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Material Selection and Design of Orbital Maneuver of Solar Sail Orbit to Explore the Outer Solar System

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Abstract. Motivation of this research is the success of several spacecraft missions that use Solar Sail propulsion such as IKAROS, Lightsail, etc, and the development of technology to create lightweight, thin, but very strong materials such as aerogel, graphite, carbon foam, and others. Each material has several parameters, such as strength, absorption coefficient, transmissivity, and reflectivity when interacting with photons. This parameter produces dynamics that are quite complicated so that we need to be simulated to maximize the momentum of the Solar Sail. Software that supported simulation is Jupyter Notebook and Matlab. This research also uses several numerical methods such as Runge-Kutta-Verner, Monte Carlo, and Bisection. The results are that graphite+molybdenum material can be used for the Outer Solar System to target Solar Sail with a minimum distance of 0.015 au from the Sun. At near 1 au from the Sun, we can assume the sun as a point source, but if Solar Sail is very close to the Sun (r >> 1 au), we have to use the Sun as an extended+limb darkening source model. The 0.01 kg/m^2 Solar Sail has a speed between 65 to 134 km/s depending on the maneuver model. At that speed, Solar Sail can reach the Kuiper Belt object (30 – 100 au) in 3.4 to 4.4 years. The 0.001 kg/m^2 Solar Sail has a speed between 32 to 414 km/s depending on the maneuver model and can reach SGL (Solar Gravitational Lens) in 7 years.

Keywords: *Solar Sail, IKAROS, Runge-Kutta-Verner, Monte Carlo, Bisection, extended source, limb darkening, graphite, molybdenum, SGL.*

1 Introduction

Solar Sail is a propulsion method of the spacecraft using photons emitted by the Sun (see Figure 1). Photons are particles as same as electromagnetic waves that carry discrete energy and momentum. The first successful Solar Sail method was IKAROS, a spacecraft made by JAXA (Japan Aerospace Exploration Agency), which was launched in 2010 and successfully performed flyby near the planet Venus (Macdonald in [1]). The IKAROS Sail size is 14 × 14 m with a total weight of 315 kg. NASA (National Aeronautics and Space Administration) in 2015, success to launched LightSail 1 and LightSail 2 in 2019 to simulate Solar Sail on the CubeSat satellite (Tang *et.al* in [2]). The LightSail size is just 5.8 m × 5.8 m and the total weight of only 5 kg.

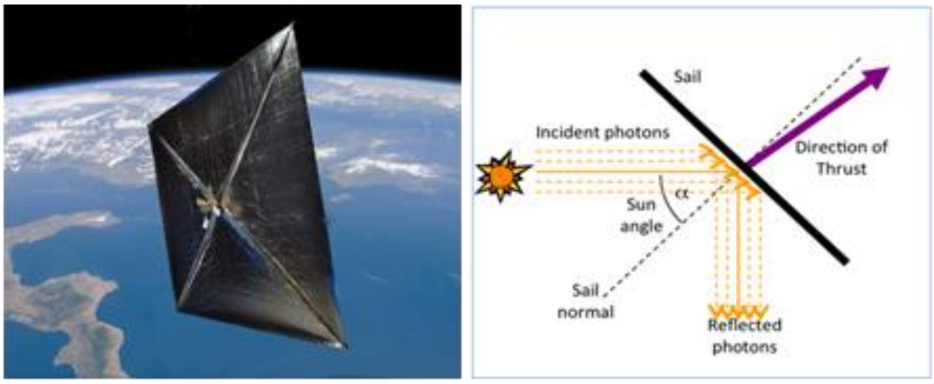

Figure 1 Simple model of the Solar Sail working principle.

The Solar Sail gains additional momentum from the photons depending on the Solar Sail's distance from the Sun, reflectivity, emissivity, and the ratio of mass per area of the sail. These factors have a relationship with one another. The main point of these factors refers to the choice of sail material. The sail must have great strength, high reflectivity and emissivity, and then very light. It takes a special material that can be made as thin as possible but very strong. Along with the development of technology, the Solar Sail can be made lighter with materials that are stronger than Kapton, such as chromium, magnesium, and beryllium (Wright in [3]). Graphite and carbon foam are extremely light and are some of the lightest materials ever made. This material is very suitable for use in Solar Sail (Heller *et.al* in [4]).

