The interplanetary missions based on Cubesats is the guiding star for research and, consequently, for invention and for new scientific and technological achievements

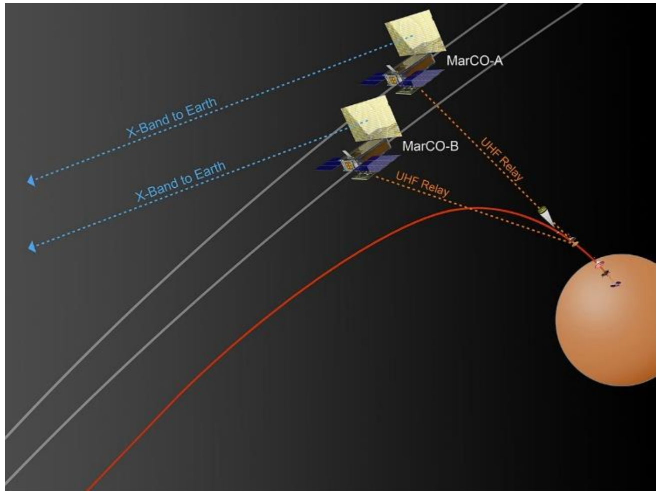
Factors govern a form-factor (size) of Cubesat

- a planet to be accessed (Moon, Mars, Venus …) – bigger planet, bigger Cubesat
- autonomous Cubesat capabilities (chemical or plasma engines):
  - powered pulse to provide trans-planet injection
  - low-thrust
- launch vehicle determines what initial orbit can be reached to start interplanetary segment of the mission):
  - near-Earth (LEO, MEO, etc)
  - trans-planet injection

Interplanetary Cubesats have already flown

- MarCO-A & MarCO-B are **the first 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/

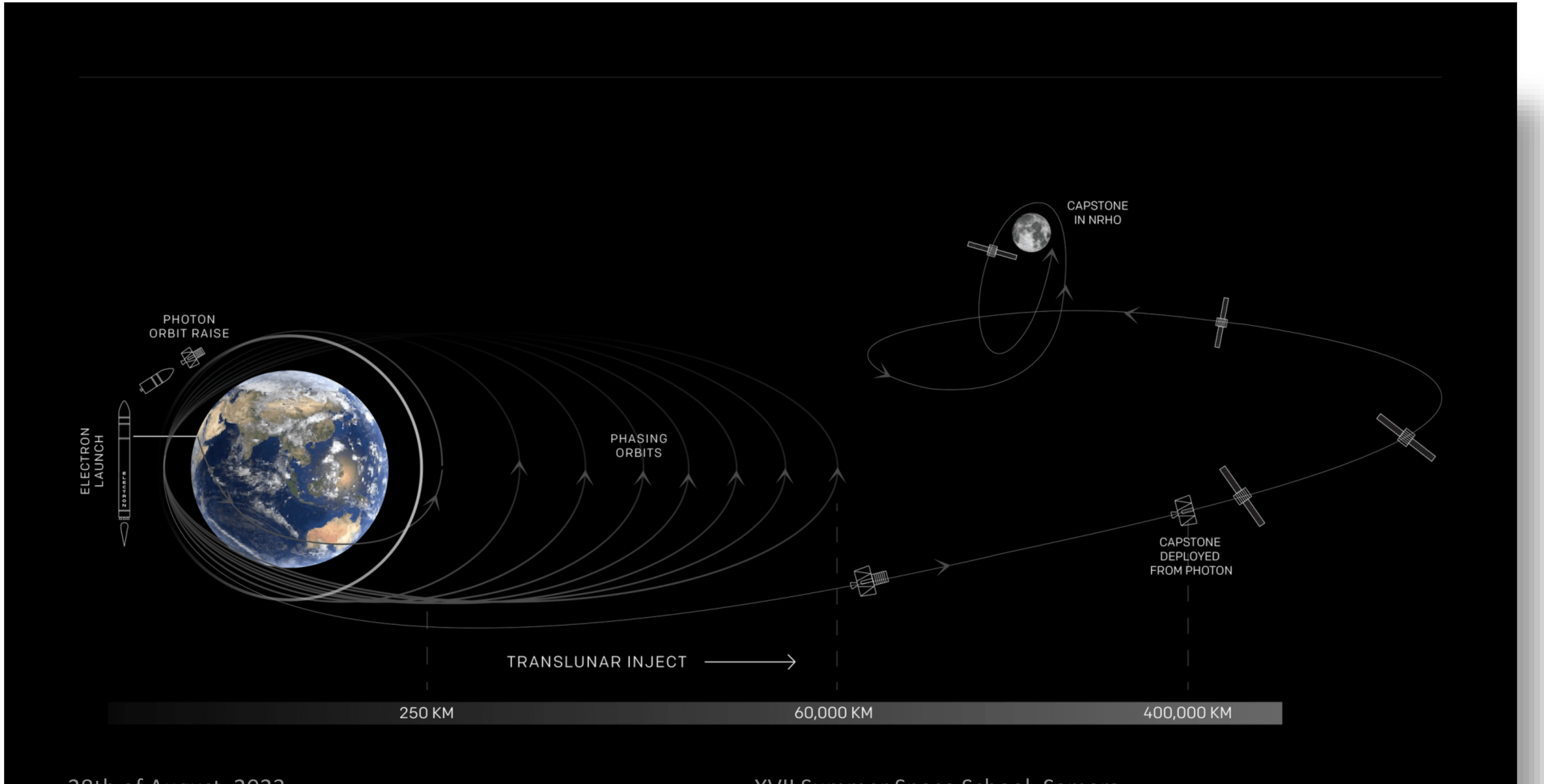
12U-Cubesat Capstone (25 kg) to the Moon designed by Rocket Lab

On June 28, 2022, Rocket Lab launched a CubeSat Capstone (25 kg) to the Moon by Electron rocket and Lunar Photon upper stage.
The Cubesat is purposed to test ballistics of GetAway

BTW, the total cost of the mission costs just $23.65 million

Credit: NASA

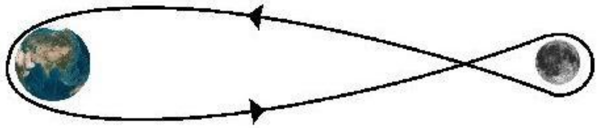
On November 14, 2022, Capstone has reached Near Rectilinear Halo Orbit (NRHO)



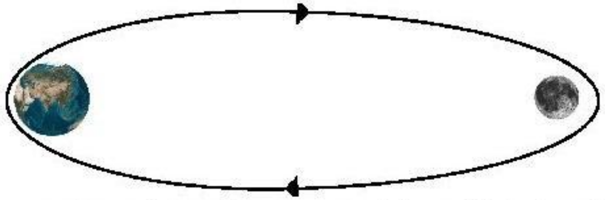
Credit: NASA

Trajectories to the Moon

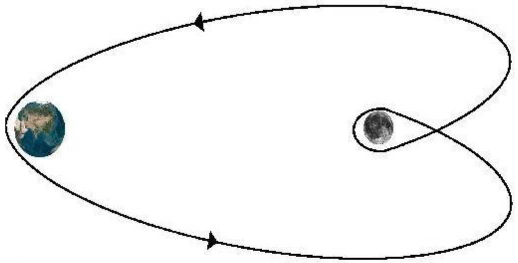
Free-return trajectory (patched two-body approximation) with the trans-lunar injection (TLI) ~3.2 km/sec



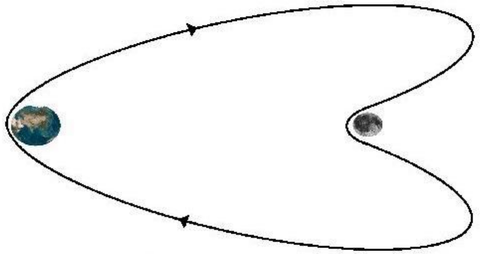
a) Coplanar circumlunar free-returns: Type Ai in inertial coordinate system (Apollo class)



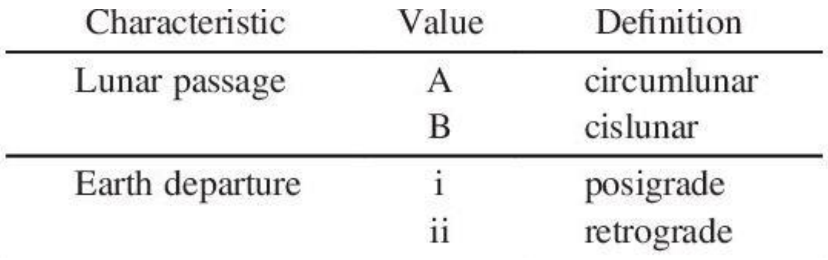
b) Coplanar circumlunar free-returns: Type Aii in inertial coordinate system



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



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

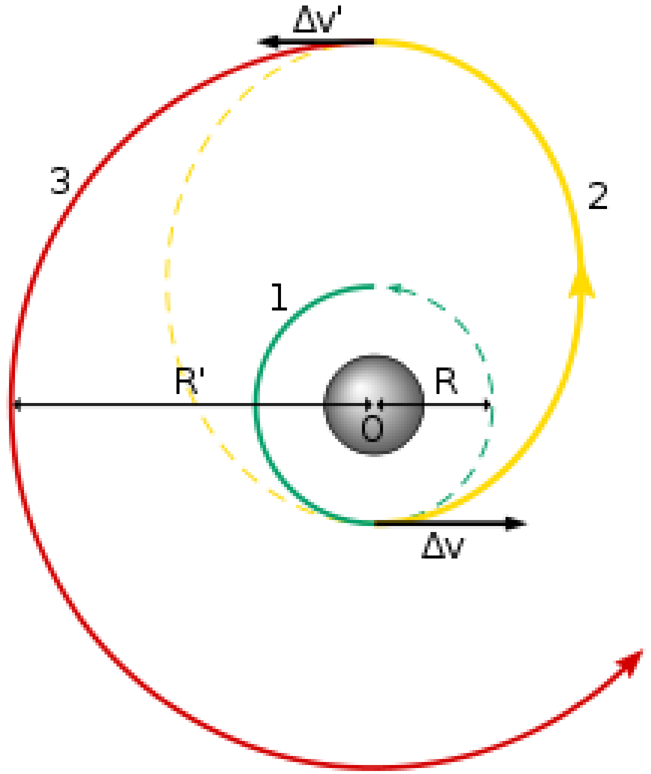


Characteristic	Value	Definition
Lunar passage	A	circumlunar
	B	cislunar
Earth departure	i	posigrade
	ii	retrograde

Hohmann transfer (1925 y)

