Scilab case study project on

Aerodynamic drag analysis on VLEO Satellite by utilizing CelestLab toolbox and its extension

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Aerospace technology, Space flight dynamics

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Abstract

There is a growing interest in research of the operation of satellites in Very Low Earth Orbit (VLEO), due to their ability to provide high-quality Earth observation and communication. In the VLEO region, atmospheric drag is a critical issue which affects the altitude control, satellite orientation and orbit prediction of satellites. This limits the operational life of the spacecraft. The drag arises due to the interaction between atmosphere (primarily the thermosphere layer) and satellite.

For the simulation and drag analysis, this project makes use of CelestLab and its extension CelestLabX, the Scilab toolboxes specialising Space Flight Dynamics. We first employ STELA tool (present in CelestLab) to create the satellite model and define its orbit. Then, we examine drag impacts on the satellite model, in both the scenarios of fixed and rotating solar arrays. Results show that fixed solar panels do not always face the sun, which can reduce their efficiency. However, rotating panels track the sun producing increased energy capture, which makes them more efficient. Furthermore, we investigate the elliptical shape of the satellite's orbit is affected by drag.

The goal is to simulate such a design of the satellite, which experiences minimum possible drag and captures maximum solar energy. This would help scientists develop drag reduction strategies, thus enhancing the satellite's performance in space missions.

1. Introduction

Spacecrafts that are operated in Very Low Earth Orbit (VLEO) [altitudes below 400 km] are of great importance. They are used for earth observation, weather monitoring, and telecommunication. These satellites are capable of taking accurate measurements of the Earth's gravitational field. In VLEO, atmospheric drag resists the motion of satellites, which can cause them to fall back to Earth. Improved drag estimation boosts the precision of orbit prediction, thus preventing satellite collisions with space debris and enabling more accurate determination of desired factors. Atmospheric drag significantly constrains the orbital period of VLEO satellites due to more consumption of the propulsion fuel. Hence mitigating aerodynamic drag is anticipated to prolong the operational lifespan of the satellite.

2. Problem Statement

In VLEO, atmospheric drag is the main source of the experienced resistance on the satellite. It is triggered by the interchange of molecular momentum between atmosphere and satellite surfaces. This not only intrigues the smooth orbital motion of the satellite but also brings about more fuel consumption. Especially for the gradiometry satellites, it is a must to eliminate disturbances resulted from atmospheric drag to ensure accurate measurements.

In order to tackle with the problem of aerodynamic drag, this project makes use of two Scilab toolboxes, namely CelestLab and its extension, CelestLabX. This program allows the user to analyse the impacts of the atmospheric drag over the surface of solar array. After executing the simulation for different orientations, the program computes optimal solar activity for the fixed solar flux, which is determined by the distance between the sun and the satellite. Furthermore, the effect of drag on semi major axis is plotted with the help of graphs, in the form of reduction in its elliptical orbit. In this way, the finest models of spacecrafts can be generated that would lead to successful space missions.

3. Basic concepts related to the topic

- Aerodynamic drag forces are generated by a spacecraft's movement through a neutral density atmosphere. These forces result from momentum exchange between the atmosphere and the spacecraft and can be decomposed into components of lift, drag, and side slip.

$$F = \frac{1}{2}\rho A C v^2$$

Here, F – drag force (in N)

A – Area (in m^2)