Several journals have simulated the dynamics of the Solar Sail with the assumption of the Sun as a point source. This assumption is quite good at a considerable distance from the Sun, but if the object is very close to the Sun, it is necessary to include the influence of the angular diameter and limb darkening of the Sun. This research will demonstrate this effect. This research sends the Solar Sail with Outer Solar System target and close enough from the Sun to get enough energy. This research utilizes Newton's Laws of Motion and Gravity with the integration method Runge-Kutta-Verner. The discrete radiation flux equation is modeled using the Monte Carlo method in calculating the effect of the angular diameter and limb darkening of the Sun. The main objective is to optimize the orbital maneuvering of the Solar Sail to obtain an optimal change in momentum. This change in momentum will be utilized by Solar Sail later in selecting its orbital model and exploring the outer Solar System objects in the shortest possible time.

2 Method

2.1 Solar Sail Force by Sun Photon

The Solar Sail receives the force from the Sun's radiation according to the following Equation 1,2,3,4,5, and 6:

$$\boldsymbol{F_{tot}} = \boldsymbol{\alpha F_a} + \tau \boldsymbol{F_\tau} + \boldsymbol{RF_R} \tag{1}$$

$$\boldsymbol{F_a} = \frac{\boldsymbol{W\cos\theta dS}}{\boldsymbol{c}}\left(\boldsymbol{n_s} + \frac{\varepsilon_b(T)B_b - \varepsilon_f(T)B_f}{\varepsilon_b(T)+\varepsilon_f(T)}\boldsymbol{n}\right) \tag{2}$$

$$\boldsymbol{RF_R} = \boldsymbol{R_s F_s} + \boldsymbol{R_d F_d} \tag{3}$$

$$\boldsymbol{F_s} = -\frac{2W}{c}\boldsymbol{\cos^2\theta dSn} \tag{4}$$

$$\boldsymbol{F_d} = \frac{\boldsymbol{W\cos\theta}}{\boldsymbol{c}}\left(\boldsymbol{n_s} - \boldsymbol{B_f n}\right)\boldsymbol{dS} \tag{5}$$

$$\boldsymbol{F_\tau} = \boldsymbol{0} \tag{6}$$

The first factor that affects the momentum of the Solar Sail is the distance r from the Sun. The distance r affects flux W received by the sail with the following Equation 7:

$$\boldsymbol{W} = \frac{L_\odot}{4\pi r^2} \tag{7}$$

The effects of radiation on spacecraft that are very close to the Sun are the influence of limb darkening, angular diameter, and Sun corona. Several journals that research the dynamics of the motion of the Solar Sail assumes that the Sun is a point source. That assumption is sufficient best applied to the Solar Sail at a certain distance from the Sun. The Solar Sail close enough to the Sun must take into account the effects of limb darkening and the angular diameter of the Sun when it receives solar radiation due to the force received Solar Sail will be very different compared to the point source model.

The flux from the point source can be divided into N sources which are discretized on a Solar plane with a certain angular diameter described by the following Equation III.3:

$$W_{ext} = \sum_{i=1}^{N} dW_i \cos(\omega_i) = \sum_{i=1}^{N} \frac{W_{point}}{N} \cos(\omega_i) \tag{8}$$

The effect of limb darkening can be entered in Equation 8 by setting the distribution of points on the angular plane of the Sun using Equation 9 with the help of the Monte Carlo method. This assumption shows that the intensity of the Sun's surface is not uniform with the edges the Sun's disk has an intensity (number of points) less than the center dish.

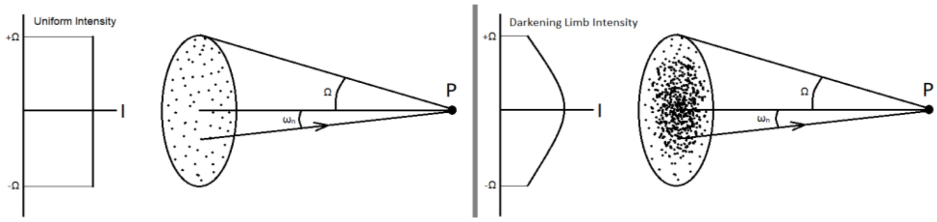

Figure 2 Comparison of the extended source model with uniform and limb darkening intensity.

