САМАРСКИЙ УНИВЕРСИТЕТ
SAMARA UNIVERSITY

XVII International Summer Space School: Future Space Technologies and Experiments in Space

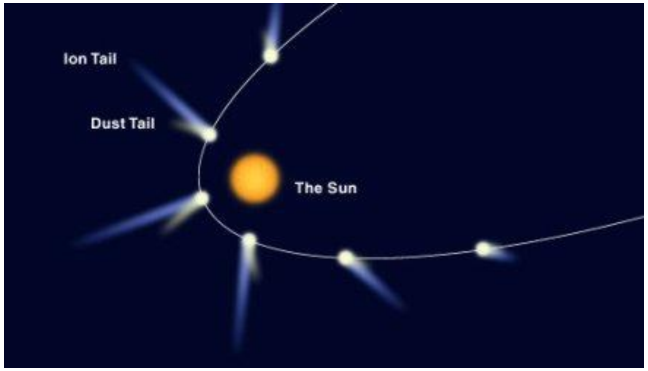
Solar sail

Prof. Olga L. Starinova

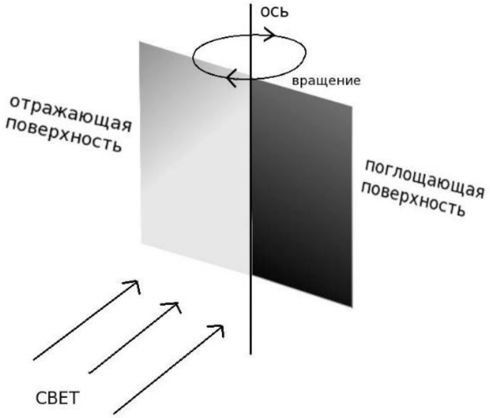
Samara National Research University
04 Sep 2023

Solar sailing

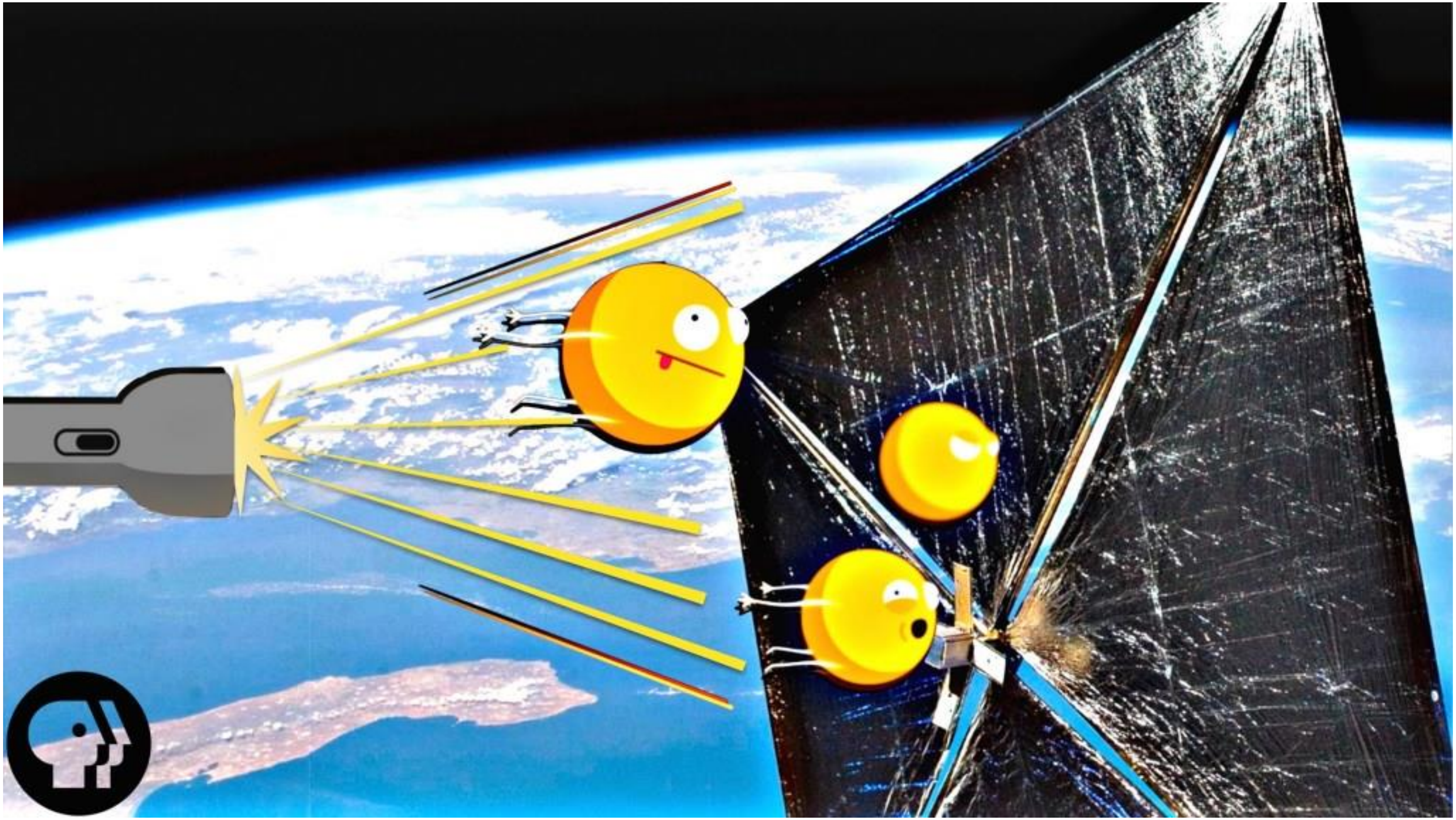
Solar power pressure



$$P_r = \frac{(1+\varepsilon)S_r}{c}$$



Solar power pressure



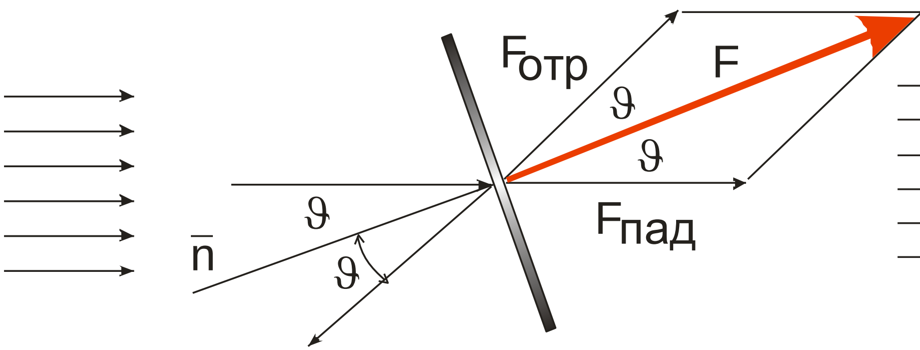


Figure 1 - Thrust magnitude and direction for a perfectly reflective sail

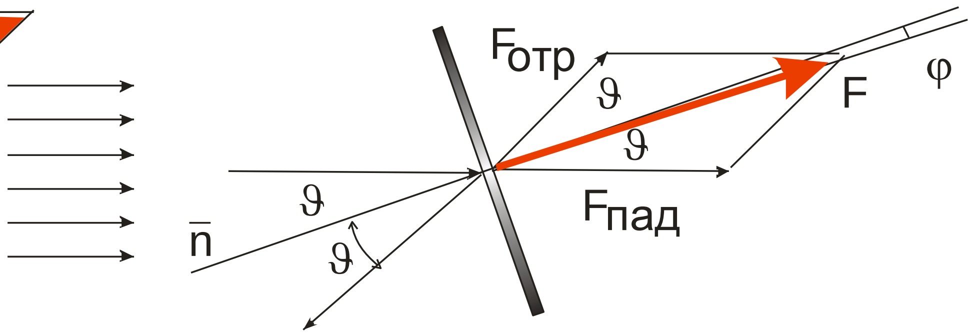
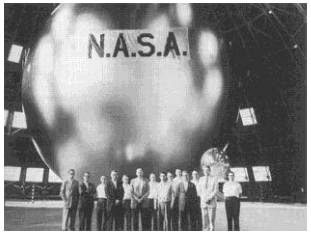


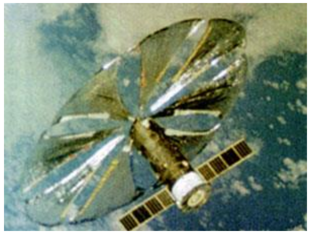
Figure 2 - Thrust magnitude and direction for a non-perfectly reflective sail

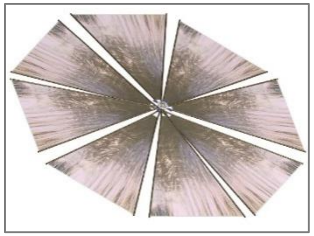
The value of light pressure on the orbits of the planets of the Solar system

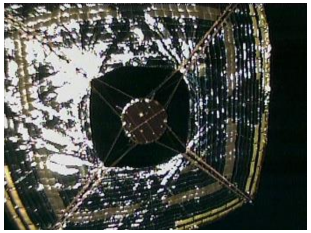
Planet	Absorbing sail	Perfectly reflective sail
Mercury	$3{,}1 \cdot 10^{-5}$	$6{,}2 \cdot 10^{-5}$
Venus	$8{,}9 \cdot 10^{-6}$	$1{,}78 \cdot 10^{-5}$
Earth	$4{,}64 \cdot 10^{-6}$	$9{,}28 \cdot 10^{-6}$
Mars	$2{,}0 \cdot 10^{-6}$	$4{,}0 \cdot 10^{-6}$
Jupiter	$1{,}7 \cdot 10^{-7}$	$3{,}4 \cdot 10^{-7}$

