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Design of a Solar Sail as the Propulsion System for a Nanosatellite

-Technical Datasheet-

by

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1. INTRODUCTION

The aim of this document is to present the main characteristics of the Solar Sail Module design. It is divided into general Solar Sail Module characteristics, specific characteristics and used materials.

2. GENERAL CONDITIONS

Solar Sail Module is a propulsion system to thrust and guide a 6U nanosatellite from GEO to the lunar target orbit.

The Solar Sail Module is able to thrust two configurations of satellites: one with $6\mathrm{kg}$ of s/c mass and are $50\mathrm{m}^2$ of solar sail area and the other with $8\mathrm{kg}$ of s/c mass and are $50\mathrm{m}^2$ of solar sail area.

The Solar Sail Module is a square-shaped solar sail with four triangular quadrants tauten by four lenticular booms. The solar sail quadrants are Z-folded and wedged in four separated solar sail containers. The booms are coiled by a boom deployment mechanism.

The Solar Sail Module (SSM) fulfills the following specifications:

- The module is designed based on Commercial-Off-The-Shelf components.
- The SSM shall be designed according to CubeSat standard ([1]) and deployer requirements ([2]).
- The SSM is able to be attached to the rest of the 6U nanosatellite.
- It is fitted into a 2U volume ($20\mathrm{cm} \text{ x } 10\mathrm{cm} \text{ x } 10\mathrm{cm}$).
- It does not exceed 2kg mass.
- Its lifetime is 5 years.
- The sail is are is $50\mathrm{m}^2$, with four boom of $5\mathrm{m}$ long.
- The materials used are:
    - LaRC™-CP1 Polyimide (Aluminized) for sail membrane.
    - Elgiloy® steel for booms.
    - Al 7075-T6 for the structure.
- The cost is 1M$

3. GENERAL CHARACTERISTICS

3.1. GENERAL DIMENSIONS

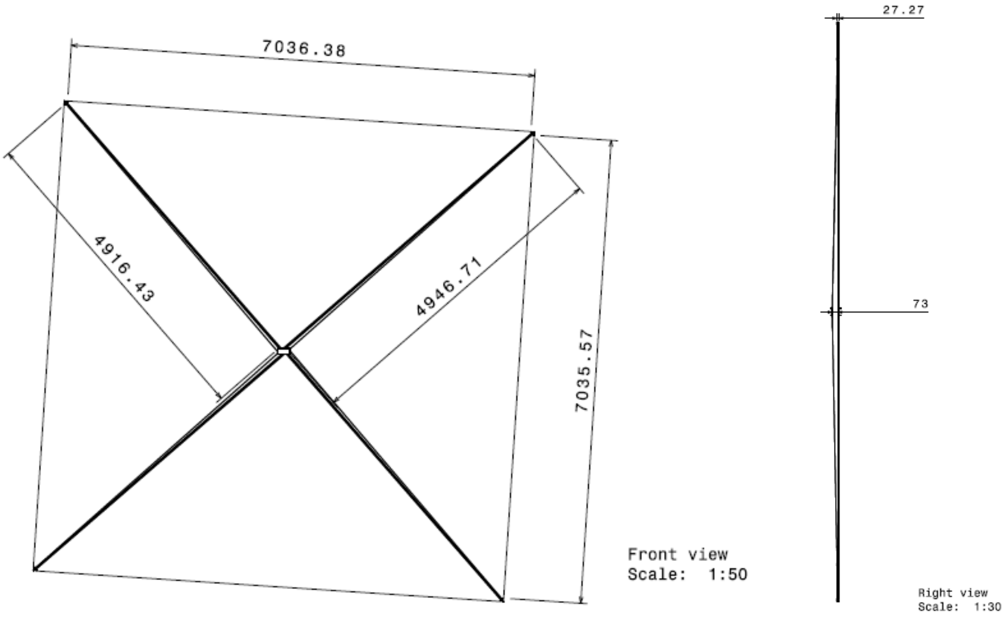

Figure 1. Main dimensions of the sola sail.