Figure 2 shows the differences in the extended source model on the disk of the Sun with an angular diameter of 2Ω. The intensity distribution model used is uniform and limb darkening intensity. The Sun's intensity (N distribution) can be modeled in the following Equation 9 (Tripathi *et.al* in [5]):

$$\frac{I(\psi)}{I(0)} = 0{,}39 - 0{,}61\sqrt{1 - \left(\frac{\sin\zeta}{\sin\Omega}\right)^2} \tag{9}$$

I(ψ) is the visible luminous intensity at point P (see Figure 3) along the line of sight whose ψ angle is the Sun's radius and I(0) is the luminous intensity at the center of the Sun's disk. The ψ angle depends on ζ (angle of a point on the observed Sun's disk P) and Ω (radius of the Sun's angle).

Another parameter that must be taken into account is the solar corona zone. The activity of the Sun's magnetic field largely forms the structure of the corona. The closed magnetic field of the Sun which forms the majority of the corona is at a distance of 1.5 – 2.5 $R_\odot$ (Kopp *et.al* in [6]). Beyond that distance, the Sun's magnetic field has an open structure and the Sun's corona has turned into a Solar Wind. The corona magnetic field model must have a radius of 2.1 – 3.1 $R_\odot$ so that the polarity of the Sun's magnetic field matches that observed on Earth.

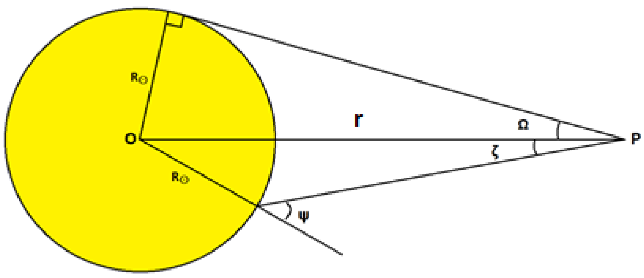

Figure 3 The geometry of the Sun limb darkening was observed at point P.

2.2 Sail Material Selection

This paper uses the Square Solar Sail model with 2 layers Sail, emission and reflection layers. The main layer (back layer, symbol b) is made of graphite nanosheet (graphite density 2.26 g/cm3) with a thickness of 100 nm (Chen *et.al* in [7]) with the following optical parameters (Wie in [8], Reyes in [9], Heaton in [10], and Starinova *et.al* in [11]):

$\varepsilon_b = \varepsilon_{gr} = 0.8$; $R_b = R_{gr} = R_{metal}$; $Rs_b = Rs_{gr} = 0.5$

$B_b = B_{gr} = 0.55$; $Rd_b = Rd_{gr} = 0.5$

As for the reflection layer (front layer, symbol f), there are several metal options as shown in Table 2 with a layer thickness of 50 nm (Kezerashvili in [12]) with the following optical parameters (Wie in [8], Reyes in [9], Heaton in [10], and Starinova *et.al* in [11]):

$\varepsilon_f = \varepsilon_{metal}$; $R_f = R_{metal}$; $Rs_f = Rs_{metal} = 0.9$

$B_f = B_{metal} = 0.79$; $Rd_f = Rd_{metal} = 0.1$

The value of ε_{metal} can be seen in Table 1, while the value of R_{metal} is obtained using Equation 10 and 11 which is the reflectivity of the metal to solar photon radiation for all wavelengths:

$$R(\lambda) = \frac{(n(\lambda)-1)^2+k(\lambda)^2}{(n(\lambda)+1)^2+k(\lambda)^2} \tag{10}$$

$$R = \frac{\sum_{i=1}^{n} f(\lambda)R(\lambda)}{\sum_{i=1}^{n} f(\lambda)} \tag{11}$$

where f(λ) is the fraction of the solar photon distribution at a given wavelength. The value of this fraction will be calculated using the Monte Carlo method on the Solar Radiation Spectrum. Parameter n (refraction index) and k (extinction coefficient) can be searched by Palik in [13].

Table 1 Parameters of emissivity, density, and melting point of some metals.

Metal	Emissivity	Density (g/cm^3)	Melting Point (K)
Aluminum	0.05	2.70	934
Beryllium	0.18	1.85	1560
Chromium	0.06	7.15	2180
Copper	0.03	8.96	1358
Gold	0.03	19.30	1337
Silver	0.03	10.49	1235
Molybdenum	0.11	10.22	2896
Nickel	0.12	8.90	1728
Platinum	0.1	21.45	2042
Tungsten	0.15	19.28	3695

A 1 m^2 Sail with graphite+metal material will be tested at a distance according to Equation 12 from the Sun. The metal layer is assumed to have a constant reflection coefficient up to temperature T = T_{mel} – 100 K. The closest distance of the Solar Sail from the Sun can be calculated by the following Equation 12:

$$r_{min} = \frac{1}{(T_{mel}-100)^2}\sqrt{\frac{\alpha L_{\odot}}{4\pi\sigma(\varepsilon_b+\varepsilon_f)}} \tag{12}$$

