

**Drag Force Enhancement by Ions Collisions on High Voltage Conductive Panel
on a Cubesat**

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Abstract

Nowadays, there are a huge explosion to launch nanosatellites into Low-Earth-orbit (LEO) since they can be easily manufactured by universities or companies. It does not require so much money to test and make experiment on space for scientific purpose which many universities are highly interested to build nanosatellites to prove and test new scientific equipment. However, this relative open accessibility to put into orbit any nanosatellites has increased space debris which now it is seen as a big issue for future missions into space. Organizations and Space agencies tried to mitigate this irreversible effect by making some requirements and specifications for nanosatellites to make them deorbiting faster and decrease the trash in space.

The purpose of this thesis is to provide another drag force, which is actually acting on all satellites, to make them decay faster into the Earth. Satellites in space are in a plasma environment, which are basically ions and electrons moving randomly in space. The interaction between a satellite and plasma is based on ions, which are many times heavier than electrons. When ions collide with the satellite surface, they produce some force due to the exchange of momentum, however, this momentum-exchanged value is too small and it is considered as a negligible force for deorbiting time calculations. This thesis is mainly focused on biasing a conductive surface on spacecraft, which will enhance plasma force and make satellites decay faster into the Earth.

Keywords

Nanosatellite, Plasma Force, Ion Current, Enhanced Force, Plasma Density

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Chapter 1 Introduction

During last decades, hundreds of launches to space were successfully achieved to test new equipment and do scientific experiments in spacecraft, especially by micro/nano satellites, whose majority is dominated by CubeSats. The total spacecraft population has increased, however, it still nearly impossible to remove spacecraft from space even though most of them had already stop working or they complete their lifetime. Those non-working spacecraft, waste of products of spacecraft operations, solid particulates from rocket exhaust, paint chip and so forth are defined as Space Debris. When spacecraft components are ejected to space, producing small objects (less than 10 cm), which move a high speed that may cause a severe damage to another spacecraft by colliding them. For an example, the impact of an object the size of a pea moving at LEO velocities is around 7000 m/s is comparable to a bowling ball moving at 60 mph [1]. Nowadays, universities and international organizations are looking to develop systems to mitigate space debris because it causes a continuous cascade event where small pieces collides into other spacecraft bodies which produce even more debris [1].

A very effective method to reduce the increase of space debris is to design spacecraft to decay faster into the earth by using the Air drag force which acts against the motion of the spacecraft. It strongly depends in the air density and the actual speed of the spacecraft. However, air density decreases dramatically giving only a weak drag force. Then the total decay time usually is more than 15 years. During this long time in space all nanosatellites complete their lifetime but they are still moving around the Earth. Their altitude is slowly decreasing until the air drag force becomes highly strong to fall down into the Earth's surface.

Another possible source of force is the interaction between plasma and spacecraft body. Plasma is made of ions and electrons which have thermal and kinetic energy and random motion. Plasma drag force is defined as the exchange momentum when ions collide into the spacecraft's body. This force is always acting on any spacecraft in orbit and its value is many times less than air drag even in altitudes where the air density is lower than plasma density. Nonetheless, there are two majors benefits if a conductive panel is negatively biased. One effect is enhancement of the number of ions colliding the surface as the sheath

formed around the biased surface will deflect the ion motion and collect ions much more than those hitting the surface without deflection. The other is enhancement of the momentum of each ion hitting the surface as the ions are accelerated by the negative bias to a velocity much faster than the orbital speed. The velocity is proportional to the square root of the bias voltage. As a consequence this enhanced force can give more drag than the air drag can give and may be used to reduce the deorbiting time.

The goal of this thesis is to look for an approximation of the enhanced ion force by biasing a conductive panel. The force is currently calculated in a ground experiment and numerical simulation. The numerical simulation is performed to calculate the deorbiting time.

1.1 Literature review

In this section, a few literature review of ion drag and numerical simulation of the ion flow will be presented, specifically on how ions act on a negative bias conductive plate. A solar panel can be considered as a conductive surface for simulation purpose. In these literatures, experiments and simulation focus on biasing a conductive surface and calculate the total ion drag produced by the collision between ion flow and the bias surface. The primarily goal is to estimate the enhanced plasma force and how much is the increase of ion current when a conductive surface is biased. Using a numerical simulation, they validated the results.

1.1.1 Numerical Analysis of Interaction of a High-Voltage Solar Array

H. Kuninaka and K. Kuriki, had studied and made a deep research of the interaction between ions and high voltage solar array. This study made some assumptions such as consider solar array as a conductive panel because interconnectors in the solar array generate a plasma sheath which overlap to other plasma sheath and in the sum solar array can be considered as conductive panel. The force obtained by biasing is 1.27×10^{-4} Newton.

1.1.2 Ion Drag for a Negatively Biased Solar Array in Low Earth Orbit

This last related literature belongs to Daniel E. Hastings and Mengu Cho, had studied ions flow collision from different angle of attack on a solar array. In addition, there are numerical simulation based on the assumption that a negative biased conductive panel is in LEO plasma They measured the ion current is enhanced by the bias panel. This study gives the method how to compare non-bias and bias forces.

1.2. Objectives of Thesis

As shown by the preceding literature review, experimental and numerical simulations have been done to calculate enhanced ion current collected by the bias area. The primary goal is to demonstrate the effectiveness of the plasma drag force to deorbit a CubeSat-class satellite based on laboratory experiments and computer simulations.

1.3. Outline of Thesis

Chapter 2 will begin by introducing the drag force on spacecraft in LEO and the definition of the enhanced parameters. Chapter 3 will describe the numerical simulation based on plasma parameters of the ground experiment. Enhanced parameters values will be obtained by comparison between the ground experiment and the simulation results. The experimental results will verify the numerical simulation for another plasma conditions. Chapter 4 will focus on deorbiting simulation by using drag force, air drag force and the enhanced plasma drag force on a spacecraft in LEO. The enhanced plasma drag force will shorten the deorbiting time. Finally a comparison between the air drag force and both drag force on deorbiting time will be present and discussed in chapter 5.

Chapter 2 Drag forces

The most basic definition of a drag force is a force acting opposite to the velocity of any object. In space, more precise in LEO the only significant drag force is the air drag produced by the air molecules still in high altitudes, even though the number is far less than the number on the Earth. The force decreases rapidly in high altitudes. Using ions to increase the drag on spacecraft is possible since a biased surface may increase the ion flow collision. This chapter will focus mostly on the plasma drag force and force equations when the ion current is enhanced due to a biased conductive plate.

2.1 Air drag Force

Air drag force equation states as follows:

$$F_{air} = \frac{1}{2} C_d \rho_{\infty} S_{sat} V_o^2 \quad (1)$$

Where S_{sat} is the total cross section area of the satellite area, ρ_{∞} is the air density, C_d is the drag coefficient and V_o is the orbital speed that depends of the altitude. The major variables on this equation are the velocity and the air density. Air density is a function of the altitude decaying exponentially with it, which make the air drag force almost a negligible force to deorbiting spacecraft from high altitude beyond 700km.

2.2 Plasma force

In space, there is plasma, which is composed by electrons and ions. Basically those particles move with their thermal speed around space. This random movement in space may produce a force to spacecraft once collided via momentum exchange between charged particles and spacecraft's surface which is actually moving around the Earth. When electrons collide to any object, the its insignificant mass can not produce a significant change in the spacecraft's momentum. From this view the only option is to use ions to make a significant force to deorbit satellites. A good approximation of the plasma force on spacecraft is as follows:

$$F_{plasma} = \frac{I_{ram}}{e} m_i V_o \quad (2)$$

Where e is the electron fundamental charge, m_i is the ion's mass, V_o is orbital speed and I_{ram} is the ion ram current which is defined as:

$$I_{ram} = en_i V_o S \quad (3)$$

Where n_i is the ion density and S is the facing area which ions hit. To produce a force, it is necessary a continuous ions flow which collide into the spacecraft. Particularly, the ion flow, we will denominate as ion current generated by the collision. Orbital speed is considered as ion's velocity since the orbital velocity is much faster than the ions' thermal velocity [2]. In the plasma drag force equation, mass and orbital velocity values depend on the spacecraft altitude and plasma environment, however, the ion current can be increased by biasing the surface panel.