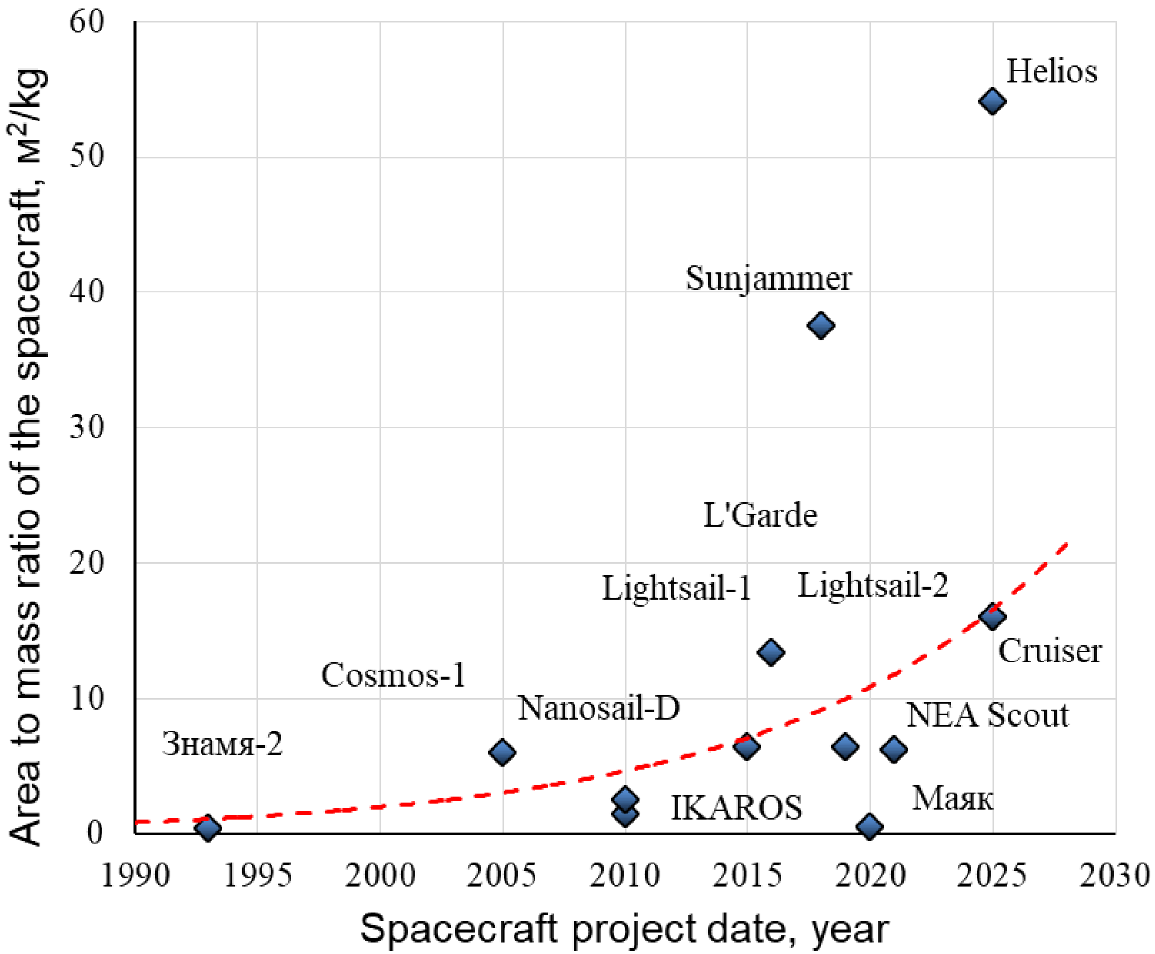
Design parameters of solar sails

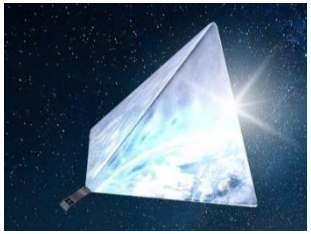


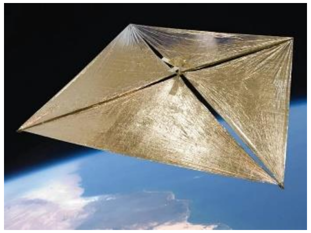


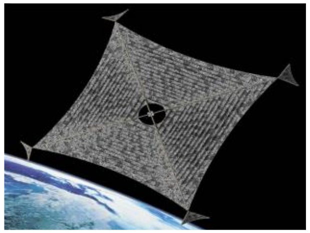




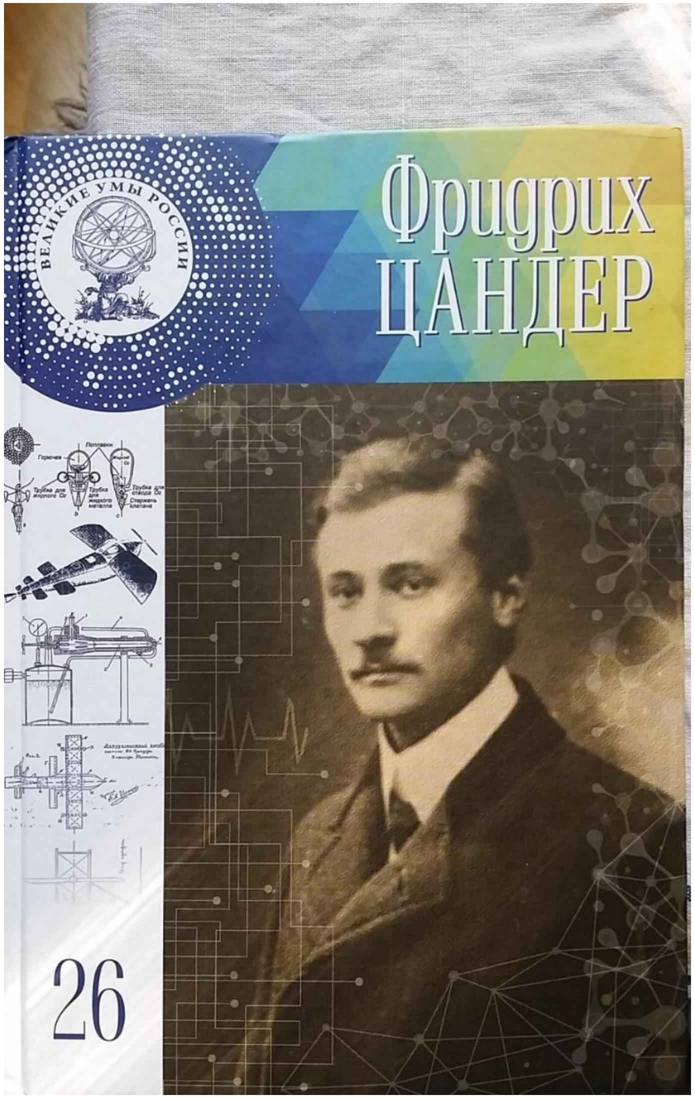


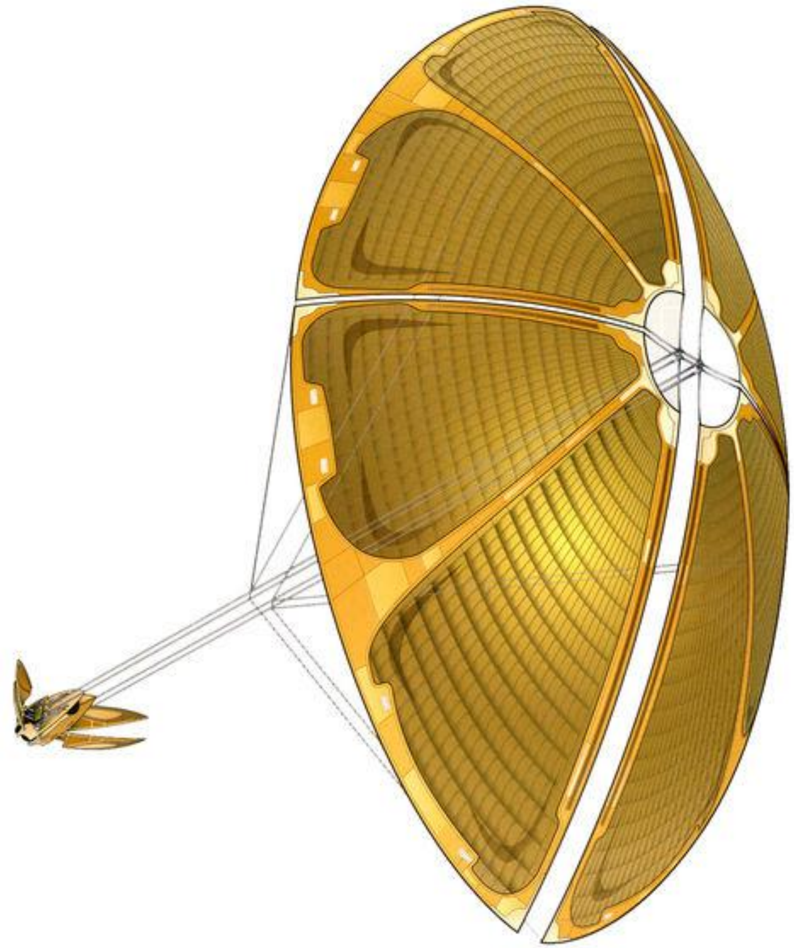






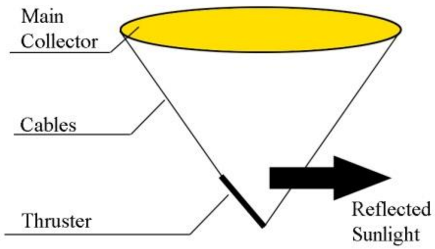
Solar power pressure



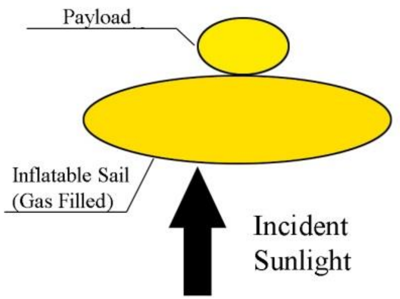


Design types of solar sails

Parabolic Sail
(Solar Photon Truster)



Hollow Body (Pillow Sail)

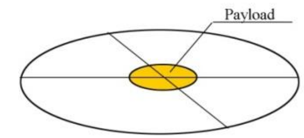


Inflatable
- Hollow body
- Inflatable reflectors
- Inflatable frame

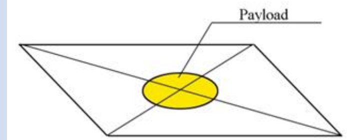
Rotating
- Rotating the canvas
- Petal
- Heliogyro

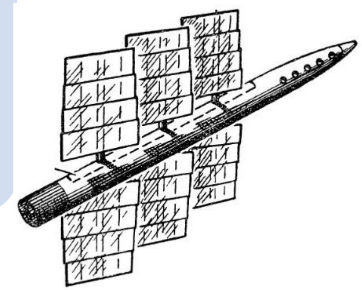
Frame
- Single-layer
- Box layered

Disc Sail

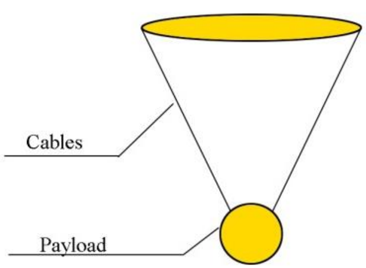


Square Sail (Yankee Clipper)

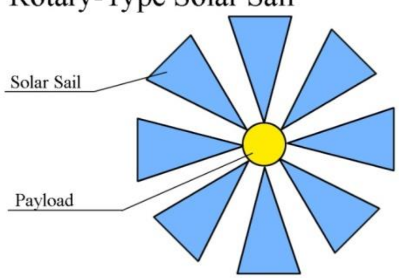




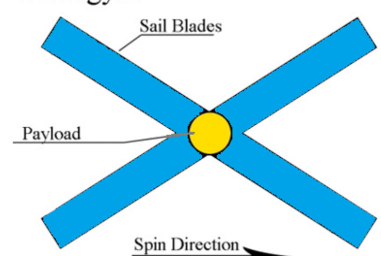
Parachute Sail



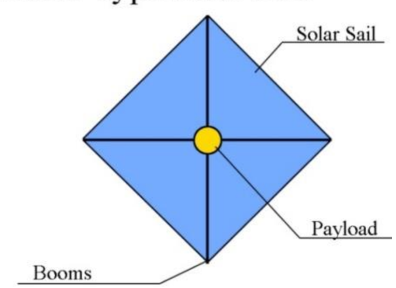
Rotary-Type Solar Sail



Heliogyro



Frame-Type Solar Sail



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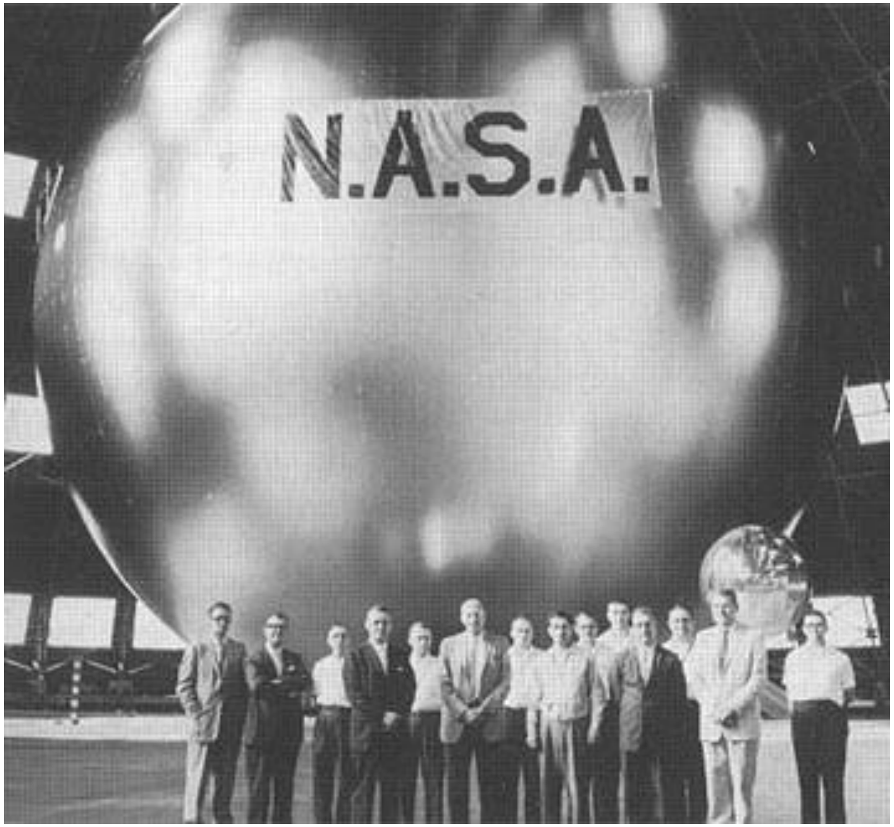
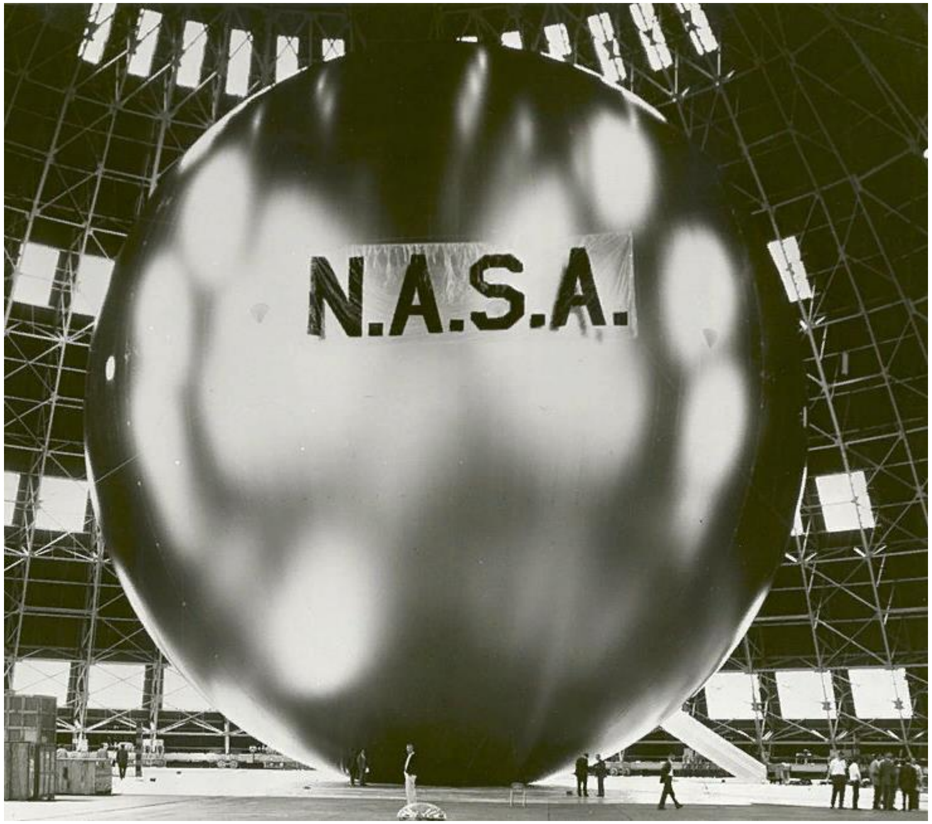
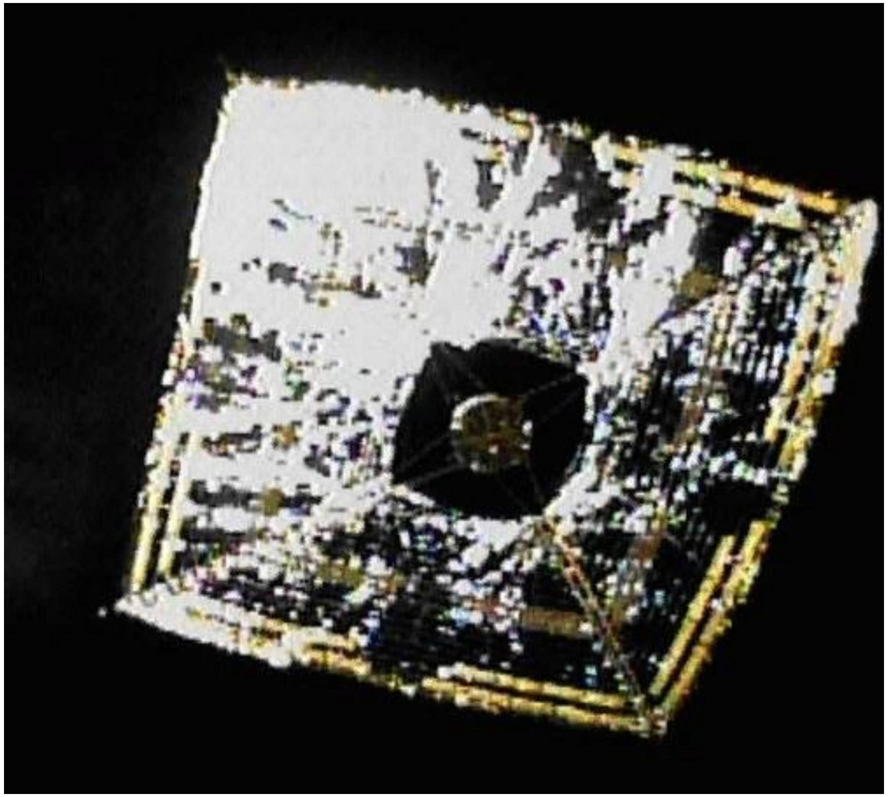
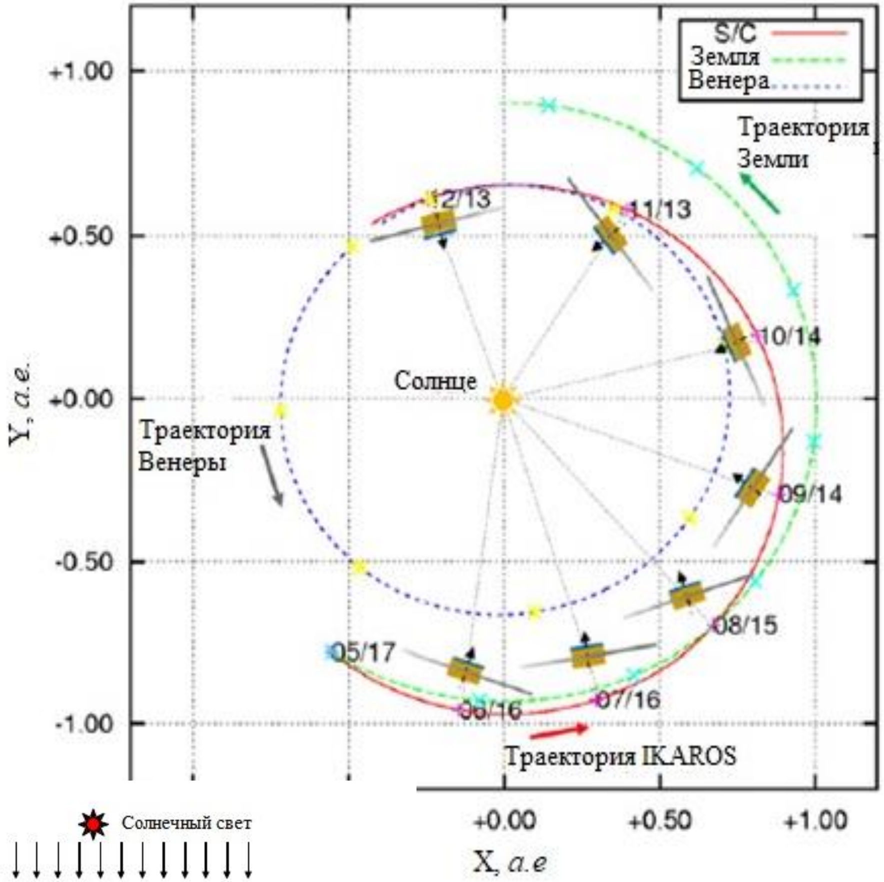


