ANALYSIS AND PREDICTION OF IN-ORBIT LIFETIME OF SATELLITES IN LOW EARTH ORBIT

Nicholas Gan[1], Duan Ning Xin[2], Chiew Jingyi[3]
[1]Eunoia Junior College, 2 Sin Ming Place, Singapore 573838
[2]Raffles Girls' School (Secondary), 2 Braddell Rise, Singapore 318871
[3]Defence Science and Technology Agency, 1 Depot Road, Singapore 109679

Abstract

The functional orbital lifetime of satellites in Low Earth Orbit (LEO) depends on various factors such as orbital altitude, spacecraft specifications (e.g. surface area, mass, etc.), propulsion capability and the effects of the space environment on spacecraft mission-critical components. This project summarizes existing background information and research on the relationships between these factors and satellite lifetime, suggests suitable models for estimation and prediction of some factors affecting in-orbit lifetime of any given satellite in LEO, which are then validated with real data.

Introduction

Satellites in LEO are subjected to a harsh space environment. LEO is a geocentric orbital region between 160-2000km[1] above the Earth's surface. Due to environmental factors such as drag, all satellites have a certain time before which their orbit decays, known as their 'in-orbit lifetime'. Factors such as radiation and atomic oxygen damage electronics which compromise the mission lifetime. This paper attempts to analyse and evaluate the space environmental factors resulting in both satellite mission failure and subsequent end of orbital lifetime, presenting models for such factors in order to estimate the overall lifetime of any given satellite in LEO. Validation with empirical data from real satellites and from presumably more accurate simulation software is also done in order to judge the degree of accuracy to which the models presented hold true.

Materials and Methods

I. Literature Review

Much research has been conducted on the LEO space environment. In a satellite, failure of a number of components can result in a satellite being either unable to complete its intended mission or de-orbit due to its inability to station-keep. We will examine some of the factors in space that might exacerbate such failures. Additionally, atmospheric drag in LEO will result in a satellite's orbital altitude to drop over time if no propellant is used to counteract the decrease.
We will address each of these significant factors by conducting a literature survey on existing research.

Radiation exposure

Satellites in the LEO space environment are subjected to high amounts of radiation from different sources. Galactic Cosmic Rays contain highly energetic stream of protons, electrons and gamma radiation which can damage electronics if the spacecraft does not have adequate shielding.

Fortunately, at orbit inclinations below 45 degrees[2], the earth's magnetic field offers sufficient protection against protons and electrons, making gamma radiation the main concern for LEO satellites orbiting at angles below that inclination. Gamma radiation is the most penetrating of all types of radiation, being able to penetrate the aluminium shielding around the electronics. Thus, it is important to take into account the effect of gamma radiation on semiconductors as it could affect electronics system function. Radiation in space also varies depending on solar activity. The eleven-year solar cycle is split into seven years of solar maxima, where solar activity is higher, and two years of solar minima, where solar activity is at a minimum. During periods of solar maxima, radiation bombarding the spacecraft peaks, and during solar minima it drops.

Radiation damage can cause failure of electronics, either from single-particle events or total ionising dose (TID). Firstly, energetic protons, electrons and neutrons cause atomic displacements, affecting the electrical properties of the semiconductor chip. Radiation introduces energy into the semiconductor crystal lattice, causing the crystals to break down over time[3][4][5]. The surface of the satellites may also undergo significant charging and cause currents to flow through the satellite, damaging sensitive electronics. There may also be Single Event Upsets(SEUs) in which a highly energetic particle is able to penetrate the earth's magnetic field and the satellite's shielding, severely damaging the electronics. However, we will not be calculating SEUs as it is not a rate-based calculation and thus cannot be accurately used to predict the degradation of spacecraft function.

Atomic Oxygen

In LEO orbits, oxygen exists mainly as atoms instead of diatomic molecules. This results in more severe corrosion and erosion[6] of certain metals or polymers on the spacecraft, compromising the spacecraft function. For example, a spacecraft with exposed silver interconnectors for its solar panels will have them oxidised, increasing the resistance of the interconnectors and thus reducing the power output of the solar panels, compromising spacecraft functionality. However, surfaces protected by an unreactive material such as gold will not encounter this problem.

Atmospheric Drag

LEO satellites experience small but non-negligible atmospheric drag. This is the primary cause of a satellite falling out of orbit.[7] As the atmospheric density increases as altitude decreases, the satellite falls out of orbit at an increasing rate. As such, a model is needed to account for the varying density of the atmosphere at different altitudes.

Debris and Micrometeoroids

Orbital debris in space include defunct satellites, fragments from collisions and rocket bodies. Micrometeoroids pose an equally significant danger to satellites. While the majority of the debris in LEO is quite small, all debris and particles in LEO travel at a speed of about 7-8km/s and can wear down a satellites shielding over multiple impacts. As such, long-term exposure might eventually damage critical components and threaten spacecraft's full functionality. However, we chose not to focus on debris impact rate prediction as all estimates of collision with larger debris are largely probability-based[8]. This means that an accurate prediction of a satellite's lifetime is less achievable and less significant as luck plays a larger role. For impacts with smaller debris or particles, not enough detailed research has been done on the debris flux (uncertainty in current debris population assessment as sensors are currently incapable of detecting debris with tiny sizes[9]) and rate of impact in LEO and we are unable to obtain such data ourselves.

Natural degradation of satellite components

Some satellite components are predisposed to degrade or decrease in functionality over time. For example, degradation of lithium-ion batteries occurs naturally over many charge cycles[10]. However, this information is generally specified by component manufacturers and should already be taken into account when acquiring satellite components to meet the expected mission lifetime.