C – Coefficient of drag

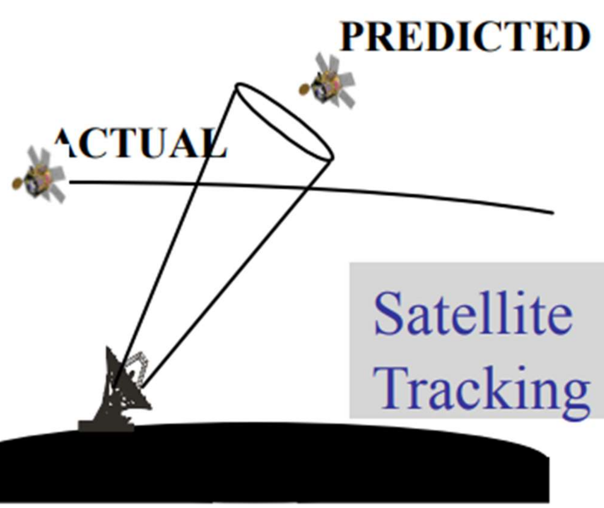
v – Spacecraft speed with respect to atmosphere (in m/s)

ρ – atmospheric mass density (kg/m^3)

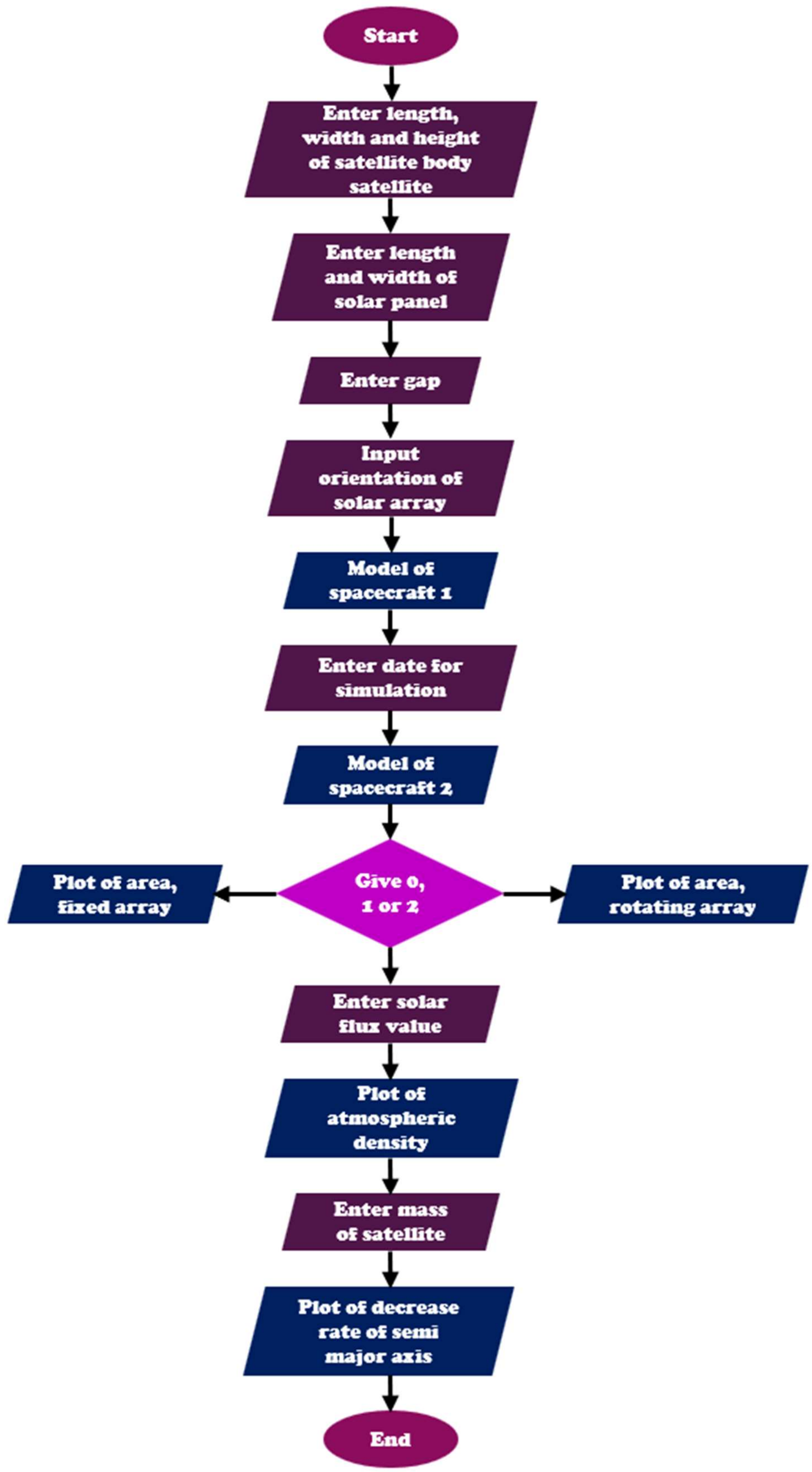
- In the thermosphere the density is a function of temperature. It is the outer gaseous shell of a planet's atmosphere that exchanges energy with the space plasma environment.
- The drag force is considered the most dominant force on low earth orbiting spacecrafts and serves to change the energy of the spacecraft through the work done by the drag force.

