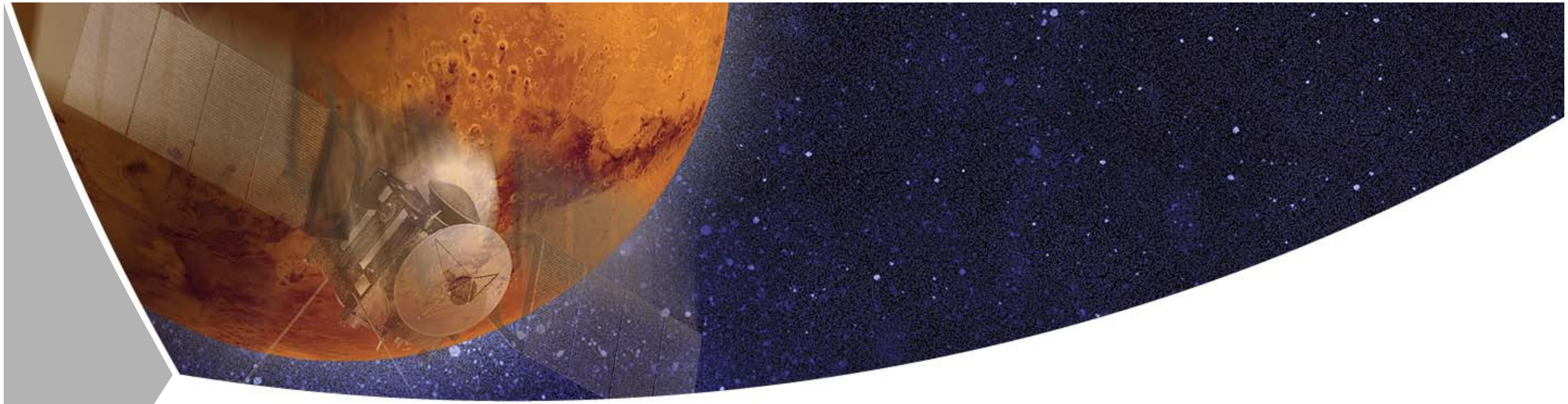

Stability and Evolution of Orbits around Binary Asteroids:

Applications to the Marco Polo-R Mission Scenario

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Friedrich Damme, Fabian Lüdicke, Valery Lupovka, Sven Bauer

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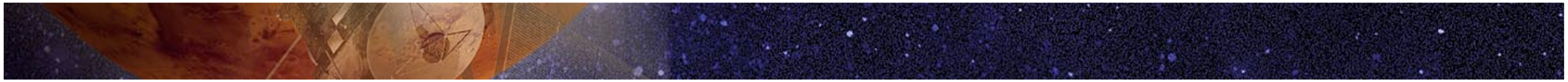
Objective

In order to support the Marco-Polo-R mission we have carried out numerical simulations of spacecraft trajectories about the binary asteroid 175706 (1996 FG3) under the influence of various perturbations.

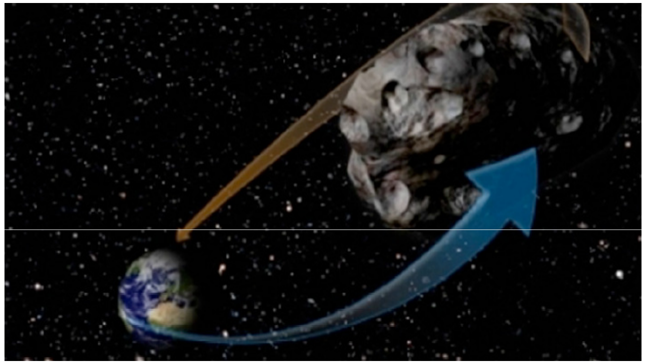
⇨ Prof. Jürgen Oberst is part of the Marco-Polo-R science team responsible for landing side selection

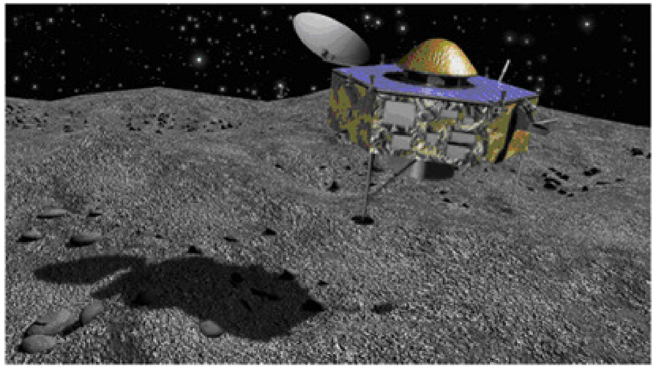


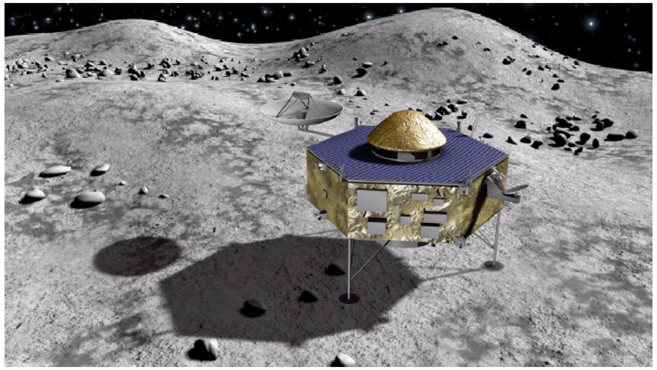
Marco-Polo-R Mission

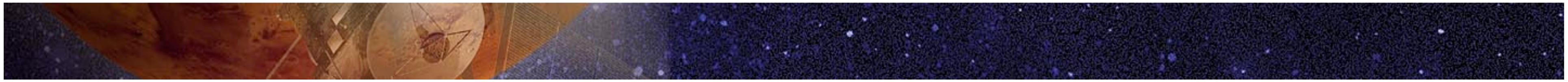
Overview

- **primary objective is a sample return from a primitive Near-Earth Asteroid**
- currently in assessment phase in the framework *of ESA's Cosmic Vision M3 Program*
- planned to be launched between 2020 to 2024

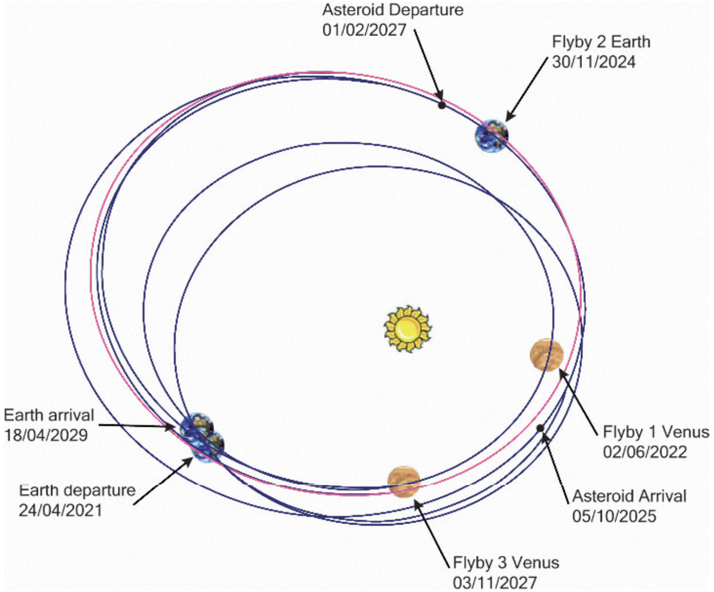




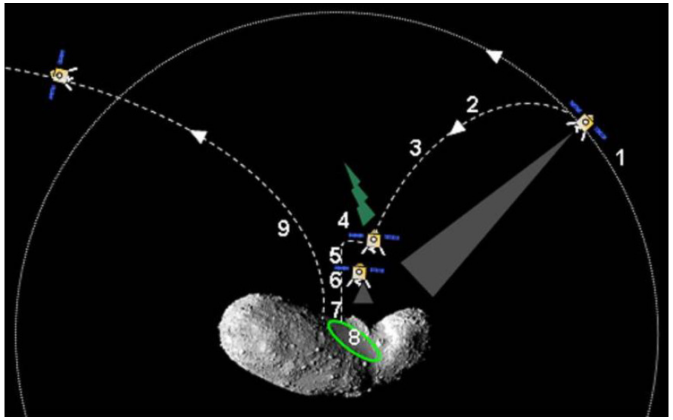




Mission Concept



- After approximately 4 years of cruise and several flybys the spacecraft will arrive at the Asteroid and go into a Self-stabilized terminator orbit (SSTO) around the binary system for six months.
- During SSTO the surface will be mapped and the gravity potential will be measured. Both are needed for the approach and landing phase (landing site selection).
- Afterwards the S/C will land, take a sample and send it back to earth