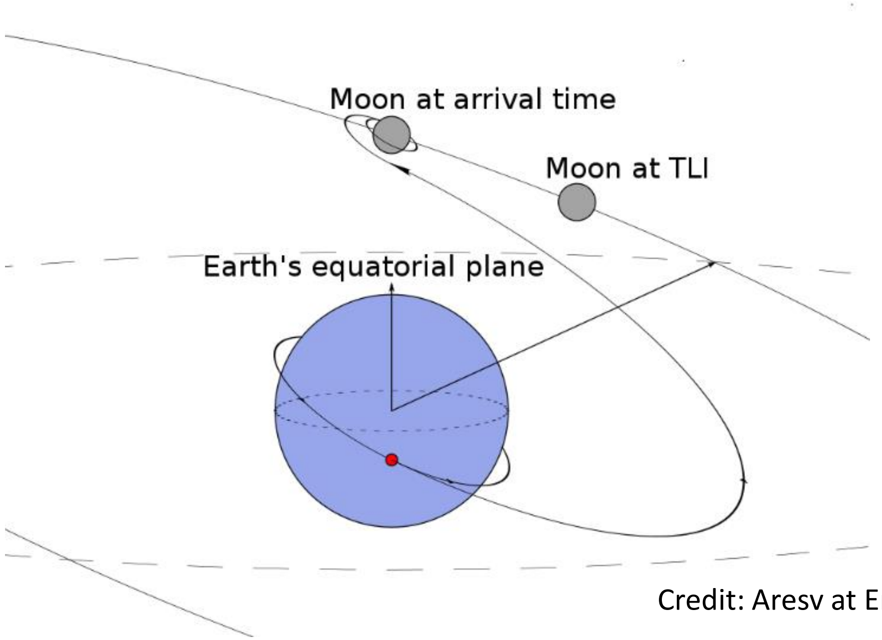
Hohmann transfer orbit (2), from an orbit (1) to a higher orbit (3)

Not possible for Cubesats and even for small SC (requires two powered pulses)



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

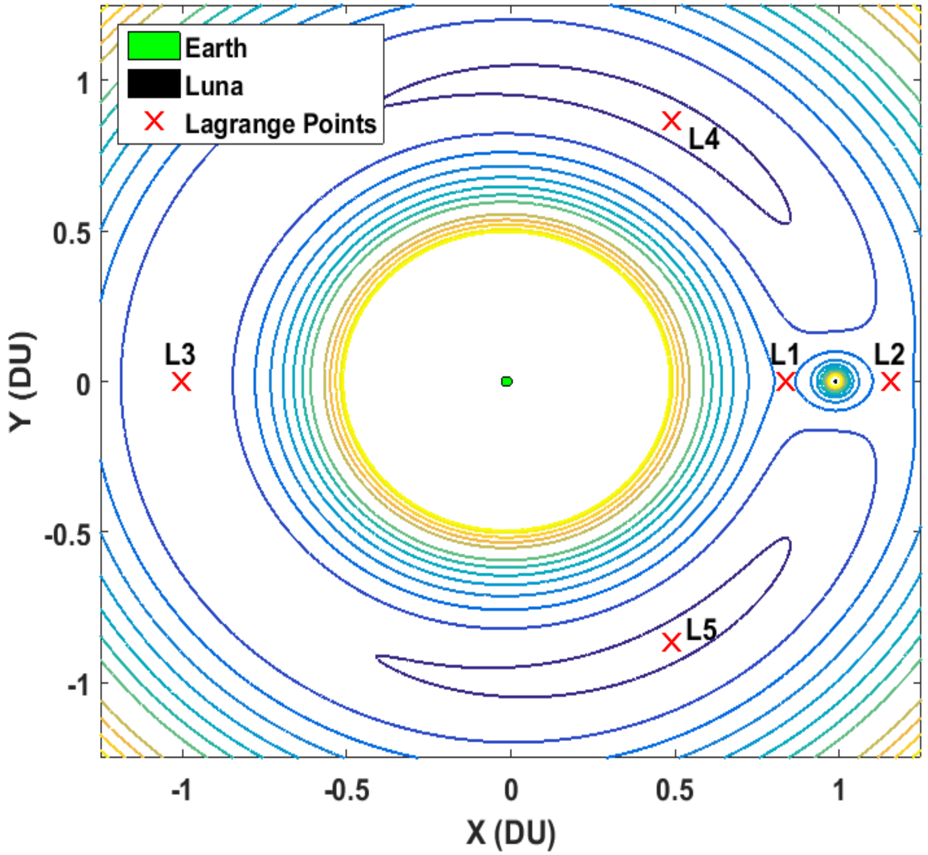
There is opportunity to insert LEO, MEO, GEO, GTO

While a low-thrust engine is available onboard then Circular Restricted Three Body Problem can be considered and study results can be used

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 SC 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*

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

- Microspacecraft **35-37 kg**, 10 times smaller than SMART-1 (closer to Cubesat)
- Smaller 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, Proceedings of the 71st International Astronautical Congress, 12-14 October 2020 — IAC CyberSpace Edition, 12-14 October 2020, IAC-20-C1.4.13, 8p.