2.3.1 Enhanced Plasma Drag Force

To increase the ion current, it is necessary to capture more ions into the same surface. As ions are charged particles, their trajectories can be deflected using an electric field. A high negative bias panel can easily attract more ions since the plasma sheath around the surface expands and more ions are deflected towards the surface. The plasma force using this method is enhanced. We define three main parameters to estimate this increase in the force and use it to calculate the deorbiting time.

2.3.1.1 Enhancement Parameters

Focusing Factor (f)

When a conductive panel is biased to a negative voltage, more ions are deflected toward the bias panel's area.

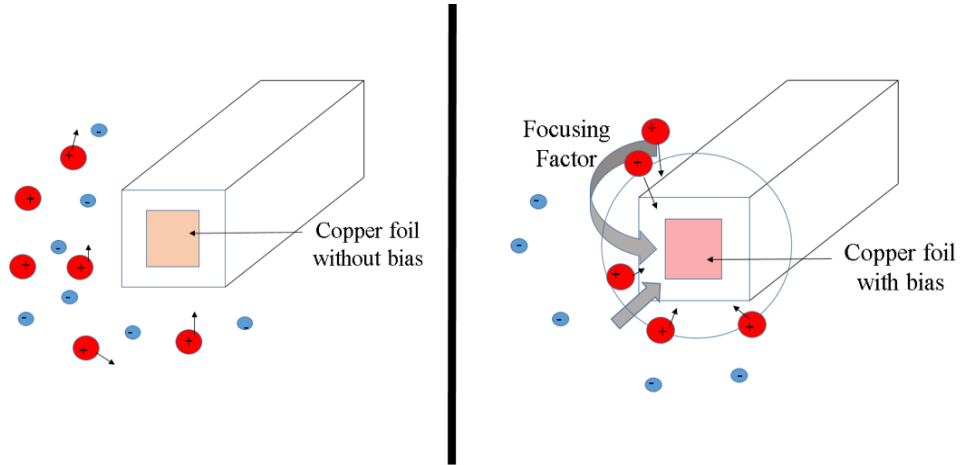


Figure 1. Focusing Factor

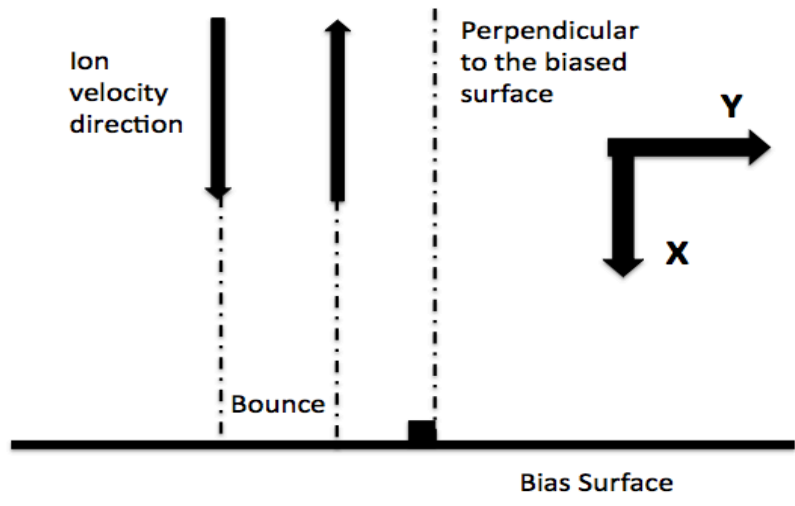
The ratio between the biased current and non-biased current is defined as follows:

$$I_{enh,ram} = I_{ram}f \quad (4)$$

Where $I_{enh,ram}$ is the enhanced ion current caused by biasing the area and f is the focusing factor value. Furthermore, ions accelerate and hit the surface area with a higher velocity than the orbital speed.

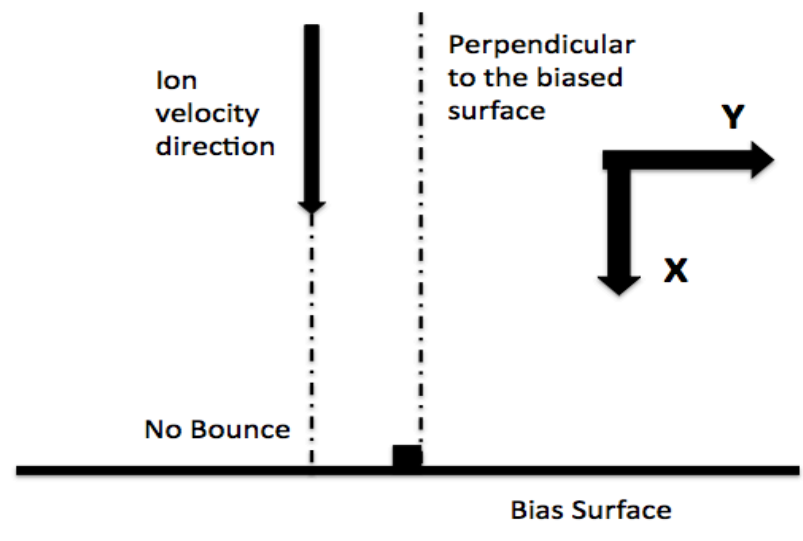
Accommodation Factor α

When ion particle collides to the surface, there are three possibilities, 1) a direct collision which means ion hits the surface and bounce back. The effective exchange of momentum is doubled as shown in fig 2, a. 2) Similar to the previous case a collision takes place again, however, the charge of the ion particle is neutralized with the negative bias surface and sticks in the surface as shown in fig 2, b.



$$\alpha = 0$$

(a)



$$\alpha = 1$$

(b)

Figure 2. Accommodation Factor Cases

The accommodation value vary between 0 and 1. The $\alpha = 0$ represents the mirror reflection. The $\alpha = 1$ means that ion particle sticks into the surface.

Angle factor β

The incident angle is defined as the ion velocity direction and its component, which lies into the x-axis as shown in figure 3. The angle factor is defined as follows:

$$\beta = \overline{\cos\theta} \quad (5)$$

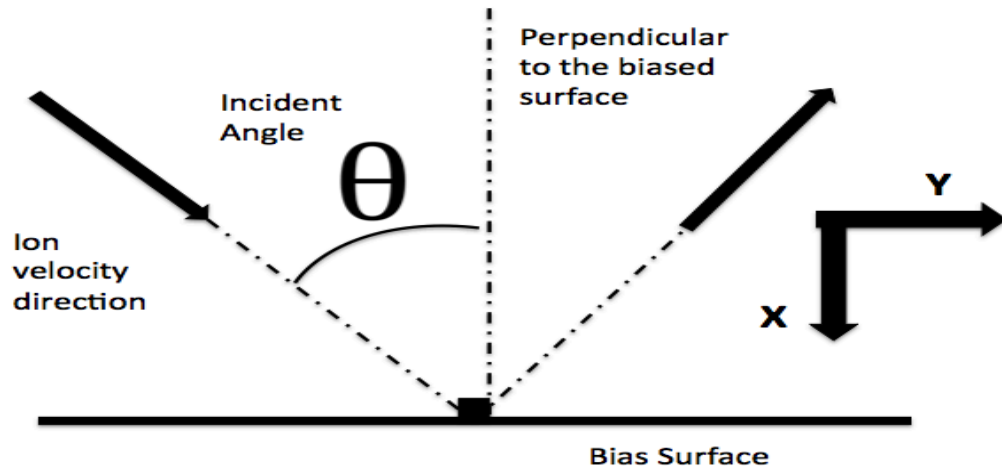


Figure 3. Angle Factor

This definition takes the average cosine value over a large number of ion collisions into the surface. A similar mathematical expression to the enhanced plasma drag force can be derived by changing the orbital speed in Equation 2. The Enhanced plasma drag force is defined as:

$$F_{enh,plasma} = \frac{I_{ram}}{e} \cdot m_i \cdot f \cdot \overline{\cos\theta} (2 - \alpha) \cdot \sqrt{\frac{2eV_{ol}}{m_i}} \quad (6)$$

Where I_{ram} is the ion ram current and V_{ol} is the negative bias voltage applied. Alpha and beta mathematical expression can be derived together to cover all three above cases to obtain a final mathematical expression, equation 6.

