

# Using Solas Sails to stabilize orbits around asteroids with irregular gravitational fields

**MSc. Lucas Gouvêa Meireles<sup>1</sup>**

PhD. Antônio Fernando Bertachini de Almeida Prado<sup>1</sup>

PhD. Cristiano Fiorilo de Melo<sup>2</sup>

PhD. Maria Cecília Pereira de Faria<sup>2</sup>

<sup>1</sup>National Institute for Space Research

<sup>2</sup>Federal University of Minas Gerais





# Summary

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The exploration and study of asteroids has been triggering an increasing curiosity in the aerospace community:

- Information about the origin of planets and life;
- Space mining;
- Planetary defense.

A mission in which a spacecraft is sent to orbit an asteroid to study its shape and composition is of great interest to the scientific community.

# General purpose

- Investigate the use of a solar sail embarked in a spacecraft as a form of thrust for a mission in orbit around an asteroid with an irregular gravitational field;
- Implement different strategies to orient the sail's pointing direction as a function of the spacecraft's relative position regarding the asteroid;
- Seek for strategies to increase both the number of flybys and the time in which the spacecraft maintains itself orbiting the asteroid.

# Gravitational Potential

## Spherical harmonics:

$$U = \frac{\mu}{r} \left\{ 1 + \sum_{n=1}^{\infty} \sum_{m=0}^n \left( \frac{R_{ref}}{r} \right)^n \bar{P}_{nm}(\sin(\phi)) \left[ \bar{C}_{nm} \cos(m\lambda) + \bar{S}_{nm} \sin(m\lambda) \right] \right\}$$

- $U$  is the gravitational potential;
- $\mu$  is the gravitational parameter of the central body;
- $(r, \lambda, \phi)$  are polar coordinates in a body-fixed reference frame;
- $R_{ref}$  is a reference radius;
- $\bar{P}_{nm}$  are the associated Legendre functions;
- $\bar{C}_{nm}, \bar{S}_{nm}$  are normalized coefficients;
- $n$  is the degree of the expansion;
- $m$  is the order of the expansion.

# Bennu asteroid

- Relevant parameters:
  - Mass:  $7.8 \times 10^{10}$  kg
  - Gravitational parameter:  $\mu = 5.2 \text{ m}^3/\text{s}^2$
  - $R_{ref} = 246$  m

Degree (n)	Order (m)	$C_{nm}$	$S_{nm}$
0	0	1	0
1	0	0	0
1	1	0	0
2	0	-0.0175112	0
2	1	-0.0000023	0
2	2	0.0058194	-0.0000197
3	0	0.0056102	0
3	1	0.0015471	0.0015368
3	2	0.0001115	0.0000635
3	3	0.0026660	-0.0009332
4	0	0.0102498	0
4	1	0.0004360	0.0018562
4	2	-0.0021919	0.0007749
4	3	-0.0010761	0.0001024
4	4	0.0021356	0.0030684
5	0	-0.0013767	0
5	1	0.0005161	-0.0000786
5	2	0.0005464	-0.0012414
5	3	0.0004250	0.0002269
5	4	0.0013801	-0.0005038
5	5	0.0004869	0.0005241

McMahon et al. (2018)

# Solar Sail dynamics

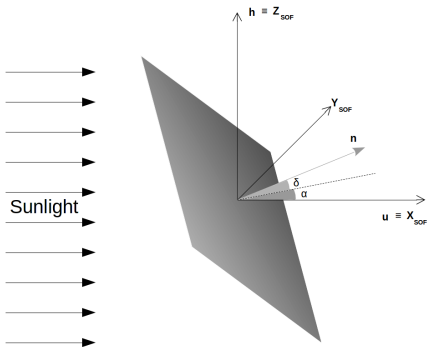
Vulpetti et al. (2015) defines the *lightness* vector as the solar sail's "thrust acceleration normalized to the local local solar gravitational acceleration":

$$\mathbf{L} = \left( \frac{1}{2} \frac{\sigma_c}{\sigma} \right) n_x [(2r_{spec} n_x + \chi_f r_{diff} + \kappa a) \mathbf{n} + (a + r_{diff}) \mathbf{u}]$$