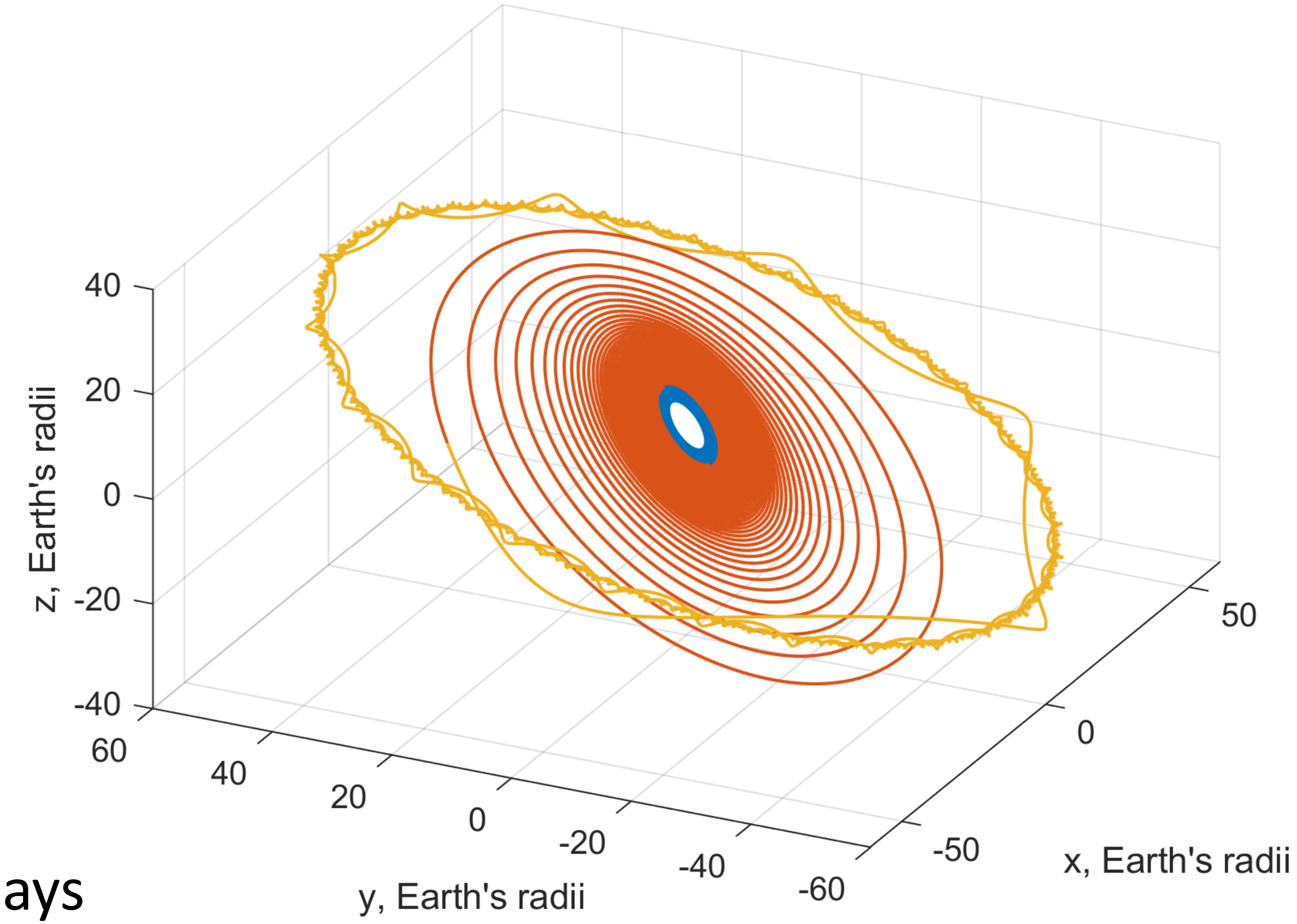
MEO-LLO transfer trajectory

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

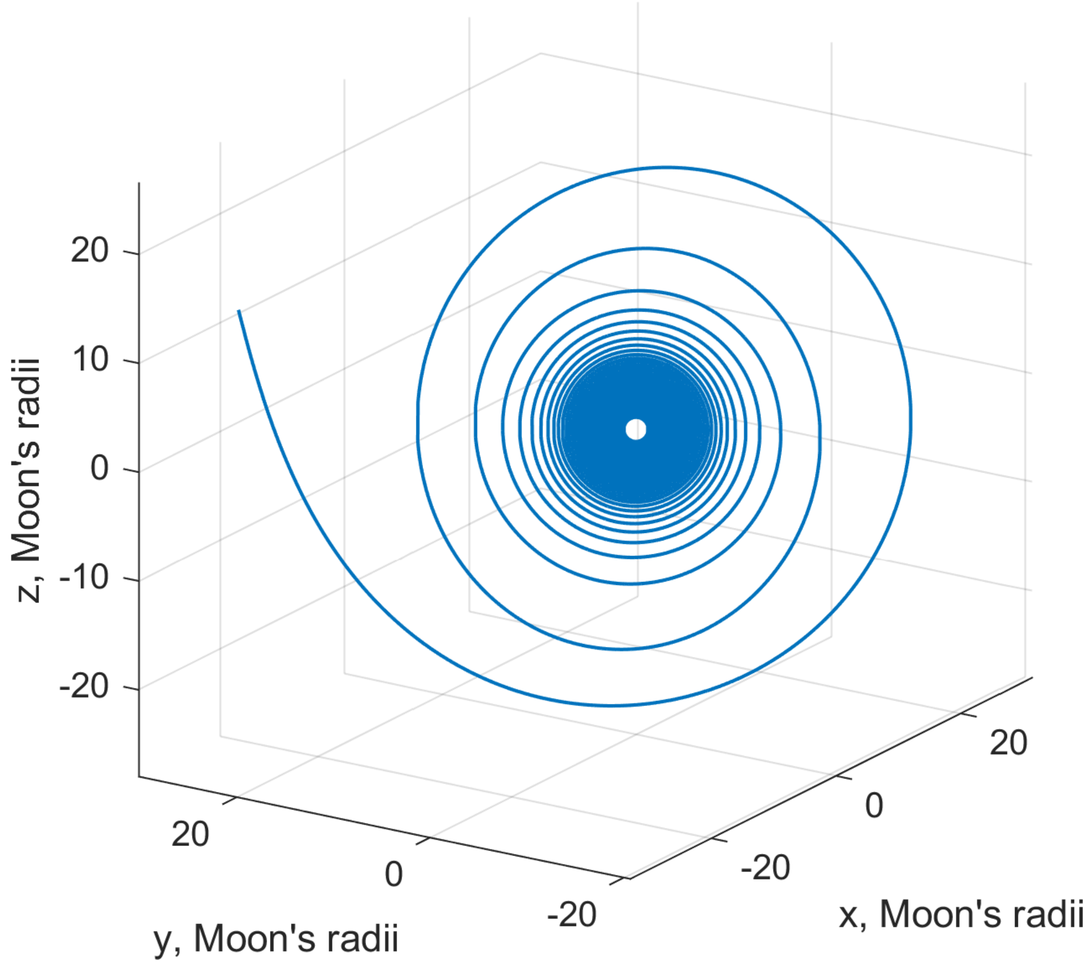
Target LLO:
polar, 100 km

Spacecraft:
m0 = 35 kg
mf = 30.6 kg

TOF (total): 443 days



Spiraling down to the 100 km LLO



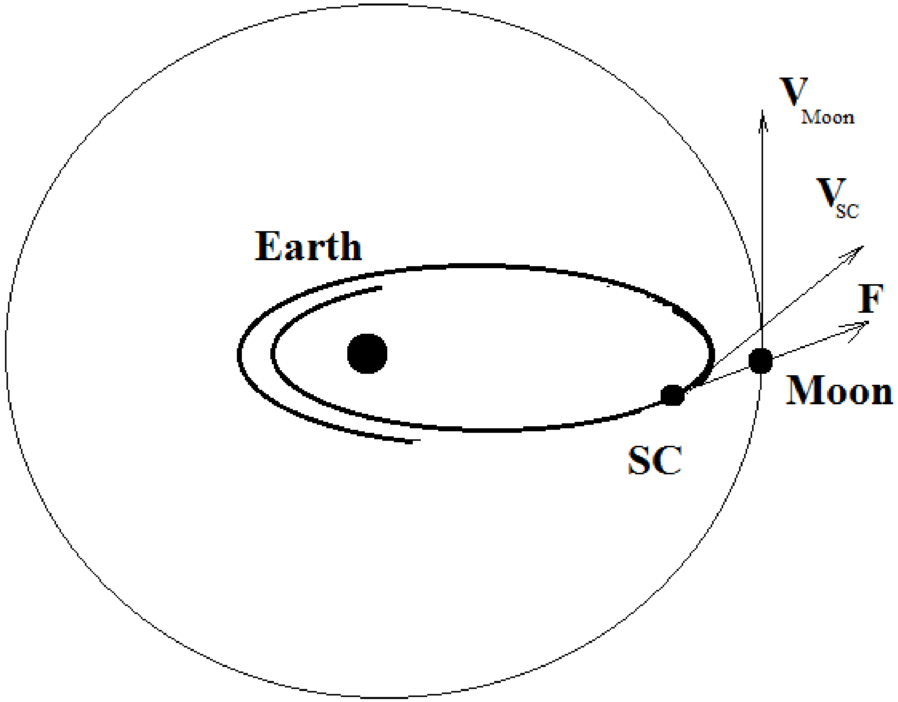
Antivelocity thrust
F = 4.9 mN

TOF since passing
the L1 bottleneck:
≈100 days

First working LLO
to start science:
polar, 100 km

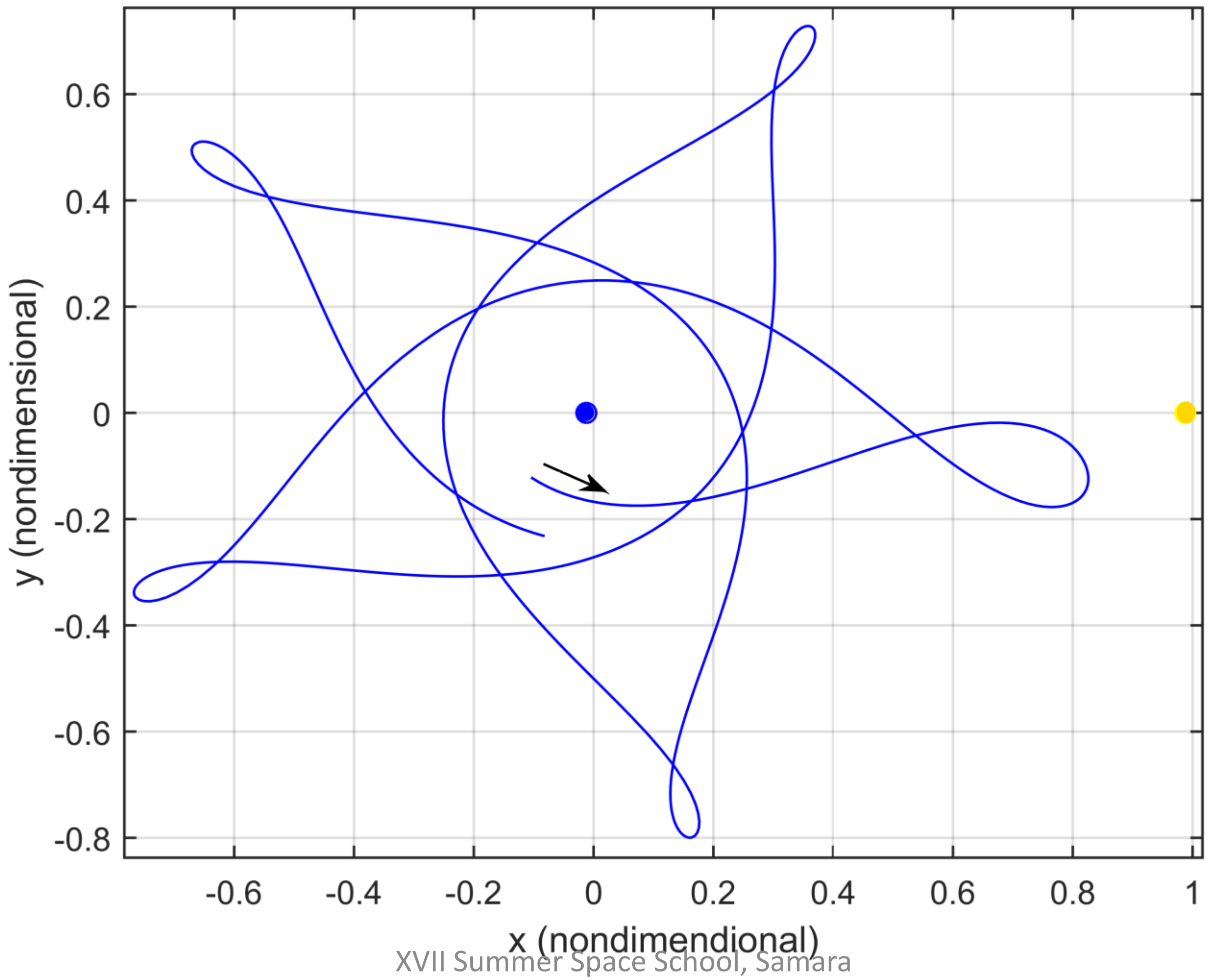
Everyday corrections
seem to be required

Resonant encounters (just idea)