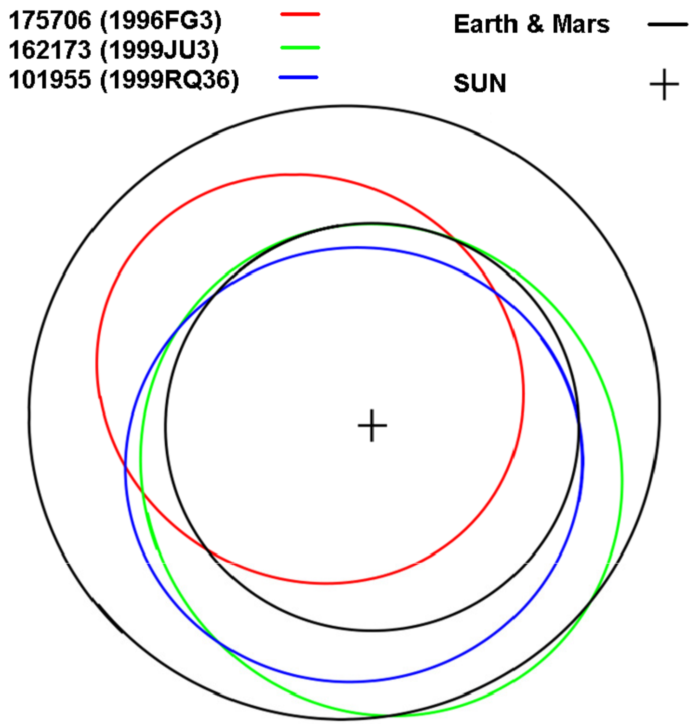


We simulated the SSTO phase

Marco-Polo-R Targets

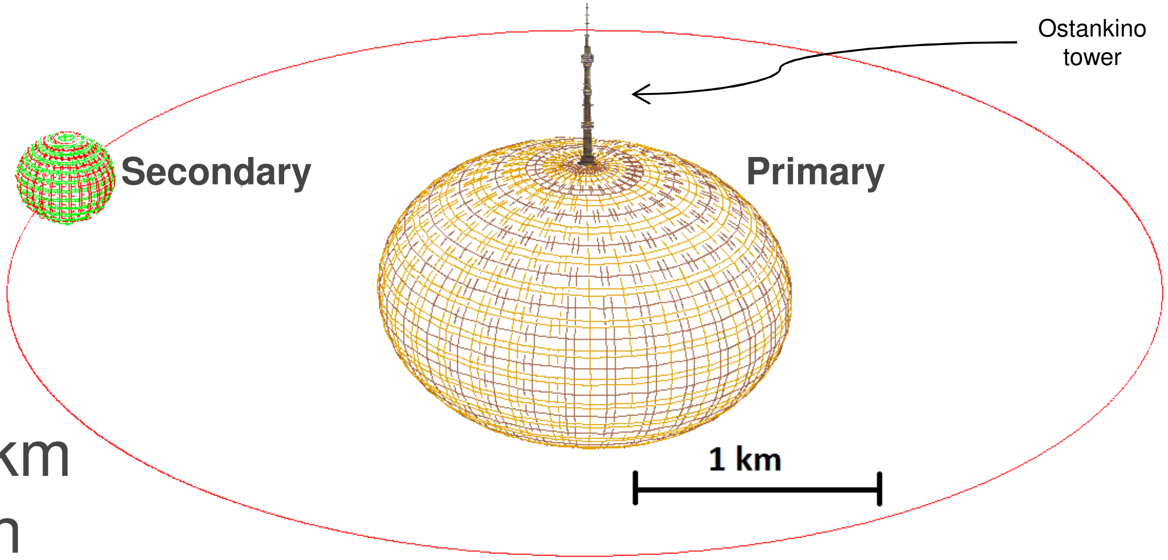
- **primary target :**
  - **1996FG3** ⇦ Binary asteroid
- Secondary targets
  - 1999 JU3
  - 1999 RQ36

Diameter of the targets ~ 1 km



asteroid	a, AU	e	I, deg
175706 (1996 FG3)	1.054	0.350	1.990
162173 (1999 JU3)	1.190	0.190	5.883
101955 (1999 RQ36)	1.126	0.204	6.035

The Binary Asteroid
(1996 FG3)

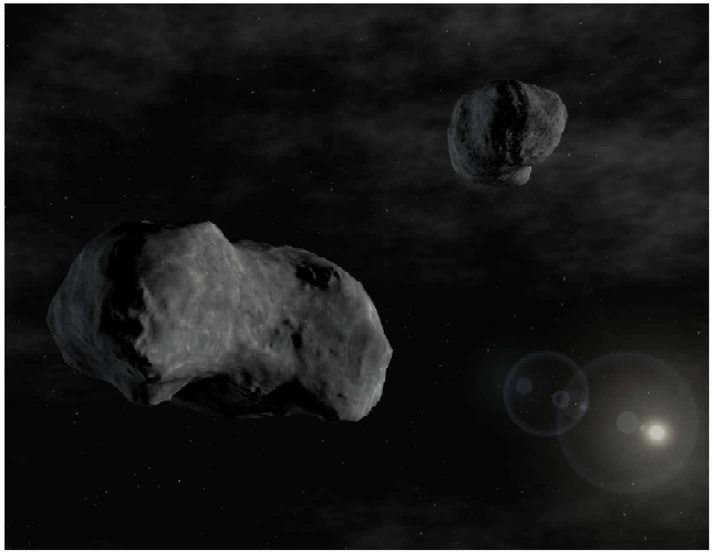


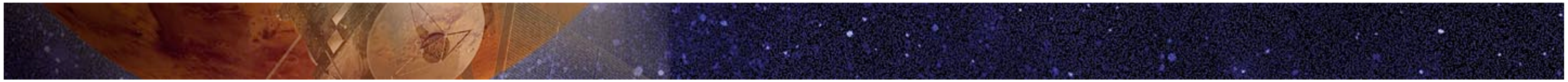
Primary:

❖ Diameter :	1.4 km
❖ spin period :	3.6 h
❖ GM:	1.4×10^{-7} km²/s³
❖ Bulk density:	1400 kg/m³

Secondary:

❖ Semi-major axis:	2.3 km
❖ Orbital period:	16.1 h
❖ Diameter:	0.2 km



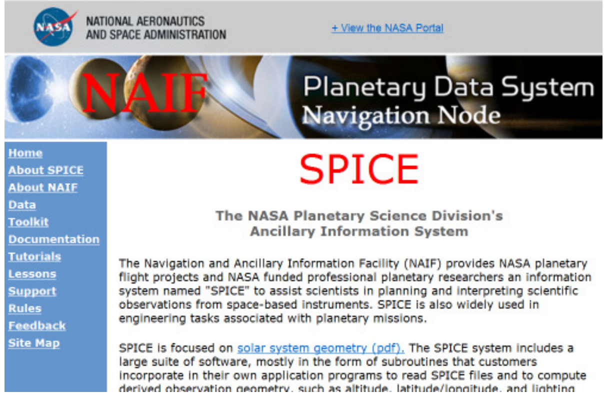


Method

The Integrator

We developed a numerical integrator at DLR Berlin which solves the equation of motion of a spacecraft.

The integrator is based on SPICE libraries.