$$\frac{dE}{dt} = F \times v = \frac{1}{2}\rho A C v^3$$

<u>Atmospheric Drag → Spacecraft Positioning Error</u>



4. Flowchart



Start
Enter length, width and height of satellite body satellite
Enter length and width of solar panel
Enter gap
Input orientation of solar array
Model of spacecraft 1
Enter date for simulation
Model of spacecraft 2
Plot of area, fixed array
Give 0, 1 or 2
Plot of area, rotating array
Enter solar flux value
Plot of atmospheric density
Enter mass of satellite
Plot of decrease rate of semi major axis
End

5. Software/Hardware used

Operating System: Windows 11

Toolbox: CelestLab Version 3.5.0, CelestLabX Version3.5.0

Hardware: Personal Computer with 12th Gen Intel Core Processor, 16GB RAM

Software: Scilab Version: 2024.0.0 and Microsoft Office 2021

6. Procedure of execution

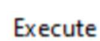
I. Launch Scilab desktop on the computer.

II. Install CelestLab and CelestLabX toolboxes using the following navigation: Atoms (Module manager) → Domain-specific modules → Install the toolboxes

III. Relaunch the Scilab software and open the Scilab file called "Aerodynamic_drag.sce".

IV. Type the command 'clc' on the console, so that the software does not crash midway due to excess memory consumption.

V. Execute the code with the help of "Execute" menu → "file with no echo" option,



or press "Ctrl + Shift + E" on the keyboard.

VI. Enter dimensions of the satellite body and solar panels.

VII. Enter the gap between spacecraft body and solar arrays, and the orientation of the arrays. This will generate the model spacecraft.

VIII. Provide the date for optimum orientation of the satellite. Observe the model in this new frame and compare its orientation with the previous model plot.

IX. Press '1' for fixed solar array analysis.

X. Press '2' for rotating solar array analysis, and '0' to exit.

XI. Enter the value of expected solar flux on the spacecraft, then observe the plot for judging the solar density.

XII. Give the approximate mass of the spacecraft in kilograms and observe the retardation of semi-major axis in the units of metre per day.

XIII. Repeat the simulation for satellite models of different sizes and orientations for the most optimum model.

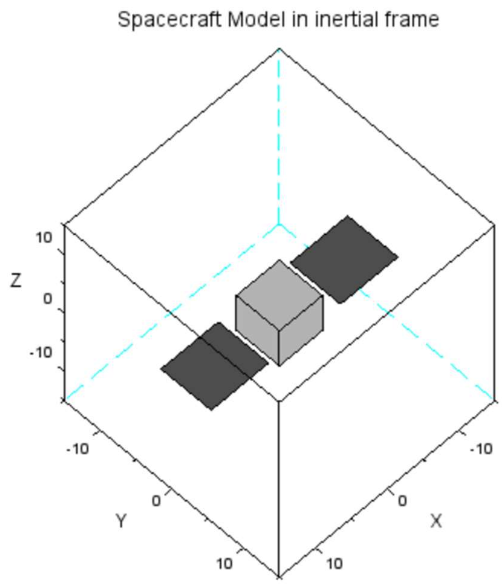
7. Result

The simulation generates spacecraft models and investigates atmospheric drag over the model. It becomes more convenient and faster if the Scilab toolboxes called CelestLab and CelestLabX are used. These are exclusively designed for space missions. The inbuilt functions in these modules involve make_spacecraft(), CL_path(), CL_deg2rad(), etc. which can be directly accessed after installing the toolboxes.