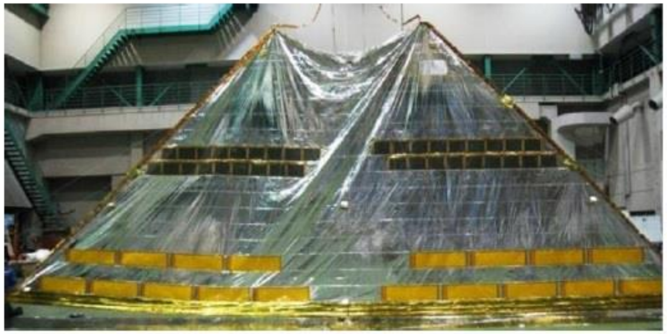


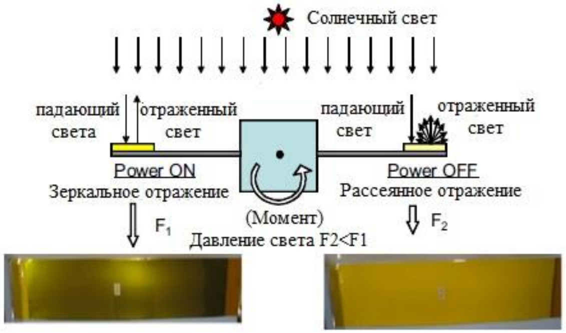
Satellites repeaters Echo-1 (12.08.1960) и Echo-2 (25.01.1964)

IKAROS – the first interplanetary solar sail spacecraft

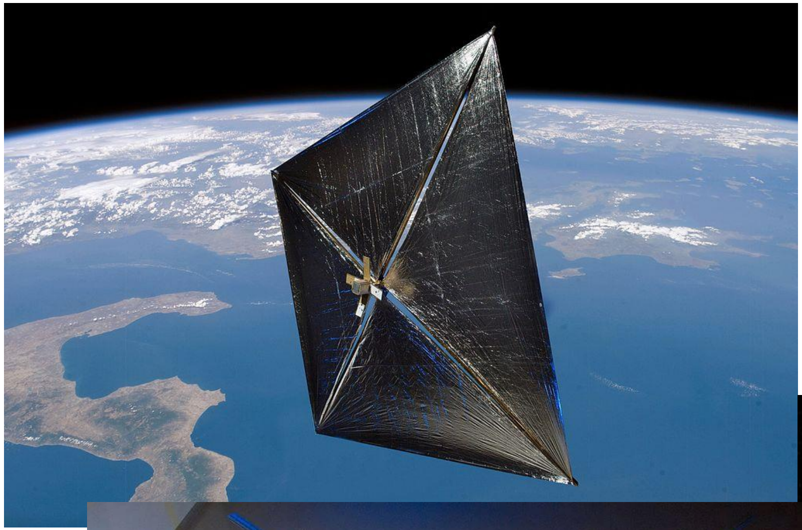


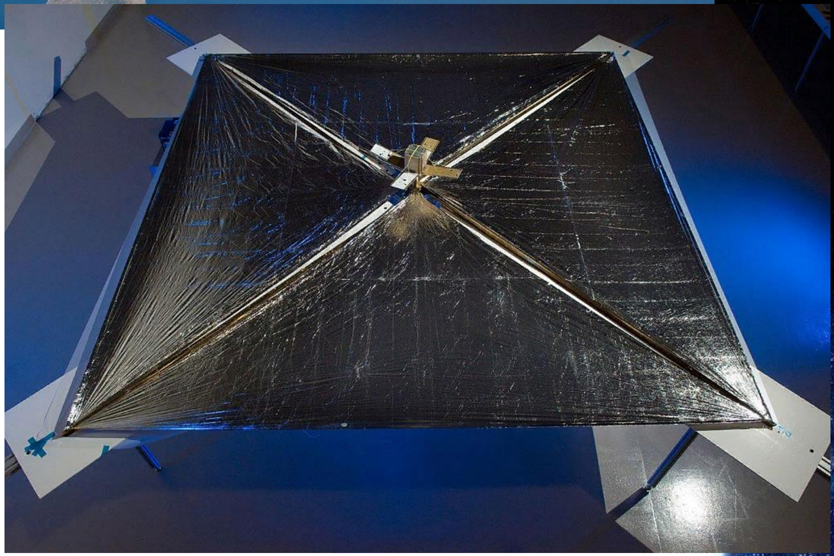


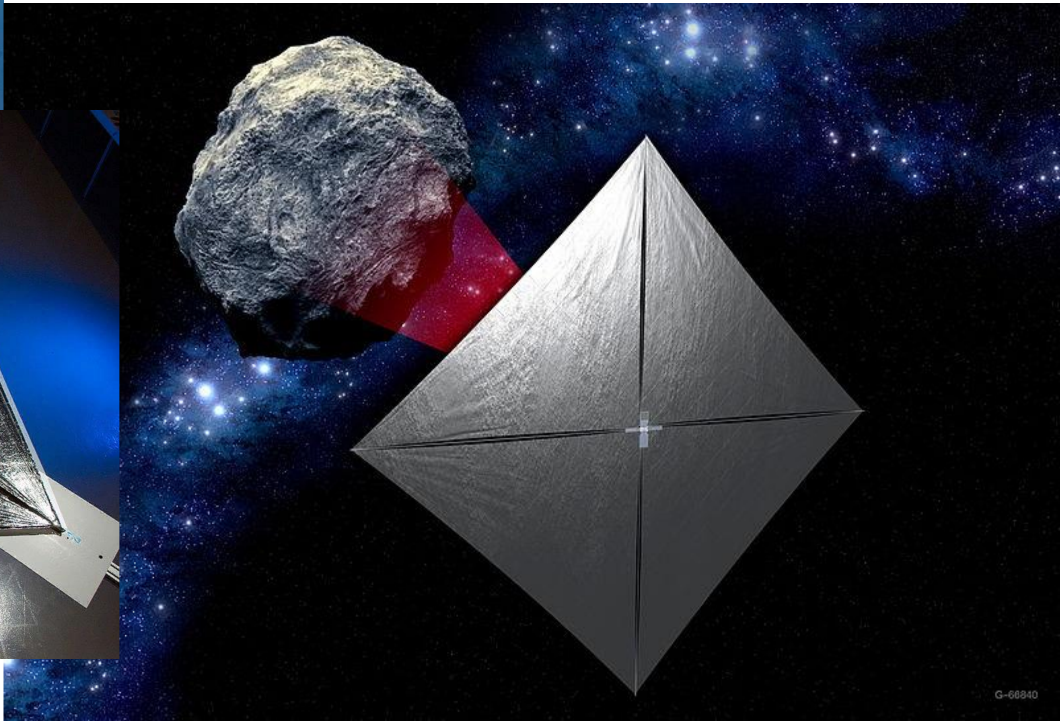


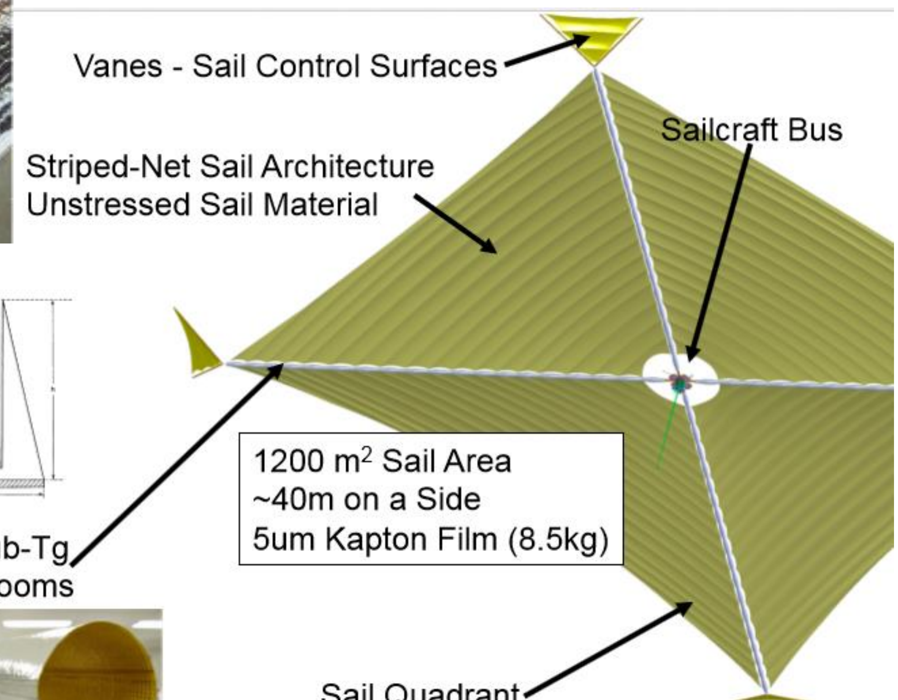


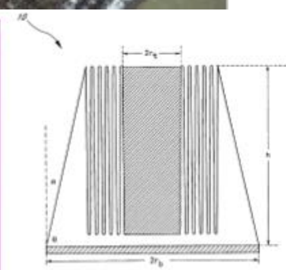
Nano-sails on nanosatellites from Nanosail D2 to NEA Scout