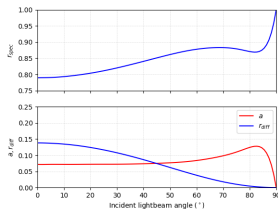
- $\sigma_c$  is the sail critical loading;
- $\sigma$  is the sail loading;
- $r_{spec}$  is the frontal specular reflectance coefficient;
- $r_{diff}$  is the frontal diffuse reflectance coefficient;
- $\chi_f$  is the frontal emission/diffusion coefficient;
- $\kappa$  is the emission/diffusion net thrust dimensionless factor;
- $a_f$  is the frontal absorptance coefficient;
- $\mathbf{n}$  is the direction normal to the sail surface;
- $\mathbf{u}$  is the direction of the incident sunlight.

# Solar Sail dynamics

Spacecraft oriented frame:



Reflectance and absorptance coefficients value:



Vulpetti et al. (2015)



# Mission specifications

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- Spacecraft specifications (inspired by LightSail-2 mission):
  - 3U CubeSat
  - Mass:  $m \approx 5 \text{ kg}$
  - Sail area:  $A \approx 32 \text{ m}^2$
- Fictional asteroid osculating orbit elements:
  - Semi-major axis:  $2 \times \text{A.U.}$
  - Eccentricity: 0.5
  - True anomaly:  $180^\circ$
  - All the other elements are null.

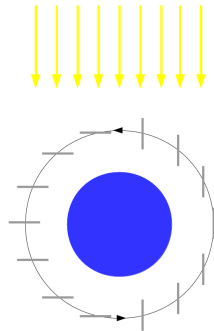


The Planetary Society (2020)

## Strategies:

- 1) Based on the LightSail-2 mission:
  - "On" / "Off" regime
  - Sail fully exposed while traveling away from the Sun
  - Sail fully concealed while traveling in the direction of the Sun
  
- 2) Maximize thrust component in the direction of travel (relative to the asteroid)
  - $\max(|\mathbf{T}_{\parallel \mathbf{v}_{23}}|)$
  
- 3) Maximize the ratio between the thrust component in the direction of travel (relative to the asteroid) and the thrust component in the spacecraft's radial direction relative to the asteroid
  - $\max(|\mathbf{T}_{\parallel \mathbf{v}_{23}} / \mathbf{T}_{\parallel \mathbf{r}_{23}}|)$

## Strategy 1 illustration:



# Orbit around asteroid

- Gravitational parameters from Bennu asteroid
- Initial osculating orbit elements:
  - Semi-major axis: 1.5 km (inspired by OSIRIS-REx Orbit-B phase)
  - All the other elements are null
- Sail loading ( $\sigma = \frac{m}{A}$ ):
  - Closed sail:  $\sigma = 100 \text{ kg/m}^2$
  - Open sail:  $\sigma = 0.15625 \text{ kg/m}^2$
  - Smaller sail ( $A \approx 0.5 \text{ m}^2$ ):  $\sigma = 10 \text{ kg/m}^2$
- Sail fully exposed to sunlight ( $\mathbf{n} \parallel \mathbf{u}$ )

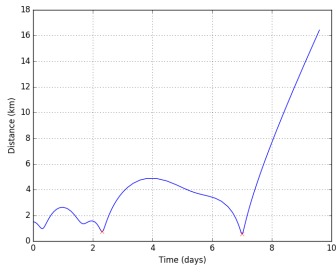
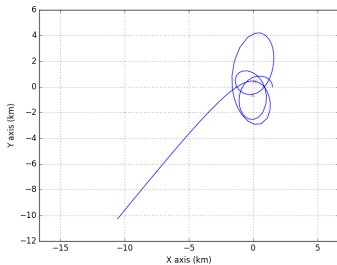
# Closed sail

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## Closest flybys (10 days):