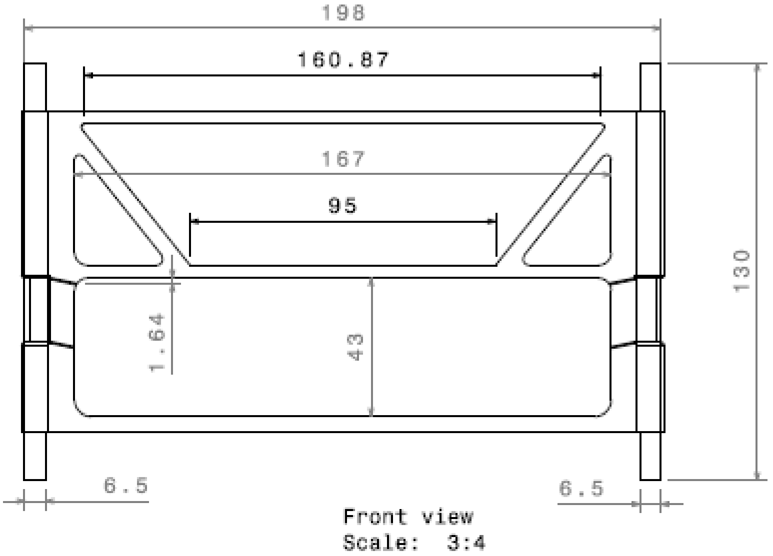

Figure 2. Primary structure front view.

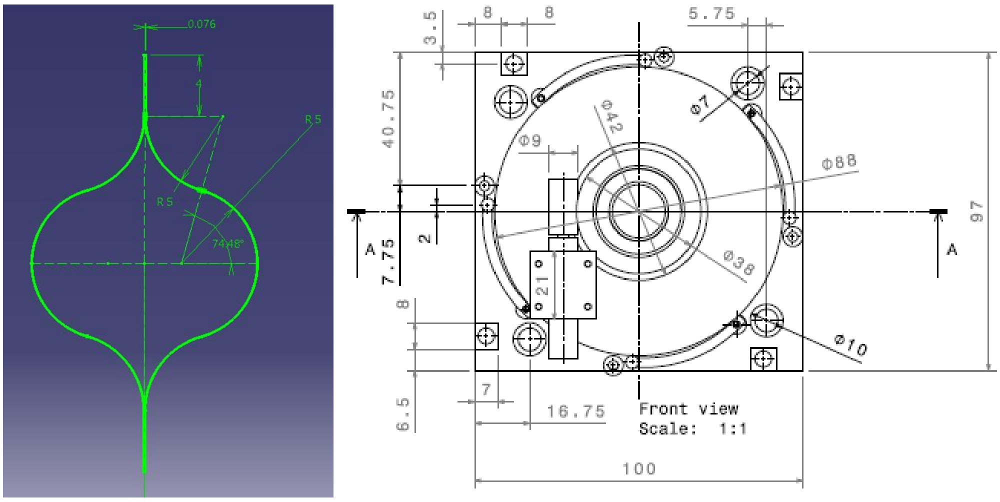

Figure 3. Cross-section of the lenticular boom (Left) and BDM (Right).

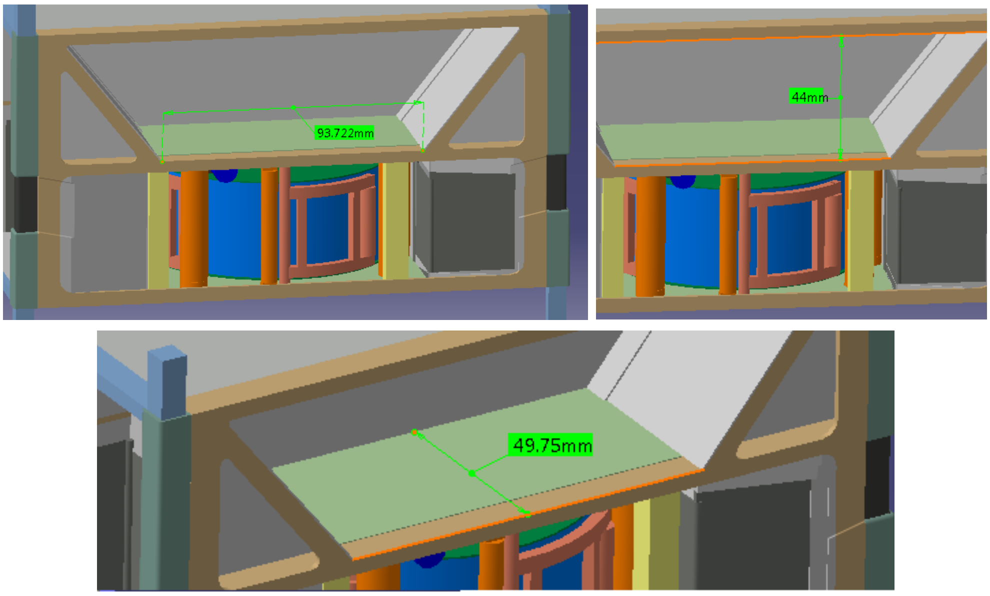

Figure 4. South sail container: $W_{cont} = 93.7\text{mm}$ (Top, left), $H_{cont} = 44\text{mm}$ (Top, right) and $P_{cont} = 49.7\text{mm}$ (Bottom). The sizes and shape are analogous for the North sail container.