The closest distance used in this research is 3$R_{\odot}$ (~0.015 AU) from the Sun (protect from closed magnetic field activity and the Sun's corona). The force of the Solar Sail due to solar radiation can be calculated using Equation 1. Result

2.3 Graphite+Molybdenum Combination Sail

The fraction of the Planck distribution of solar energy spectrum in a certain wavelength region using the Monte Carlo method gives the following results:

f(0,2) = 1% ; f(0,3) = 6% ; f(0,4) = 11% ; f(0,5) = 13% ; f(0,6) = 12% ;

f(0,7) = 19% ; f(1) = 26% ; f(2) = 10% ; f(4) = 2%

By using Equations 1, 10, 11, and 12, We produce Table 2. Table 2 shows that sail with a graphite+molybdenum alloy can produce the highest acceleration, which is imported by Solar Sail to get to the outer Solar System such as the Kuiper belt and Oort clouds. Therefore, this research uses graphite+molybdenum as a sail material for Solar Sail.

The previous calculation assumes that the emission coefficient has a constant value. The emission depends on the temperature of the system. The graphite+molybdenum material has been selected as the sail material. Research on the graphite emission coefficient has been carried out by Biasetto *et.al* in [14] with the following Equation 13, and the graphite emission coefficient has been carried out by Mukati *et.al* in [15], 2006 with the following Equation 14:

$$\varepsilon_{mo}(T) = 0{,}1016 + 0{,}000134\, T \quad (13)$$

$$\varepsilon_{grap}(T) = 0{,}7968 + 0{,}000025\, T \quad (14)$$

$$T_{eq} = \sqrt[4]{\frac{\boldsymbol{\alpha W \cos\theta}}{\sigma\left(\boldsymbol{\varepsilon_b(T)}+\boldsymbol{\varepsilon_f(T)}\right)}} \quad (15)$$

$$0{,}000159 T_{eq}^5 + 0{,}8984 T_{eq}^4 = \frac{\alpha W \cos\theta}{\sigma} \quad (16)$$

with T in Kelvin. Equations 13 and 14 are inserted into Equation 15 and produce the following Equation (non-linear equation). T_{eq} can be solved by the Bisection method to determine the root solution of Equation 16.

Table 2 Parameters of Reflectivity, r_{min}, Mass, Acceleration, and T_{max} of the Graphite+Metal Sail.

Graphite+ Metal	**R**	**r_{min} (au)**	**Mass (kg) A = 1000 m^2**	**r_{test} (au)**	**Acceleration (m/s^2)**	**T_{max} (K)**
Aluminum	0.93	0.066	0.36	0.066	5.47	834
Beryllium	0.6	0.048	0.32	0.048	9.66	1459
Chromium	0.66	0.023	0.58	0.023	22.34	2080
Copper	0.61	0.048	0.67	0.048	4.97	1258
Gold	0.91	0.051	1.19	0.051	2.48	1237
Silver	0.8	0.041	0.75	0.041	6.74	1135
Molybdenum	0.64	0.013	0.74	0.015	42.5	2587
Nickel	0.65	0.037	0.67	0.037	7.69	1628
Platinum	0.67	0.027	1.3	0.027	8.41	1942
Tungsten	0.57	0.008	1.19	0.015	25.44	2674

2.4 θ and ϕ Relation

The next research is to determine the relation of 3 main variables, namely θ, ϕ, and r for outward trajectory maneuvers on Solar Sail by producing dv_{mak}. Figure

4 shows the relationship between the parameters and to produce a dv_{mak} at 0.015 $\leq r \leq 1$ au. The graph shows that, at 130^0, the data forms a curve for all values of r.