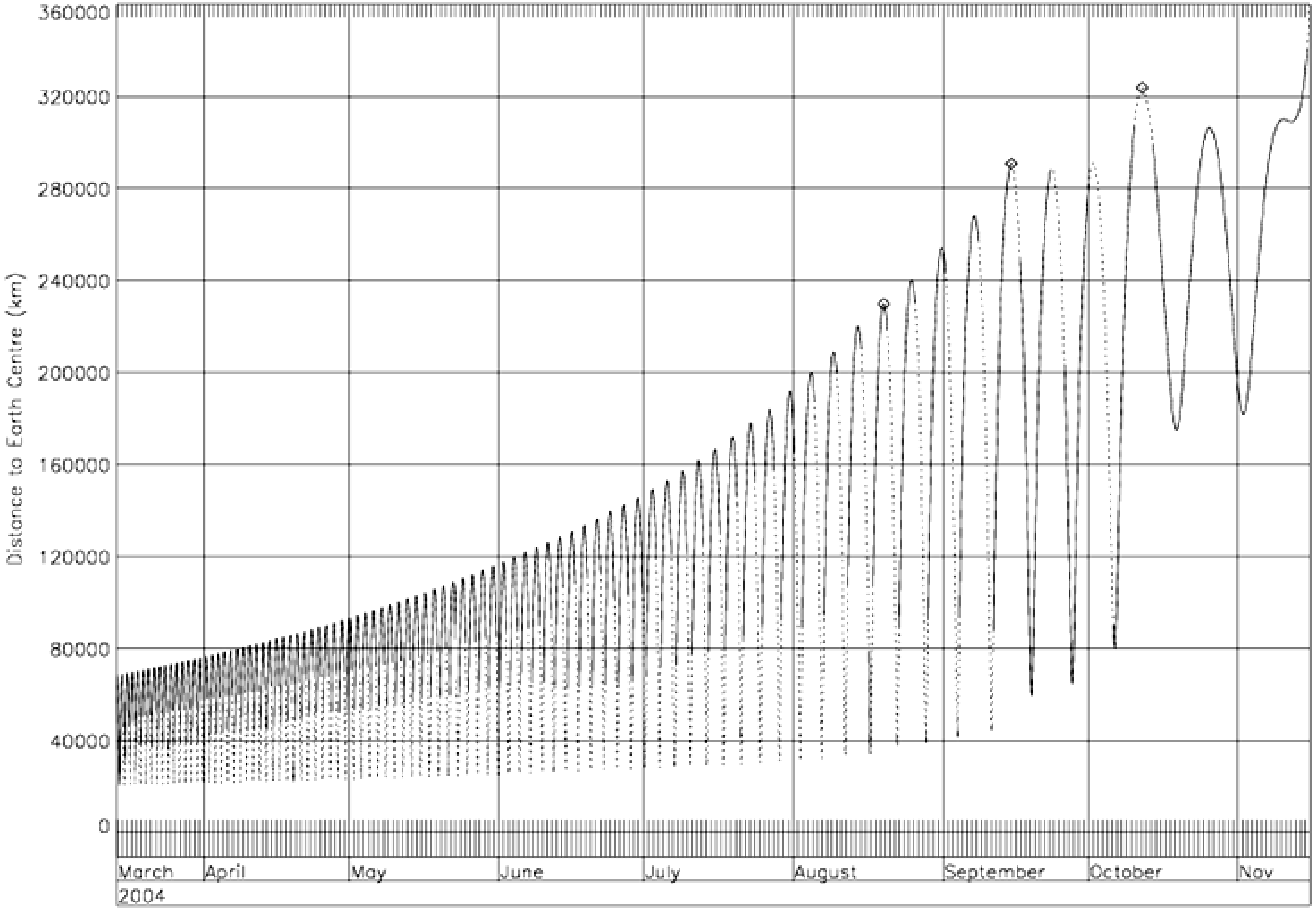


Perigee raising by using the high-altitude fly-by

Δr_π = 34,000 km

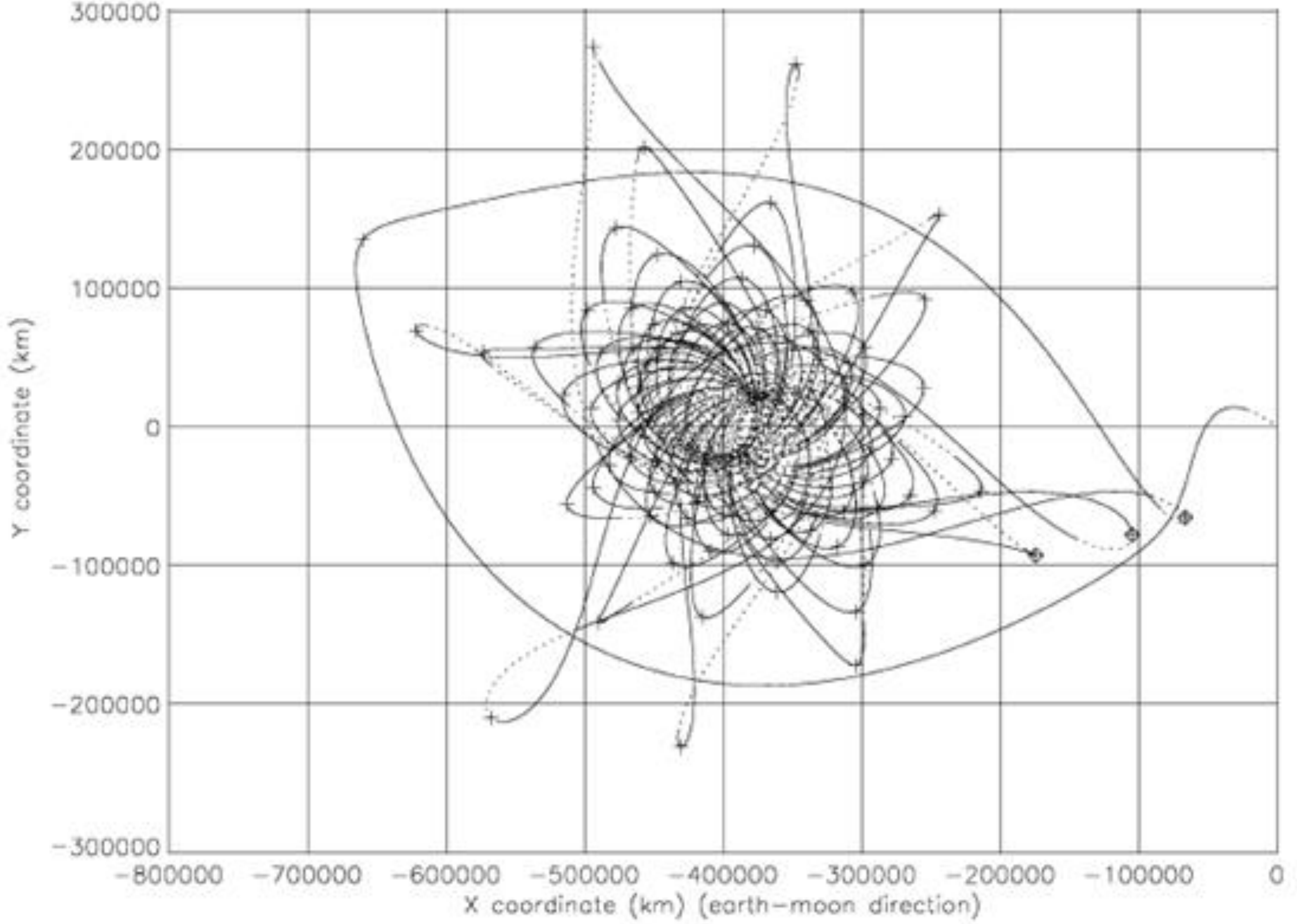


SMART-1 hopping



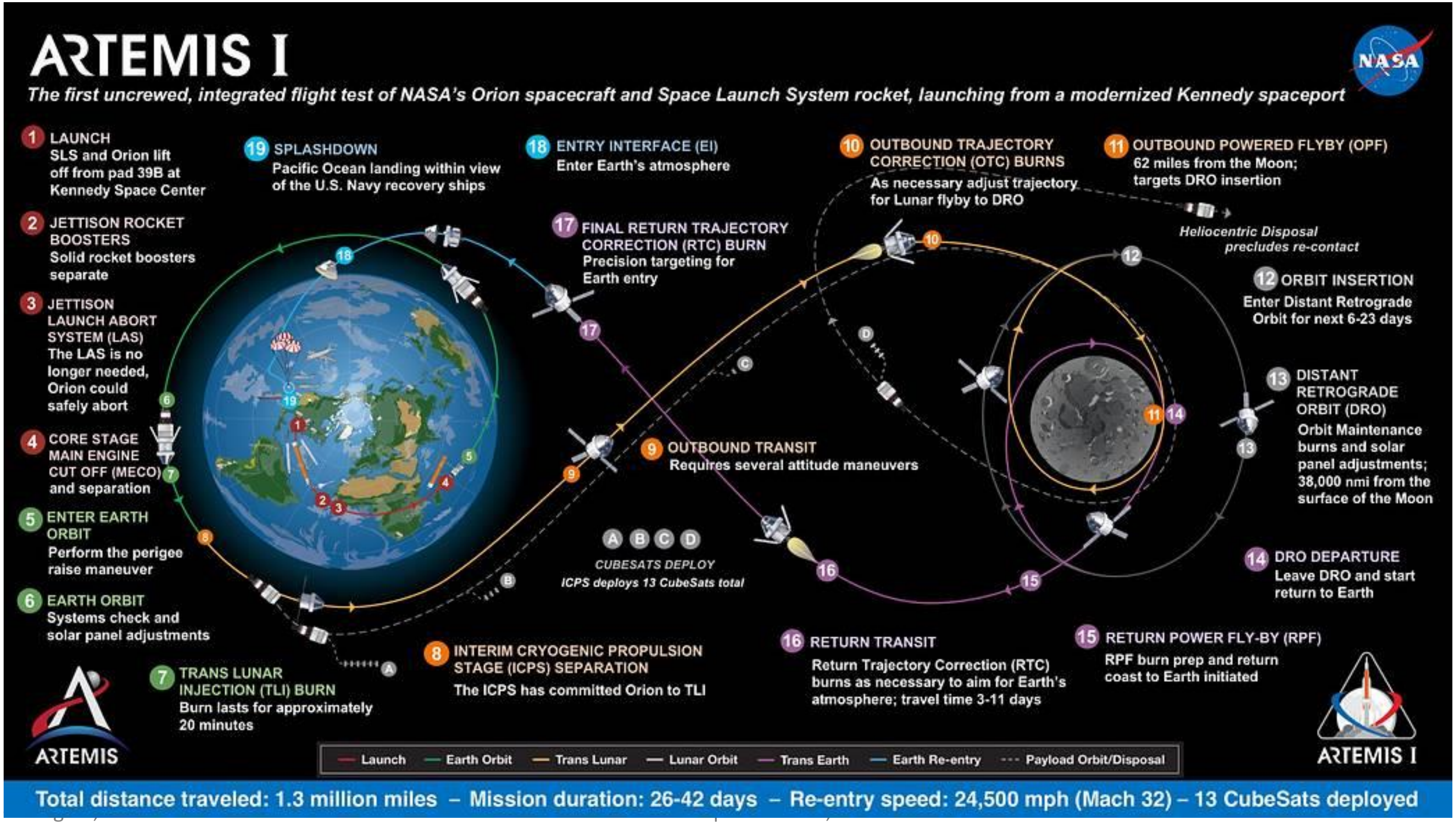
J. Schoenmaekers, ``Post-launch Optimisation of the SMART-1 Low-thrust Trajectory to the Moon,'' 18th International Symposium on Space Flight Dynamics, October 2004, Munich, Germany.

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.

10 Cubesats deployment during Artemis 1 mission



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy spaceport

1 **LAUNCH**
SLS and Orion lift off from pad 39B at Kennedy Space Center

2 **JETTISON ROCKET BOOSTERS**
Solid rocket boosters separate

3 **JETTISON LAUNCH ABORT SYSTEM (LAS)**
The LAS is no longer needed, Orion could safely abort

4 **CORE STAGE MAIN ENGINE CUT OFF (MECO) and separation**

5 **ENTER EARTH ORBIT**
Perform the perigee raise maneuver

6 **EARTH ORBIT**
Systems check and solar panel adjustments

7 **TRANS LUNAR INJECTION (TLI) BURN**
Burn lasts for approximately 20 minutes

8 **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION**
The ICPS has committed Orion to TLI

9 **OUTBOUND TRANSIT**
Requires several attitude maneuvers

A B C D
CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

10 **OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS**
As necessary adjust trajectory for Lunar flyby to DRO

11 **OUTBOUND POWERED FLYBY (OPF)**
62 miles from the Moon; targets DRO insertion

Heliocentric Disposal precludes re-contact

12 **ORBIT INSERTION**
Enter Distant Retrograde Orbit for next 6-23 days

13 **DISTANT RETROGRADE ORBIT (DRO)**
Orbit Maintenance burns and solar panel adjustments; 38,000 nmi from the surface of the Moon

14 **DRO DEPARTURE**
Leave DRO and start return to Earth

15 **RETURN POWER FLY-BY (RPF)**
RPF burn prep and return coast to Earth initiated

16 **RETURN TRANSIT**
Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 3-11 days