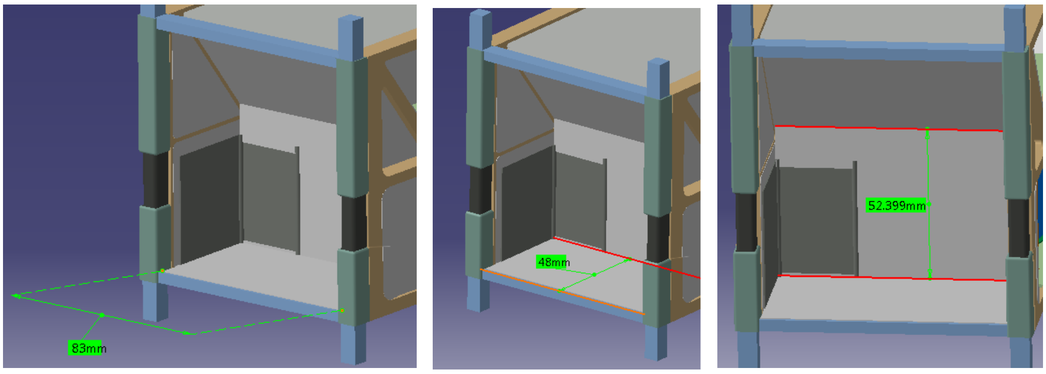

Figure 5. West sail container: $W_{cont} = 83\text{mm}$ (Left), $P_{cont} = 48\text{mm}$ (Middle) and $H_{cont} = 52\text{mm}$ (Right). The sizes and the shape are analogous for the East sail container.

3.2. MASS BUDGET

Mass budget of the SSM		
SSM element	**Mass $[\mathrm{g}]$**	**% of Total**
Sail (4 quadrants)	385	21.23
Booms (4 booms)	888	48.98
Booms Deployment Mechanism (BDM)	238	13.13
Structure (total)	302	16.66
Total mass of SSM	**1, 813**	**100**

Table 1. Mass budget of the SSM.

Mass budget of the SSM structure		
SSM structure element	**Mass $[\mathrm{kg}]$**	**% of Total**
Columns (4 columns + joints)	45	14.90
Sail cavities	108	35.76
Horizontal supports	135	44.70
Screws	14	4.64
Total mass structure	**302**	**100**

Table 2. Mass budget of the SSM structure.

3.3. CENTER OF MASS AND INNERTIA MATRIX

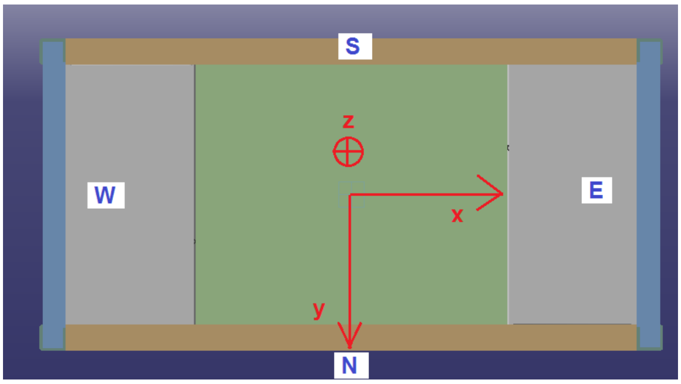

Figure 6. Origin of the reference system used in to locate the CM in the CAD design.

Position of CM for different configurations of SSM		
Parameter	**Launch**	**Operational**
G_x [mm]	-0.448	-0.448
G_y [mm]	-0.364	-0.364
G_z [mm]	33.83	33.74

Table 3. Position of the CM for different configurations of SSM.

$$[I_{launch}] = \begin{bmatrix} 0.002 & -2.127 \cdot 10^{-5} & 1.04 \cdot 10^{-5} \\ -2.127 \cdot 10^{-5} & 0.005 & 8.672 \cdot 10^{-6} \\ 1.04 \cdot 10^{-5} & 8.672 \cdot 10^{-6} & 0.005 \end{bmatrix} \left[\frac{kg}{m^2}\right]$$

$$[I_{operational}] = \begin{bmatrix} 5.582 & -1.104 \cdot 10^{-5} & 1.047 \cdot 10^{-5} \\ -1.104 \cdot 10^{-5} & 5.583 & 8.731 \cdot 10^{-6} \\ 1.047 \cdot 10^{-5} & 8.731 \cdot 10^{-6} & 11.163 \end{bmatrix} \left[\frac{kg}{m^2}\right]$$