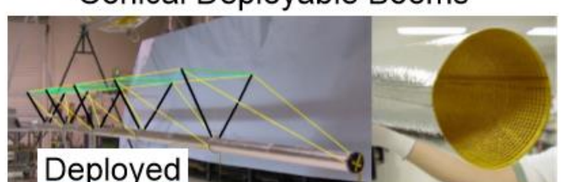






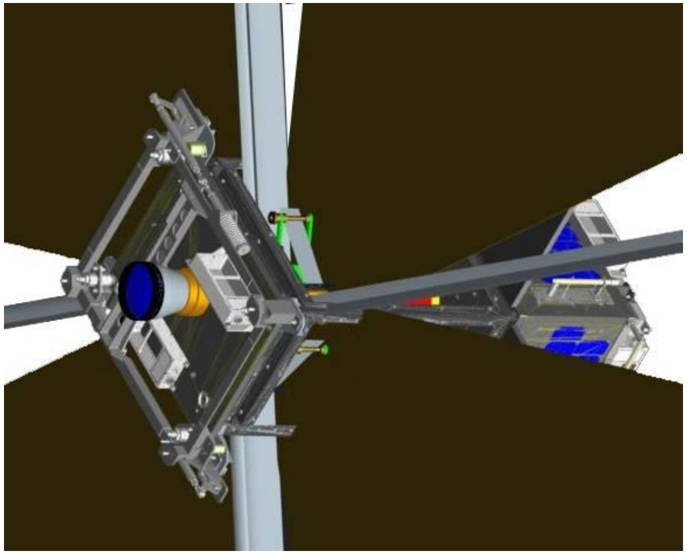


L'Garde Patented Sub-Tg
Conical Deployable Booms

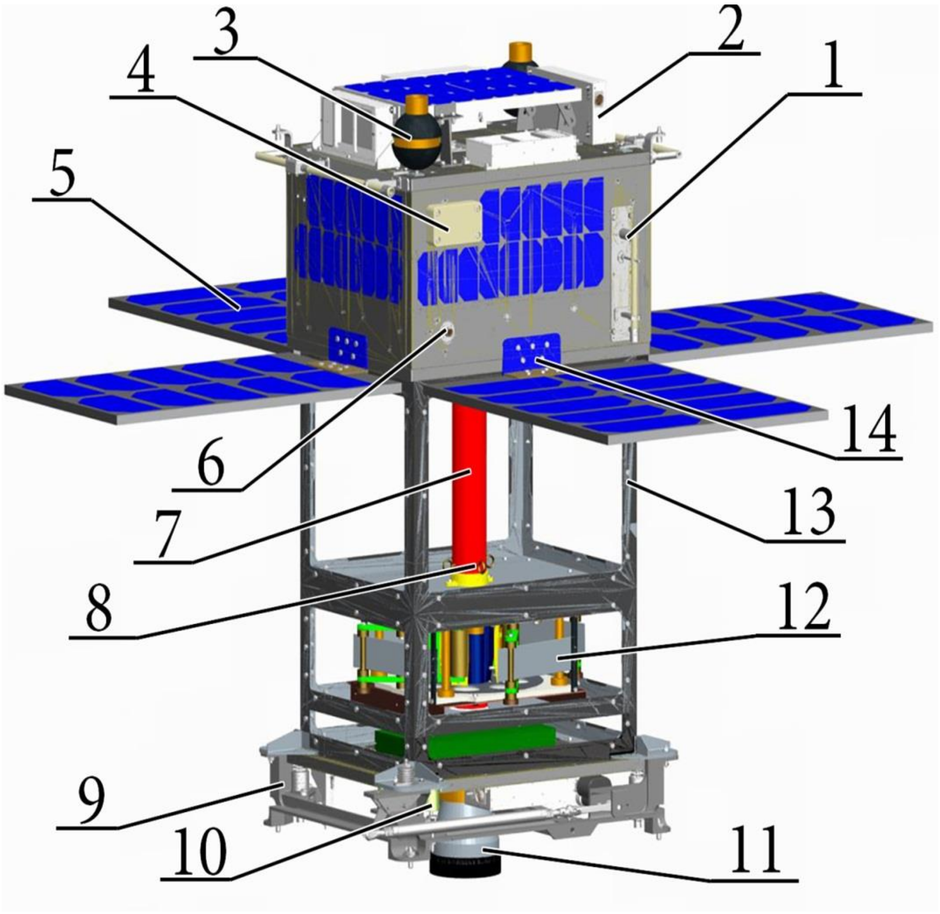


Our Solar sail spacecraft Helios has the following main design parameters

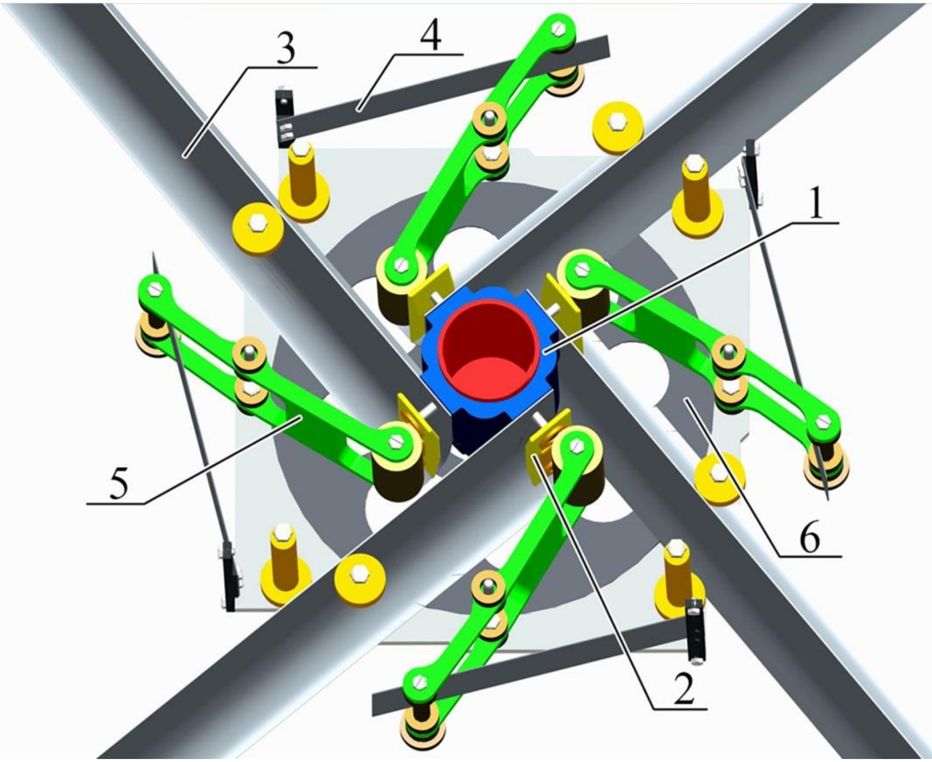
- the mass of a spacecraft is 100 kg and the total area of a solar sail is 10,000 m^2;
- the film thickness is 3.5 micrometer;
- the area to the mass ratio of the solar sail spacecraft is 100 m^2/kg;
- the optical parameters $\rho=0.98$, $\zeta=0.94$, $\varepsilon_f=0.05$, $\varepsilon_b=0.55$;
- the degraded parameters $d_\rho=0.1$, $\delta_\rho=0.231$, $d_\zeta=0.1$, $\delta_\zeta=0.139$, $d_{\varepsilon f}=0.1$, $\delta_{\varepsilon f}=0.231$;
- $T_{max} = 1000$ K.



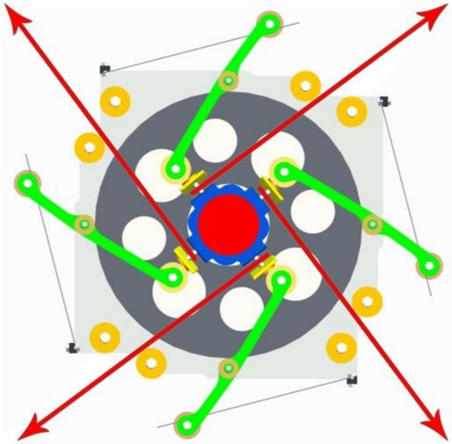
Our Solar sail spacecraft Helios

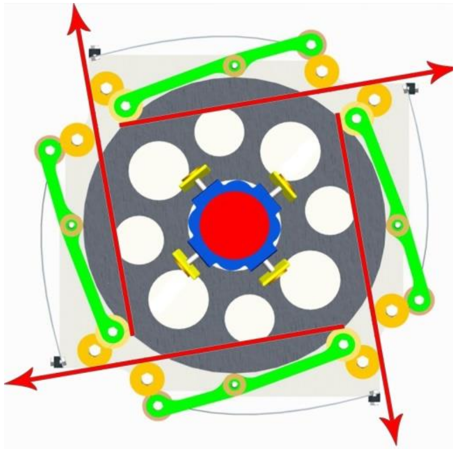


1 – Antenna-feeder device
2 – Orientation system devices
3 – Photo equipment
4 – Automatic control unit
5 – Solar panel
6 – Process connector
7 – Fixing pipe
8 – Attachment of solar sail
9 – Separation device
10 – Pin sensor
11 – Electron-optical equipment
12 –Deploying mechanism
13 – Frame Space craft
14 – Attachment of the solar panel



1 – Swivel axle;
2 – Locking clamping device;
3 – Deploying beam;
4 – Bending plates;
5 – Tension unit;
6 – Pressure plate.





Red arrows – the direction of the beam exit from the deployment mechanism

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A six dimensional state $\mathbf{x}(t)=\begin{pmatrix} r & u & V_r & V_\varphi & \Omega & i \end{pmatrix}^T \in \mathbf{X}$ describes a solar sail motion in heliocentric frame. Criterion of optimality – minimum flight time for a given mission's aim

$$\mathbf{u}_{opt}(t)=\arg\min_{\mathbf{u}(t)\in\mathbf{U}}\left\{t_m\left(\mathbf{u}(t),\mathbf{x}(t)\right)\Big|\,\mathbf{x}(t_0)=\mathbf{x}_0,\mathbf{x}(t_k)=\mathbf{x}_k,T(t)\le T_{\max}\right\}$$

Thrust vector of the solar sail:

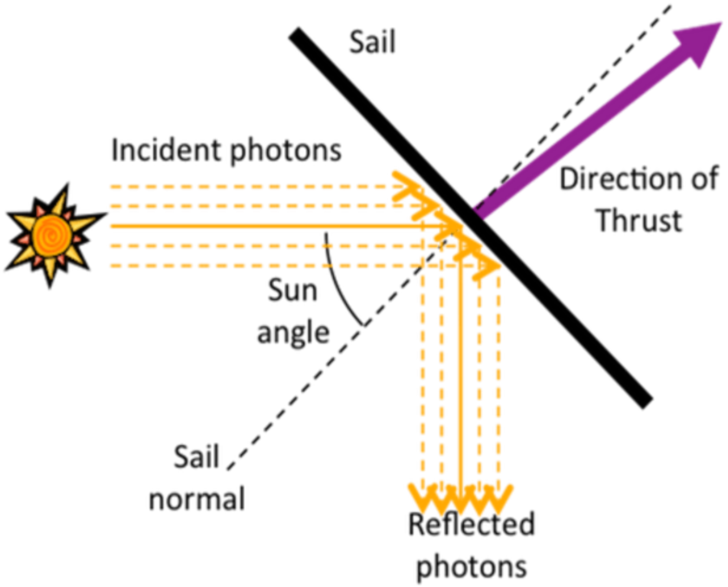
$$F_\perp = 2\frac{S_r}{c}S\cdot\cos\vartheta\cdot\left(a_1\cos\vartheta+a_2\right)$$

$$F_{||} = 2\frac{S_r}{c}S\cdot\cos\vartheta\cdot a_3\sin\vartheta$$

$$a_1=\frac{1}{2}\left(1+\varsigma\rho\right)$$

$$a_2=\frac{1}{2}\left(B_f\left(1-\varsigma\right)\rho+\left(1-\rho\right)\frac{\varepsilon_f B_f-\varepsilon_b B_b}{\varepsilon_f+\varepsilon_b}\right)$$

$$a_3=\frac{1}{2}\left(1-\varsigma\rho\right)$$



$$\dot{r} = V_r,$$

$$\dot{V}_r = \frac{V_\theta{}^2}{r} + \frac{V_\varphi{}^2 \sin^2\varphi}{r\sin^2\theta} - \frac{GM}{r^2} f + \frac{GM}{c^2 r^2} f^{-1} V_r{}^2 + \frac{fV_\varphi^2}{r} + \frac{2GJ}{c^2 r^3} fV_\varphi + a_r + f_r,$$

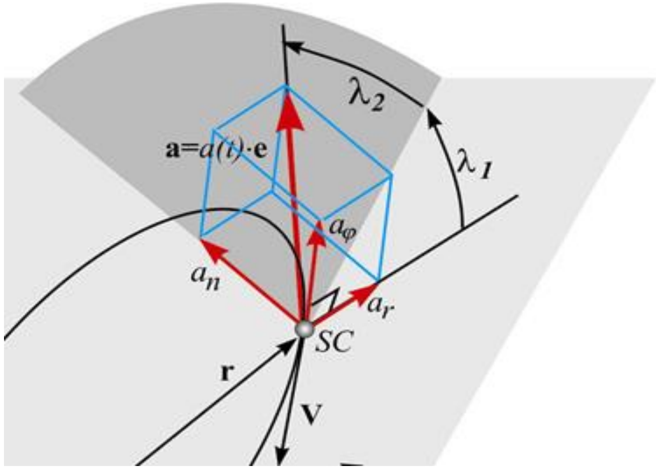
$$\dot{\varphi} = \frac{V_\varphi}{r\sin\theta},$$

$$\dot{V}_\varphi = -\frac{V_r V_\varphi}{r} - \frac{V_\varphi V_\theta \cos\theta}{r\sin\theta} + \frac{2GJ}{c^2 r^3} V_r + a_\varphi + f_\varphi,$$

$$\dot{\theta} = \frac{V_\theta}{r},$$

$$\dot{V}_\theta = \frac{V_\varphi{}^2 \cos\theta}{r\sin\theta} - \frac{V_r V_\theta}{r} - \frac{4GJ}{c^2 r^2}\frac{V_\varphi}{r}\cos\theta + a_\theta + f_\theta.$$

(1)



If we do not take into account the dependence of the optical coefficients of the sail surface on the temperature and surface degradation due to the effects of space factors, the equilibrium temperature can be calculated by formula

$$T=\left(\frac{S_r}{\sigma_{SB}}\frac{1-\rho}{\varepsilon_f+\varepsilon_b}\left(\frac{r_0}{r}\right)^2\cos\vartheta\right)^{1/4}$$

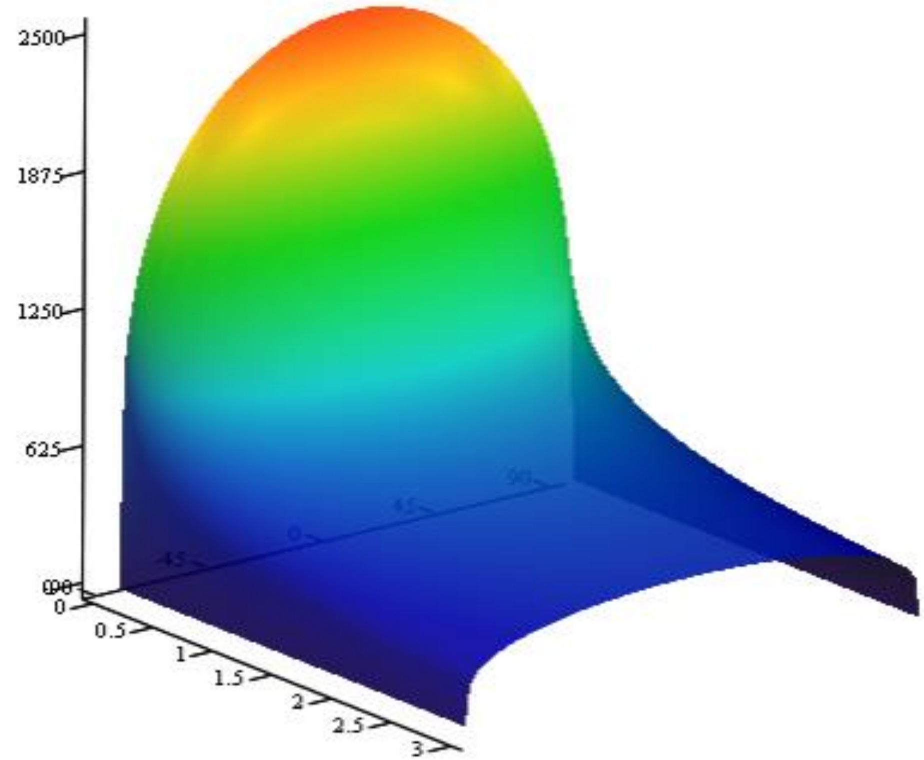
Here $\sigma_{SB}=5{,}67\cdot10^{-8}$ W·m^{-2}·K^{-4}
is the Stefan-Boltzmann constant.

Sun as an extended source of radiation pressure

$$S_r=\frac{L_0}{3\pi R_s^2}\left\{1-\left[1-\left(\frac{R_s}{r}\right)^2\right]^{3/2}\right\}$$

m is the Sun radius.