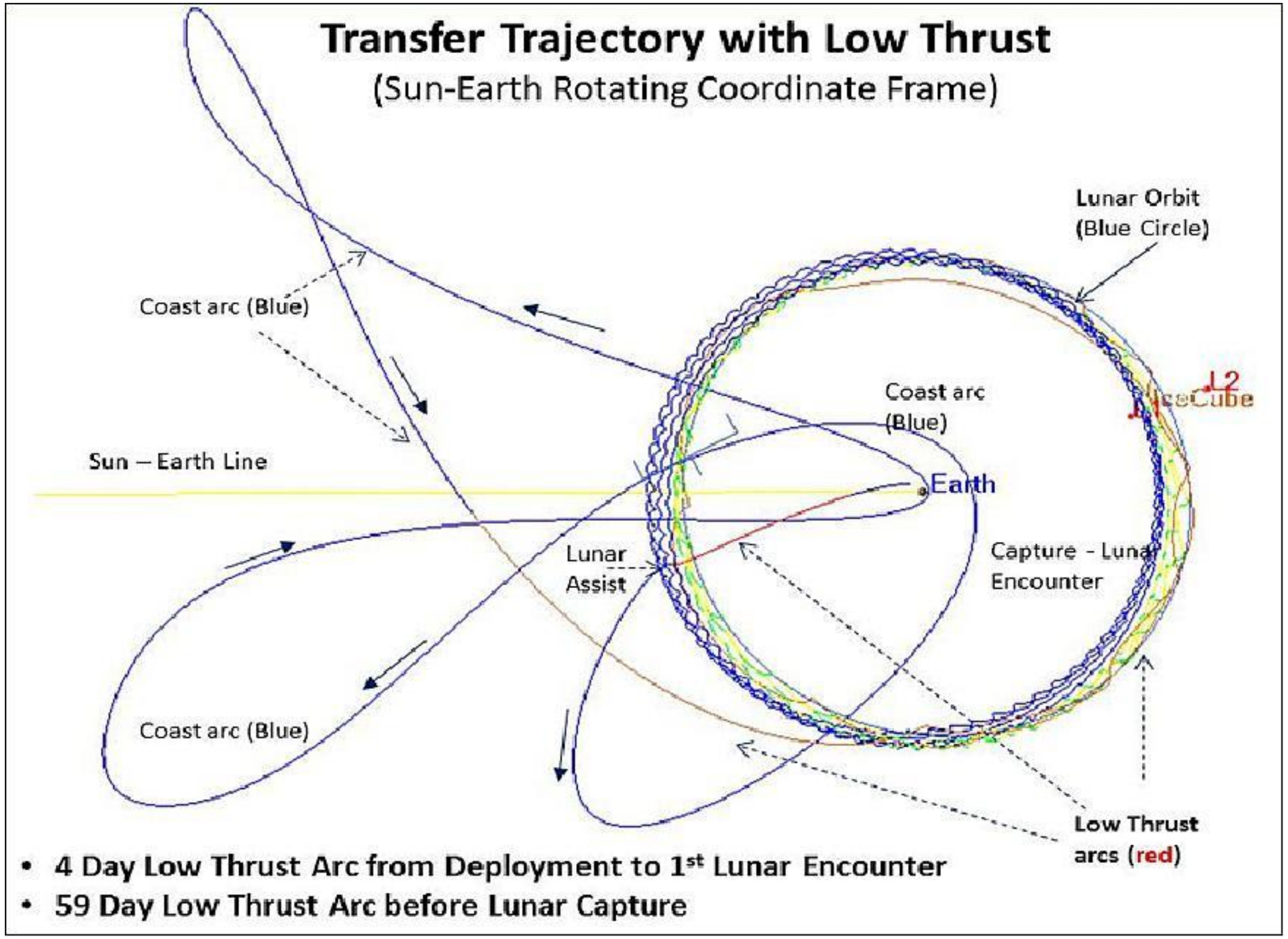
17 **FINAL RETURN TRAJECTORY CORRECTION (RTC) BURN**
Precision targeting for Earth entry

18 **ENTRY INTERFACE (EI)**
Enter Earth's atmosphere

19 **SPLASHDOWN**
Pacific Ocean landing within view of the U.S. Navy recovery ships

Total distance traveled: 1.3 million miles – Mission duration: 26-42 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

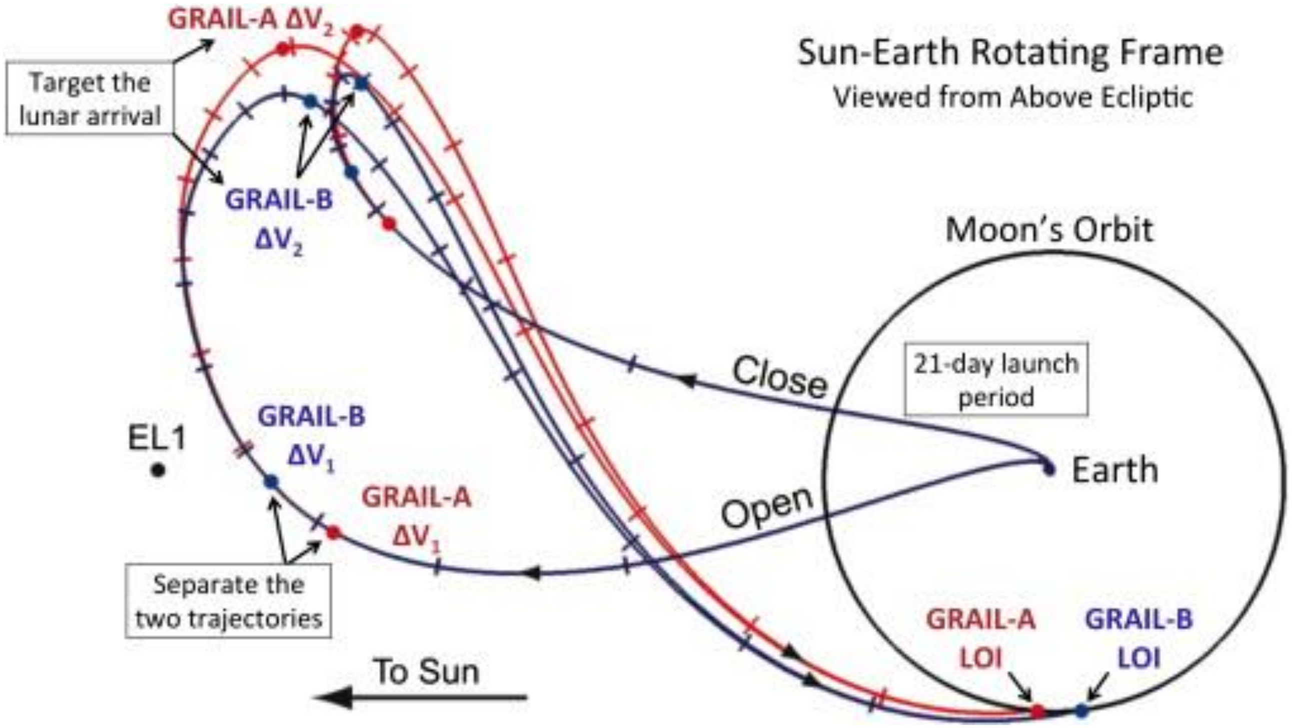
6U IceCube (Morehead State University)



- 4 Day Low Thrust Arc from Deployment to 1^{st} Lunar Encounter
- 59 Day Low Thrust Arc before Lunar Capture

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

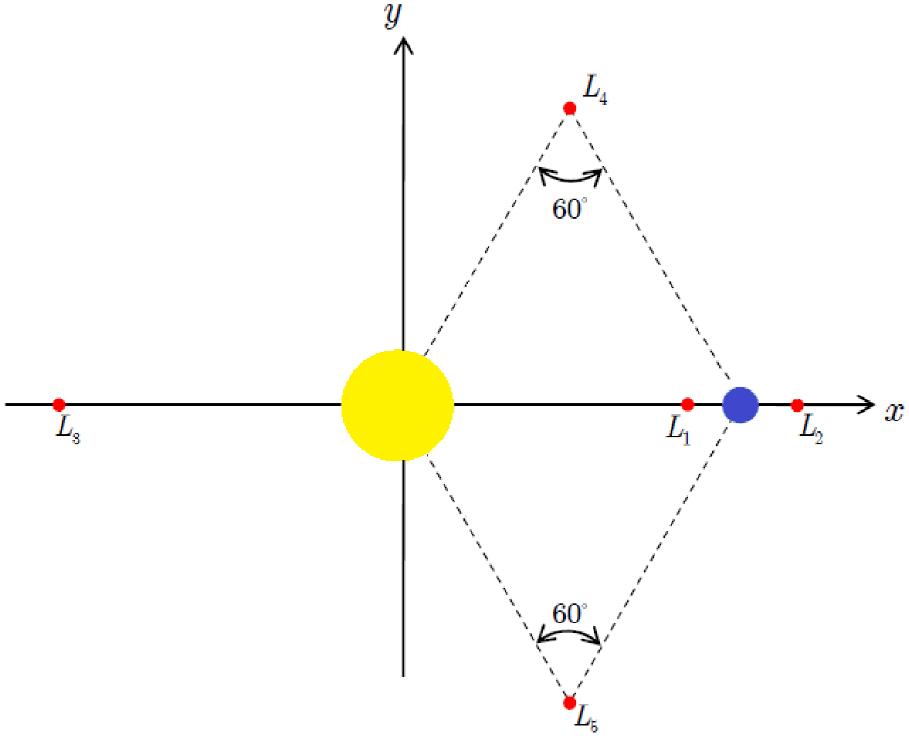
Parker, J.S., Anderson R.L., “Targeting Low-Energy Transfers to Low Lunar Orbit,” Acta Astronautica, 2013, Vol. 84, pp. 1-14.