3.4. PERFORMANCE

3.4.1. $m = 6kg$ & $A = 50m^2$

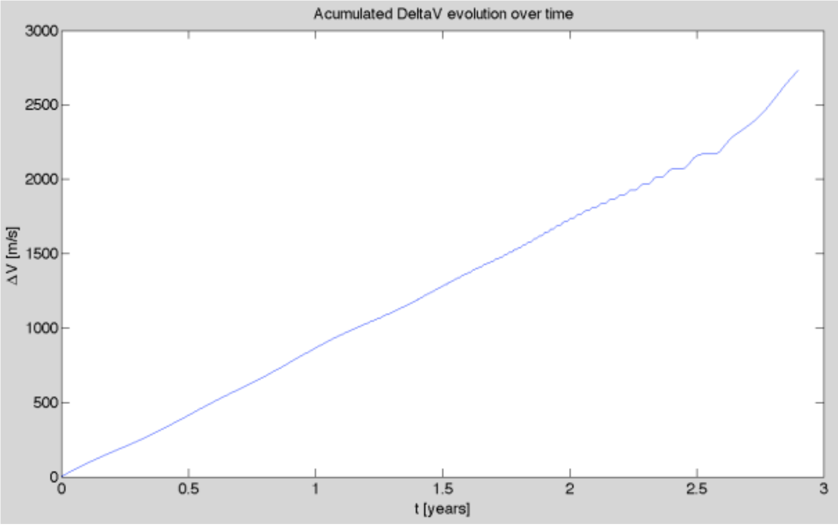

Figure 7. Evolution of accumulated Δv for $m = 6kg$. From $t = 0$ years to $t = 2.9$ years

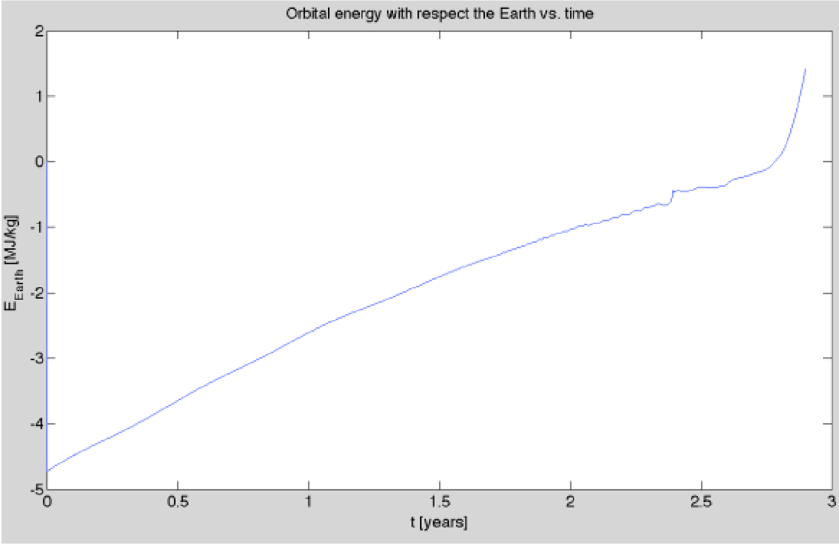

Figure 8. Evolution oF s/c orbital energy with respect to the Earth for $\mathbf{m = 6kg}$. From $\mathbf{t = 0\ years\ to\ t = 2.9\ years}$.

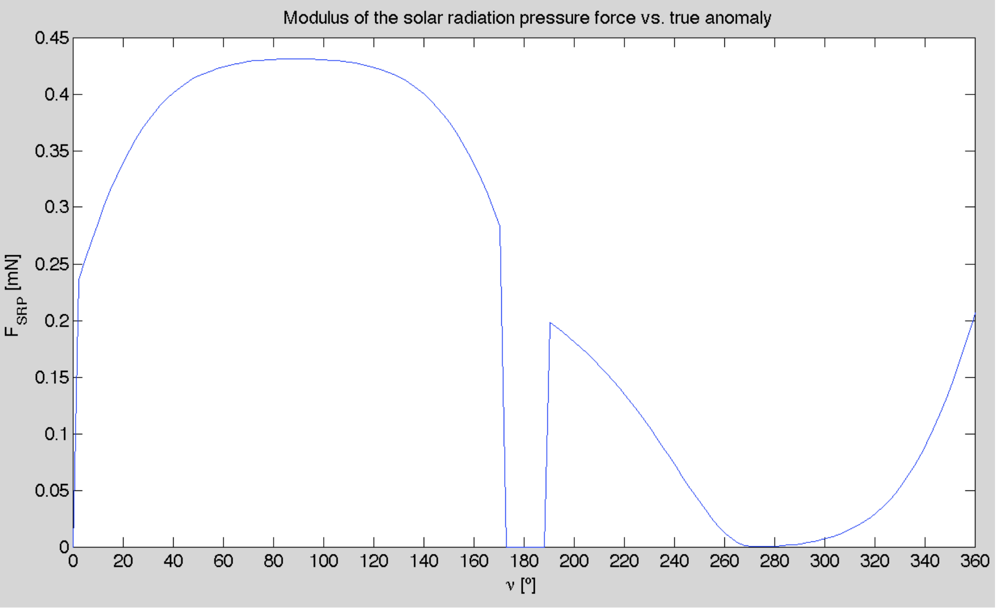

Figure 9. Evolution of SRP force modulus vs. true anomaly in one turn for $\mathbf{m = 6kg}$. 1 day in GEO orbit when the Sun is at the vernal equinox.