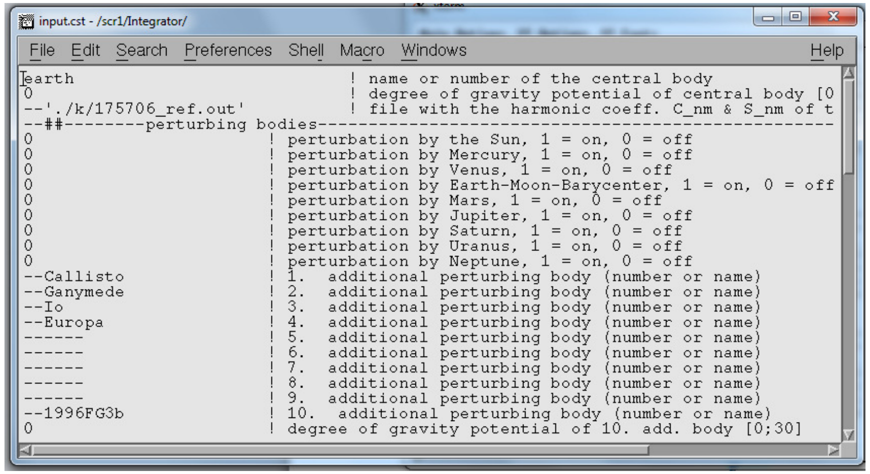


SPICE

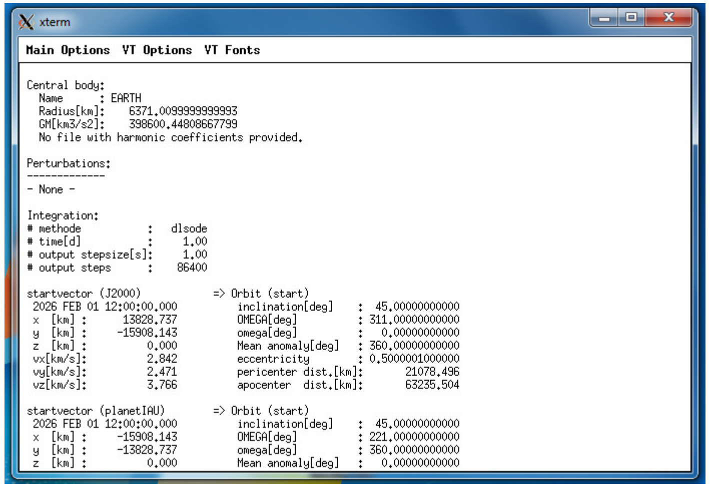
The NASA Planetary Science Division's
Ancillary Information System

The Navigation and Ancillary Information Facility (NAIF) provides NASA planetary flight projects and NASA funded professional planetary researchers an information system named "SPICE" to assist scientists in planning and interpreting scientific observations from space-based instruments. SPICE is also widely used in engineering tasks associated with planetary missions.

SPICE is focused on solar system geometry (pdf). The SPICE system includes a large suite of software, mostly in the form of subroutines that customers incorporate in their own application programs to read SPICE files and to compute derived observation geometry, such as altitude, latitude/longitude, and lighting



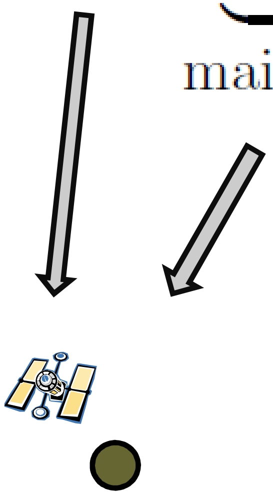
```
earth                           ! name or number of the central body
0                               ! degree of gravity potential of central body [0
--'./k/175706_ref.out'          ! file with the harmonic coeff. C_nm & S_nm of t
--##--------perturbing bodies---------------------------------------------------
0                       ! perturbation by the Sun, 1 = on, 0 = off
0                       ! perturbation by Mercury, 1 = on, 0 = off
0                       ! perturbation by Venus, 1 = on, 0 = off
0                       ! perturbation by Earth-Moon-Barycenter, 1 = on, 0 = off
0                       ! perturbation by Mars, 1 = on, 0 = off
0                       ! perturbation by Jupiter, 1 = on, 0 = off
0                       ! perturbation by Saturn, 1 = on, 0 = off
0                       ! perturbation by Uranus, 1 = on, 0 = off
0                       ! perturbation by Neptune, 1 = on, 0 = off
--Callisto              ! 1.  additional perturbing body (number or name)
--Ganymede              ! 2.  additional perturbing body (number or name)
--Io                    ! 3.  additional perturbing body (number or name)
--Europa                ! 4.  additional perturbing body (number or name)
------                  ! 5.  additional perturbing body (number or name)
------                  ! 6.  additional perturbing body (number or name)
------                  ! 7.  additional perturbing body (number or name)
------                  ! 8.  additional perturbing body (number or name)
------                  ! 9.  additional perturbing body (number or name)
--1996FG3b              ! 10.  additional perturbing body (number or name)
0                       ! degree of gravity potential of 10. add. body [0;30]
```



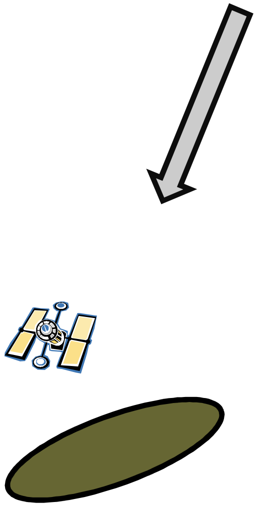
```
Central body:
  Name      : EARTH
  Radius[km]:    6371.0099999999993
  GM[km3/s2]:    398600.44808667799
  No file with harmonic coefficients provided.

Perturbations:
-------------
- None -

Integration:
# methode           :   dlsode
# time[d]           :     1.00
# output stepsize[s]:     1.00
# output steps      :    86400

startvector (J2000)          => Orbit (start)
 2026 FEB 01 12:00:00.000       inclination[deg]    :  45.0000000000
 x  [km] :      13828.737       OMEGA[deg]          : 311.0000000000
 y  [km] :     -15908.143       omega[deg]          :   0.0000000000
 z  [km] :          0.000       Mean anomaly[deg]   : 360.0000000000
 vx[km/s]:          2.842       eccentricity        : 0.5000001000000
 vy[km/s]:          2.471       pericenter dist.[km]:      21078.496
 vz[km/s]:          3.766       apocenter  dist.[km]:      63235.504

startvector (planetIAU)      => Orbit (start)
 2026 FEB 01 12:00:00.000       inclination[deg]    :  45.0000000000
 x  [km] :     -15908.143       OMEGA[deg]          : 221.0000000000
 y  [km] :     -13828.737       omega[deg]          : 360.0000000000
 z  [km] :          0.000       Mean anomaly[deg]   :   0.0000000000
```

Equation

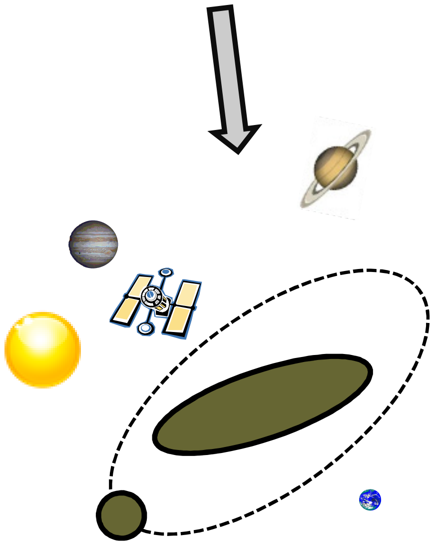
$$\ddot{\vec r} = \underbrace{-\frac{GM}{r^3}\vec r}_{\text{main body}} + \underbrace{\ddot{\vec r}_{HT}(\vec r,t)}_{\text{higher terms}} + \underbrace{\sum_{SB}\ddot{\vec r}_{SB}(\vec r,t)}_{\text{sec. bodies}} + \underbrace{\ddot{\vec r}_{SRP}(\vec r,t)}_{\text{solar rad. press.}}$$



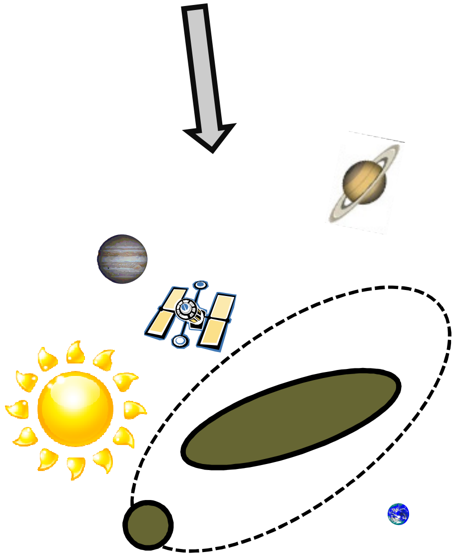
Point mass



mass distribution



Perturbing Bodies



Radiation pressure

Constraints

Precisely known constraints:

- ✓ Primary spin period : 3.6 h
- ✓ Secondary Orbital period: 16.1 h

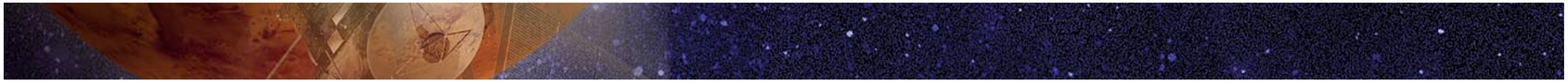
- ✓ Binary ephemeris

Constraints

Uncertain constraints:

- primary’s mass, shape, and rotational parameters
- secondary’s mass, shape, and orbit parameters
- spacecraft’s mass, surface area, and reflectivity
- the time of arrival, and therefore the relative position to the sun and planets

Taking into account the 6 starting elements our simulation depends on 17 independent parameters (17 dimensional feature space)



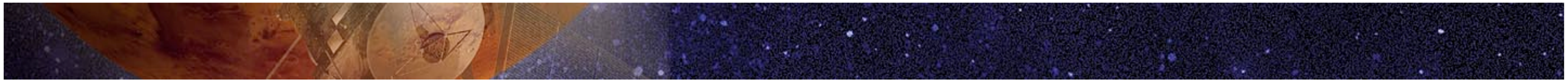
Feature Space

Parameter values used in the numerical simulations.

In the reference scenario the orbital integrations are started at
UTC 01-Feb-2026 06:00:00.

	range	reference value
Initial conditions		
semi-major axis	6 to 16 km	11 km
eccentricity	0.0 to 0.2	1×10^{-8}
inclination	0 to 180°	120°
longitude of asc. node	0 to 360°	20°
argument of pericenter	0 to 360°	0°
mean anomaly	0 to 360°	0°
Primary asteroid		
density	700 to 2800 $\mathrm{kg/m^3}$	1406 $\mathrm{kg/m^3}$
GM-value	0.7×10^{-7} to 2.8×10^{-7} $\mathrm{km^3/s^2}$	1.4×10^{-7} $\mathrm{km^3/s^2}$
period of revolution	3.6 h	3.6 h
spin pole orientation	$\lambda = 282°$, $\beta = -87°$	$\lambda = 282°$, $\beta = -87°$
shape (axes a, b, c)	(0.6, 0.59, 0.49) to (1.9, 0.63, 0.3) km	(0.84, 0.77, 0.56) km
Secondary asteroid		
density	1427 $\mathrm{kg/m^3}$	1427 $\mathrm{kg/m^3}$
GM-value	3.1×10^{-9} $\mathrm{km^3/s^2}$	3.1×10^{-9} $\mathrm{km^3/s^2}$
rotation period	16.15 h	16.15 h
shape	$R = 0.2$ to (0.22, 0.22, 0.16) km	$R = 0.2$ km
Spacecraft properties		
mass	1275 kg	1275 kg
size and shape	$(1 \times 1 \times 1)$ to $(4 \times 4 \times 4)$ m	$(4 \times 4 \times 1)$ m
reflectivity (platform)	0.8	0.8
size of solar panel	10 $\mathrm{m^2}$	10 $\mathrm{m^2}$
reflectivity (solar panel)	0.21	0.21

Angles are given in the J2000 Earth equator system. An exceptions is the orientation of the spin-pole (longitude, latitude) which is given in ecliptic coordinates

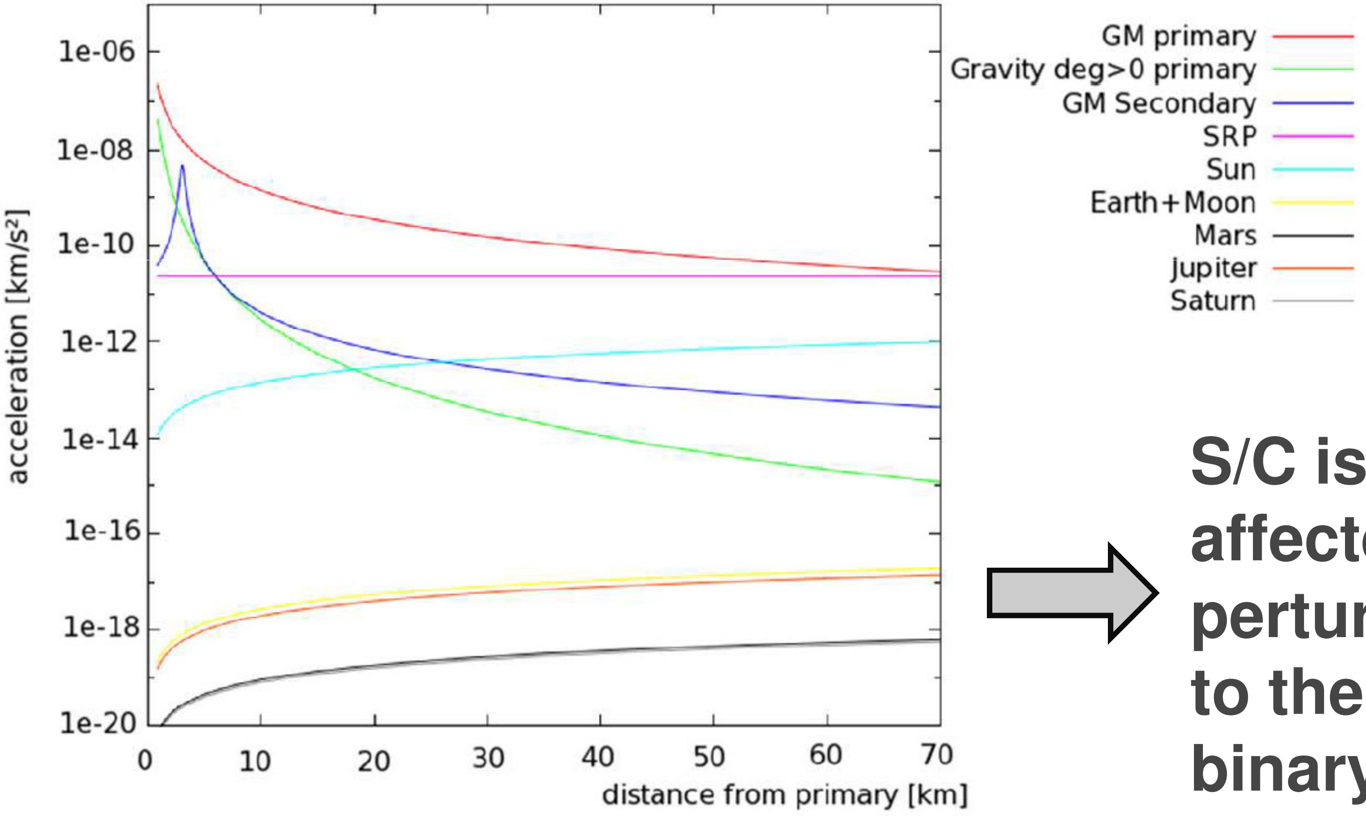


Results

(selection)

Accelerations

To get a general overview on the perturbations acting on the spacecraft, we compared the resulting accelerations.