Our design model of sail has a following optical parameters:
$\rho=0.88$, $\varepsilon_f=0.05$, $\varepsilon_b=0.55$

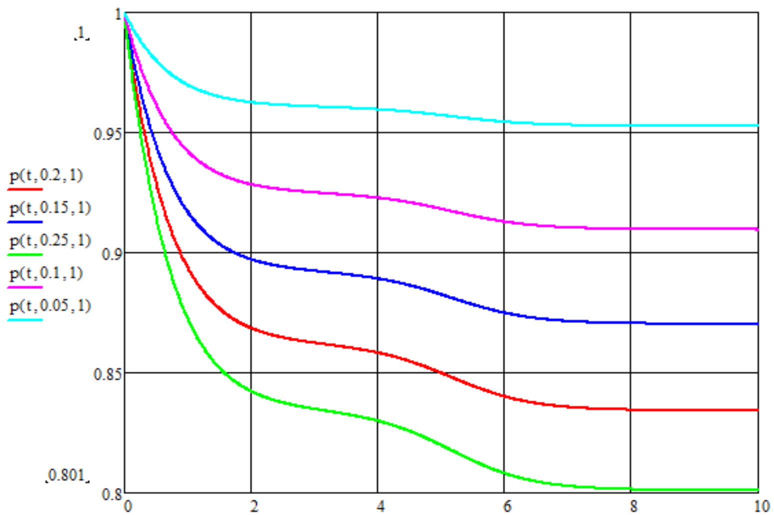


Dependence the surface equilibrium temperature to the heliocentric distance and the installation angle

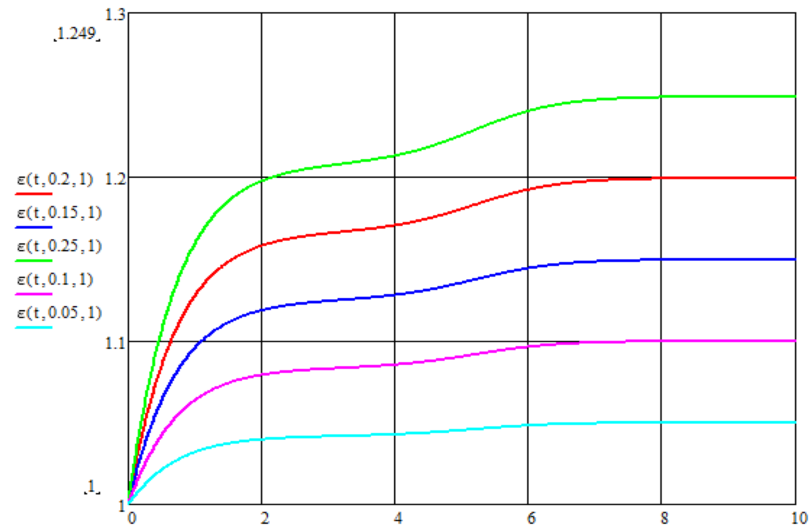
The change in the optical parameter p in time depends on the total dose of solar radiation obtained the sail

$$\frac{p(t)}{p_0}=\begin{cases}\dfrac{1+de^{-\lambda\Sigma(t)}}{1+d} & if\ \ p\in\{\rho,\varsigma\}\\ 1+d\left(1-e^{-\lambda\Sigma(t)}\right) & if\ \ p=\varepsilon_f\\ 1 & if\ \ p\in\{\varepsilon_b,B_f,B_b\}\end{cases}$$

$$\tilde{\Sigma}_0=15{,}768\cdot 10^{12}$$



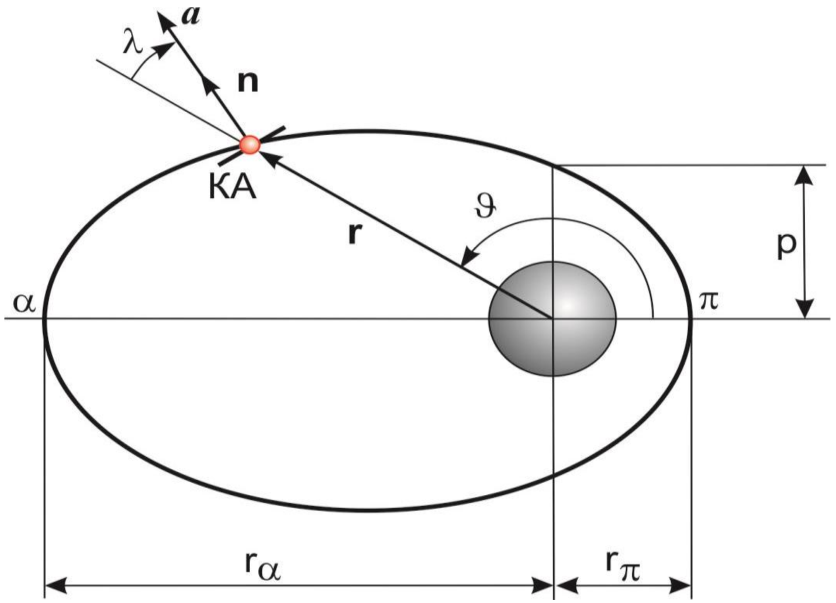
Dependence the reflection coefficient of the sail surface to the lifetime



Dependence the emission coefficient of the sail surface to the lifetime

We use the planar Keplerian osculated elements to choosing control laws. All equations of Keplerian elements have form

$$\frac{dK}{dt} = f_1(p,e,\vartheta)\cos^3\lambda_1 + f_2(p,e,\vartheta)\cos^2\lambda_1 \sin\lambda_1$$



If we need keeping the element K constant, then steered angle has to be

$$\left[\begin{array}{l} tg\lambda_1 = -\dfrac{f_1(p,e,\vartheta)}{f_2(p,e,\vartheta)}, \\ \lambda_1 = \pm\dfrac{\pi}{2}. \end{array}\right. \qquad (2)$$

For the most rapid change of the Keplerian element steering angle has to be

$$\lambda_1 = \frac{1}{2}\arcsin\frac{f_2(p,e,\vartheta)\left(f_1(p,e,\vartheta) - \sqrt{9f_1(p,e,\vartheta)^2 + 8f_2(p,e,\vartheta)^2}\right)}{3\left(f_1(p,e,\vartheta)^2 + f_2(p,e,\vartheta)^2\right)} \qquad (3)$$

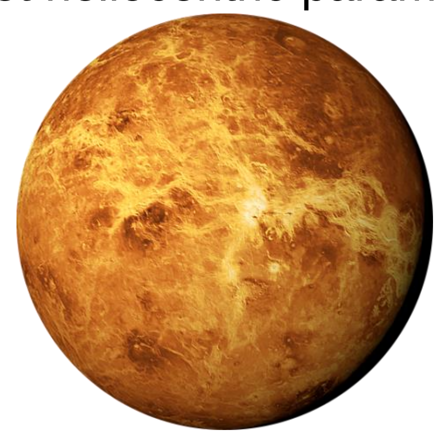
Method of the heliocentric movement calculation

$$x(t_0) = \begin{pmatrix} r_E \\ \varphi_E \\ V_{rE} \\ V_{\phi E} \\ i_E \\ \Omega_T \end{pmatrix}$$

$$x(t_k) = \begin{pmatrix} r_{Pl} \\ \varphi_{Pl} \\ V_{rPl} \\ V_{\phi Pl} \\ i_{Pl} \\ \Omega_{Pl} \end{pmatrix}$$

Initial moment of the system
(Earth heliocentric parameters)

Final moment of the system
(Planet heliocentric parameters)



Step of numerical solution (1)

Eccentricity , parameter and true anomaly calculation

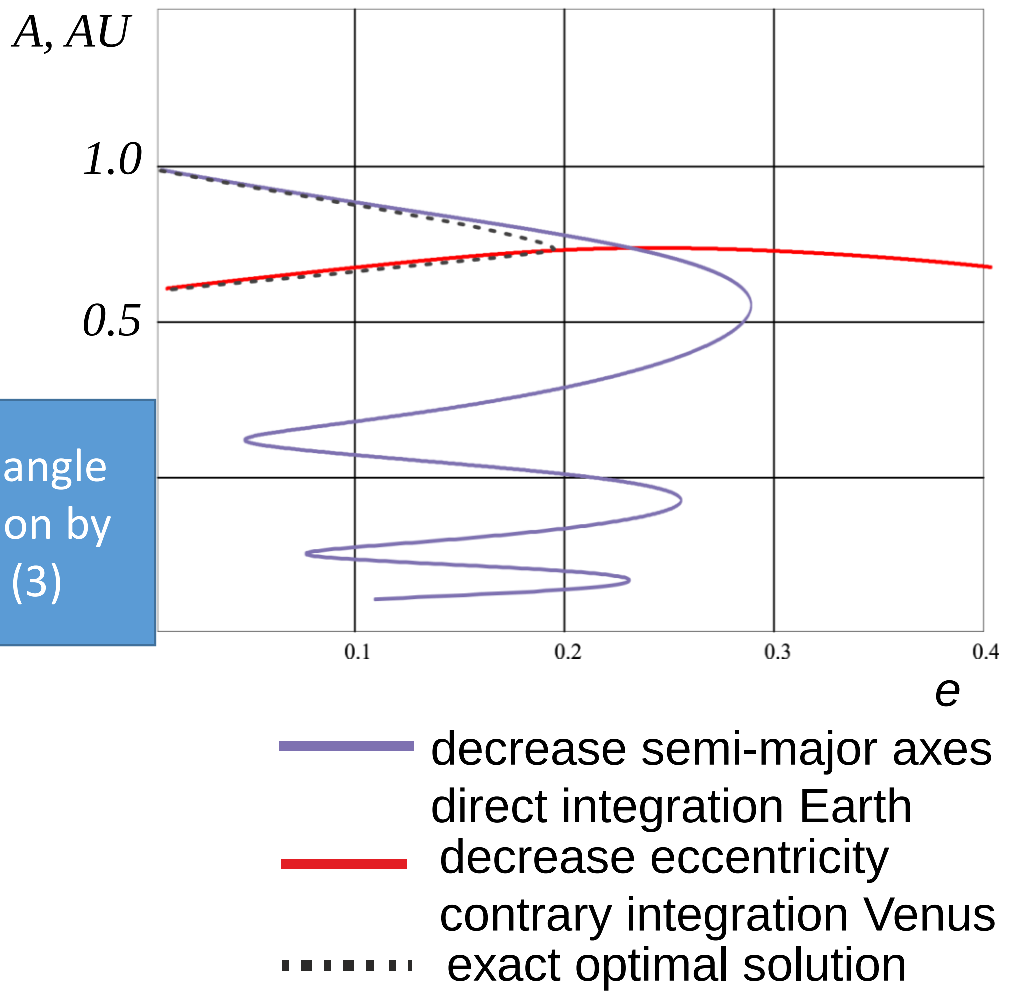
Control angle calculation by (2) or (3)

$$\sin\vartheta = \frac{rV_\varphi V_r}{\sqrt{\left(rV_r^{\ 2}-1\right)^2+\left(rV_\varphi V_r\right)^2}}$$

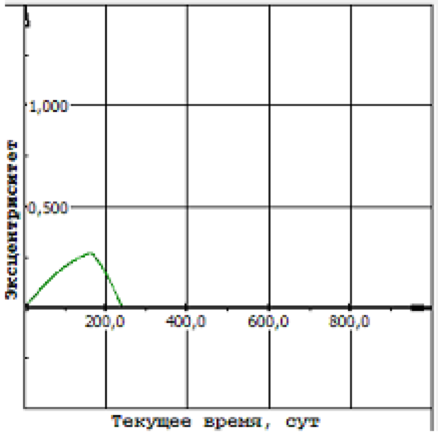
$$\cos\vartheta = \frac{rV_r^{\ 2}-1}{\sqrt{\left(rV_r^{\ 2}-1\right)^2+\left(rV_\varphi V_r\right)^2}}$$

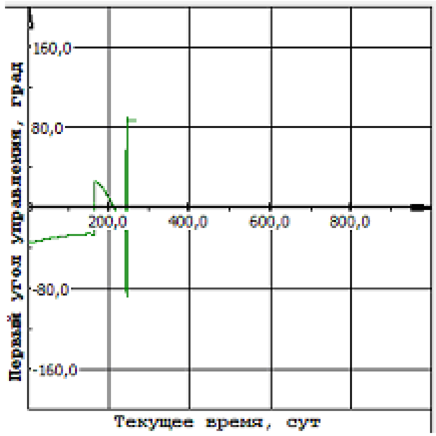
$$e = \sqrt{\left(rV_r^{\ 2}-1\right)^2+\left(rV_\varphi V_r\right)^2}$$

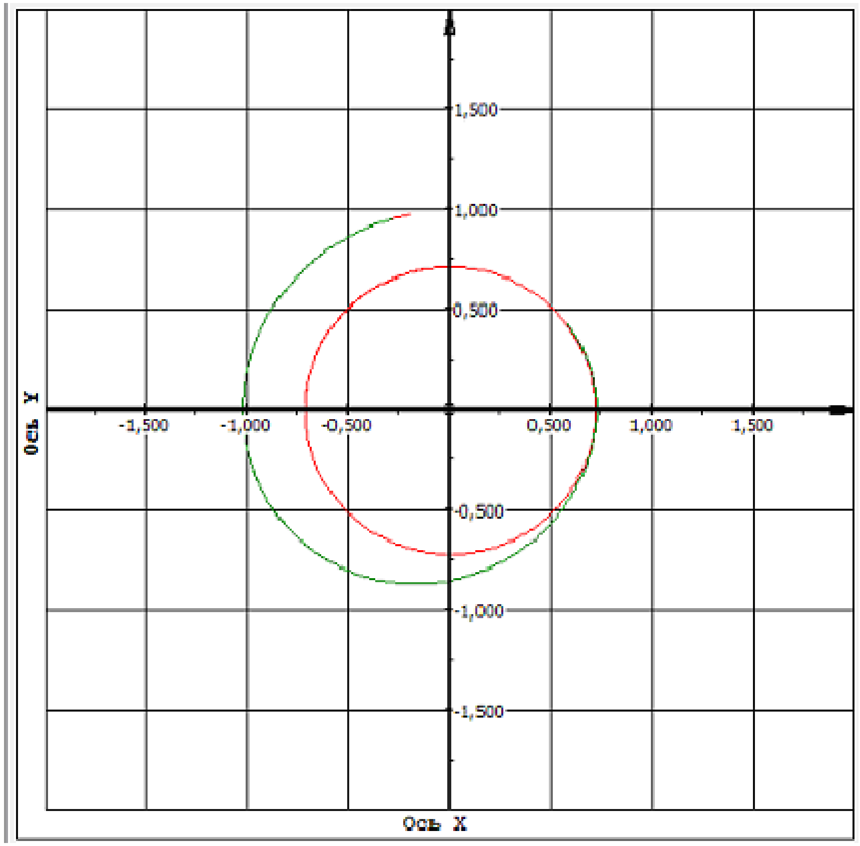
$$p = r\left(1+e\cos\vartheta\right)$$



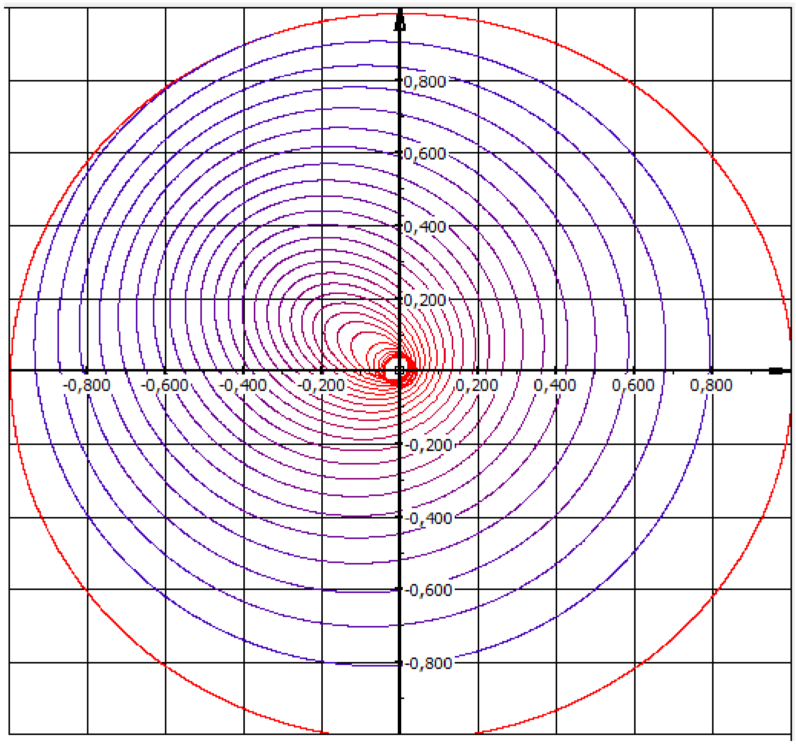
The orbit parameters were selected in two stages:
Stage 1 - the fastest reduction of the semi-axis (165 days).
Stage 2 - the fastest reduction of eccentricity (78 days).
The heliocentric movement of SSSP to Venus lasts 243.0 days.
Including maneuver set parabolic speed, the full flight time is 593 days.