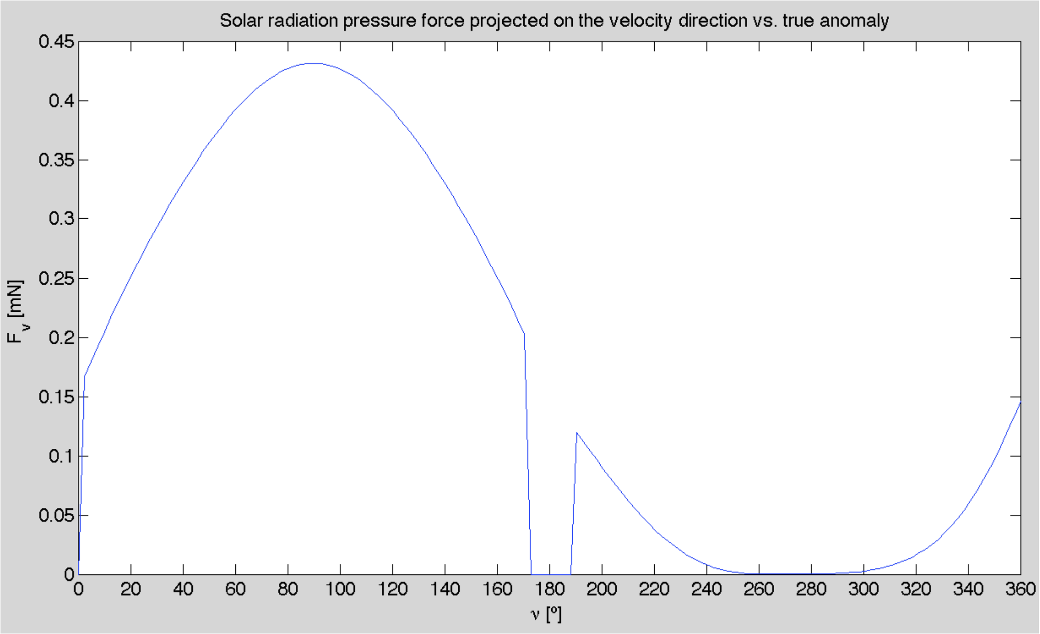

Figure 10. Evolution of SRP force projected on the velocity direction vs. true anomaly in one turn for $m = 6kg$. 1 day in GEO orbit when the Sun is at the vernal equinox.

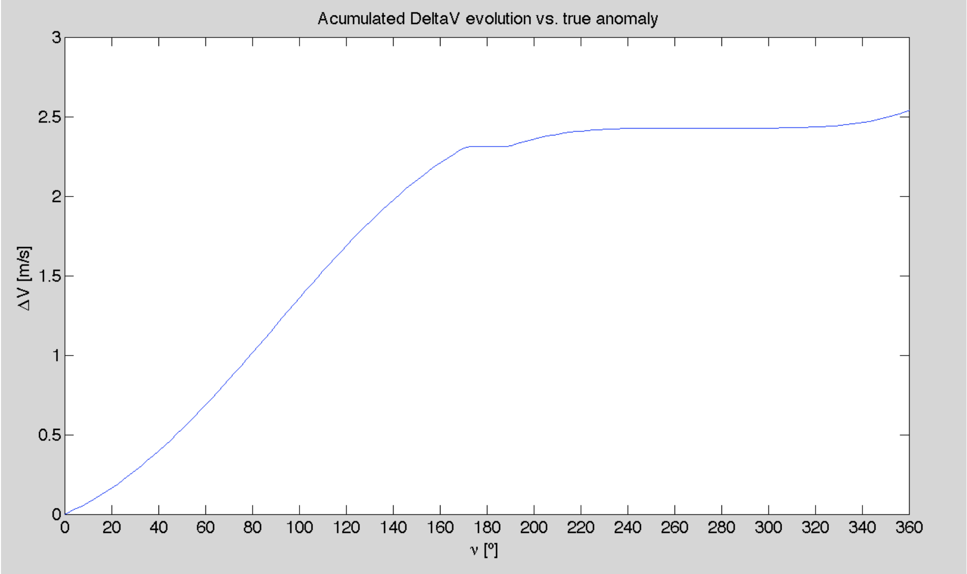

Figure 11. Evolution of accumulated Δv vs. true anomaly in one turn for $m = 6kg$. 1 day in GEO orbit when the Sun is at the vernal equinox.