Chapter 3 Estimating Enhanced Parameters

To estimate the enhanced parameters values, a ground experiment is performed using a 3U cubesat model inside a vacuum chamber. The plasma density and electron temperature values were obtained using a spherical Langmuir probe. The ion current obtained was compared to the numerical simulation results using the same plasma parameters of the experiment. This comparison improves the first estimation of focusing factor.

3.1 Ground Experiment

This experiment uses a conductor plate installed on 3U cubesat mockup (10cmx10cmx30cm) as shown in Figure 4. In one of the front surface, a copper foil of 0.004 m² is attached. This cubesat mockup is hanging up from the ceiling of the vacuum chamber (Figure 5).

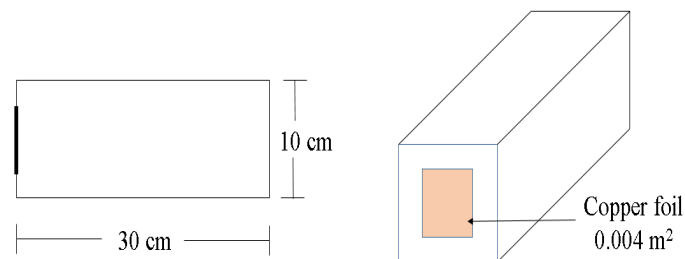


Figure 4. Cubesat mockup

The ground experiment was performed in a square chamber which dimensions are 115x100x75 cm at Laboratory for Spacecraft Environment Interaction Engineering (LaSEINE) of Kyushu Institute of Technology . The plasma was made by an Rf generator (13.56 Mhz model: T857-2) combined with a matching box (L/CON300PF and C-102Y). Argon gas was fed at a flow rate of 50 ccm controlled by a flow-meter (STEC Mass flow system, Model: PAC-3HS) and the power level was set to 40W. Figure 5 shows that the conductive surface is connected to one resistor (100kohm) and the same resistor is connected to the negative output of power supply outside of the chamber. When the negative high

voltage is applied to the copper foil (conductive panel), the negative high voltage on the surface attracts the positive ions to the proximity of the conductive surface. Ions collide with the copper foil and the ion current is measured by the voltage value across the 100kohm resistor.

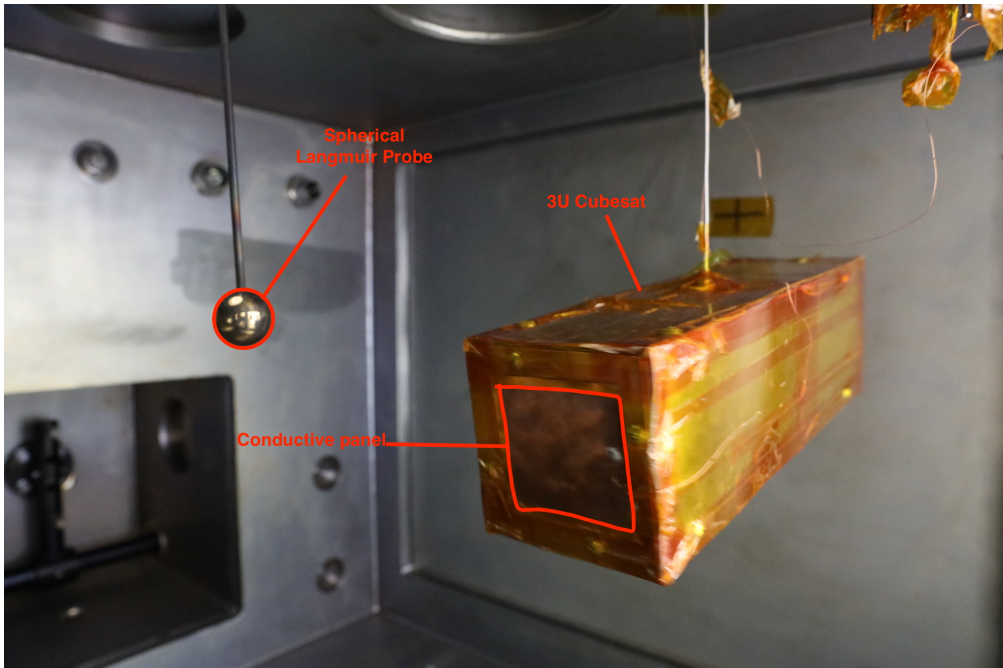


Figure 5. Arrangement of the Experiment

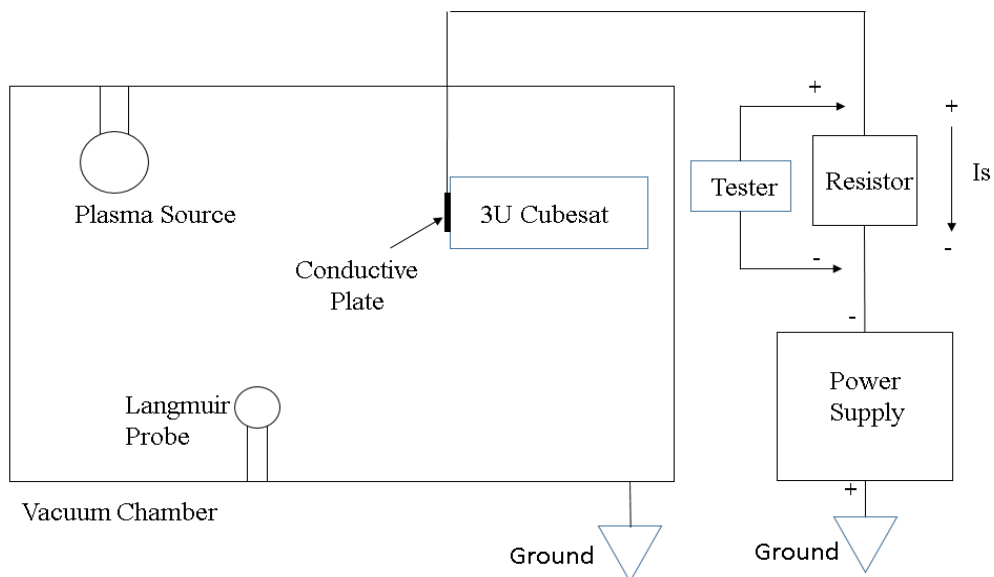


Figure 6. Experiment Schematic

Five sets of negative bias voltage (-100V, -200V, -300V, -400V and -500V) were applied and the current for each bias voltage was measured. At the same time, the plasma density of chamber was measured using a spherical Langmuir probe of 15mm radius. The measurement data is shown on the Table 1:

Table 1. Square Chamber Test Measurement Data

Parameters			
Plasma density [particles/m³]	Electron Temperature [eV]	Debye Length [cm]	Argon Ion's Mass [Kg]
2x10 ¹³	3.1	2.9	6.668x10 ⁻²⁶

Cubesat Data	
Voltage [Volt]	Current [A]
-100	9.43x10 ⁻⁵
-200	1.32x10 ⁻⁴
-300	1.60x10 ⁻⁴
-400	1.90x10 ⁻⁴
-500	2.18x10 ⁻⁴

To have a comparison with the current measured in the experiment, it was necessary to use the saturation current defined as:

$$I_{is} = 0.6en_iS \sqrt{\frac{kT_e}{m_i}} \quad (7)$$

On this equation, k is the Boltzmann constant and T_e is the electron temperature. This current is used instead of the ion ram current equation since the average ion's speed in the chamber is much less than the orbital speed. As a consequence, the focusing factor shall be calculated by the ratio of the saturation current and the current measured in the experiment, Eq (8). We list the focusing factor f , in Table 2 for each bias voltage case.