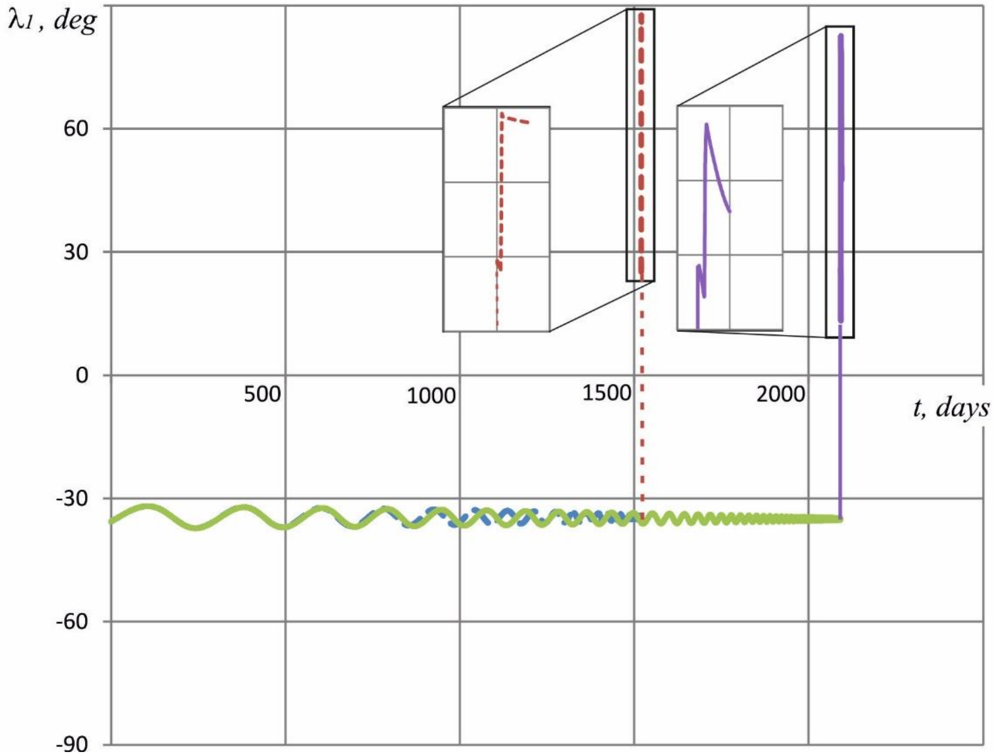


Results for flight to near sun vicinity

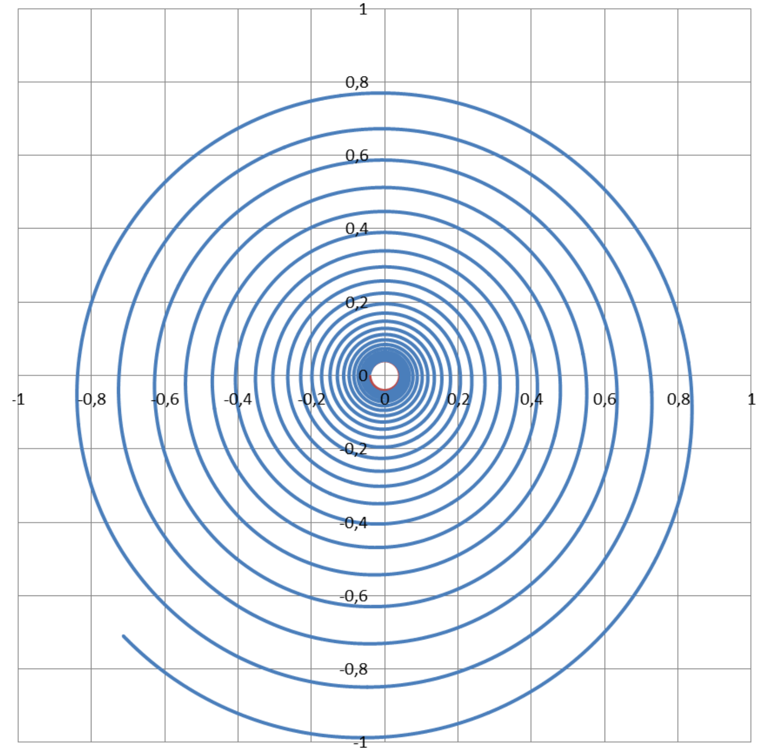


Start mass of spacecraft, kg	100
Area of sail, m^2	2000
Mirror reflection coefficient of the front surface of the sail (Be)	0,98
Secondary emission coefficient of the front surface of the sail (Be)	0,01
Secondary emission coefficient of the rear surface of the sail (Cr)	0,75
Date of withdrawal from the Earth	10.01.2022
Duration of the phase of reduction of the radius of the pericenter, days	2102,7
The duration of the plot reduce the eccentricity of the orbit, days	37,5
Date of formation of the working orbit	14.10.2027
The maximum steady-state temperature of the sail surface Be/Cr*, K	1139

Simulation results for flight to near sun vicinity without the temperature restriction

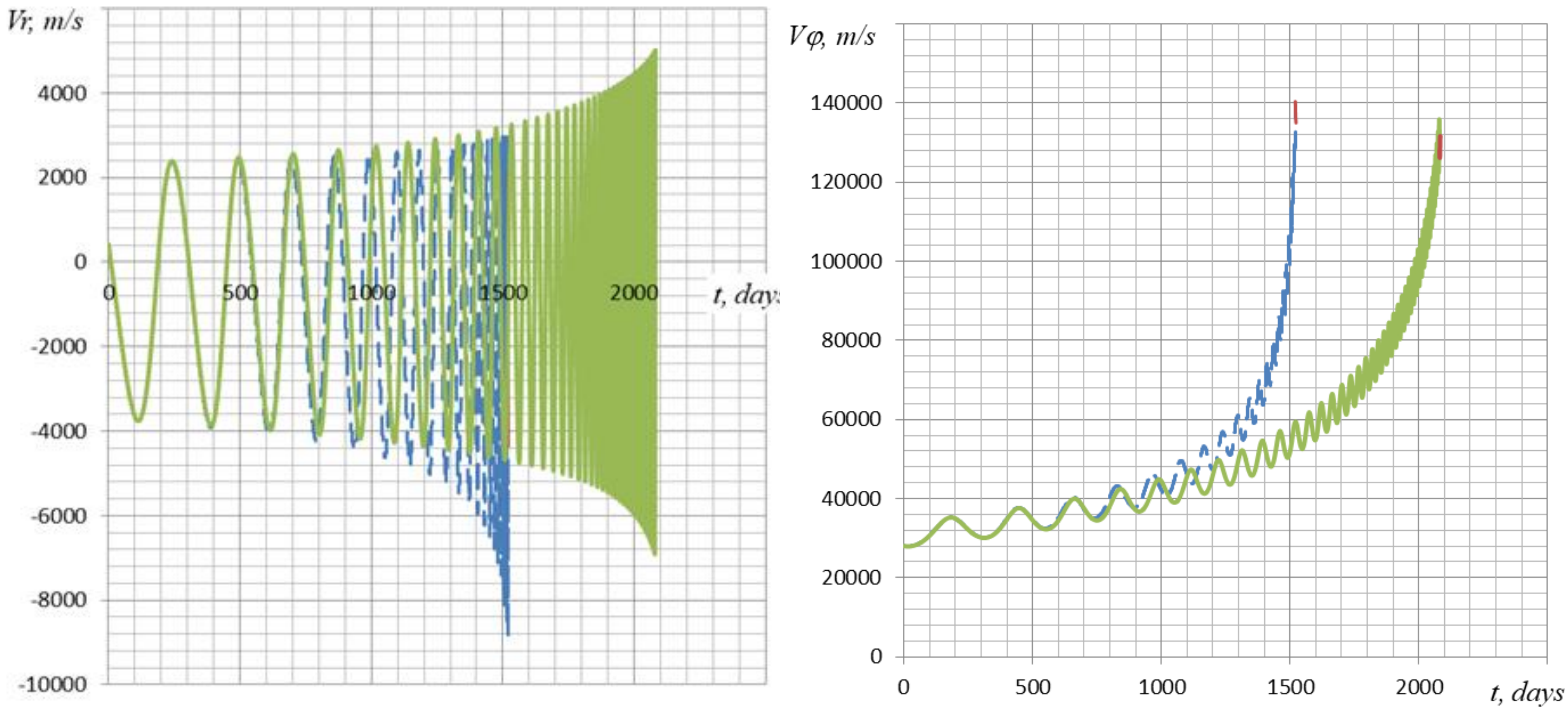


a)



b)

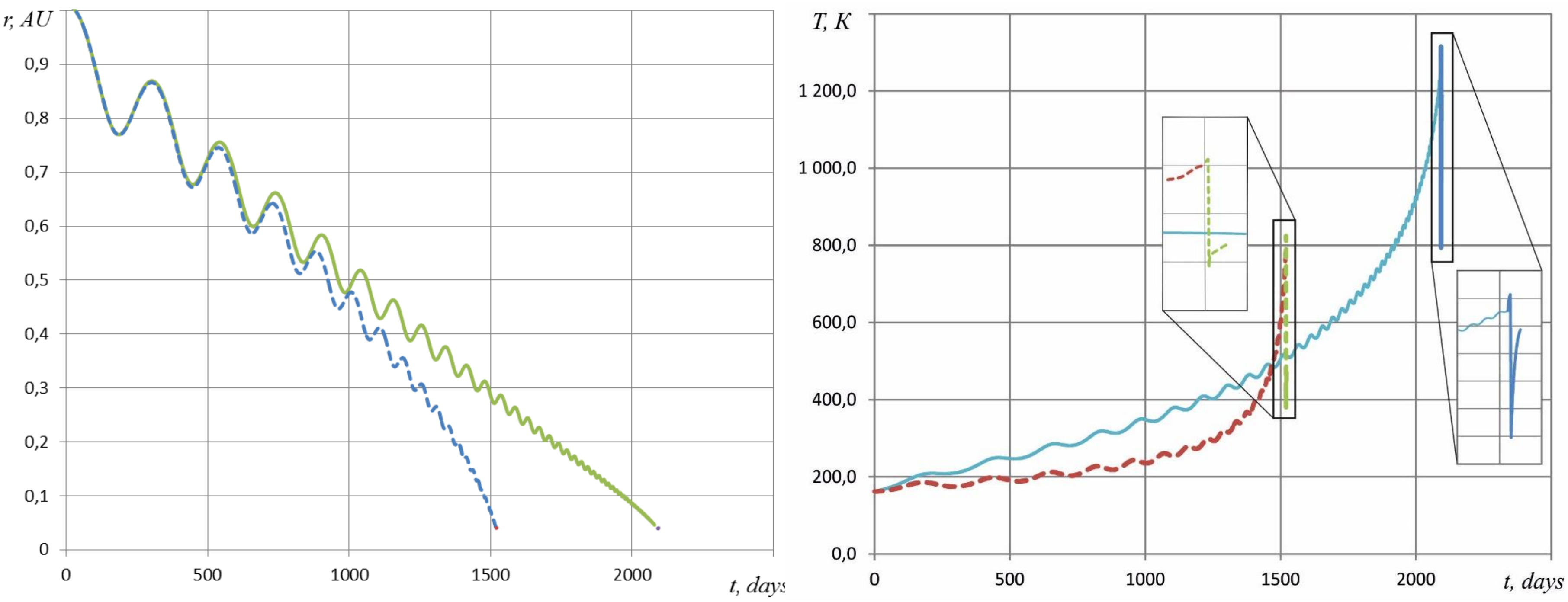
The local-optimal control law (a) and the corresponding flight trajectory (b) without the temperature restriction



a) b)

The dependence of the radial (a) and transversal components (b) of heliocentric velocity on flight duration without the temperature restriction