3.4.2. $m = 8kg$ & $A = 50m^2$

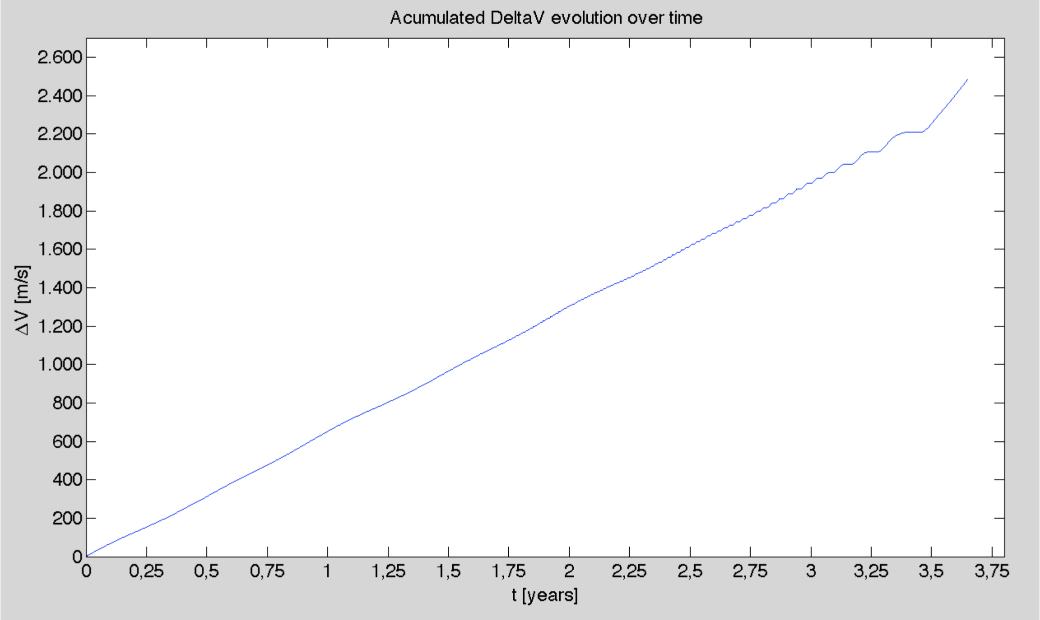

Figure 12. Evolution of accumulated Δv for $m = 8kg$. From $t = 0$ years to $t = 3.65$ years.

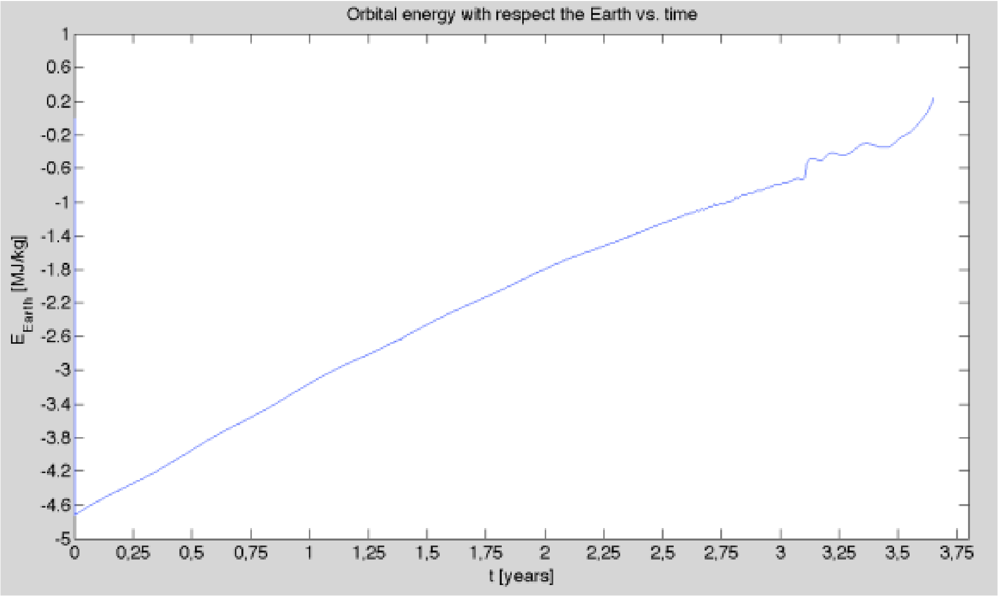

Figure 13. Evolution of accumulated Δv (Left) and s/c orbital energy with respect to the Earth (Right) for $m = 8kg$. From $t = 0$ years to $t = 3.65$ years.