$$I_{measured} = I_{is}f \quad (8)$$

Table 2. Focusing Factor Determination

Voltage [Volt]	Focusing factor	Ion Saturation Current [A]	Ion Current Measured [A]
-100	4.28	2.2×10^{-5}	9.43×10^{-5}
-200	6	2.2×10^{-5}	1.32×10^{-4}
-300	7.27	2.2×10^{-5}	1.60×10^{-4}
-400	8.63	2.2×10^{-5}	1.90×10^{-4}
-500	9.90	2.2×10^{-5}	2.18×10^{-4}

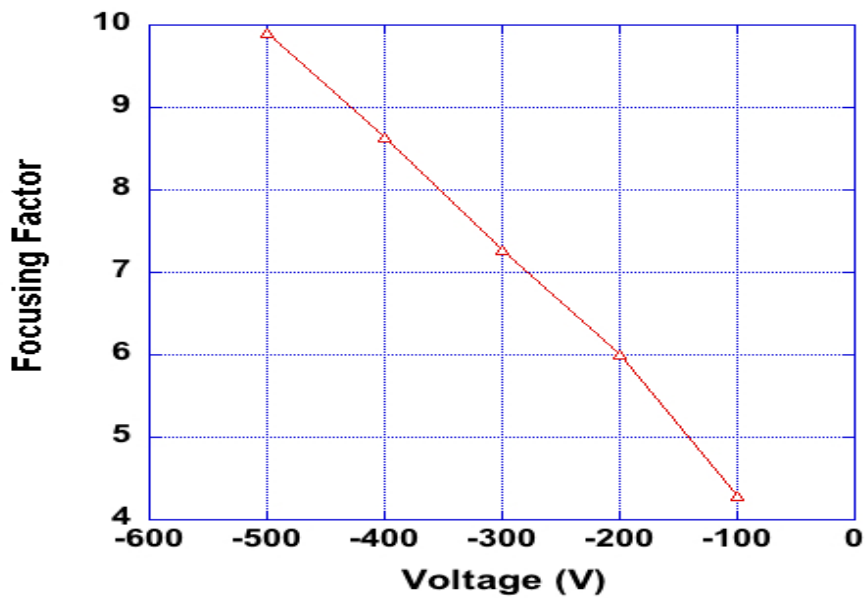


Figure 7. Focusing Factor by the Bias Voltage

Focusing factors indicate how much ion saturation current is enhanced by the bias voltage. Using this focusing factor and Eq. (4), a first assumption on the enhanced ion ram current can be estimated.

3.2 Computer Simulation

Ground Experimental data were validated through simulations using a combination of Particle-in-Cell and Particle Tracking algorithm. The algorithm is explained in Ref. [5]. The simulation consists of an iterative calculation of the electric potential and the ion current.

3.2.1 Simulation Model

The rectangular prism model and plasma simulation parameters are shown in figure 8 and Table 3 below respectively. This configuration formed a prism of dimension length 30cm, width of 6cm and height of 6cm. One of the prism surfaces is biased at different voltages. The other surfaces are fixed to zero potential. The computational domain is 128cmx64cmx64cm with each grid of 1cm. The computational boundary is fixed at zero potential. The plasma was injected from the boundary according to the plasma condition specified. No magnetic field is included in the simulation as the ion motion is not affected much.

The simulation parameters are listed in Table 3 below. The plasma parameters were chosen to compare the ground experiment results with the ion current measured.

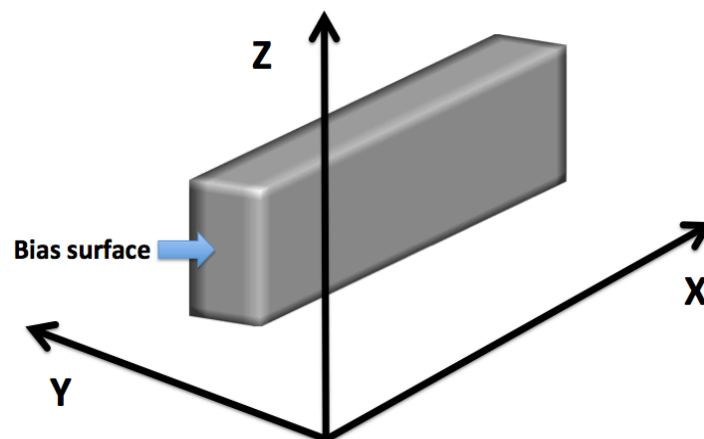


Fig. 8. Simulated Rectangular Prism

Table 3. Simulation Parameters

Simulation Parameters	Values
Domain Grid (cm)	128 x 64 x 64
Object size (cm)	30 x 6 x 6
Plasma density (m^{-3})	2×10^{13}
Plasma temperature (eV)	3.1
Prism surface potential (V)	-100, -200, -300, -400, -500

3.2.2 Simulation Conditions

At the beginning of the simulation, the computational domain is uniformly filled with maxwellian plasma. The plasma does not have a drift velocity since on the ground experiment there is not ion flow. All the body surface potential is zero at the initial condition. One prism surface (-X in Fig.9) is biased to a negative potential. The plasma surrounding the prism responds and forms a plasma sheath around the prism. This process is calculated using the PIC algorithm [5]. Ions and electrons motion is tracked while keeping all the electric potential constant. The number of electrons and ions reaching to the body surfaces are counted to calculate the current collected by the surface. The simulation is continued until the plasma environment surrounding the body settles to the steady state. The current collected by the body also becomes steady.

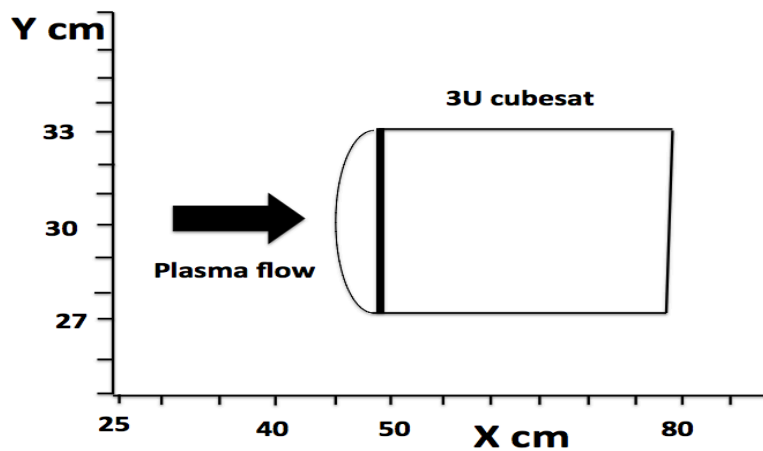


Fig. 9. Plasma flow is always perpendicular to the panel

3.2.3 Simulation Results

After simulation, the main outputs were the ion current collected by the bias surface and the histogram of the incident angle. Figure 10 shows ion current collected by all the body surfaces. The ion current that is necessary for the research is the one surface which face the y-z plane. Moreover, This figure assures that most of the ion current is collected by the bias surface, the other surface just collect an thermal ion current from the plasma environment.