Time (days)	Distance (km)
2.31	741.80
7.01	576.41



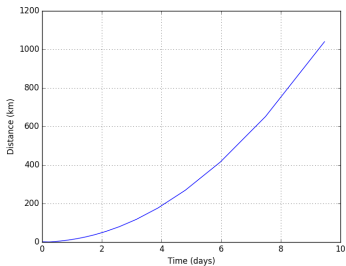
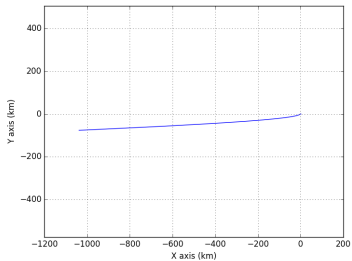
# Open sail

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Closest flybys (10 days):

Time (days)	Distance (km)
-	-



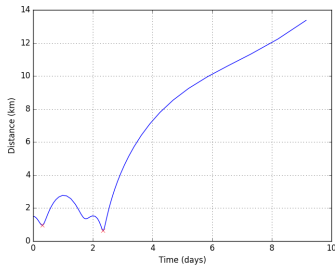
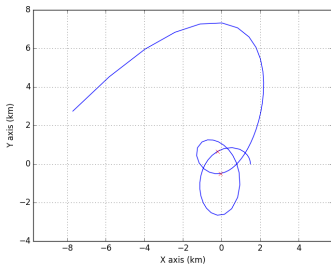
# Smaller sail

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Closest flybys (10 days):

Time (days)	Distance (km)
0.30	964.49
2.35	640.90



# Strategy combination

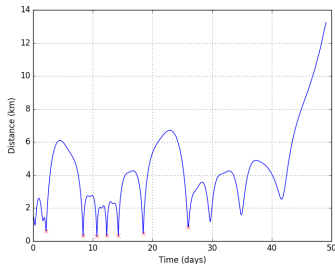
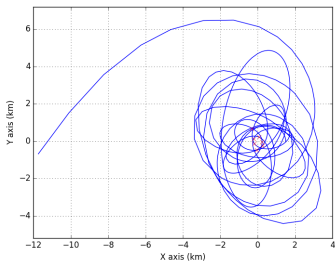
- A combination of 2 strategies is used based on the spacecraft's behaviour. A Strategy is employed in the initial N days and then the Strategy is switched.
- The term "Negative Strategy" is used when a Strategy is employed to maximize the value in the opposite direction.

n <sup>o</sup>	Combination
1	Negative Strategy 2 + Strategy 1
2	Negative Strategy 2 + Strategy 2
3	Negative Strategy 2 + Strategy 3
4	Negative Strategy 3 + Strategy 1
5	Negative Strategy 3 + Strategy 2
6	Negative Strategy 3 + Strategy 3

# Smaller sail - Combination 1 (N = 10)

Closest flybys (50 days):

Time (days)	Distance (km)
2.17	618.04
8.36	307.70
10.68	284.32
12.33	323.30
14.26	319.97
18.44	469.73
25.99	840.45

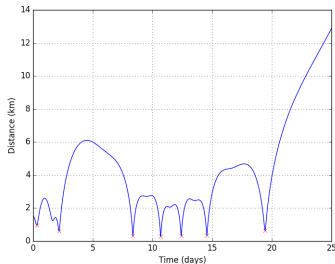
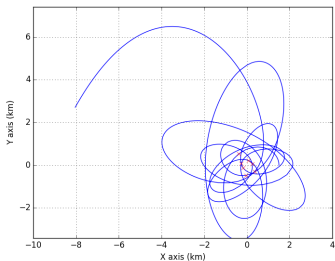




# Smaller sail - Combination 2 (N = 10)

Closest flybys (25 days):