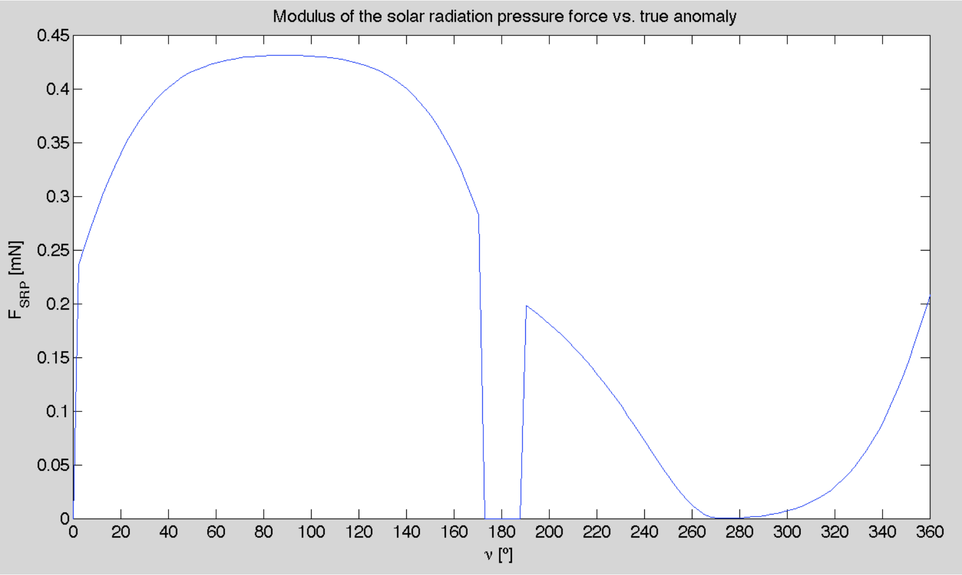

Figure 14. Evolution of SRP force modulus vs. true anomaly in one turn for $\mathbf{m = 8kg}$. 1 day in GEO orbit when the Sun is at the vernal equinox.

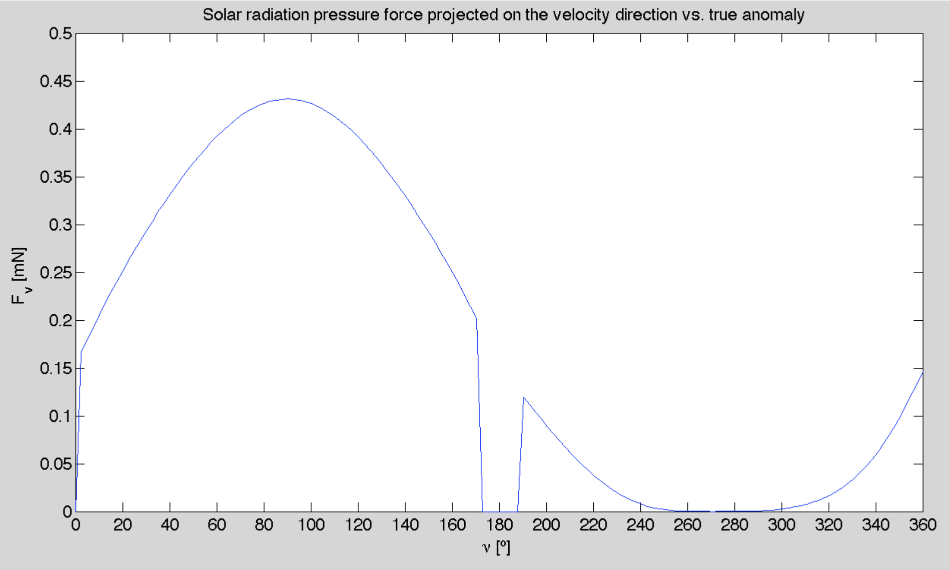

Figure 15. Evolution of SRP force projected on the velocity direction vs. true anomaly in one turn for $\mathbf{m = 8kg}$. 1 day in GEO orbit when the Sun is at the vernal equinox.