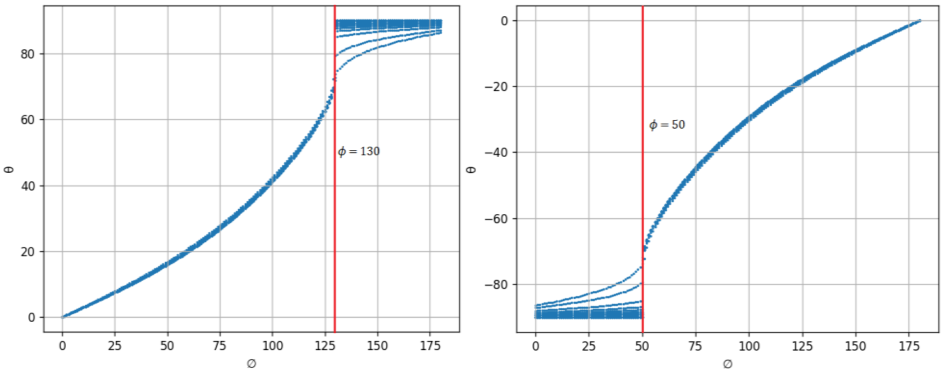

Figure 4 The relationship between θ and ϕ for dv_{mak} on outward (left) and for -dv_{mak} on inward trajectory (right) at $0.015 \leq r \leq 1$ au.

The next research is to determine the relationship of 3 main variables (θ, ϕ, and r) for the inward trajectory maneuver on the Solar Sail to produce -dv_{mak}. Figure 3 shows that the inward trajectory curve resembles the outward trajectory curve with a relationship in Equation 17 and 18 as follows:

$$\phi_{in} = 180 - \phi_{out} \tag{17}$$

$$\theta_{in} = -\theta_{out} \tag{18}$$

2.5 Simulation

2.5.1 0.01 kg/m2 Solar Sail Orbital Maneuver

Solar Sail with $\rho = 0.01$ kg/m^2 (graphite+molybdenum) and an area of 1000 m^2 has a Sail weight of around 0.74 kg as shown in Table 2. The total weight of the Solar Sail (Sail + payload) allowed is 10 kg. Then the total weight of the payload that can be transported is 9.26 kg (NanoSat weight range). Solar Sail with an area of 10000 m^2 can carry a payload with a total weight of 92.6 kg (MicroSat weight range).

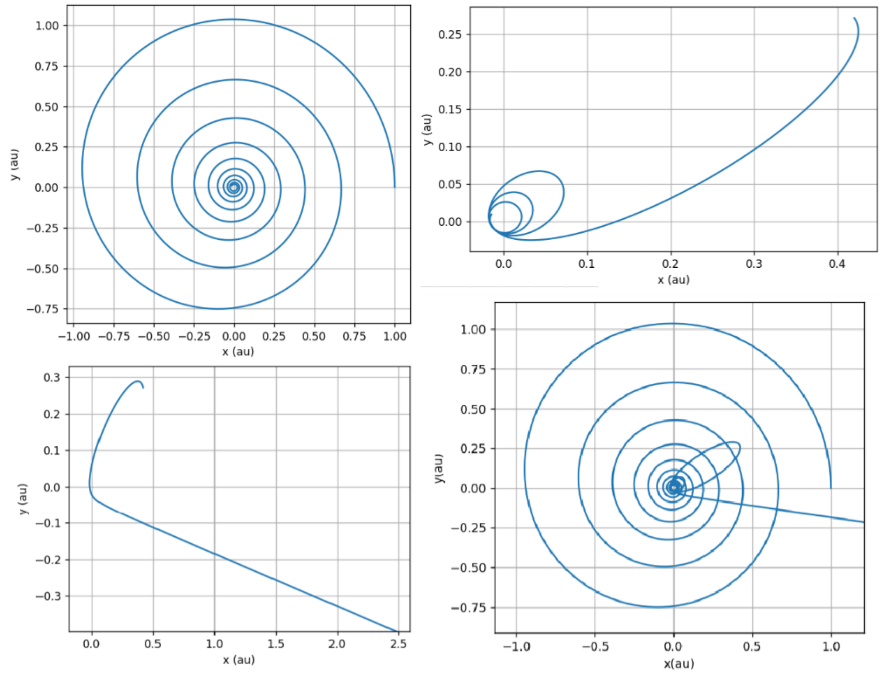

Figure 5 (top left) ITM, (top right) SOTM, (bottom left) ETM, and (bottom right) all combined maneuvers for ra_f = 0.5 au.

2.5.1.1 Inward Trajectory Maneuver (ITM)

Solar Sail is assumed to be 1 au from the Sun in a circular orbit. Based on these assumptions, the initial input for the simulation is as follows:

x, y, z, vx, vy, vz = 1, 0, 0, 0, 2π, 0

Solar Sail performs ITM (using the relation between θ and ϕ) until Solar Sail produces an inward spiral orbit and produces a final perihelion rp_f ~0.0144 au. The value of 0.0144 au was obtained from the simulation and the reasons will be explained in the next step. Figure 5 shows ITM on Solar Sail. This maneuver causes the Solar Sail to approach the Sun slowly (about 1,852 years) until it reaches an orbital rp_f of ~0.0144 au. It is also seen that ITM can reduce the major axis of the Solar Sail's orbit by half continuously and so the orbital energy continues to decrease.