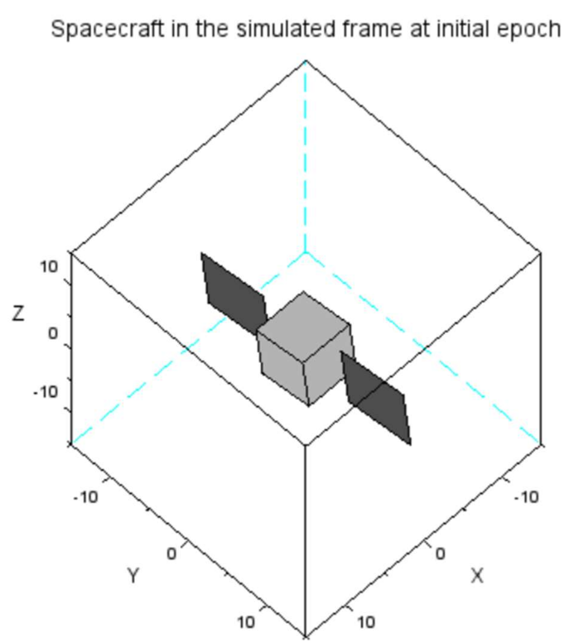
A realistic satellite with solar arrays

```
Startup execution:
  loading initial environment

Start CelestLab => Version 3.5.0

Start CelestLabX
        Load macros
        Load gateways
        Load configuration
        Load Java packages
        Load STELA => Version 3.2 (embedded version)
        Load help


--> exec('C:\Users\Naini Diwan\OneDrive\CelestLab_FOSSEE_Project\Aerodynamic_drag.sce', -1)

Range of the dimensions of satellite body ~ 0.1 m to 7 m
Range of the dimensions of solar arrays ~ 0.0025 m to 9 m

*****Provide the following in meters, all dimensions must be positive*****

Enter the length of the satellite body: 6

Enter the width of the satellite body: 6

Enter the height of the satellite body: 6

The size of solar panels is largely decided by the electric power it generates, and size of the satellite body, on which they are to be affixed.

Enter length of the solar panel: 8

Enter width of the solar panel: 7

Enter the gap between solar panels and body of the satellite: 2

Enter angle (in degrees) in which solar array is tilted about x axis: 180
```

Upon entering the appropriate dimensions, the program generates a model spacecraft.



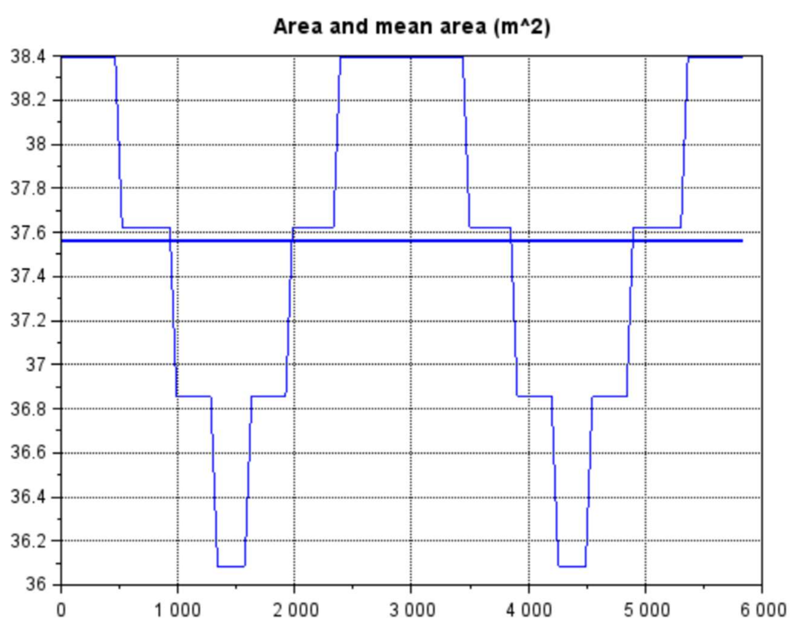
➤ If this model appears suitable (valid orientation of the solar arrays, etc.) the user has to proceed by providing the date of concern. This model will decide the actual positioning of the spacecraft on its orbit, and not mere its inertial frame. In the spacecraft frame, the axes are parallel to the local orbital frame. It is ensured that the solar arrays are correctly oriented even if they don't rotate.