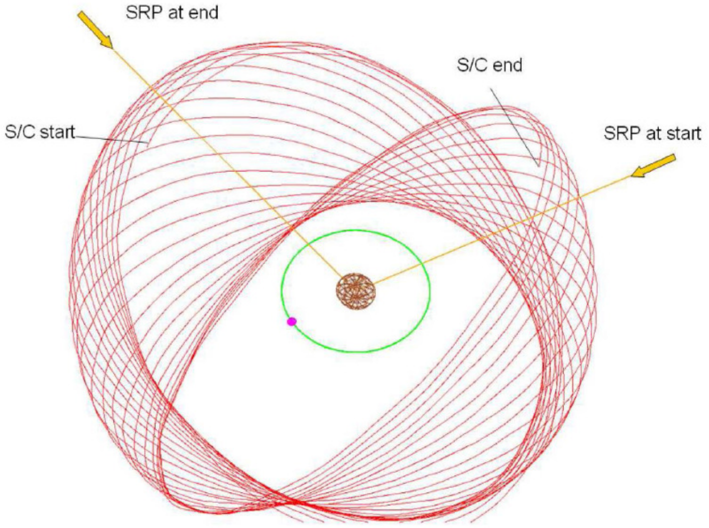
S/C is highly affected by external perturbations due to the low-mass binary

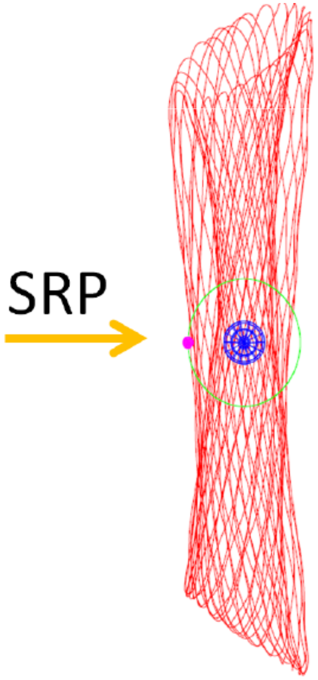
Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Solar radiation pressure (SRP)

- The initial orbital plane has to be perpendicular to the incoming radiation
- The longitude of ascending node and the inclination define the orientation of the orbital plane

Stable orbit around the binary in J2000 mean earth equator system. The spacecraft orbit’s orientation follows the sun by itself

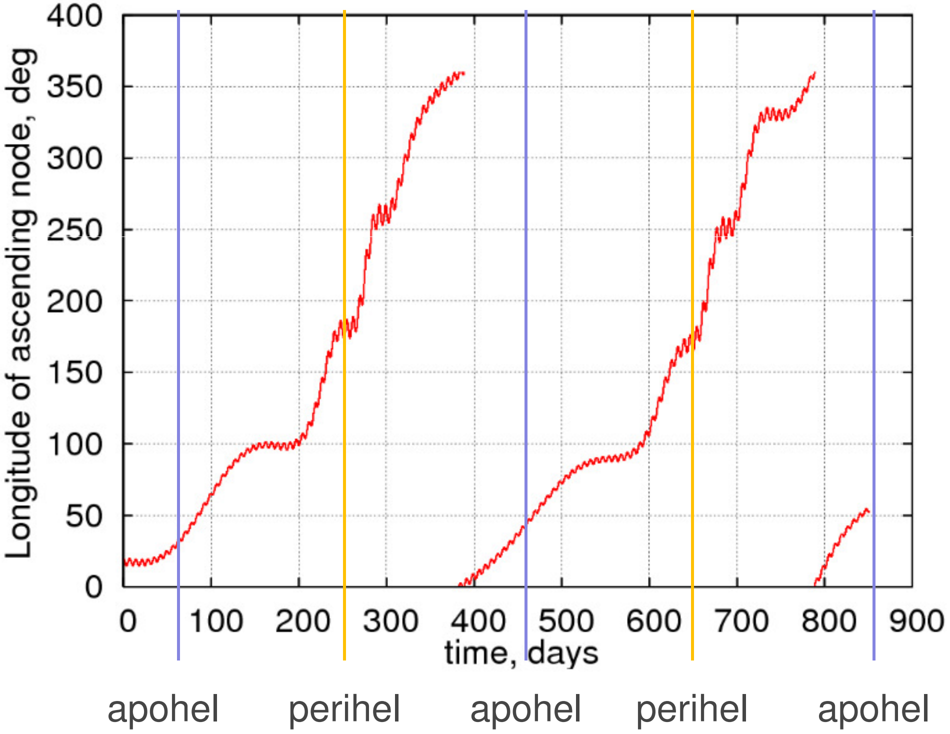


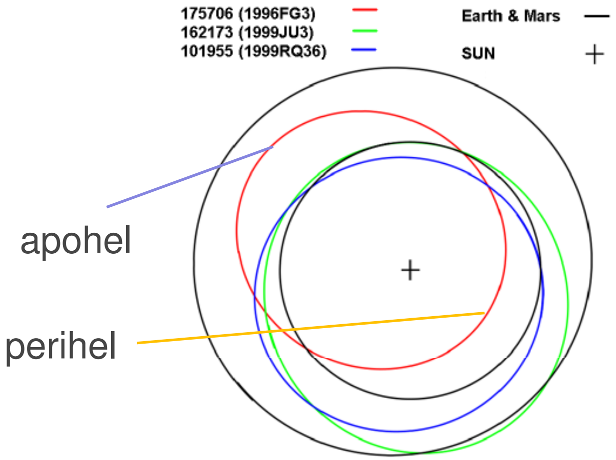


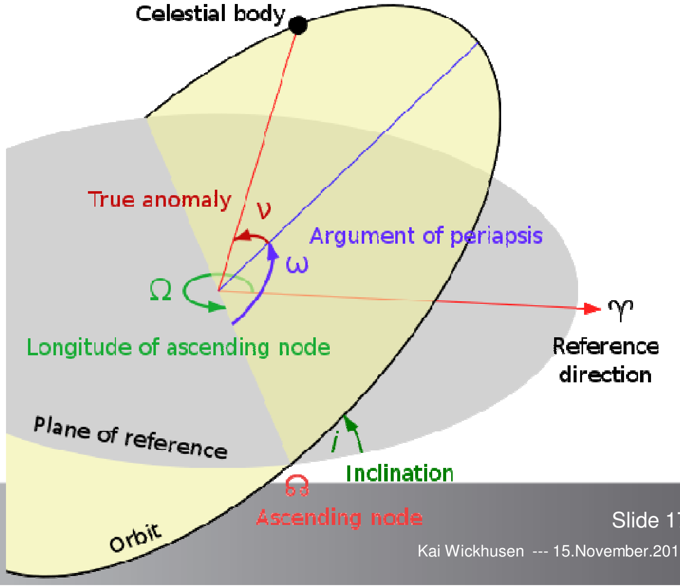
Same orbit transferred into a heliocentric system rotating according to the asteroid revolution around the sun.

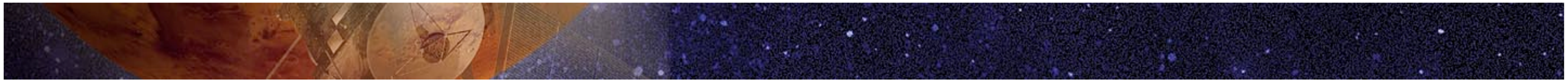
Solar radiation pressure (SRP)

- ❖ The orbital plane stays perpendicular to the incoming radiation





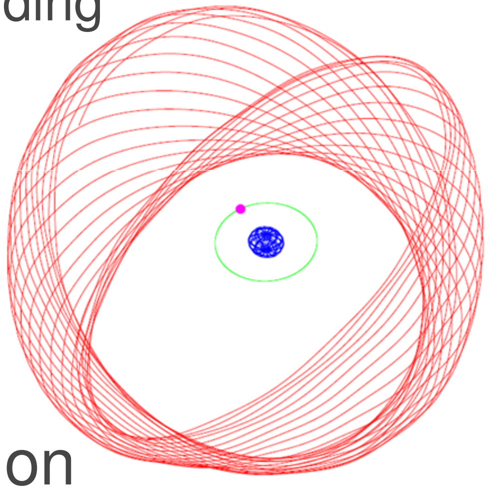




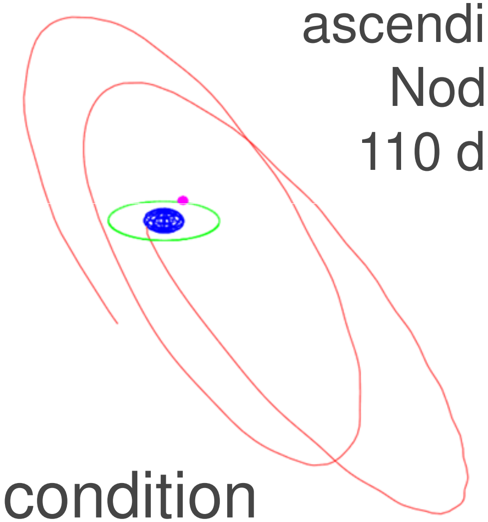
Solar radiation pressure (SRP)

- ❖ The SRP has one of the highest influence on the orbits
- ❖ SRP can cause the S/C to crash on the Asteroid or to escape from its gravity

