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

MSc. Lucas Gouvêa Meireles[1]
PhD. Antônio Fernando Bertachini de Almeida Prado[1]
PhD. Cristiano Fiorilo de Melo[2]
PhD. Maria Cecília Pereira de Faria[2]

[1]National Institute for Space Research
[2]Federal University of Minas Gerais

2021

Sumary

Relevance

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:

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

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

Bennu asteroid

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

Degree (n)	Order (m)	$\bar{C}_{nm}$	$\bar{S}_{nm}$
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

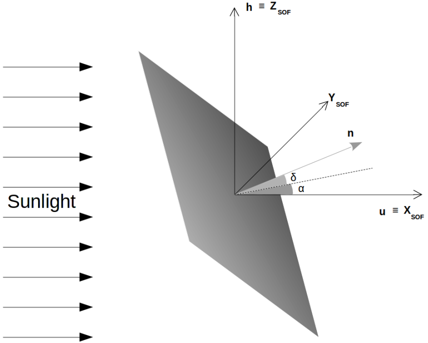
Vulpetti et al. (2015) defines the *lightness* vector as the solar sail's "thrust acceleration normalized to the local local solar gravitational acceleration":

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

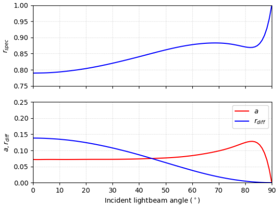
- σ_c is the sail critical loading;
- σ is the sail loading;
- r_{spec} is the frontal specular reflectance coefficient;
- r_{diff} is the frontal diffuse reflectance coefficient;
- χ_f is the frontal emission/diffusion coefficient;
- κ is the emission/diffusion net thrust dimensionless factor;
- a_f 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

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

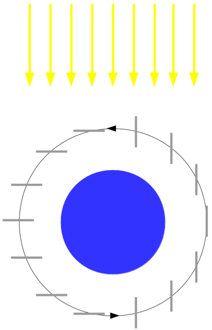
The Planetary Society (2020)

Attitude Strategies

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)
  - $max(|\mathbf{T}_{||\mathbf{v}_{23}}|)$
- 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
  - $max(|\mathbf{T}_{||\mathbf{v}_{23}}/\mathbf{T}_{||\mathbf{r}_{23}}|)$

Strategy 1 illustration:



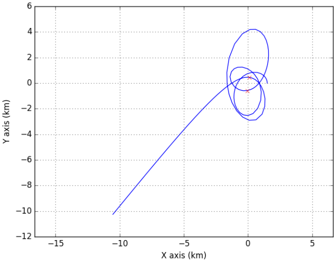
Orbit around asteroid

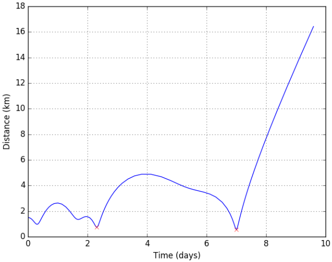
- Gravitational parameters from Bennu asteroid
- Initial osculating orbit elements:
  - Semi-major axis: $1.5\,\mathrm{km}$ (inspired by OSIRIS-REx Orbit-B phase)
  - All the other elements are null
- Sail loading ($\sigma = \frac{m}{A}$):
  - Closed sail: $\sigma = 100\,\mathrm{kg/m^2}$
  - Open sail: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

Closed sail

Closest flybys (10 days):

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

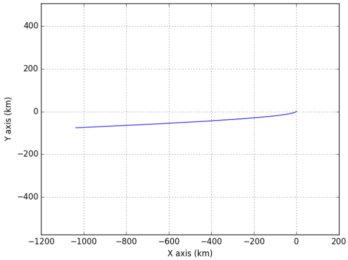


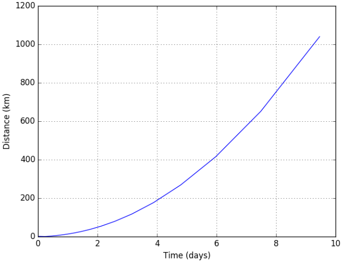


Open sail

Closest flybys (10 days):

Time (days)	Distance (km)
-	-

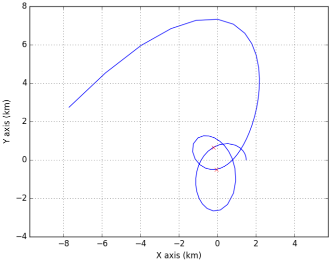


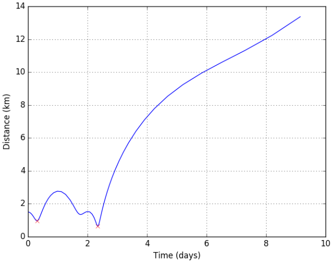


Smaller sail

Closest flybys (10 days):

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





Strategy combination

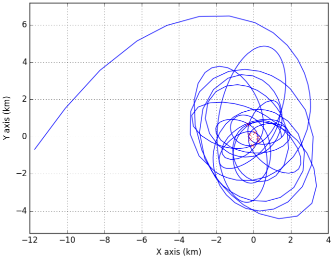
- A combination of 2 strategies is used based on the spacecraft's behaviour. A Strategy is employed in the initial N days and then the Strategy is switched.
- The term "Negative Strategy" is used when a Strategy is employed to maximize the value in the opposite direction.