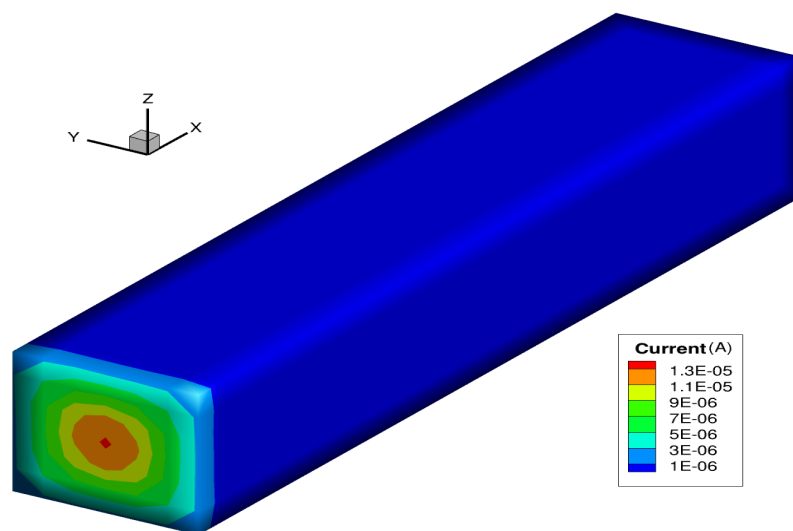


Fig. 10. Ion current collected by the simulated object

The program just calculated the ion current and in what angle the particle collide into the surface. However, it is not possible to calculate the total force produced by the ion current. Figure 11 shows the physical phenomena may occurs when a particle collide into the bias surface. The collision momentum is decomposed in P_x and P_y to be parallel to the main x and y-axis. When a particle hits the surface it exchanges its momentum with the bodies. Then the collision force is generated. Moreover, there is a possibility that the particle may be reflected by the body. Figure 11 summarize all collision and reflection force. The reflection momentum may not occur in all particle which collides into the surface however simulation cannot compute these physical phenomena.

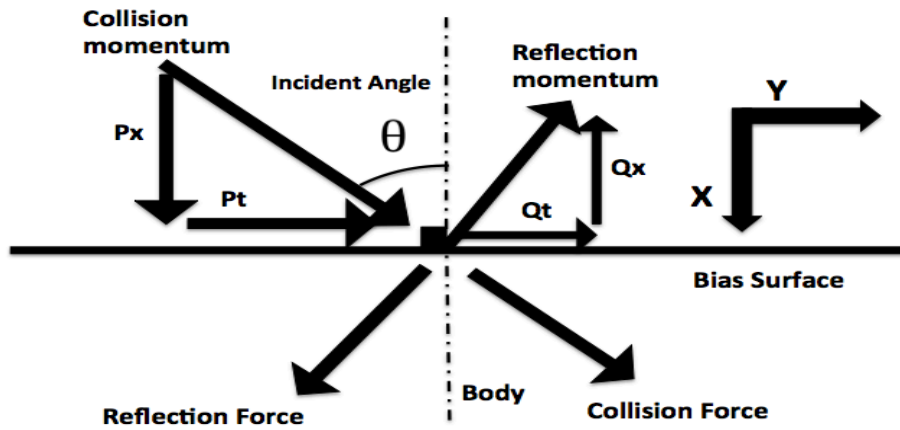


Fig. 11. Geometry and notation of particle collision with the surface

Table 4. Ion Current Simulation Results

Voltage [Volt]	Ion Current measured[A]	Ion Current simulated [A]
-100	9.43×10^{-5}	6.34×10^{-5}
-200	1.32×10^{-4}	1.03×10^{-4}
-300	1.60×10^{-4}	1.54×10^{-4}
-400	1.90×10^{-4}	1.79×10^{-4}
-500	2.18×10^{-4}	2.22×10^{-4}

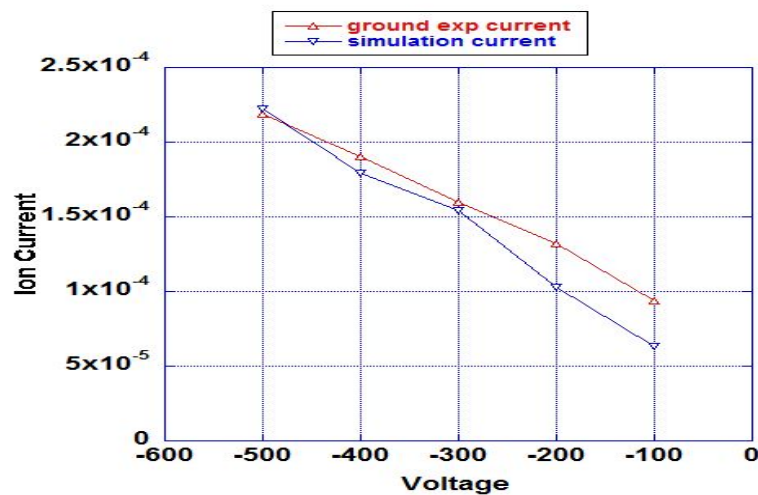


Fig. 12. Comparison between Ion current measured and simulated

Figure 12 shows that ion current values are closer when a high bias voltage is applied in the conductive panel.

3.3. Calculation of Enhancement factors for orbiting conditions

Previous analysis validates our focusing factor values. Another simulation is performed but the plasma parameters are changed to orbit conditions to find how much ion current can be obtained. Table 5 lists the parameters used for the simulation in orbit condition. Although the orbital velocity varies from 7.39 (km/s) to 7.79 (km/s) between 200 and 1000km, it was assumed to be 7.7(km/s) for simplicity. Also for simplicity, the ion mass was assumed to be 2.66×10^{-26} (kg) assuming the plasma is made of atomic oxygen only. It is assumed that the ion current is collected by a biased conductive plate of 6cmx6cm at the front of 3U CubeSat facing the ram direction.

Table 5. Ion Current Simulation Results

Plasma density (m^{-3})	Plasma temperature (eV)	Bias voltage (V)	Ion Ram current (A)	Collected current (A)	Focusing factor, f	$\sqrt{\frac{2eV_{ol}}{m_i}}$ (m/s)	$\overline{\cos\theta}$
1×10^{10}	0.2	-500	4.44×10^{-8}	2.53×10^{-6}	56.9	77,557	0.556
2×10^{10}	0.2	-500	8.88×10^{-8}	3.85×10^{-6}	43.3	77,557	0.616
5×10^{10}	0.2	-500	2.22×10^{-7}	7.84×10^{-6}	35.3	77,557	0.666
1×10^{11}	0.2	-500	4.44×10^{-7}	1.35×10^{-5}	30.3	77,557	0.679
2×10^{11}	0.2	-500	8.88×10^{-7}	2.28×10^{-5}	25.6	77,557	0.693
5×10^{11}	0.2	-500	2.22×10^{-6}	4.44×10^{-5}	19.9	77,557	0.688
1×10^{12}	0.2	-500	4.44×10^{-6}	6.61×10^{-5}	14.8	77,557	0.719
2×10^{12}	0.2	-500	8.88×10^{-6}	1.42×10^{-4}	15.98	77,557	0.627
1×10^{11}	0.1	-500	4.44×10^{-7}	1.38×10^{-5}	31.0	77,557	0.720
1×10^{11}	0.2	-100	4.44×10^{-7}	2.79×10^{-6}	6.2	34,684	0.880
1×10^{11}	0.2	-200	4.44×10^{-7}	5.42×10^{-6}	12.2	49,051	0.813
1×10^{11}	0.2	-300	4.44×10^{-7}	7.95×10^{-6}	17.9	60,075	0.761
1×10^{11}	0.2	-400	4.44×10^{-7}	1.09×10^{-5}	24.5	69,369	0.718