Long. of ascending Node : 20 deg



Long. of ascending Node : 110 deg



Initial condition

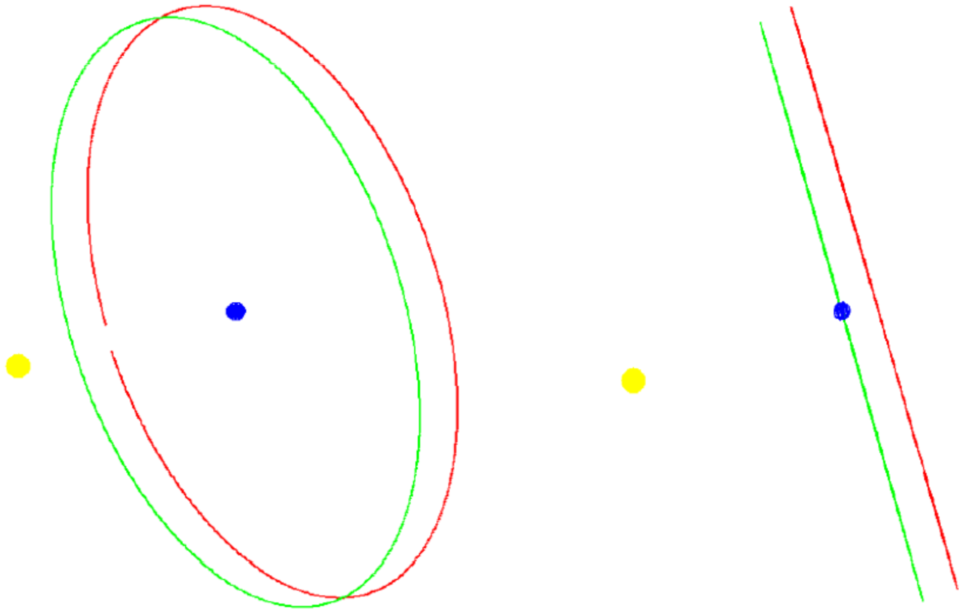
Semi-major axis:	11 km
Eccentricity :	0
Inclination:	120 deg
Long. of ascending node:	20 deg
Argument of perigee:	0 deg
Mean anomaly:	0 deg

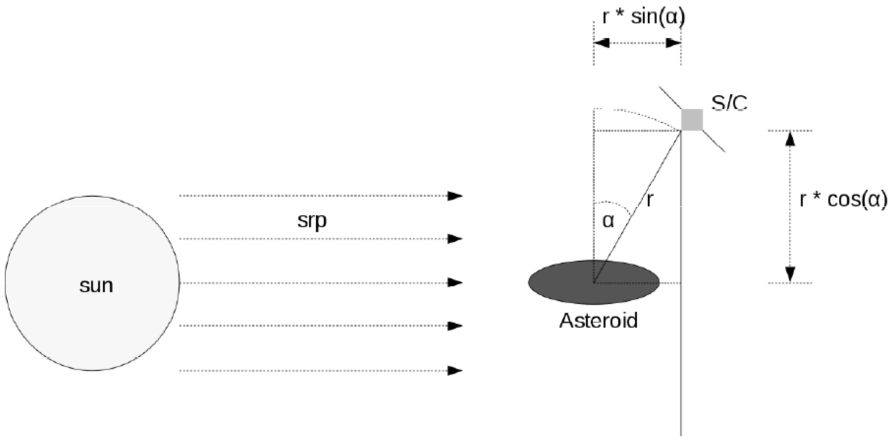
Initial condition

Semi-major axis:	11 km
Eccentricity :	0
Inclination:	120 deg
Long. of ascending node:	110 deg
Argument of perigee:	0 deg
Mean anomaly:	0 deg

Solar radiation pressure (SRP)

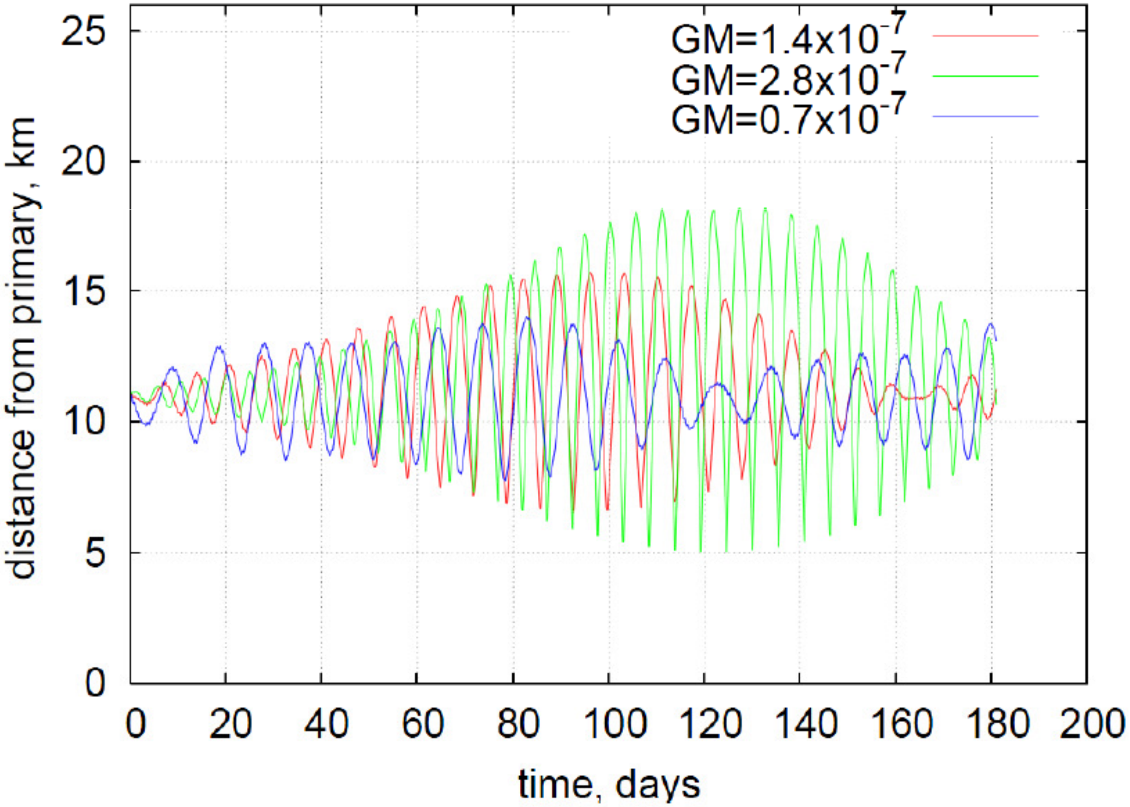
- The orbital plane is shifted away from the centre of mass (the focal point is equal to the centre of gravity)