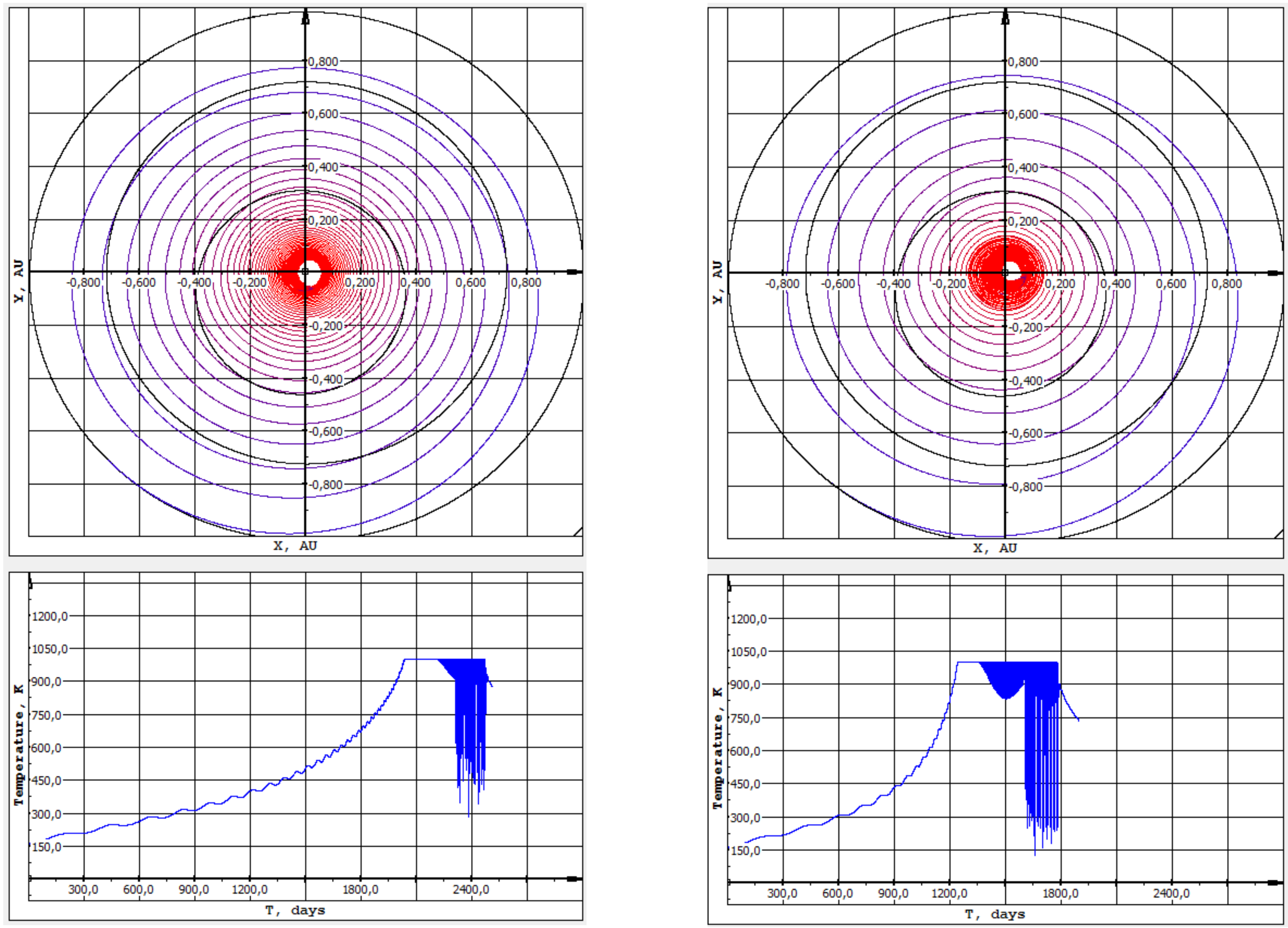
Simulation results for flight to near sun vicinity without the temperature restriction



a) b)

The dependence of the heliocentric radius-vector (a) and the equilibrium temperature (b) on flight duration without the temperature restriction

ул. Московское шоссе, д.34, г.Самара, 443086, тел.: +7 (846) 335-18-26, факс: +7 (846) 335-18-36, сайт: www.ssau.ru, e-mail: ssau@ssau.ru



a) b)

The flight trajectories to SSSC with σ=20 kg/m^2 (a) and σ=30 kg/m^2 (b) obtained with the help of our software

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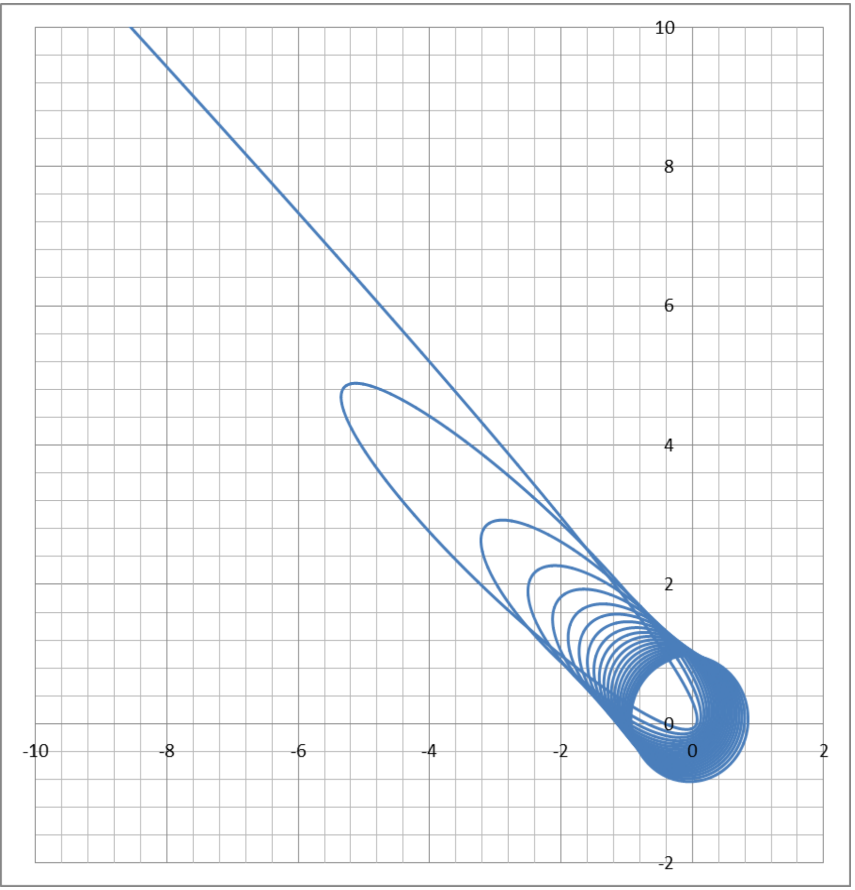
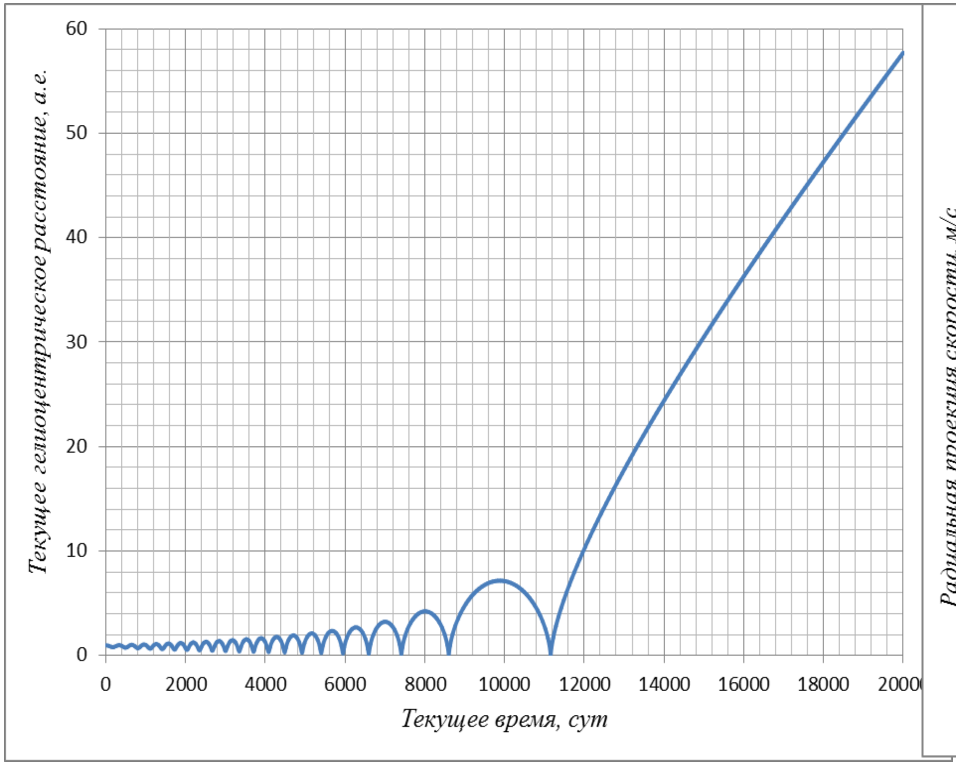
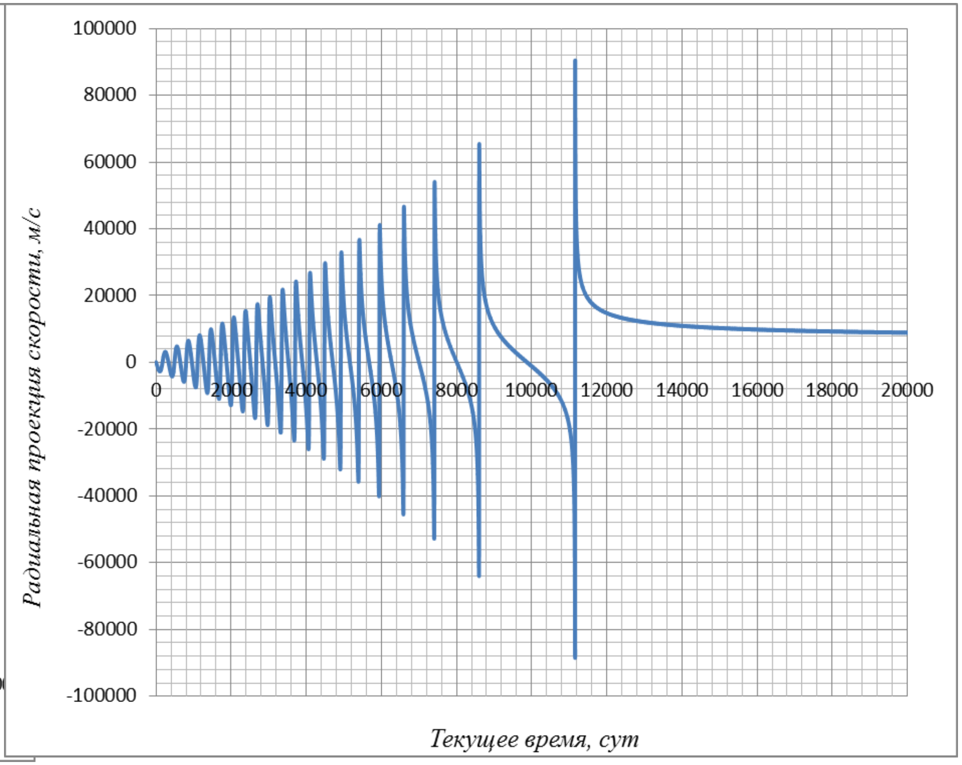


Start mass, kg	100
Area of sail, m2	2500
Reflection coefficient of front sail's surface (Be)	0,98
Emission coefficient of front sail's surface (Be)	0,01
Emission coefficient of back sail's surface (Cr)	0,75
Date of withdrawal from the Earth	10.01.2022
The duration of plot of increasing the eccentricity of the orbit, days	15000
Date of leaving the Sun	12.10.2076
he minimum heliocentric distance, A.U.	0,056
The maximum equilibrium temperature of the sail's surface Be/Cr*, K	480,26