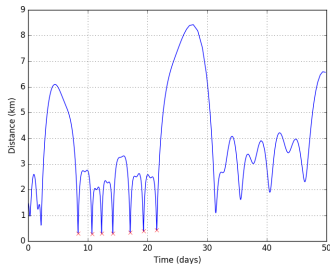
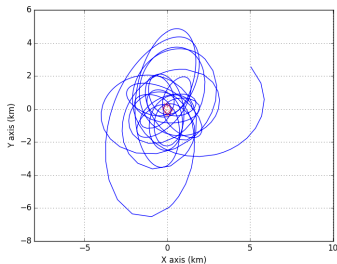
Time (days)	Distance (km)
0.32	971.15
2.17	618.04
8.36	307.70
10.69	284.05
12.41	333.15
14.56	349.84
19.43	645.52



# Smaller sail - Combination 3 (N = 10)

Closest flybys (50 days):

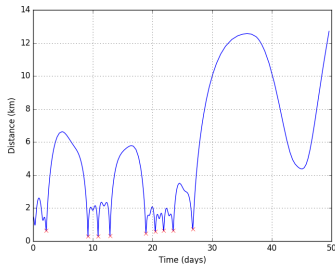
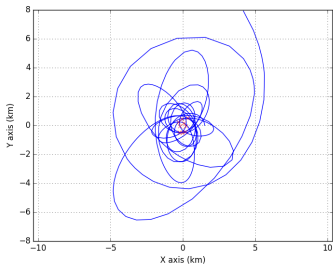
Time (days)	Distance (km)
8.36	307.70
10.69	281.84
12.31	298.62
14.19	296.53
17.10	339.11
19.33	385.50
21.56	422.60



# Smaller sail - Combination 4 (N = 10)

Closest flybys (50 days):

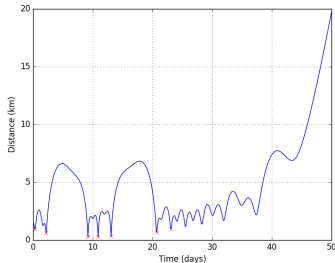
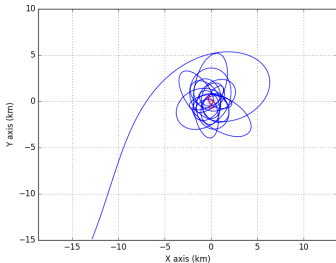
Time (days)	Distance (km)
2.19	630.71
9.18	280.55
10.88	301.08
12.87	323.67
18.91	476.68
20.46	588.86
21.87	631.56
23.45	628.40
26.74	731.64



# Smaller sail - Combination 5 (N = 10)

Closest flybys (50 days):

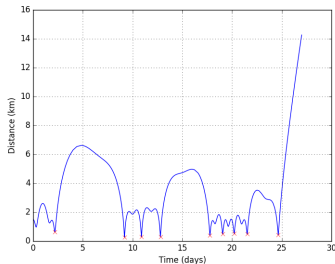
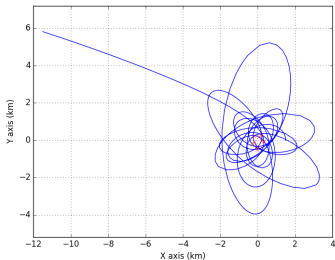
Time (days)	Distance (km)
0.31	967.57
2.19	630.71
9.18	280.55
10.89	304.84
13.07	353.48
20.69	670.83
23.08	965.48



# Smaller sail - Combination 6 (N = 10)

Closest flybys (30 days):

Time (days)	Distance (km)
2.19	630.71
9.18	280.55
10.89	300.19
12.80	301.97
17.78	410.45
19.05	505.74
20.21	528.66
21.52	486.47
24.64	436.29



# Final discussion

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- The employment of a smaller solar sail (already beneficial from an attitude control and structural point of view), offers smaller accelerations, which, in this case, serves in favor of the purpose of this study;
- The use of a combination of strategies offers great advantages:
  - Combination 2, despite being the worst result achieved, still increases the stage of the mission in over 10 days and triples the number of flybys;
  - Combination 3 increases in over 40 days the stage of the mission, while also offering the greatest number of the closest flybys recorded;
- This study proves the advantages offered by the employment of a solar sail in asteroid exploration missions.

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meireleslg@gmail.com