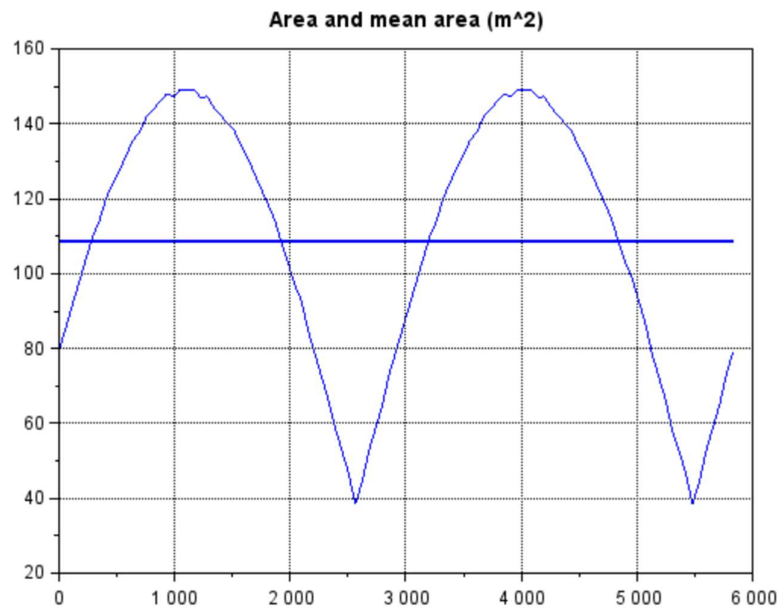
- The solar arrays can be fixed or rotating. However, each aspect has its own pros and cons. Fixed arrays require simpler manufacturing, but there's no accumulation of solar energy when not facing the sun. On the other hand, the rotating panels adjust accordingly. This ensures more solar energy harvesting and less fuel consumption. But these demand rigorous engineering, which creates problems such as increased space occupancy and torque balance issue. Therefore, both the notions need to be acknowledged before constructing the satellite.

```
Provide a suitable month and year for the satellite's orientation

The month is [range ~ 1 to 12]: 1

The year is: 2025


Enter 0 to exit
For fixed solar panel analysis, enter 1
For rotating solar array, enter 2

Enter a number: 1

Enter a number [0, 1 or 2]: 2

Enter a number [0, 1 or 2]: 0
```

Fixed solar panels:



We observe that for rotating arrays, the variation is much smoother and hence more optimum. Subsequent graph is shown below:

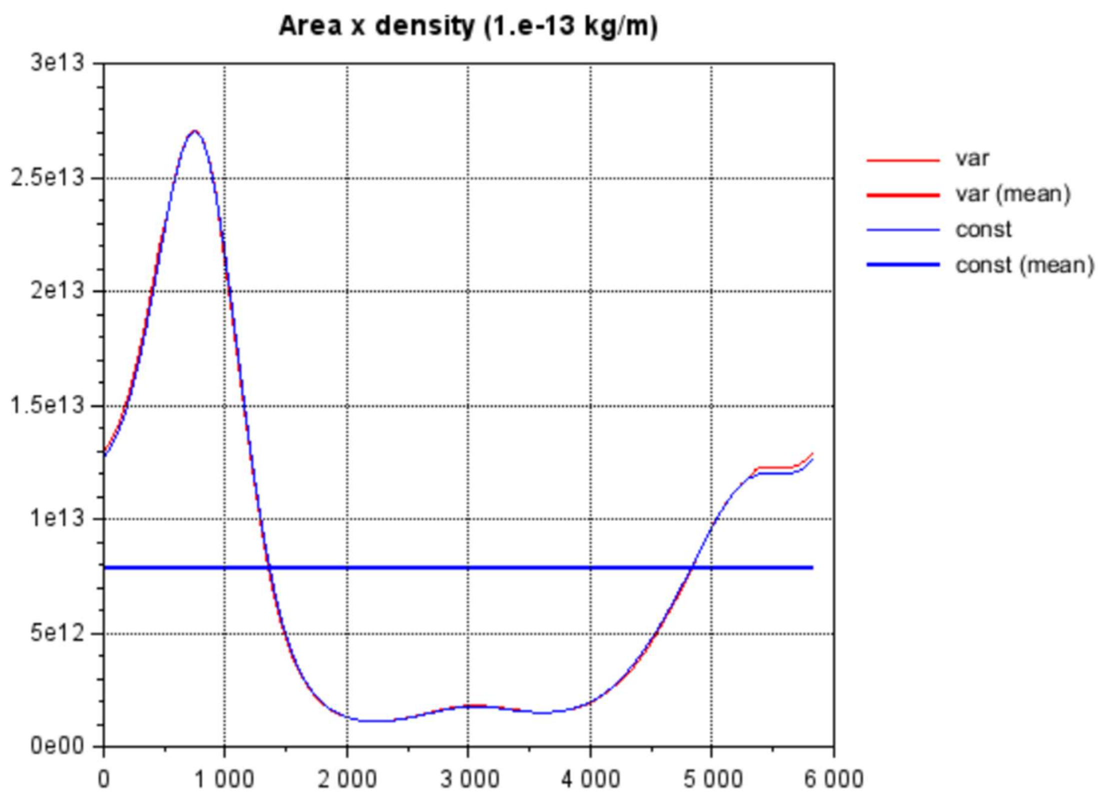


Then the console prompts for the solar flux. It is a prominent factor governed by the satellite's position in space. The spacecraft that is being simulated, would revolve around the earth. Hence the value of flux entered agrees with the spacecraft's location.