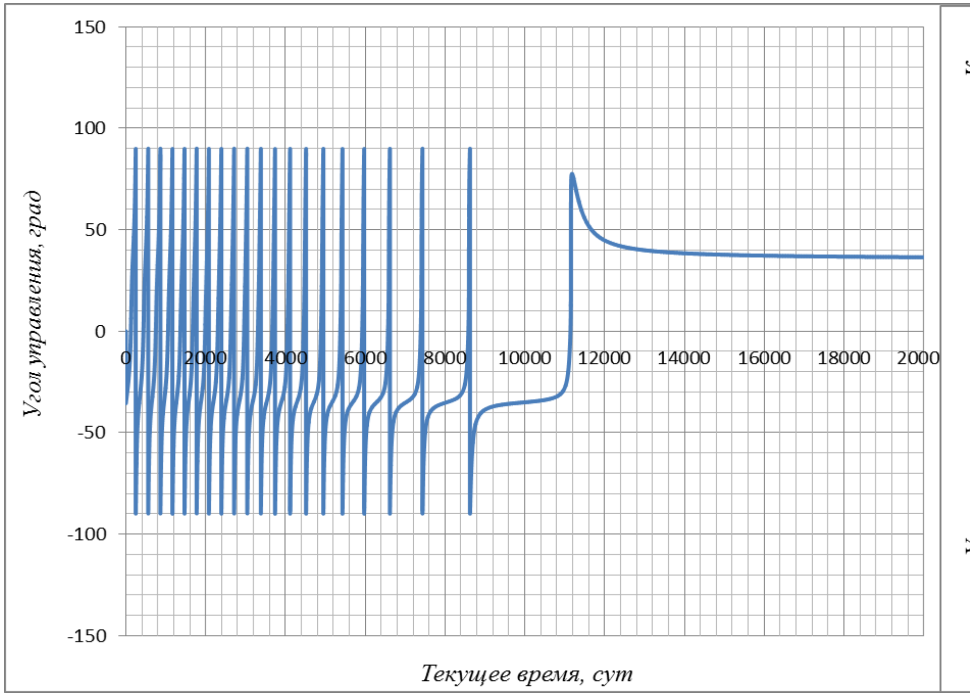


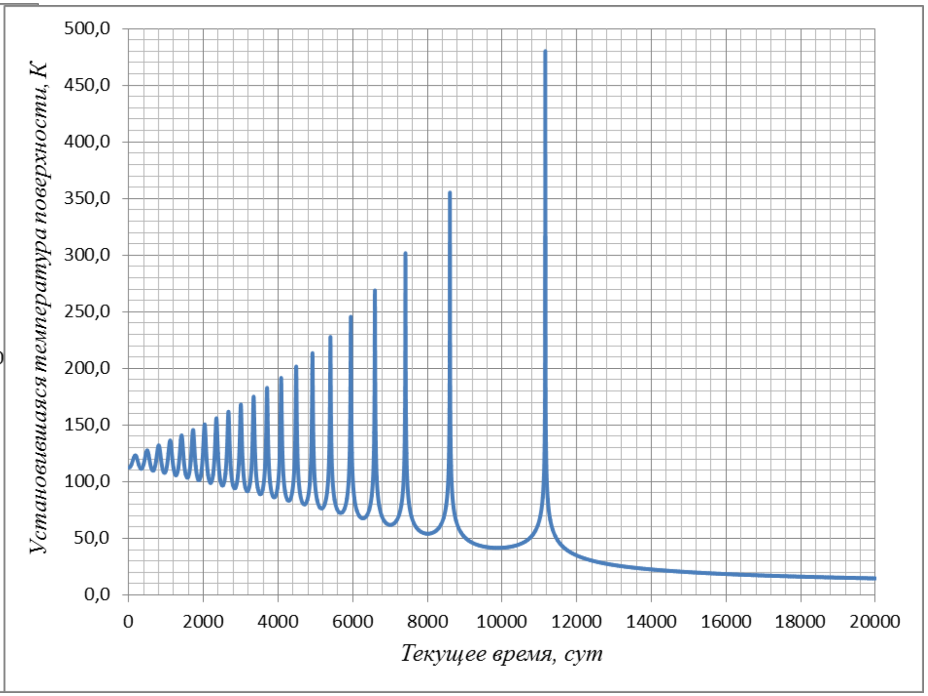
Heliocentric radius-vector of SSSP



Radial projection of the SSSP velocity

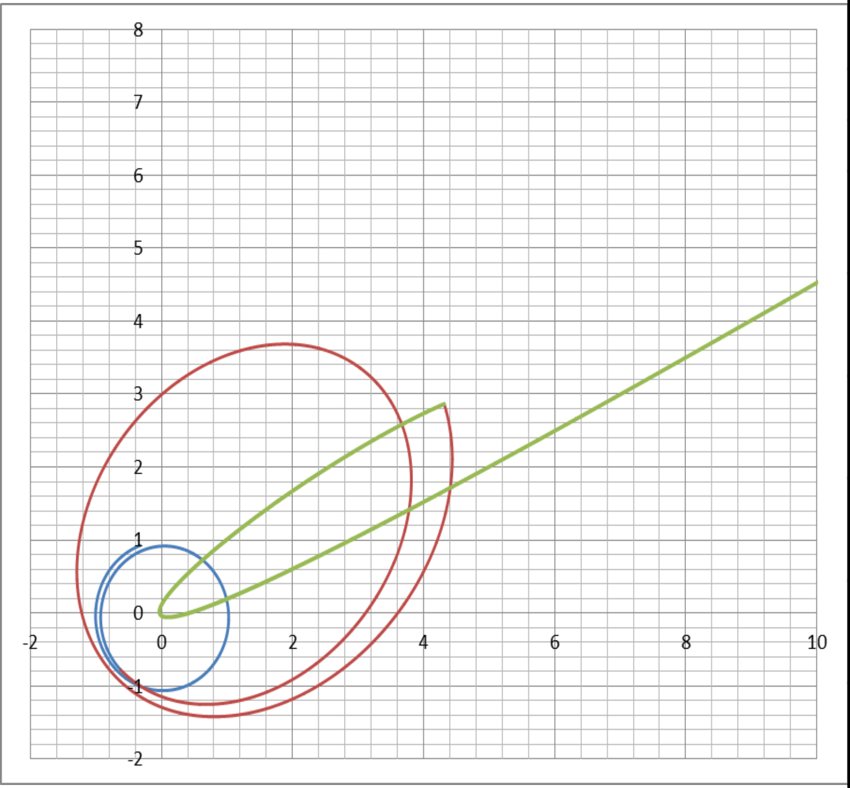
Results for flight to inter stars space



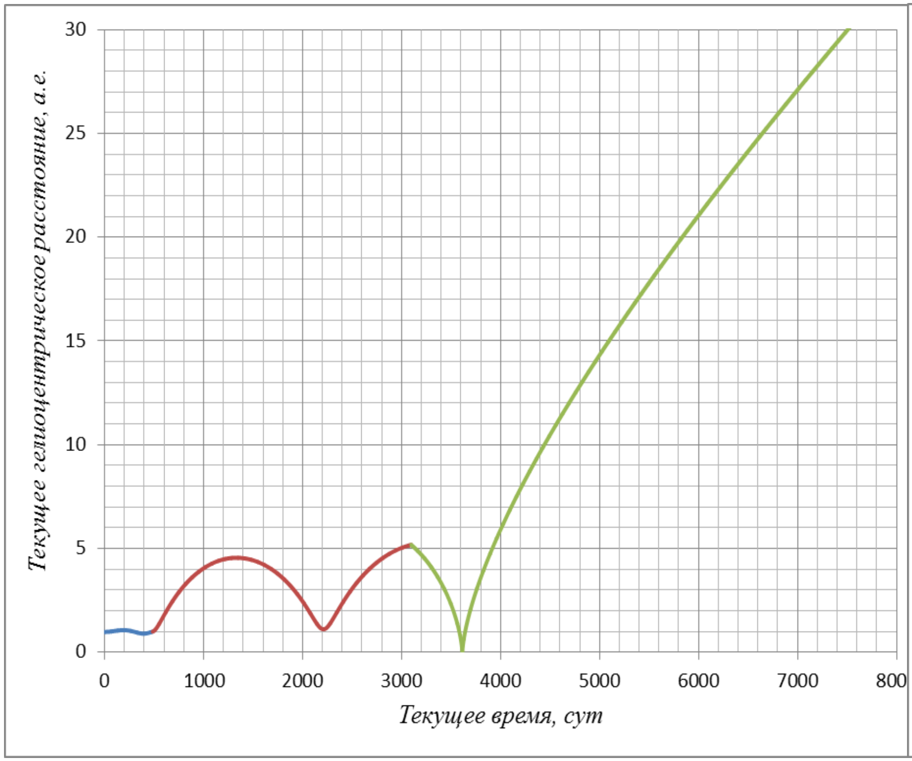


Installation angle of SSSC

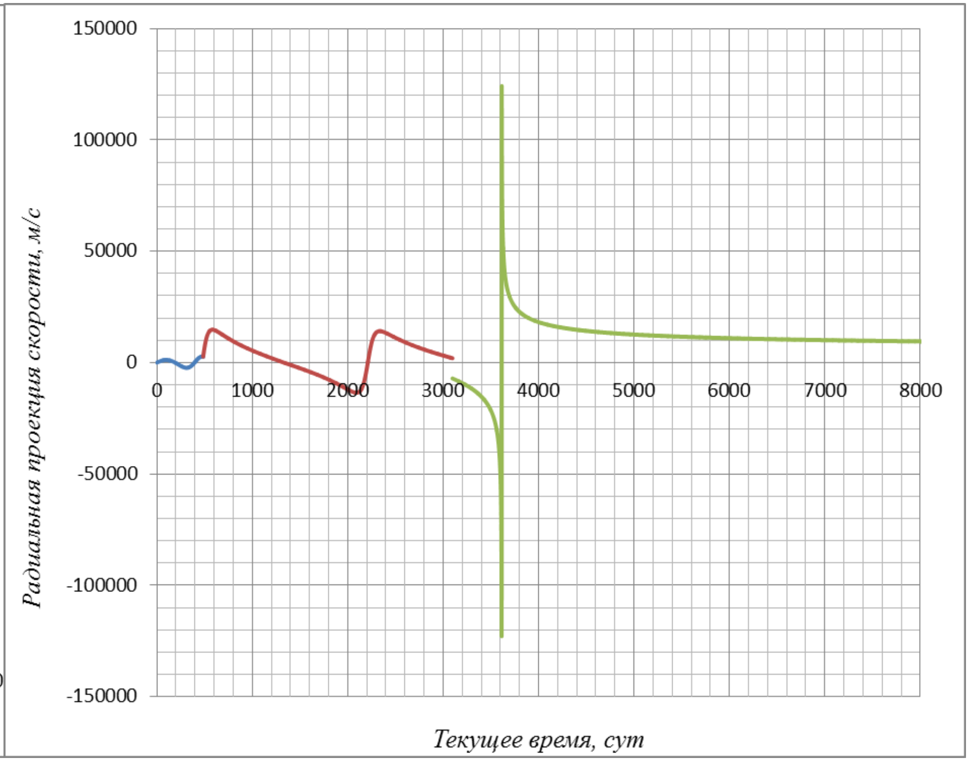
Equilibrium temperature of SSSC surface



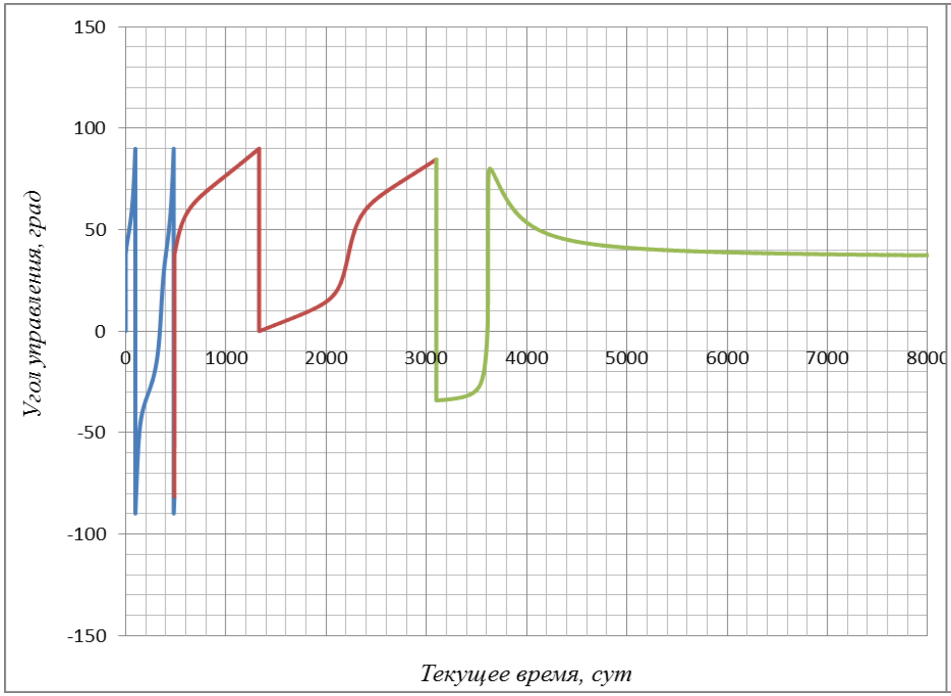
Start mass, kg	100
Area of surface, m^2	2500
Reflection coefficient of sail's front surface (Be)	0,98
Emission coefficient of sail's front surface (Be)	0,01
Emission coefficient of sail's back surface (Cr)	0,75
Date of the exit in the Earth action sphere	10.01. 2022
The length of the phase of increasing the orbit eccentricity, days	485,6
Date of the gravity assist in the Earth action sphere	10.05. 2023
The duration of the phase of increase of the radius of apoapsis, days	2611
Date of the gravity assist in the Jupiter action sphere	3.07. 2030
Date of leaving the Sun's action sphere	12.03.204 4
The minimum heliocentric distance, A.U.	0,056
The maximum equilibrium temperature of the sail's surface Be/Cr*, K	480,26

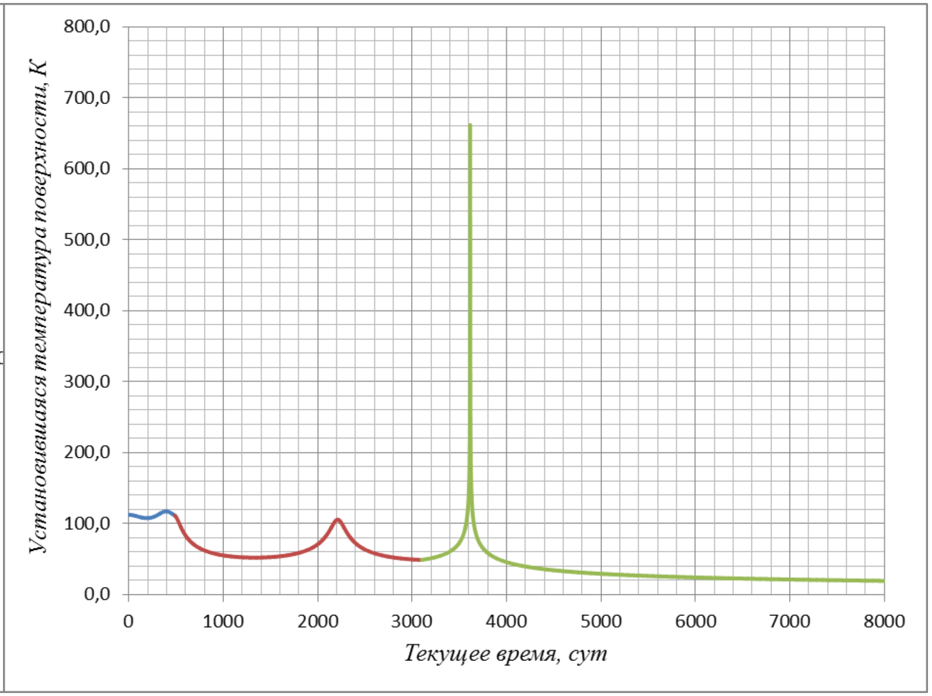


Heliocentric radius-vector of SSSP



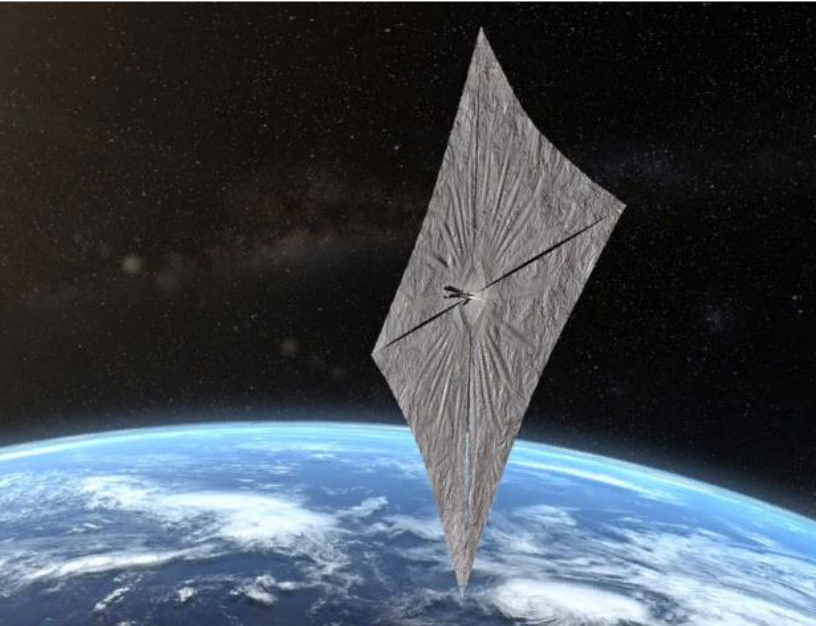
Radial projection of the SSSP velocity





Installation angle of SSSC

Equilibrium temperature of SSSC surface

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SAMARA UNIVERSITY

THANK YOU FOR YOUR ATTENTION

ул. Московское шоссе, д. 34, г. Самара, 443086
Тел.: +7 (846) 335-18-26 , факс: +7 (846) 335-18-36
Сайт: www.ssau.ru, e-mail: ssau@ssau.ru