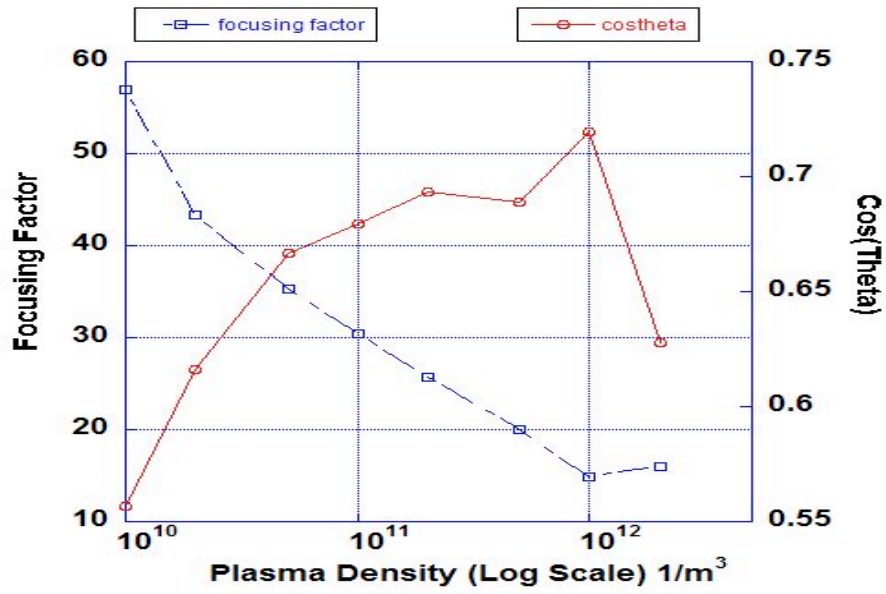


Fig. 13. Doble Plot Focusing factor and $\cos \theta$ at -500 V

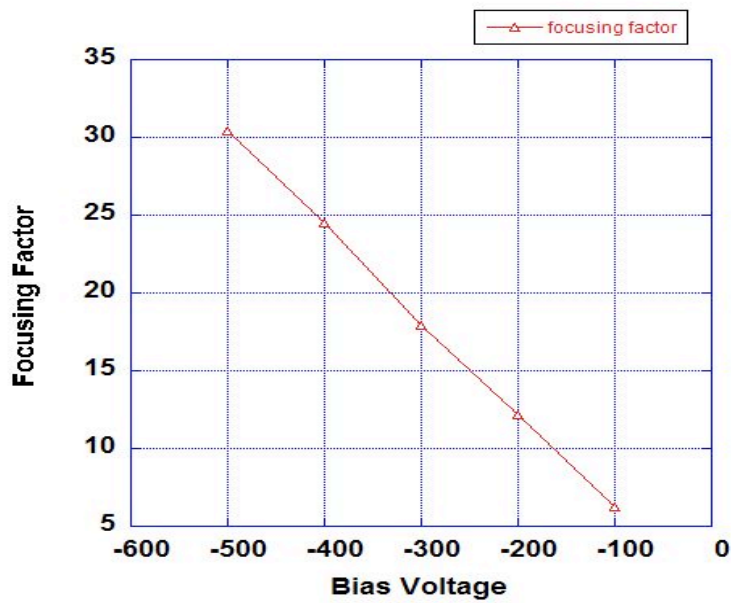


Fig. 14. Focusing factor from plasma density: $1 \times 10^{11} \text{ m}^{-3}$

Table 6. Simulation Parameters for Orbit Condition

Plasma Density [particles/m³]	Electron Temperature [eV]	Drift velocity [m/s]	Atomic Oxygen Ion's Mass [Kg]
9x10 ¹¹	0.2	7.7x10 ³	2.66x10 ⁻²⁶
Simulation Results			
Voltage[V]		Simulated Ion Current [A]	
-500		6.05x10 ⁻⁵	

Table 7. Enhanced plasma Force estimation

Voltage [V]	Ion Current Simulation [A]	Ion Ram Current [A]	Focusing Factor f^2	$\cos\theta$	α	Force [N]
-500	6.05 x10 ⁻⁵	4.00x10 ⁻⁶	15.1	0.72	0	1.55x10 ⁻⁶
-500	6.05 x10 ⁻⁵	4.00x10 ⁻⁶	15.1	0.72	1	7.78x10 ⁻⁷

Chapter 4 Deorbiting Simulation

When we know the plasma density of environment and the focusing factor of the biased conductor plane, the new enhanced plasma drag force can be calculated. In order to compare the air drag force and the enhanced plasma drag force. Several simulations were done using the data of the air density and plasma density from 100km to 1000km altitude above the Earth's surface [9]. Figure 15 shows the air and the plasma density used to calculate the air and plasma drag enhancement. Mostly plasma drag force depends on the atomic oxygen ion ($m_{oxy} = 2.6567 \times 10^{-26}$ kg) since its mass is heavier than the other molecules and a good percentage of the plasma is atomic oxygen ion between altitudes of 200km and 1000 km. The enhanced plasma drag force is calculated by the plasma density values and a conductive surface bias by -500 voltages.

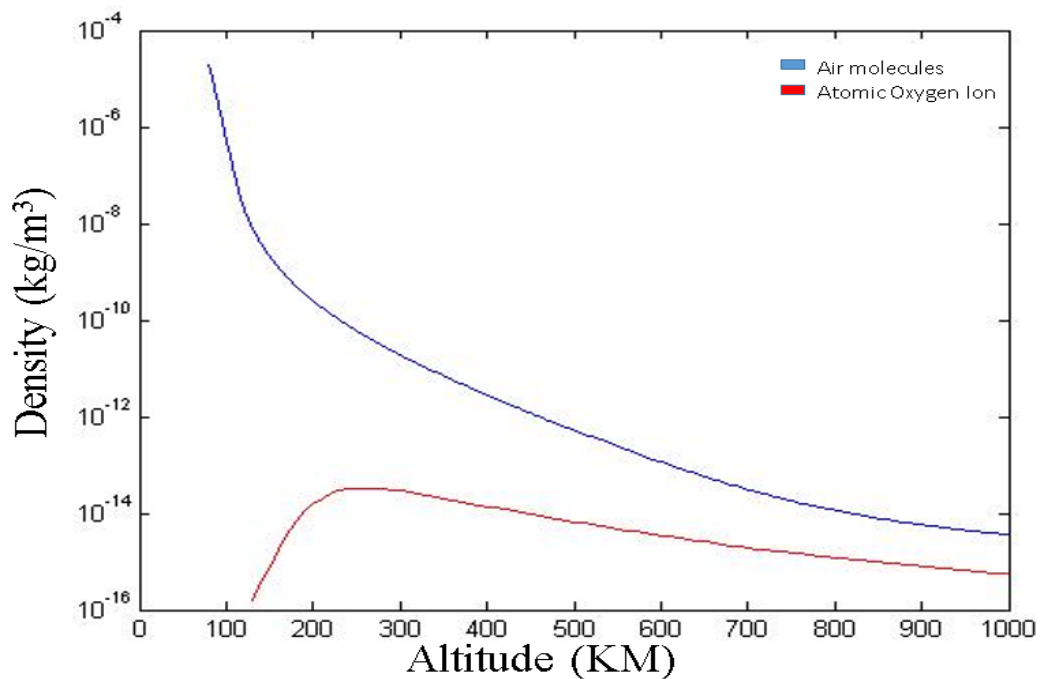


Figure 15. Plasma density and Air Density

To calculate the enhanced plasma drag force, the focusing factor used was $f=15.1$ from the previous section. For the beta factor, we assume $\cos \theta = 0.72$. For the accommodation coefficient, we plot the two extreme cases of $\alpha = 0$ and $\alpha = 1$. The maximum force is when $\alpha = 0$ and the minimum force is when $\alpha = 1$. Figure 16 shows the minimum enhanced plasma drag force compared to the air drag force and the sum of both forces. Even though the magnitude is still weak, the force does not decay as the air drag force does because the plasma density does not decay as fast as the air density on the high altitude (Figure 15). Figure 17 shows maximum enhanced plasma drag force.