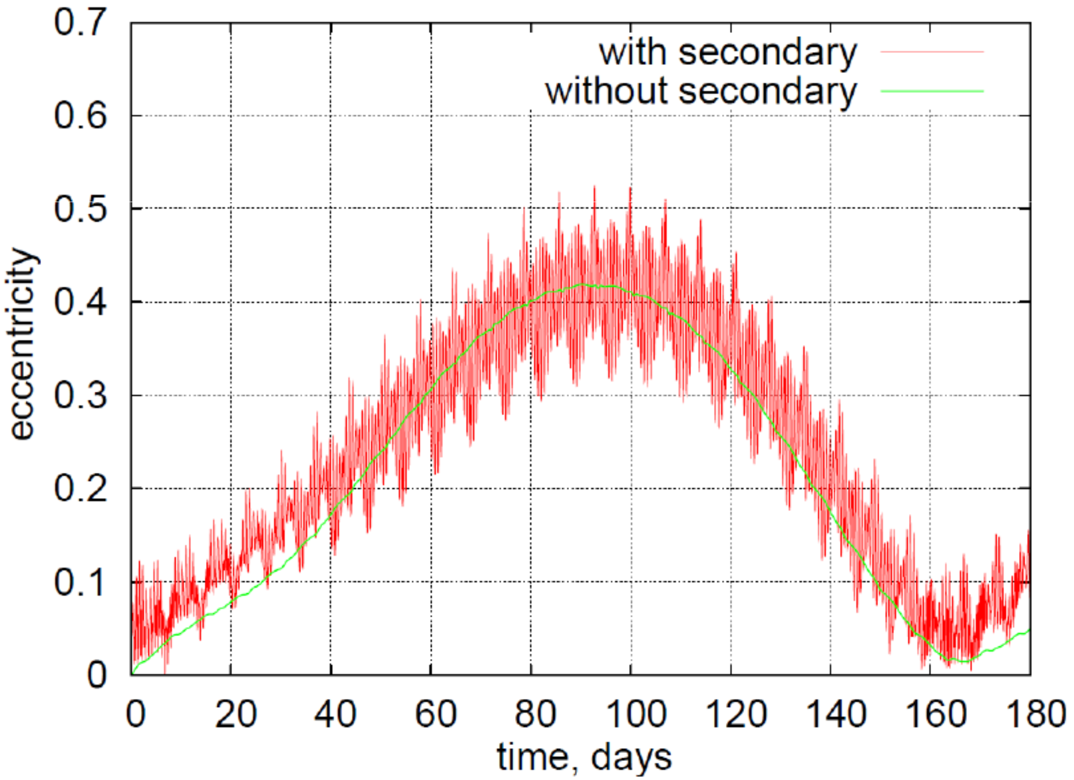
Influence of the mass

- In our reference model the central body is a tri-axial ellipsoid with axes (0.84 × 0.77 × 0.56) km and GM = 1.4×10^{-7} km³/s²
- Mass changes the orbital period (10, 7, and 5 days for GM's shown in the figure)
- Mass and mass distribution has a minor influence on stability



Influence of the secondary

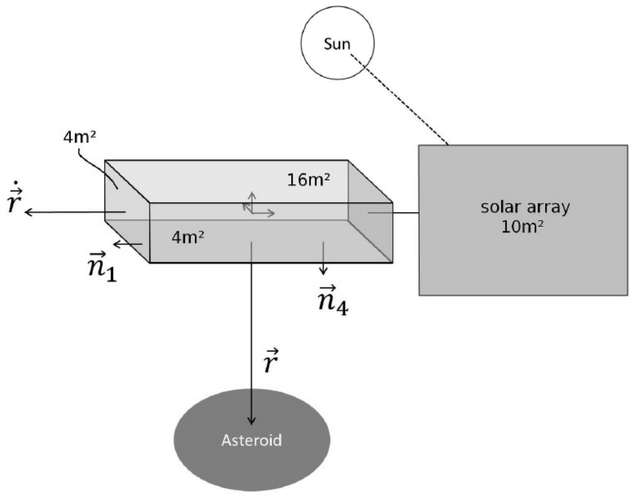
In the preferred orbit the secondary asteroid would not affect the orbital stability. It would have only minor influences on the spacecraft trajectory



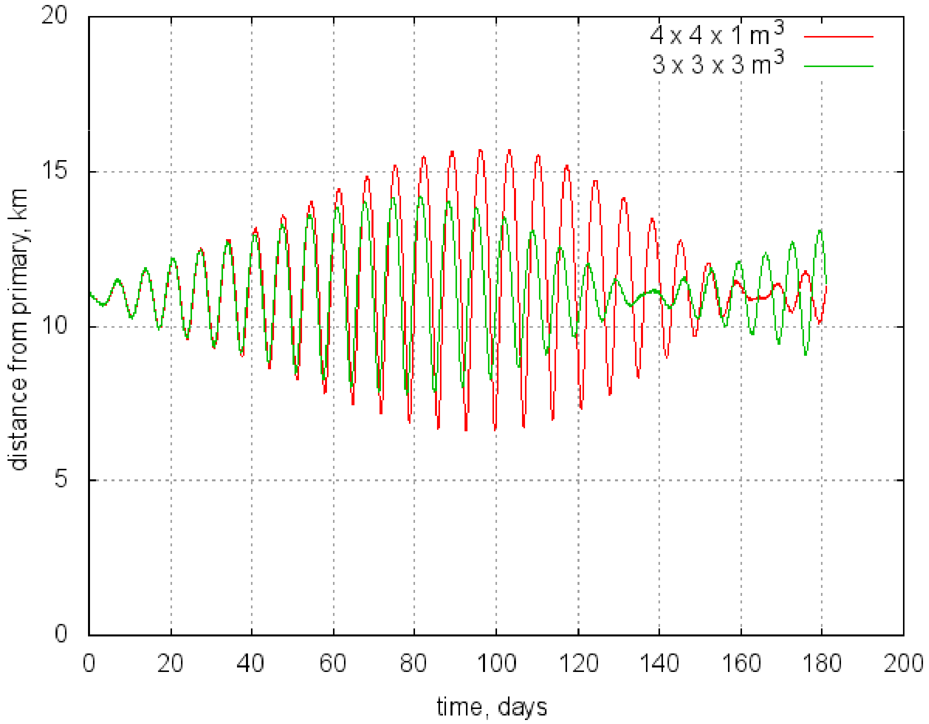
Orbital eccentricity of the spacecraft without (green) and with (red) gravitational perturbations by the secondary asteroid (solar radiation pressure included). The short period terms of the red curve appear due to orbital period of the secondary

Influence of the S/C Area-to-mass ratio

- The Area-to-Mass ratio as well as the reflectivity has a strong effect on the trajectory, but not on the initial conditions.



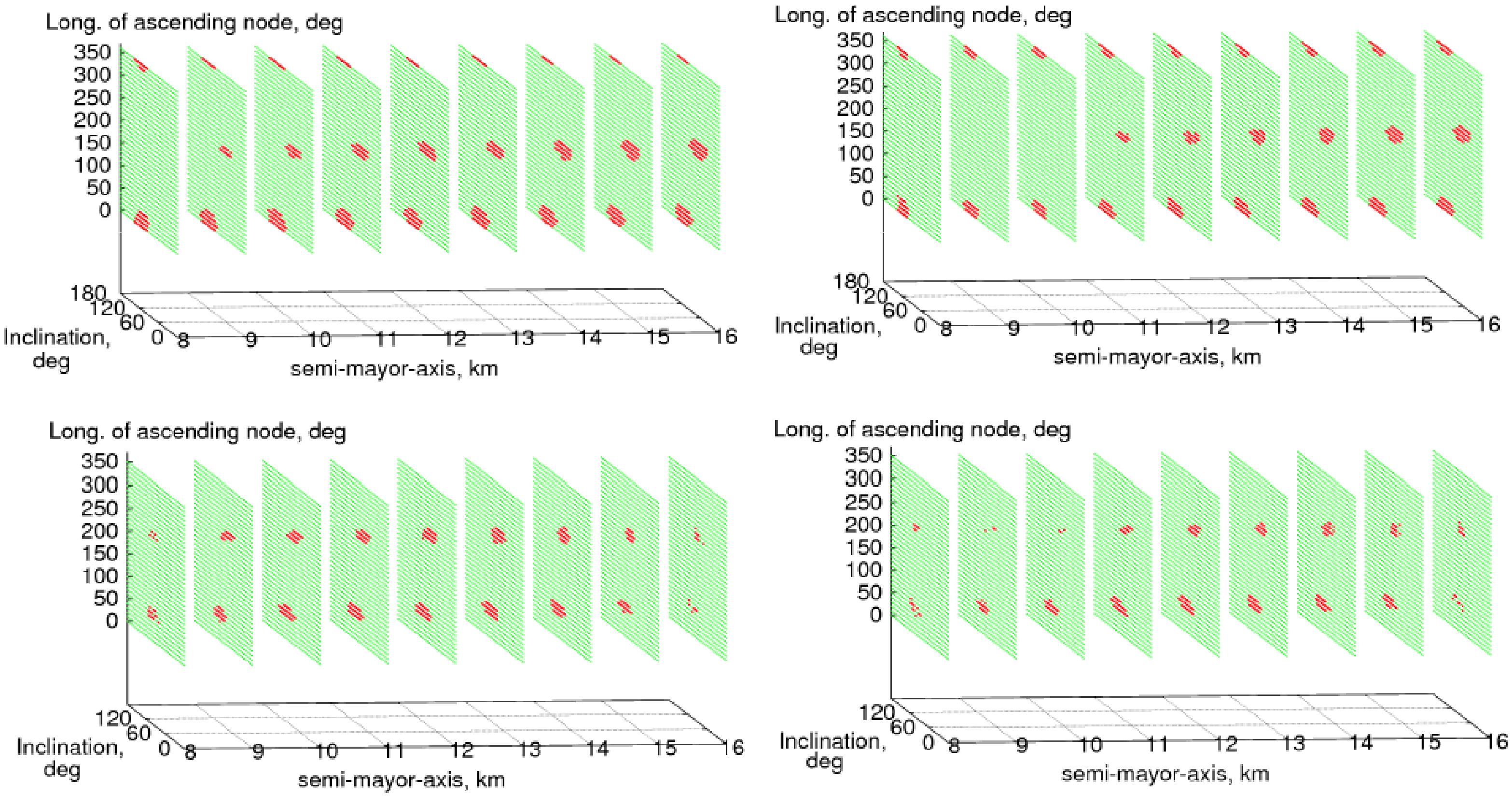
Reference model (4x4x1m³) . Side 4 is always facing the Asteroid. The solar panel always faces the sun