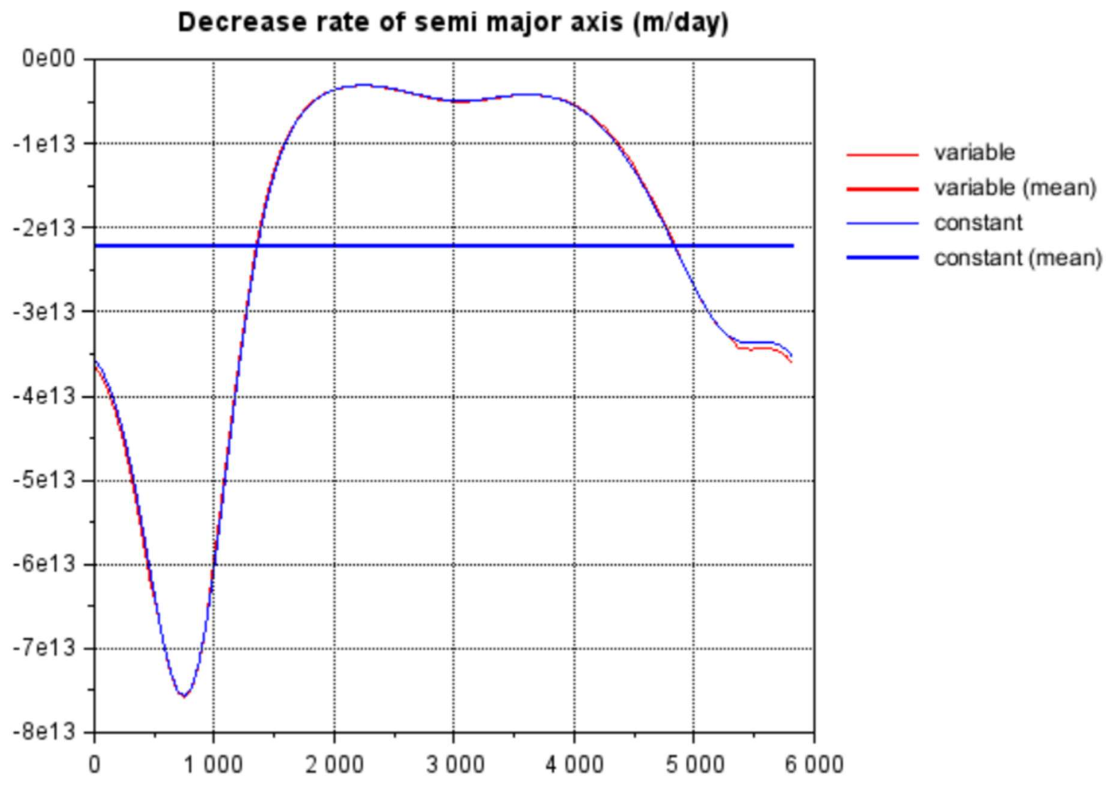
```
Solar flux intensity throughout the solar system (it decreases on receding the sun):
Location                  Average solar flux (W/m2)
Mercury                   8,750
Venus                     2,857
Earth                     1,400
Mars                      622
Jupiter                   52
Saturn                    15
Uranus                    4
Neptune                   2
Pluto                     1

Solar flux [Greater than or equal to 1]: 1500

Enter mass of the spacecraft in kilograms: 900

Winding up. . .
Thank you
```

Satellites are disturbed by solar activity both implicitly and explicitly. High-energy particles from the sun can ruin sensitive microchips. Additionaly, the external charged particles can get collected inside electronics. This can result in destructive arcing and false signals. Arcing is known to occur in a solar panel which is overloaded.

The following plot appears immediately after entering the solar flux. It gives the average solar activity, also known as atmospheric density over the spacecraft. Since the curve does not head off towards infinity, arcing is would not happen.

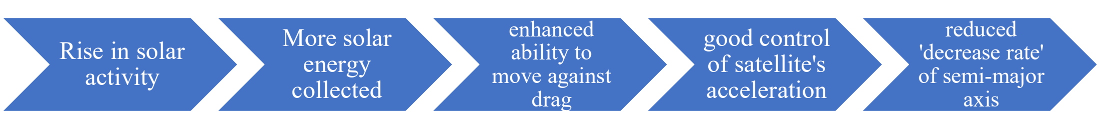


Finally, to estimate the impact of drag on the satellite's acceleration, reduction of its semimajor axis is plotted. For this purpose, the mass of the satellite is inquired.



The above plot makes it evident that in the first 800 days, the orbit undergoes a sharp decline in its elliptical area. Later, it increases rapidly and remains approximately constant for several thousand days.

The concavity (quality of curving in) of this plot is opposite to that of the previous plot. An inference can be drawn: as solar activity increases, decreasing of semi-major axis is reduced.



<u>Conclusion:</u>

From the simulation, it's clear that the most optimum satellite model has rotating solar arrays. These must be tilted about the x-axis by nearly 45 degrees. Furthermore, the spacecraft would best follow the expected path if its weight does not exceed a thousand kilograms.

8. References

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