2.5.1.2 Semi-Outward Trajectory Maneuver (SOTM)

SOTM starts when ITM has reached orbit with an rp_f of ~0.0144 au. At that time, the Solar Sail was more than 0.015 au from the Sun, so it was still above the lower limit of the Sun's corona. When Solar Sail performs SOTM, the perihelion point is lifted from 0.0144 au to 0.015 au. If in ITM, Solar Sail produces an orbit with an rp_f of 0.015 au, then in SOTM, the perihelion point will be raised by more than 0.015 au so that the photon energy received is less than optimal. SOTM is a combination of two maneuvers, namely the outward trajectory and the 90^0 maneuvers. The 90^0 maneuver refers to the Solar Sail angle of 90^0 where at that angle, the Solar Sail barely receives the force from the Sun's photons. It aims to maintain orbit stability by the desired orbital model. This principle is almost the same as the Oberth maneuver, which is the maneuver to change the speed near the perihelion point to make the spacecraft's kinetic energy change as large as possible. SOTM uses two angular limits on the Solar Sail orbit, namely a and b with the following conditions:

Outward Trajectory = $a > \nu \geq b$; 90^0 Maneuvers = $b > \nu \geq a$

This maneuver aims to increase orbital energy by enlarging the end aphelion point of the ra_f without changing the rp_f in the Solar Sail orbit. The simulation in this research uses several ra_f values with the angle rules a and b as shown in Table 3. Angles a and b are obtained by repeating the simulation to get the desired orbit.

Table 3 Parameter data in the 0.01 kg/m^2 Solar Sail Orbital Maneuver Simulation.

X	ν ITM (degree)	ra_f SOTM (au)	a (degree)	b (degree)	c (degree)	Velocity at 100 au (km/s)
0.0144	≥ 0	0.1	282.0	109.24	194.5	65.071
0.0144	≥ 0	0.2	282.6	130.63	298.0	104.526
0.0144	≥ 0	0.3	279.5	100.36	182.6	116.718
0.0144	≥ 0	0.4	279.1	102.81	181.7	122.171
0.0144	≥ 0	0.5	278.8	104.39	181.3	125.466
0.0144	≥ 0	0.6	278.8	105.45	181.0	127.612
0.0144	≥ 0	0.7	278.7	106.16	180.8	129.104
0.0144	≥ 0	0.8	279.0	106.73	180.7	130.208
0.0144	≥ 0	0.9	278.2	107.25	180.6	131.056
0.0144	≥ 0	1.0	278.3	107.63	180.5	131.676
0.0144	≥ 0	1.5	278.7	108.61	180.3	134.032
0.0144	≥ 0	2.0	278.4	109.24	180.1	134.555

2.5.1.3 Escape Trajectory Maneuver (ETM)

ETM starts when SOTM has reached its orbital ra_f (r = ra, = 180^0) which is the initial distance r_i ETM. ETM is the same as SOTM, but the escape trajectory results in an escape orbit from the Sun's gravity at high speed. ETM is also a combination of two maneuvers, namely outward trajectory and maneuver 90^0. The outward trajectory maneuver is used when the Solar Sail approaches the Sun for the last time and slingshots near the Sun until it leaves the Solar System. ETM uses a limit angle on the Solar Sail orbit, which is c with the following conditions:

90^0 maneuvers = c > $\nu \geq 180^0$; Outward Trajectory = $\nu \geq$ c

This maneuver aims to escape the Sun's gravity at high speed. The simulation in this research uses angle c as shown in Table 3. Angle c is obtained by repeating the simulation to get the highest final velocity with a slingshot distance of ~0.015 au from the Sun. Figure 5 shows the final result of the simulation of the Solar Sail orbital maneuver with a ra_f in SOTM 0.5 au. It is also seen that the determination of angles a, b, and c in the simulation aims to produce orbits as close as possible to 0.015 au.

2.5.2 0.001 kg/m2 Solar Sail Orbital Maneuver

Solar Sail (graphite+molybdenum) with an area of 1000 m^2 has a sail weight of only 0.74 kg. The total weight of the Solar Sail (sail+payload) allowed is 1 kg. Then the total payload weight that can be transported is just 0.26 kg (NanoSat weight range). Solar Sail with an area of 10000 m^2 can carry a payload with a total weight of 2.6 kg (NanoSat weight range).