Stability Matrix

Top-row: insertion date: 01-Feb-2026;
top-left: e = 0; top-right: e = 0.1
bottom row: insertion date: 01-May-2026
bottom-left: e = 0; bottom-right: e = 0.1

- ★ stable
- ★ unstable

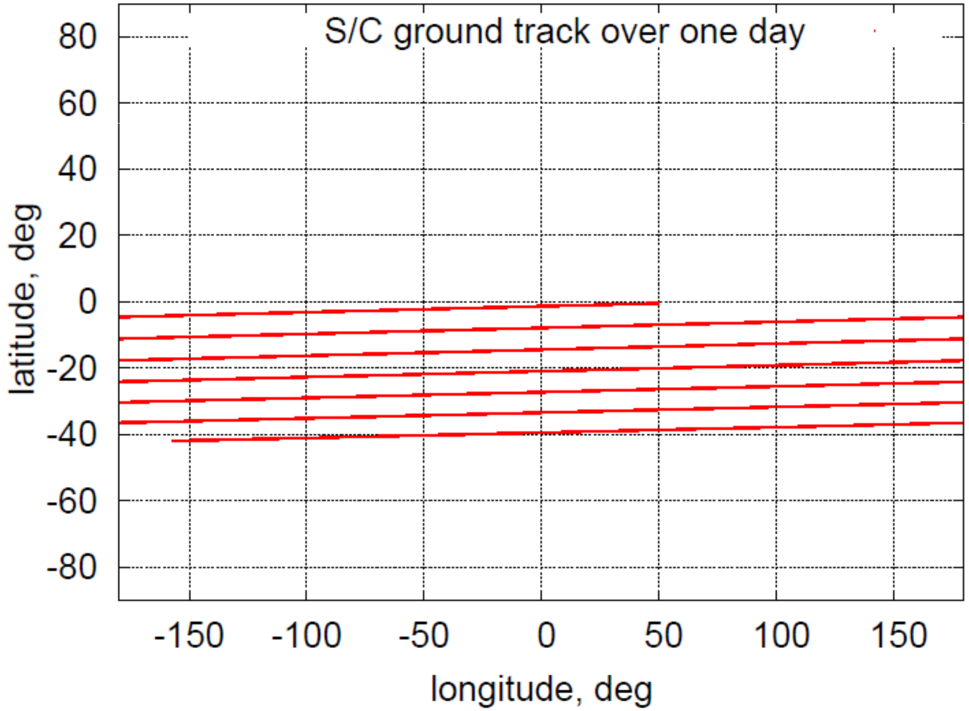


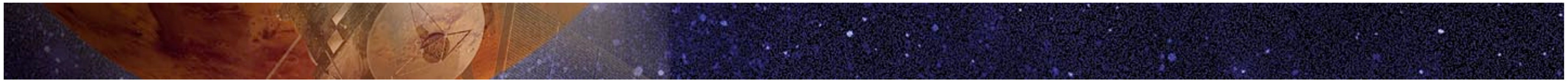
Ground coverage

- ❖ Ground track of the nadir-pointing spacecraft over one day

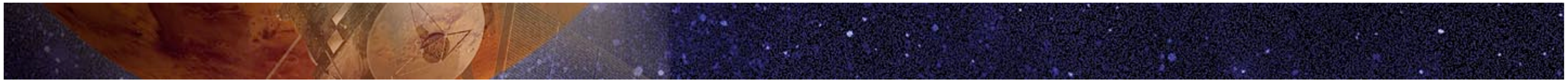
- ❖ Sampling rate 1 Hz

Entire surface can be covered within 6 months





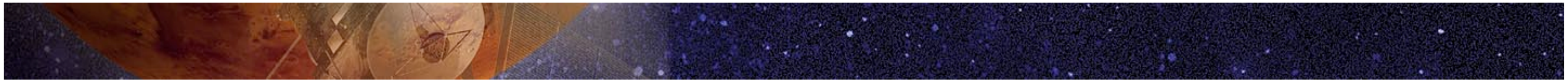
Conclusions and Outlook



Conclusions

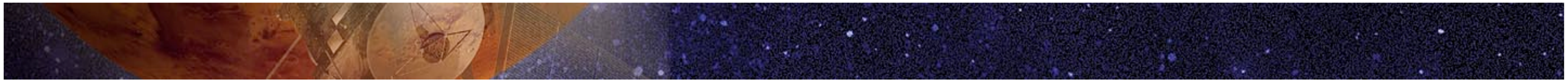
- ❖ the trajectory of a spacecraft in orbit around the binary is critically depending on the solar radiation pressure
- ❖ All orbits have to be considered as chaotic
- ❖ Most (partially) stable orbits are terminator orbits
- ❖ The influence of the secondary on stability is minor during SSTO phase

⇨ **We can determine the mass (mass distribution) and select a landing site during the SSTO phase**



Outlook

- ❖ Simulate trajectory for the secondary targets
- ❖ Simulate approach and landing phase
- ❖ Simulated orbit around the secondary
- ❖ Determine a mass-sma-srp ratio for stability



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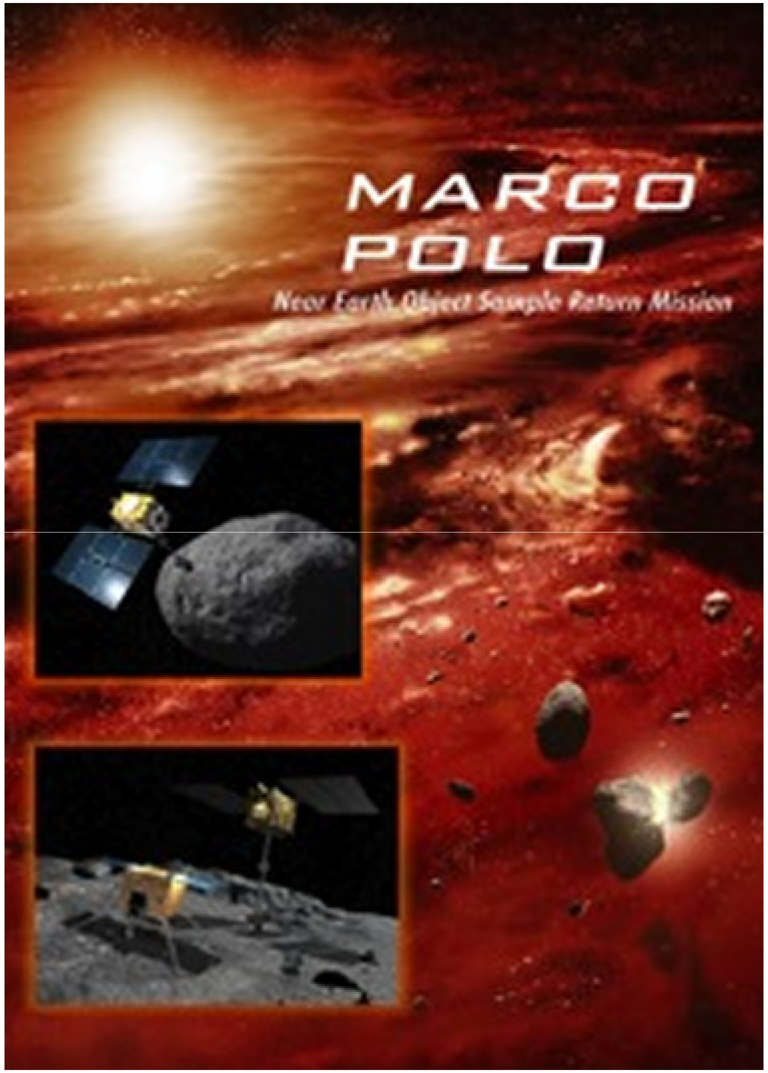

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