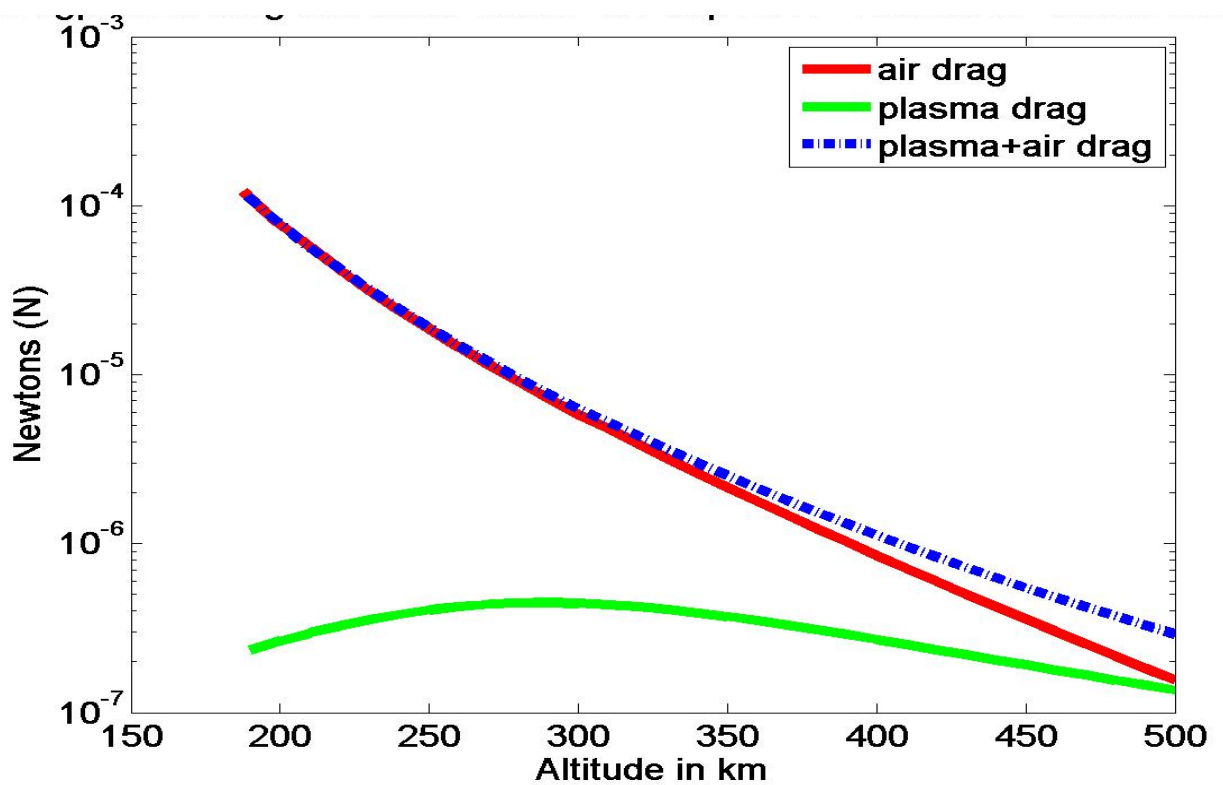


Figure 16. Air Drag Force and Enhanced Plasma Drag Force (Minimum magnitude)

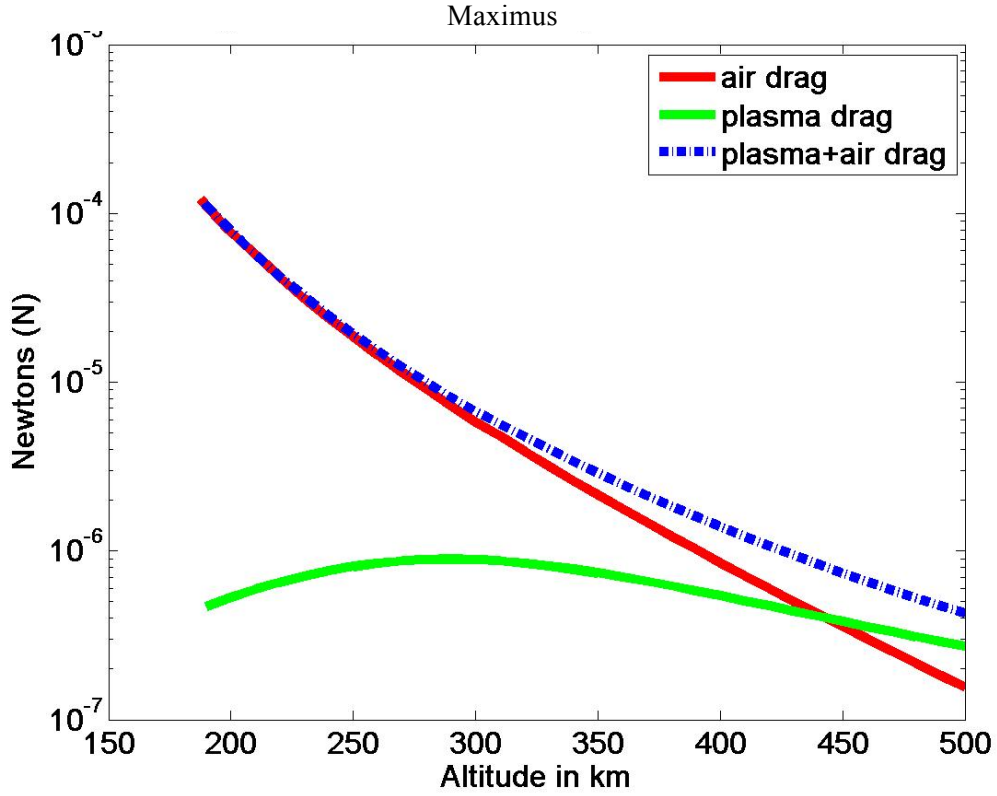


Figure 17. Air Drag Force and Enhanced Plasma Drag Force (Maximum magnitude)

Orbit decay time is calculated in the case of air drag force and the case of plasma drag force plus air drag force. This simulation was made using equation (6) and (11) and orbital period change of the satellite, equation (12).

$$P = 2\pi \sqrt{\frac{\mu}{r}} \quad (11)$$

$$\frac{dP}{dt} = 3\pi \sqrt{\frac{r}{\mu}} \frac{dr}{dt} \quad (12)$$

$$\frac{dr}{dt} = \frac{2F}{m_{sat}} \sqrt{\frac{r^3}{\mu}} \quad (13)$$

From the equation (12) and equation (13), the period change can be presented by drag force with equation (14). Using the equation (14), the orbit period changes are calculated in equation (15) and equation (16) with the each drag force (air drag force and plasma drag force).

$$\frac{dP}{dt} = \frac{6\pi Fr^2}{\mu m_{sat}} \quad (14)$$

$$\frac{dP_{air}}{dt} = \frac{-3\pi C_d \rho_{air} S_{sat} r}{m_{sat}} \quad (15)$$

$$\frac{dP_{plasma}}{dt} = \frac{-6\pi n_i S f \overline{\cos\theta} (2-\alpha)}{m_{sat}} \sqrt{\frac{2r^3 m_i e V_{ol}}{\mu}} \quad (16)$$

We used several assumptions for the simulation. The mass of satellite (m_{sat}) is 0.492 kg, the area of air drag surface (S_{sat}) is 0.01 m², the biased conductor plate area (S) is 0.0036 m², drag coefficient C_d is 1 and the bias voltage is -500V. For the focusing factor, we use $f=15.1$ from the previous section. For the beta factor, we assume $\cos\theta = 0.72$. For the accommodation coefficient, we plot the two extreme cases of $\alpha=0$ and $\alpha=1$. Moreover, plasma density depends on the altitude and location around the Earth, however, the major rate of change depends mostly on the altitude and those values are used in each iteration of the program as altitude decrease. Additionally, we assume the attitude of satellite keeps the front surface to the direction of satellite velocity for the continuous decaying. Figure 18 shows the result of simulation using the minimum value of enhanced plasma drag force, and it shows that a couple of years can be saved by using plasma drag force with the biased conductor plate (-500V) and the air drag force together. This result is for the best conditions of the attitude of spacecraft, keeping its front surface to the velocity direction continuously since the plasma is always hitting.