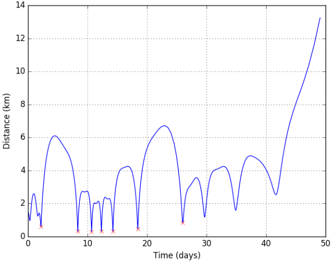
n°	Combination
1	Negative Strategy 2 + Strategy 1
2	Negative Strategy 2 + Strategy 2
3	Negative Strategy 2 + Strategy 3
4	Negative Strategy 3 + Strategy 1
5	Negative Strategy 3 + Strategy 2
6	Negative Strategy 3 + Strategy 3

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

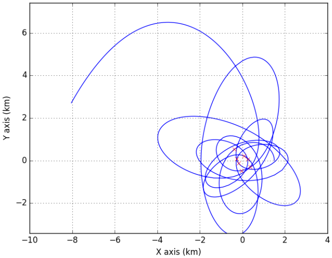


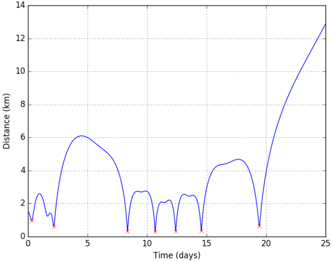


Smaller sail - Combination 2 ($N = 10$)

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

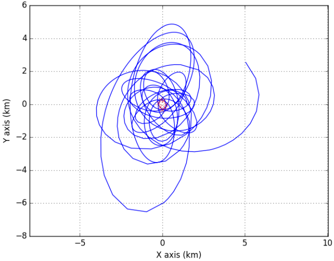


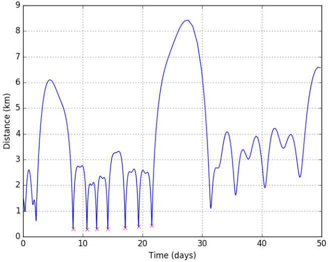


Smaller sail - Combination 3 (N = 10)

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

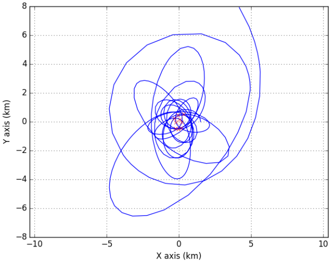


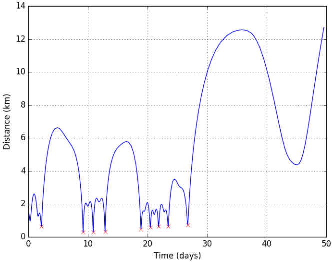


Smaller sail - Combination 4 ($N = 10$)

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

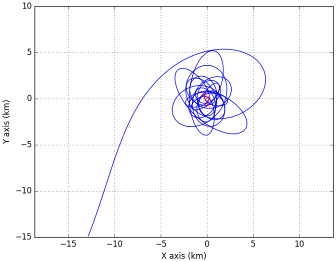


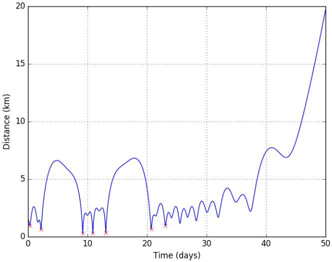


Smaller sail - Combination 5 (N = 10)

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

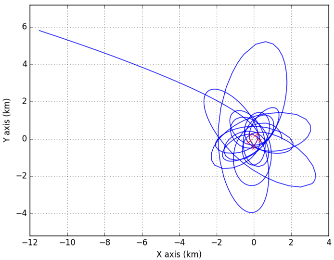


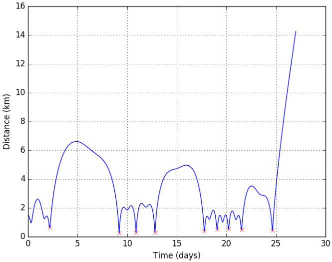


Smaller sail - Combination 6 (N = 10)

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

- 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.

References

McMahon, J. W., Scheeres, D. J., Hesar, S. G., Farnocchia, D., Chesley, S., and Lauretta, D. (2018). The osiris-rex radio science experiment at bennu. *Space Science Reviews*, 214:43.

The Planetary Society (2020). Lightsail 2 mission control.

Vulpetti, G., Johnson, L., and Matloff, G. L. (2015). *Solar Sails*. Copernicus Books, Nova Iorque. 277 p.

Zuber, M. T. (2000). The shape of 433 eros from the near-shoemaker laser rangefinder. *Science*, 289:2097–2101.

Thank you!

The authors would wish to express their appreciation for the support provided by the grants # 406841/2016-0 and 301338/2016-7 from the National Council for Scientific and Technological Development (CNPq); grants # 2018/19959-0 and 2016/24561-0 from São Paulo Research Foundation (FAPESP), to the financial support from the National Council for the Improvement of Higher Education (CAPES).

meireleslg@gmail.com