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 solution of linearized equations of motion near L2

For planar motion eigenvalues are $\pm\lambda$ and $\pm iv$

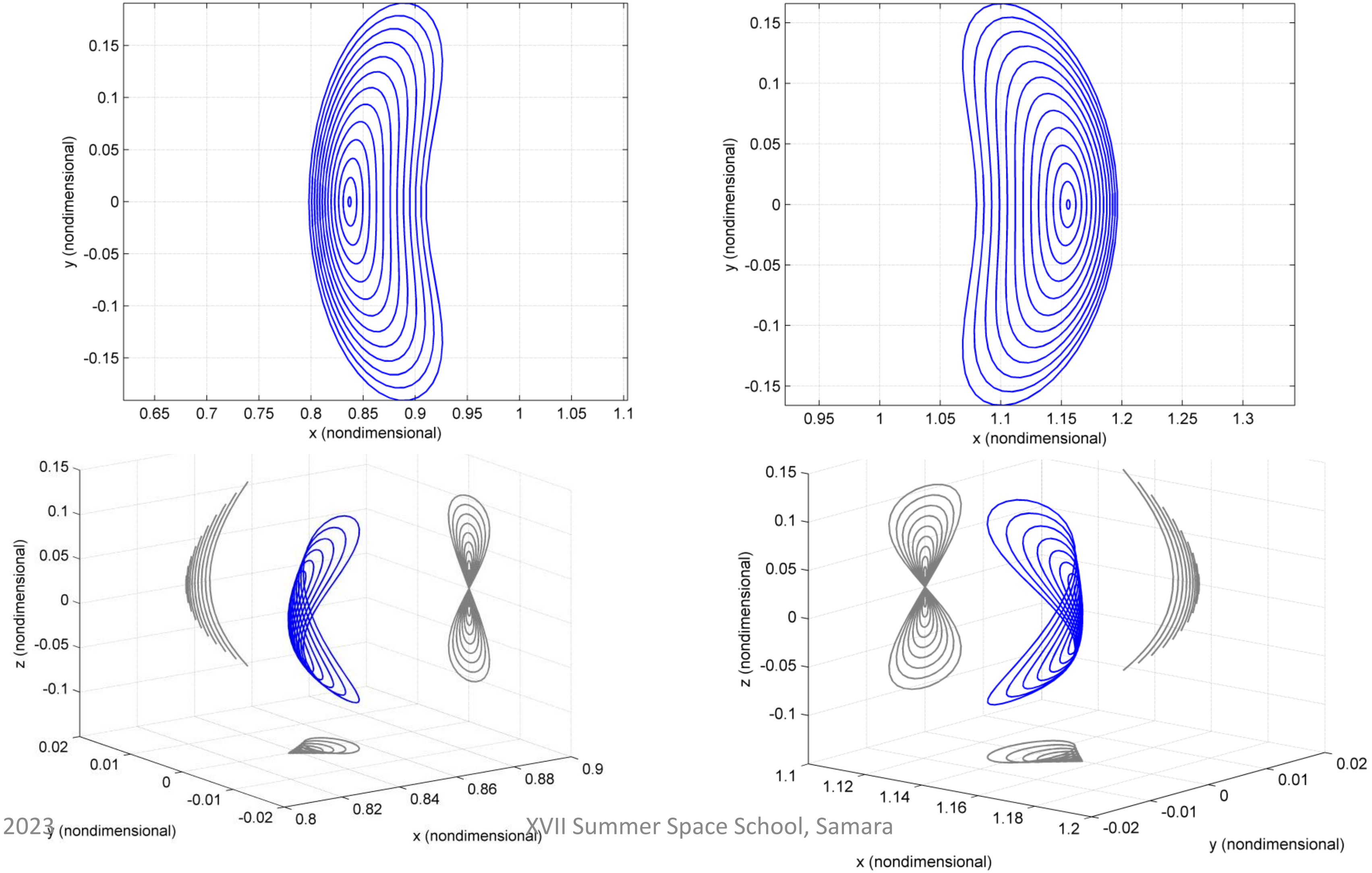
For spatial motion they are $\pm iw$

$x = A\cos(vt + \varphi 1) + C\exp(\lambda t) + D\exp(-\lambda t)$,

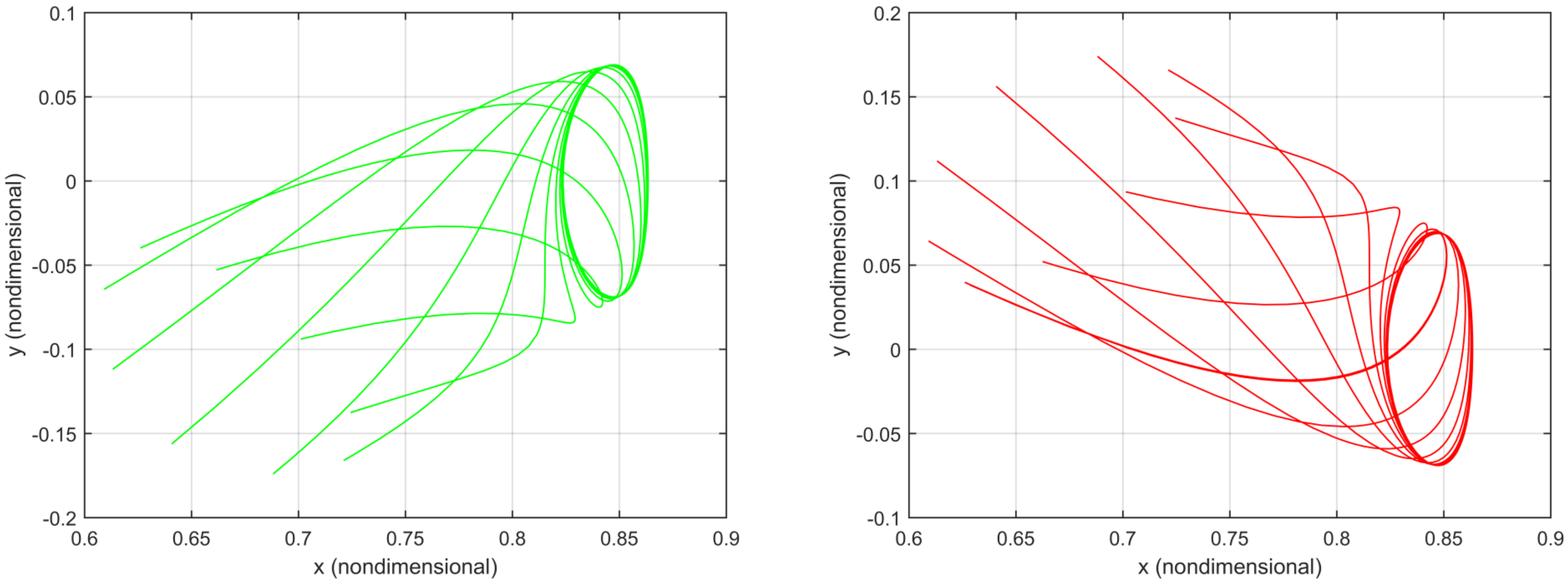
$y = -k2\, A\sin(vt + \varphi 1) + k1[\, C\exp(\lambda t) - D\exp(-\lambda t)]$,

$z = B\cos(wt + \varphi 2)$

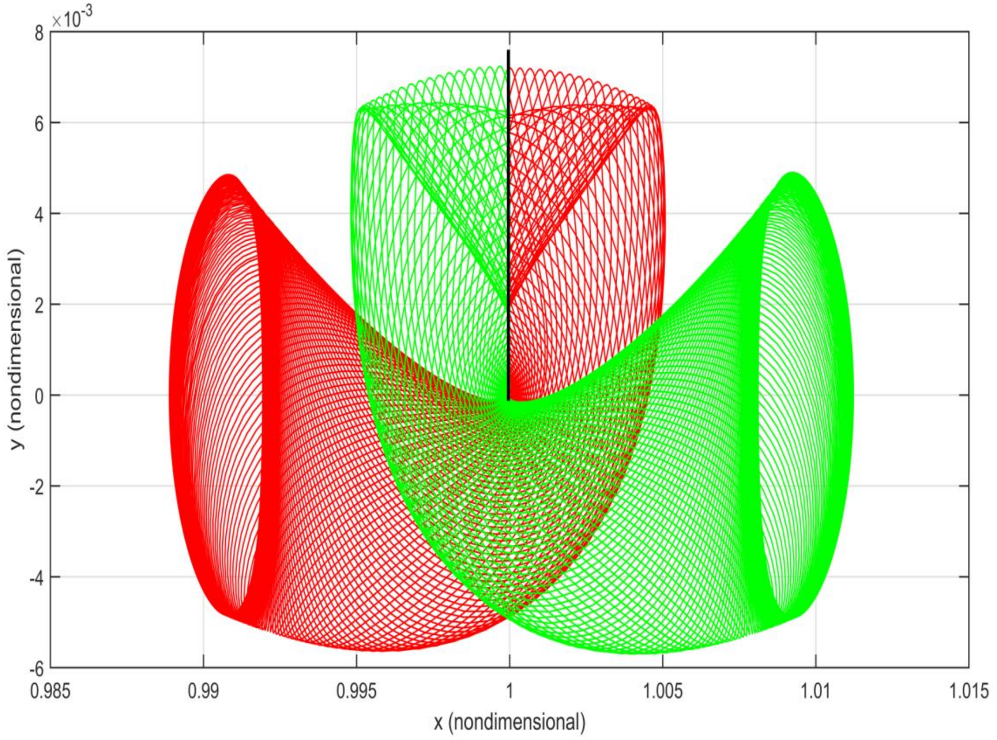
Planar and vertical Lyapunov orbits in the EM system