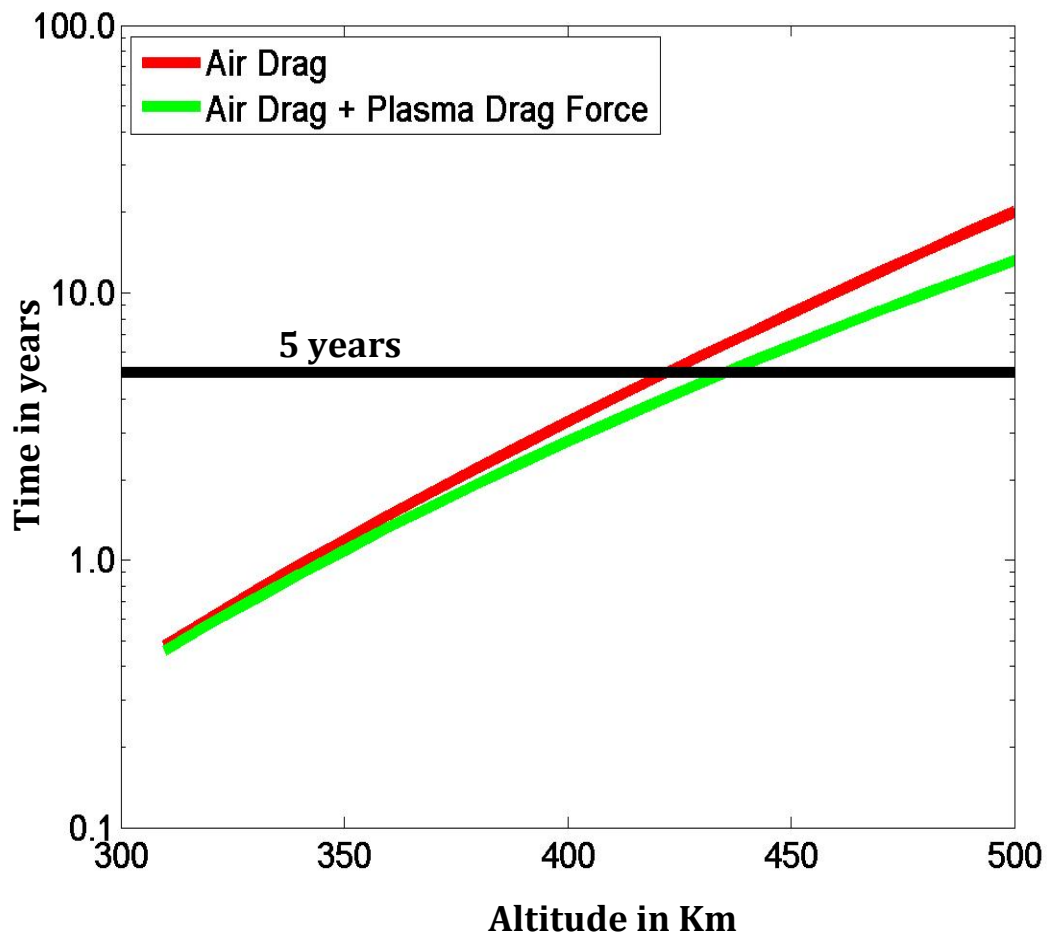


Figure 18. Orbit Decay from 1000km by Air Drag and Plasma Drag Force (-500V)

Using same assumptions and configuration of the satellite, the orbit decay time program is calculated again with the maximum magnitude of the enhanced plasma drag force with the various initial altitudes. Figure 19 shows shows the result of simulation using the maximum value of enhanced plasma drag force, and it shows that a 10 years can be saved by using plasma drag force with the biased conductor plate (-500V) and the air drag force together from 500km of altitude.

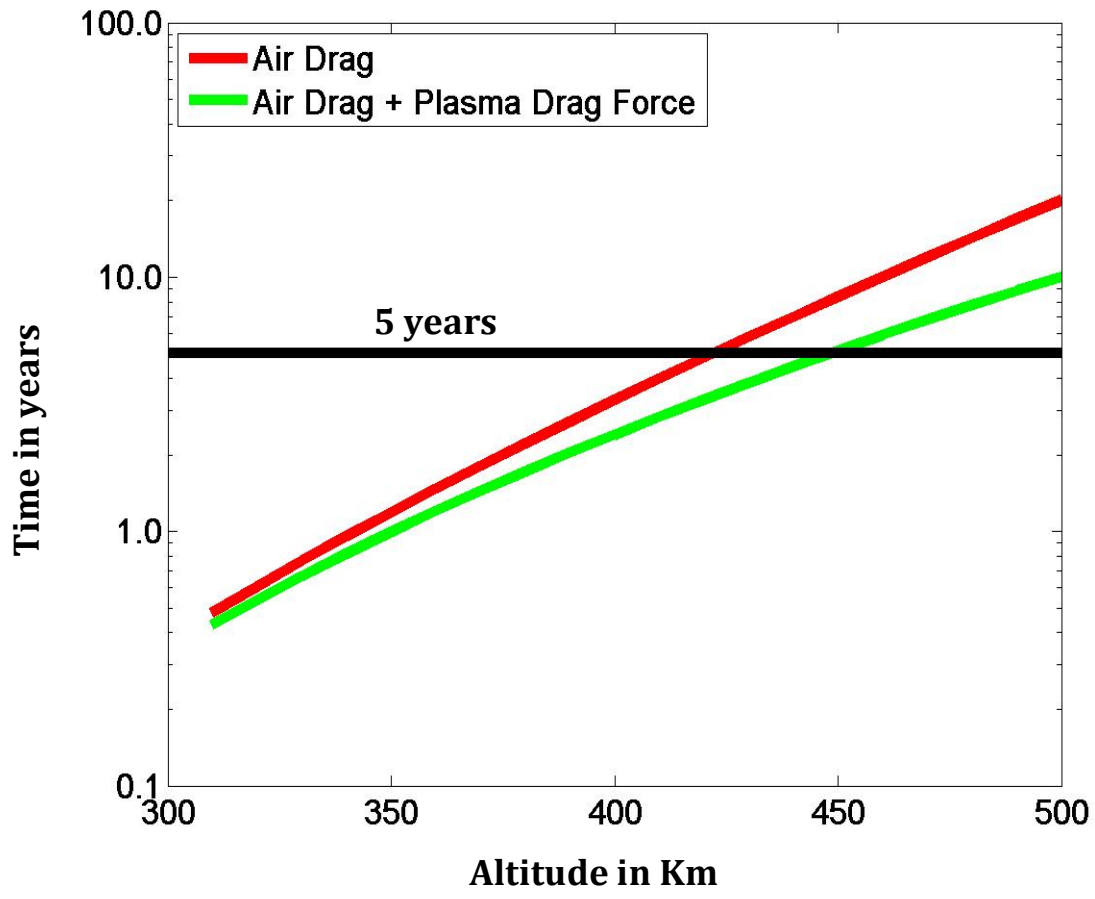


Figure 19. Altitude vs. Decay time by Air drag and Plasma Drag Force (-500V)

Chapter 5 Conclusions

In this thesis, biasing a conductive surface will increase ion flow and derive into enhanced plasma force. The total phenomena due to collision can be summarizing using the enhanced parameters because they relate plasma force from non-bias and bias case. Then, the deorbiting time it is calculated using air and plasma drag forces. For the final conclusion the estimating deorbiting time is less than using a just the air drag force. This enhanced plasma drag force allows more space mission in high altitudes.

5.1 Summaries of Thesis

In the first chapter, two literature reviews were presented concerning about high negative bias conductive surface and ion drag. They make some assumption for their studies as well they show how the angle of attack affects directly into the total ion drag on the solar array.

Chapter 2 introduces drag forces and enhanced parameters definitions and proposes a first approximation of enhanced drag force equation.

Chapter 3 shows how was calculated the ion current and the enhanced ion current in the square chamber. Some assumptions were taken into account to calculate focusing factor. The computer simulation is then used to calculate the ion current with the same plasma parameters as the vacuum chamber.

Chapter 4 presents another numerical simulation to calculate the deorbiting of a cubesat. Deorbiting equations based of the air drag force and plasma drag forces are used to estimate the time. The final results show that enhanced plasma drag force can be considered as useful drag force for altitudes above 400 km.

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