2.5.2.1 Direct Maneuver (DM)

DM is quite simple, the Solar Sail is assumed to be 1 au from the Sun in a circular orbit. Based on these assumptions, the initial input for the simulation is as same as before. Next, Solar Sail performs an outward trajectory maneuver until the Solar Sail produces an escape orbit from the Sun because the Solar Sail is very light so it gets a large enough force, even 1 au from the Sun. But the final speed is quite small, in 10 years, the Solar Sail is only 70 au from the Sun at speed of 6.783 au/yr or 32.15 km/s (see Figure 6).

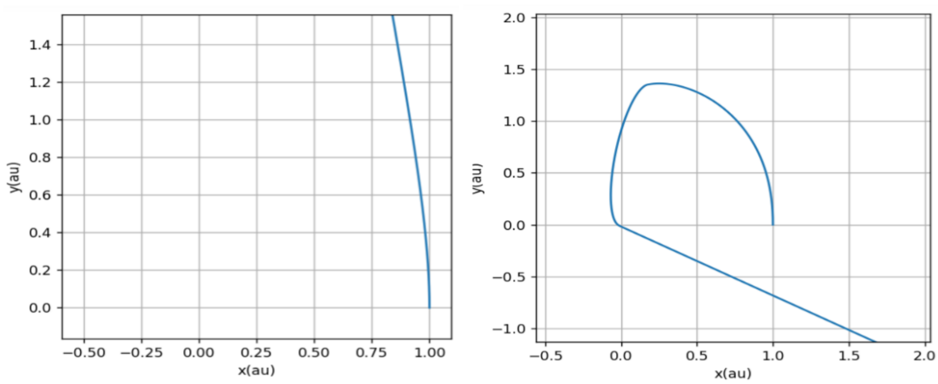

Figure 6 (left) DM, and (right) SFM on 0.001 kg/m^2 Solar Sail.

2.5.2.2 Sun-Flyby Maneuver (SFM)

SFM is a combination of ITM and ETM at 0.01 kg/m^2 Solar Sail, but without using SOTM. Solar Sail is assumed to be 1 au from the Sun in a circular orbit (initial as same as before). Solar Sail performs ITM until Solar Sail produces a final perihelion orbit of rp_f ~0.012 au. In this case, Solar Sail is able to produce a final perihelion orbit of rp_f ~ 0.012 au in 0.59 years because Solar Sail is so light. The value of 0.012 au is obtained from the simulation and the reasons will be explained in the next step. Solar Sail performs an ETM by maneuvering an outward trajectory to a slingshot near the Sun (~0.015 au) until it leaves the Solar System with a high speed. ETM uses one angular limit on the Solar Sail orbit, with the following conditions:

90^0 maneuvers = $180.56^0 \geq \nu \geq 180.476^0$; Outward Trajectory = $\nu > 180.56^0$

This maneuver aims to escape the Sun's gravity at high speed. 180.56^0 is obtained by doing the simulation repeatedly so that it gets the highest final velocity with a slingshot distance of ~0.015 au from the Sun (see Figure 6).

3 Discussions

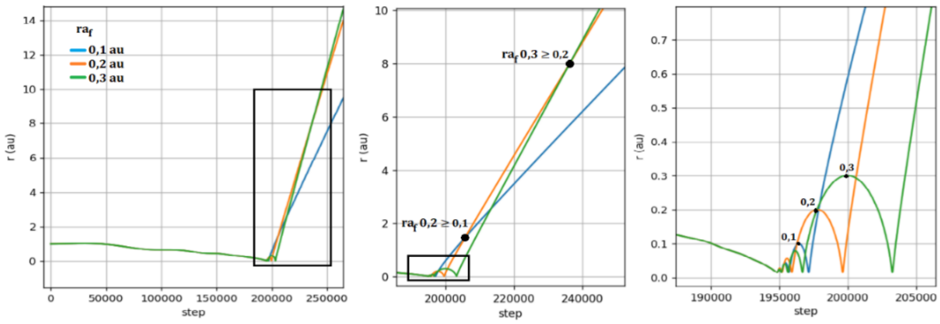

Figure 7 Step vs distance on the 0.01 kg/m2Solar Sail Orbit simulation with ra_f 0.1, 0.2, and 0.3 au.