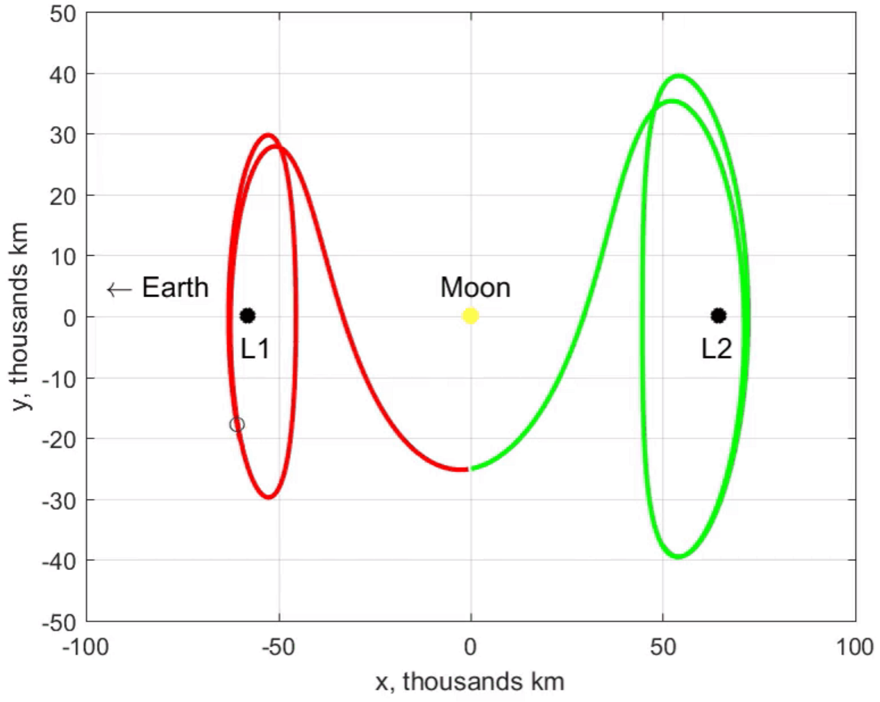


Stable (green) and unstable (red) manifolds near EM L1 halo orbit

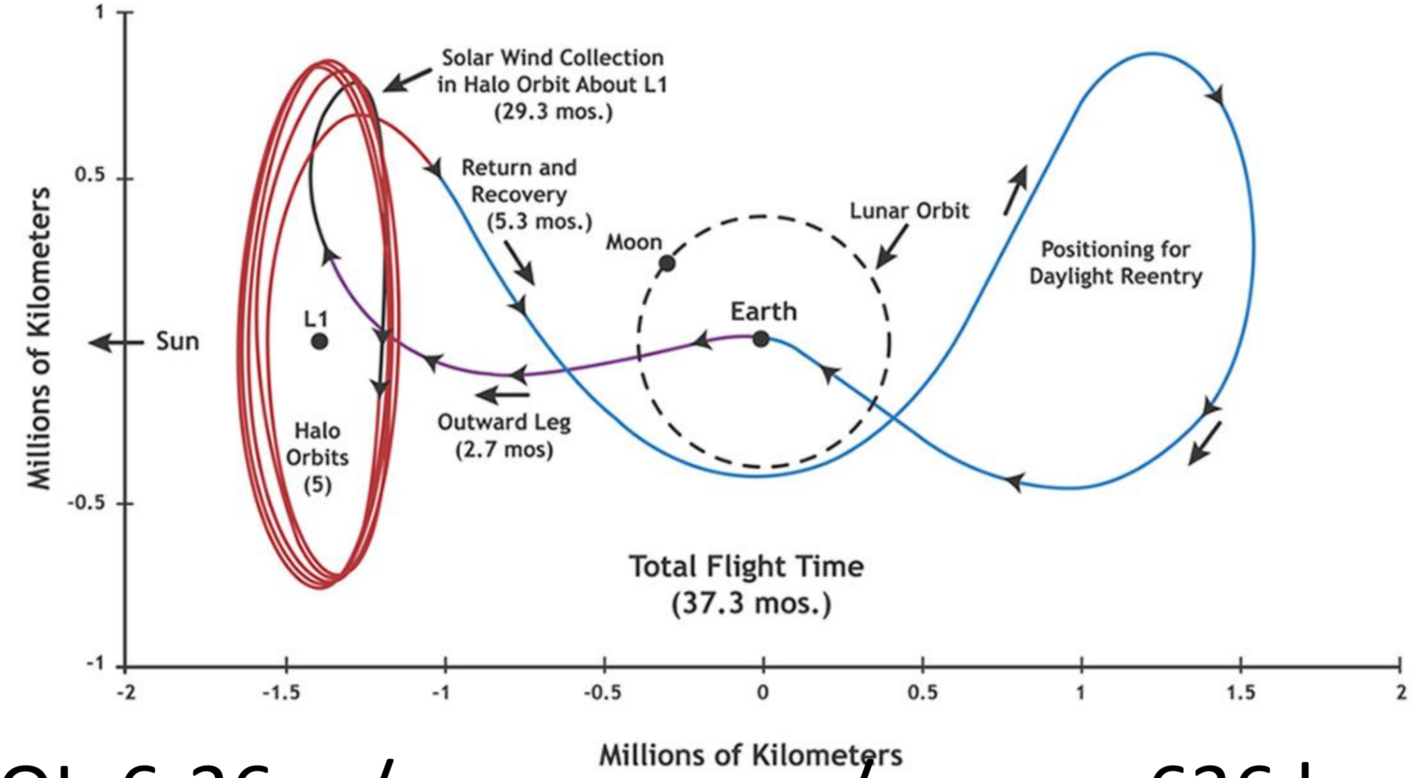


Transfers between halo orbits near EM L1 and L2 along unstable (red) and stable (green) invariant manifolds





The Genesis trajectory



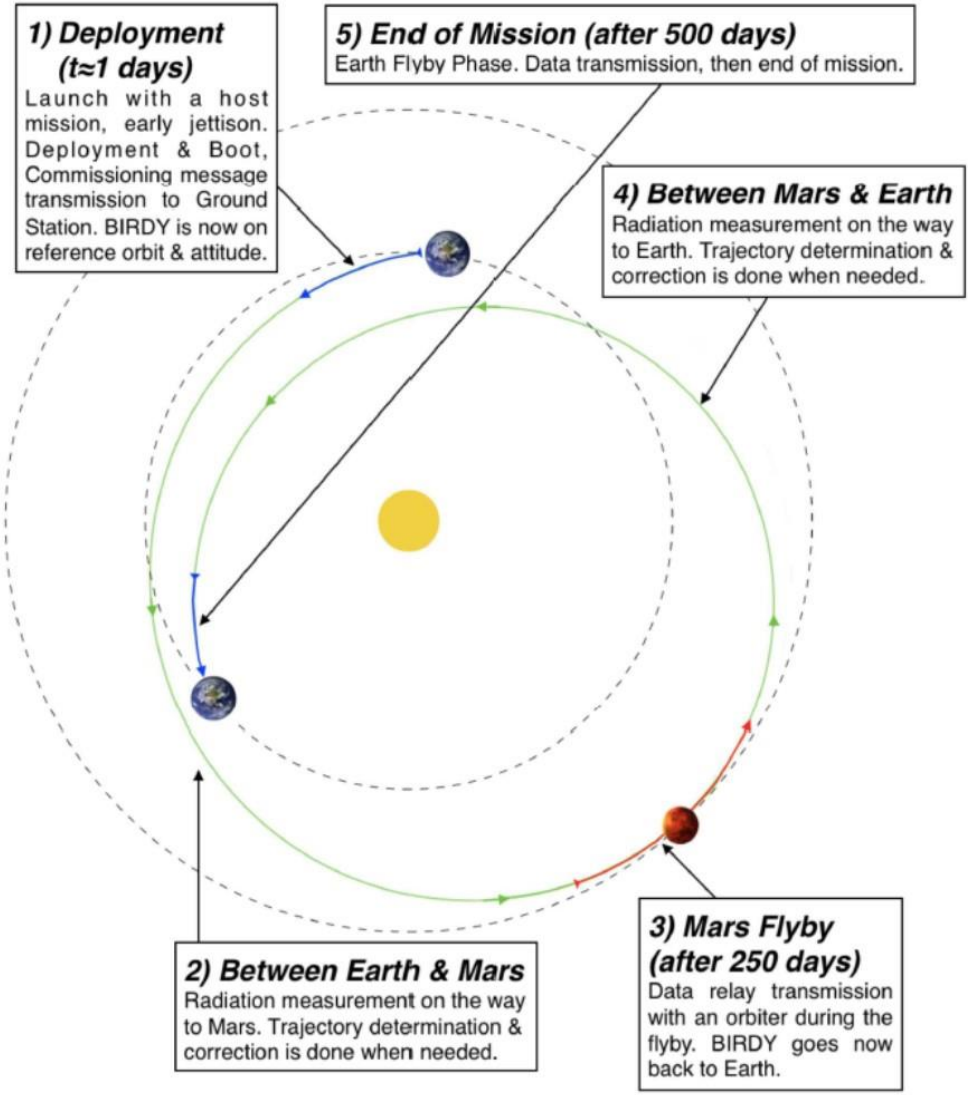
- LOI: 6-36 m/s
- SK: 9 m/s/year
- s/c mass: 636 kg
- Az = 450,000 km

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



1) Deployment (t≈1 days)
Launch with a host mission, early jettison. Deployment & Boot, Commissioning message transmission to Ground Station. BIRDY is now on reference orbit & attitude.

2) Between Earth & Mars
Radiation measurement on the way to Mars. Trajectory determination & correction is done when needed.

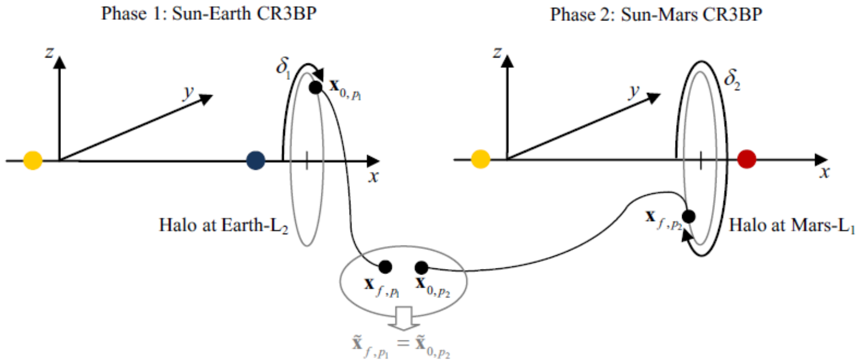
3) Mars Flyby (after 250 days)
Data relay transmission with an orbiter during the flyby. BIRDY goes now back to Earth.

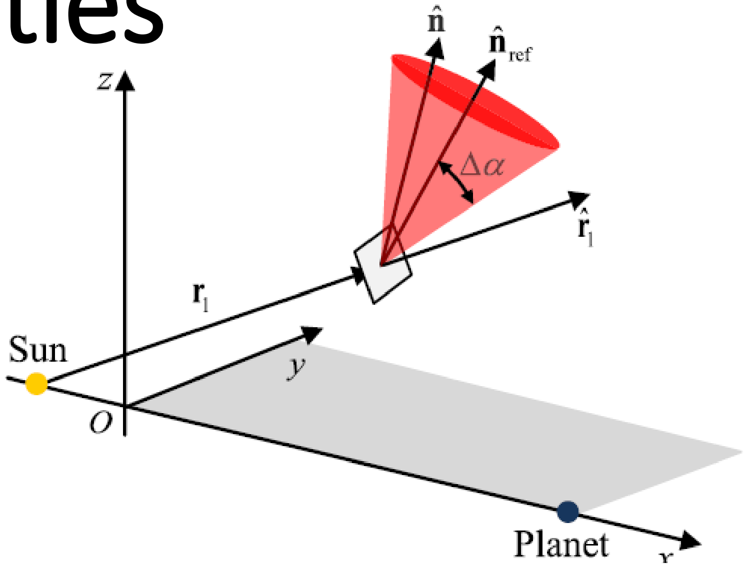
4) Between Mars & Earth
Radiation measurement on the way to Earth. Trajectory determination & correction is done when needed.

5) End of Mission (after 500 days)
Earth Flyby Phase. Data transmission, then end of mission.

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.