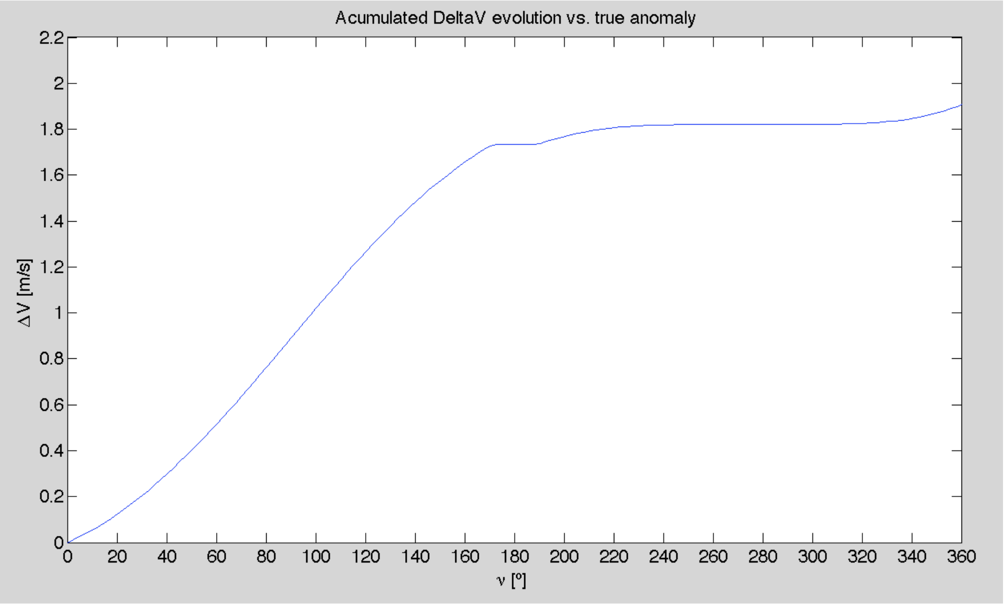

Figure 16. Evolution of accumulated Δv vs. true anomaly in one turn for $\mathbf{m = 8kg}$. 1 day in GEO orbit when the Sun is at the vernal equinox.

4. MATERIALS

Aluminized CP-1$^{\text{TM}}$ Properties			
Type of property	**Name**	**ASTM Method**	**Value**
Physical and Mechanical Properties	Tensile Strength (1 mil, 23ºC)	D882-02	87MPa
	Young Modulus (23ºC)	D882-02	2GPa
	Tensile Elongation at break	D882-02	16%
	Density	D792-08	1540kg/m^3
	Poisson ratio	--	0.35
Optical Properties	Solar Absorptance (1mil)	E903-96	0.08
	Solar Transmittance (1mil)	E903-96	0.83
	Solar Reflectance (1mil)	E903-96	0.09
	Infrared Emissivity (hemispherical & 1mil)	E408-71	0.45
Nominal thicknesses	$2.5\mu\text{m}, 5\mu\text{m}, 12\mu\text{m}$ & $25\mu\text{m}$.		

Table 4. Summary of the main properties of the Aluminized CP-1$^{\text{TM}}$ used in the solar sail membrane.

Elgiloy$^{®}$ Steel Properties			
Name	**Value**	**Name**	**Value**
Tensile Strength	1600MPa	Density	8300kg/m^3
Young Modulus (23ºC)	190GPa	Poisson ratio	0.226
Tensile Elongation at break	$\geq 1\%$		

Table 5. Summary of the main physical and mechanical properties of Elgiloy$^{®}$ steel used in the booms.

7075 Aluminum alloy composition			
Component	**Amount (wt. %)**	**Component**	**Amount (wt. %)**
Aluminum	87.1 – 91.4	Manganese	Max. 0.3
Chromium	0.18 – 0.28	Silicon	Max. 0.4
Copper	1.2 – 2	Titanium	Max. 0.2
Iron	Max. 0.5	Zinc	5.1 – 6.1
Magnesium	2.1 – 2.9	Other, total	Max. 0.15

Table 6. Summary of the typical composition of 7075-T6 Aluminum alloy used in the structure.

Properties of the 7075-T6 Aluminum alloy			
Name	**Value**	**Name**	**Value**
Ultimate Tensile Strength	572MPa	Density	$2810\mathrm{kg/m^3}$
Tensile Yield Strength	503MPa	Poisson ratio	0.33
Elongation at Break (1.6mm thickness)	11%	Fatigue Strength	159MPa
Brinell Hardness (500kg load, 10mm ball)	150	Shear Modulus	26.9GPa
Young Modulus (23^{o}C)	71.7GPa	Shear Strength	331MPa

Table 7. Summary of the main properties of Al 7075-T6 used in the structure.

5. REFERENCES

[1] S. Lee, A. Hutputanasin, A. Toorian and W. Lan. *CubeSat Design Specification (CDS).* The CubeSat Program. California Polytechnic State University (San Luis Obispo, CA, US).

[2] SpaceFlight Services. *Secondary Payload Planners Guide.* (Tukwila, WA, US).

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