The step vs distance graph in Figure 7 shows three (out of 12) ra_f values in this research, namely 0.1, 0.2, and 0.3 au on the 0.01 kg/m^2 Solar Sail. The graph shows the intersection of the lines (middle) of blue, orange, and green. Graph 0.1 (blue) shows that the orbit with the ra_f will leave the Sun first, then 0.2 and 0.3. However, at a certain step, the 0.2 charts managed to cut/catch up the 0.1 charts and the 0.2 charts also managed to cut/catch up the 0.3 charts. The intersection of these lines is the effective distance limit by the ra_f. This distance limit can be seen in Table 4. For example, a Solar Sail with an effective ra_f of 0.5 au (fastest time) was applied to hit targets with a range from 37 to 64 au (Kuiper Belt zone) with duration only 3.4 to 4.41 years.

The final speed in this research refers to the speed of the Solar Sail at a distance of 100 au, because at a distance of 1 to 10 au the speed of the Solar Sail still decreases significantly. A longer distance will give a more accurate final speed, but 100 au is considered quite accurate. The final speed produced by the 0.01 kg/m^2 Solar Sail ranges from 65 to 134 km/s (13.73 to 28.39 au/yr) depending on the raft selection. A large ra_f value will result in the fastest final speed, not that it will hit the target in the fastest time. A large ra_f value has a longer SOTM duration so that the selection of a ra_f depends on the distance of the target to be achieved.

Table 4 ITM Duration, SOTM Duration Limit Distance, and Duration(yr) for that the 0.01 kg/m2Solar Sail with a variation of ra_f.

ITM Duration (yr)	ra_f SOTM (au)	SOTM Duration (yr)	Limit Distance (au)	Duration (yr)
1.8517339	0.1	0.015638	1.47	1.96
1.8517339	0.2	0.028481	8.03	2.25
1.8517339	0.3	0.049313	18.93	2.69
1.8517339	0.4	0.066234	37.36	3.40
1.8517339	0.5	0.085160	64.13	4.41
1.8517339	0.6	0.105495	102.48	5.84
1.8517339	0.7	0.127470	150.19	7.59
1.8517339	0.8	0.150230	211.20	9.81
1.8517339	0.9	0.175740	306.77	12.50
1.8517339	1.0	0.201870	479.34	15.80
1.8517339	1.5	0.353585	2000	47
1.8517339	2.0	0.523870	> 2000	> 47

The 0.001 kg/m^2 Solar Sail has a final speed from 32,15 km/s to 413.96 km/s (6,783 to 37,389 au/yr) depending on maneuver selection (DM and SFM). SFM maneuvers are very suitable for use by Solar Sail for more distant targets, such as SGL and Oort clouds. The weakness of this Solar Sail is only brings a small payload so that it can only carry simple and light instruments.

4 Conclusion

The combination of graphite-molybdenum is very well applied as a sail material on the Solar Sail with maneuvers near the Sun with Outer Solar System target. Solar Sail which is $r \sim 1$ au can assume the Sun as a point source so that it makes calculations easier. However, for $r \ll 1$ au, the effects of angular diameter and limb darkening of the Sun need to be taken into account. The Solar Sail with ρ = 0.01 kg/m^2 has a final speed up to 134 km/s (28.39 au/yr) depending on ra_f selection. Solar Sail with a ra_f of 0.5 au has the fastest time targeting Kuiper belt objects (30 – 100 au) such as Sedna, Makemake, Eris, etc. with a duration from 3.4 to 4.41 years. A Solar Sail with an SGL (Solar Gravitational Lens) target at r > 500 au can use maneuvers with a ra_f of 1 au with a duration of 17 years. The Solar Sail with $\rho = 0.001$ kg/m^2 has a final speed up to 413.96 km/s (37,389 au/yr) depending on maneuver selection (DM and SFM). Solar Sail targets Kuiper belt objects (30 – 100 au) that need a duration of 1.2 to 2 years and SGL target has a duration of 6.89 years.

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Nomenclature

B	=	Lambertian coefficient
c	=	Speed of light (m/s)
d	=	Diffusion
dS	=	Sail area (m^2)
$L_\odot$	=	Sun luminosity
$\boldsymbol{n}$	=	Sail surface vector
$\boldsymbol{n_s}$	=	Photon coming vector
R	=	Reflectivity
$R_\odot$	=	Sun radius
s	=	Specular
α	=	Absorptivity
ε	=	Emisivity
θ	=	Angle between vector n and the Sun
ν	=	Orbital true anomaly
ρ	=	Mass per area ratio
τ	=	Transmisivity

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