Earth-Mars mission by combination of trans-Mars injection and plasma low-thruster

Start: 8th of October, 2026

TOF to Mars: 422 days

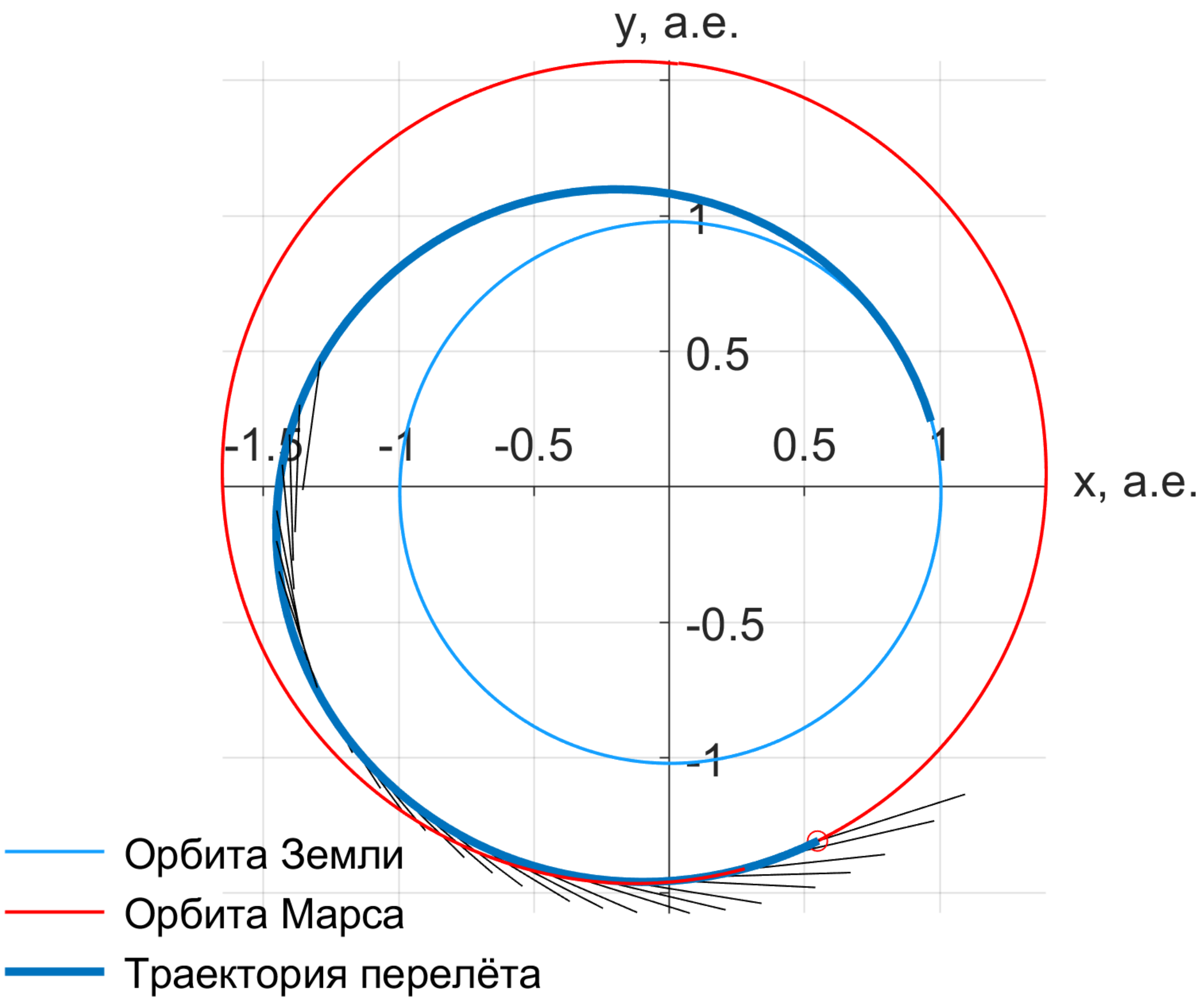
Total mass: 156 kg

Dry mass including payload: 92 kg

Active thruster segment: 256 days

Xenon consumption: 38 kg

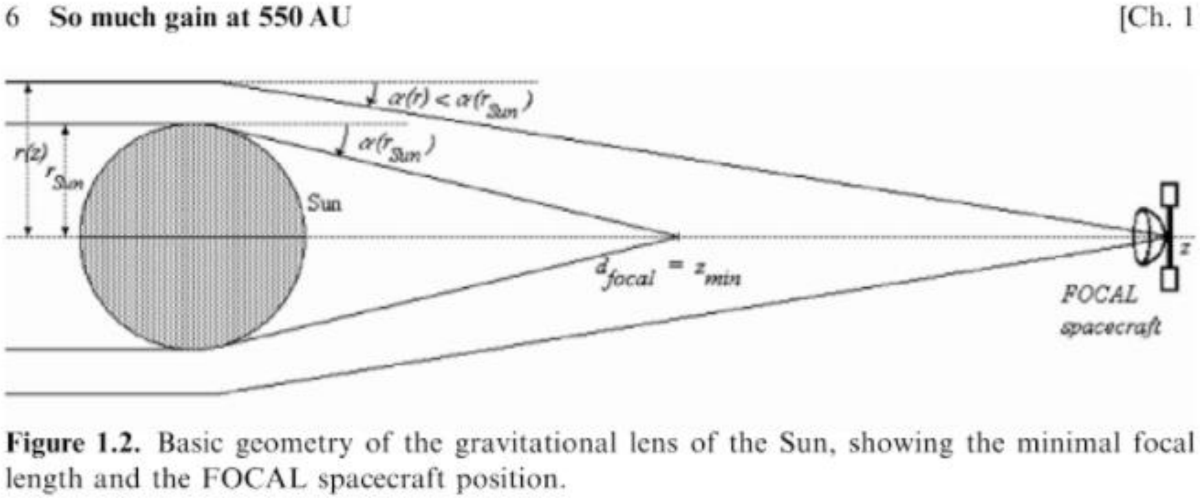
Hyperbolic excess velocity: 2994 m/s



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

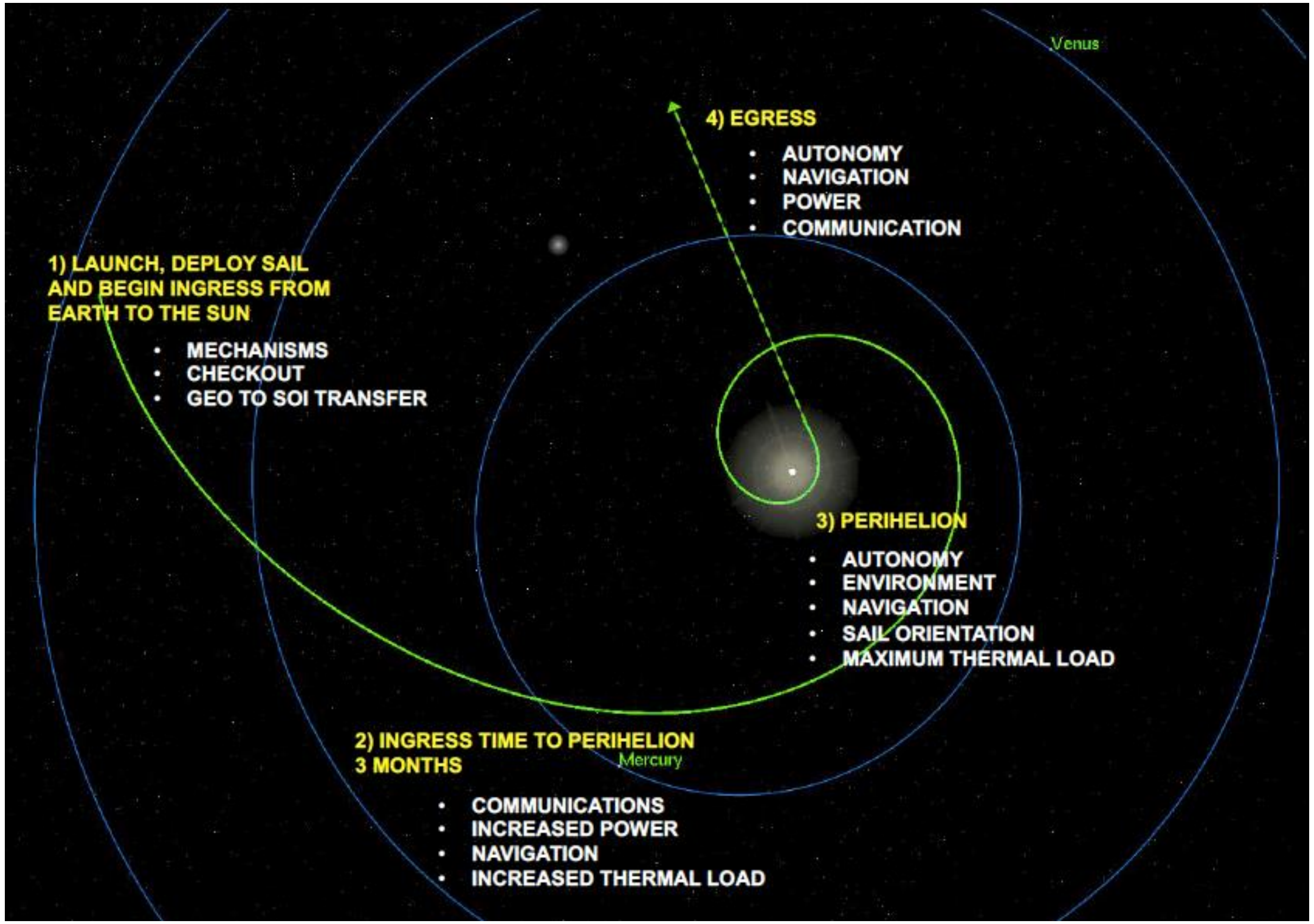
The Oberth effect is to be used

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 2

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



1) LAUNCH, DEPLOY SAIL AND BEGIN INGRESS FROM EARTH TO THE SUN
- MECHANISMS
- CHECKOUT
- GEO TO SOI TRANSFER

2) INGRESS TIME TO PERIHELION 3 MONTHS
- COMMUNICATIONS
- INCREASED POWER
- NAVIGATION
- INCREASED THERMAL LOAD

3) PERIHELION
- AUTONOMY
- ENVIRONMENT
- NAVIGATION
- SAIL ORIENTATION
- MAXIMUM THERMAL LOAD

4) EGRESS
- AUTONOMY
- NAVIGATION
- POWER
- COMMUNICATION

Credit: Slava Turyshev

Conclusion-like

- While an upper-stage to provide a trans-orbit injection and planet-capture pulse engine are available then direct flight via Hohmann transfer orbit can be used (3-5 days to the Moon)
- While near-Earth orbit is available then spiral can be used (more a year to the Moon)
- While SC is in the near-Earth orbit and trans-planet injection is possible then low-energy trajectories (weak stability boundary or invariant manifolds) can be used (a few months to the Moon)
- Trans-planet injection can provide free-return mission

Thank you for your attention!