Software failure

Software failure could potentially lead to mission failure, for example, in the NASA's Mars Climate Orbiter. However, estimating the time or probability of software failure requires an in-depth understanding of the software in question, which is not possible for more generalised cases.

II. Evaluation of Existing Models and Methodology

Existing models

The Space Environment Information System (SPENVIS) provides us with tools to model the space environment. However, it has its limitations, for example, it does not take drag into account. Therefore, any models we present is due to the fact that SPENVIS does not present us with a suitable alternative. Where SPENVIS models are available, it would be used as SPENVIS is a highly reliable system solely dedicated to supplying accurate modelling and simulation. Thus, it should satisfy our objectives to a higher degree of accuracy. STK is also another software that provides lifetime estimation of some form in its program. However, it is more inaccessible as the function requires the purchase of STK Pro to use. NASA's public catalogue of software(2017-2018) also provides some viable program options, but the ones we need have U.S. only restrictions for download.

Satellite natural decay (atmospheric drag)

We have taken the effects of drag into account and we consider it the main factor for the natural orbital decay of the satellite. The model we used consists of 3 differential equations (1, 2, 3):

(1) $$\dot{v} = -\frac{D}{m} - g\cos\theta$$

(2) $$\dot{\theta} = \left(\frac{g}{v} - \frac{v}{r}\right)\sin\theta$$

(3) $$\dot{r} = v\cos\theta$$

m: The satellite's mass

D: The drag force as calculated by: $\frac{1}{2}\rho A C_d v^2$

r: The radial distance between the satellite and the centre of the planet

g: The gravitational acceleration the satellite experiences at radial distance r = $g_0\left(\frac{r_0}{r}\right)^2$

ρ: The density of air at a certain altitude: $\rho_0 exp\left(-\frac{r-r_0}{H}\right)$

r_0: The earth's radius

H: A reference height which varies with altitude

which can be solved numerically to predict the approximate trajectory of the satellite over time. We also accounted for the fact that the atmospheric density decreases with altitude. The drag cross-sectional area is assumed to be constant since satellites have attitude control and hence have a near-constant orientation and thus constant drag cross-sectional area. Although we took into account the effects of altitude on the density of air, we do not have a complete model as some of the constants vary with the altitude and will induce inaccuracies in the calculations.

Radiation exposure

SPENVIS also has tools for modelling the radiation in space. However, it does not take both proton and gamma radiation into account when predicting the TID faced by the satellite, hence the need for a new model. We calculated[1] the contribution of the protons to the TID using the following model[11].

(4) $D = \int_0^t \frac{dD}{dt} dt$

(5) $\frac{dD}{dt} = \frac{N_{Si}}{\rho_{Si}} \int_{\frac{x}{a}^{1/r}}^{\infty} \left(\sigma_{Si}(E^*) E^* \frac{d\varphi}{dE} \right) dE$

(6) $E^* = \left(E^r - \frac{x}{a} \right)^{1/r}$

(7) $\sigma_{Si}(E^*) = 4\pi {a_0}^2 {Z_{Si}}^2 \frac{{E_R}^2}{M_{Si} E^* E_d}$

E^*: Energy of a particle with original energy E after penetrating shield

$\sigma_{Si}(E^*)$: Silicon scattering cross section for a proton with energy E^*

$\frac{d\varphi}{dE}$: differential flux(The flux of protons with particular energy level)

a & r: shielding material constants

$\frac{N_{Si}}{\rho_{Si}}$: Ratio of the number density of silicon atoms to silicon's density

a_0: Bohr radius

Z_{Si}: Silicon nuclear charge

E_R : Rydberg energy

M_{Si}: Molecular mass silicon

E_d : energy required to displace one silicon atom from the lattice

We decided to evaluate the effectiveness of aluminium and gold as radiation shields as these 2 are commonly used radiation shields. We focused on calculating proton radiation dose for a silicon chip as they pose the greatest threat to the satellite's mission lifetime, being larger than electrons and hence causing more displacement damage due to their larger Linear Energy Transfer value[2][12]. Should one like to apply these results to a LEO context, models for varying flux and energy levels distributions from the space environment would have to be applied to the one presented to gain a result more representative of that experienced by a satellite in the LEO environment. The gamma ray flux and energy used is also an inexact constant. Additionally, the space radiation environment varies depending on the inclination and altitude of the spacecraft, which we have not accounted for. Furthermore, the effect of the solar cycle on the radiation flux has not been accounted for due to its unpredictable nature. We have not accounted for electron bombardment at all, as the damage caused by electrons is much smaller due to its lower LET value[12]. For our results, we simulated one of the highest radiation exposure possible at an orbital altitude of 600km and 90-degree inclination.

Atomic Oxygen

While SPENVIS has models which outputs the total thickness of material eroded in a satellite's orbit, it does not provide us with a time plot of the data. We decided to calculate the rate of erosion of silver interconnectors on spacecraft solar panels, used for its high electrical conductivity but susceptible to performance degradation with even small erosion depths. Silver oxide flakes off, leaving a fresh layer of silver to be oxidised. Hence, to quantify the severity of erosion, we calculated the erosion depth using equation (8).

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[1] The values of constants a and r are calculated from fitting the values from [13]

[2] A higher LET value means that a larger proportion of the energy of the particle is transferred to the material when the particle strikes the material

$$(8) \quad \frac{d}{dt}(tox) = \frac{K_{ox}\varphi}{M\left(1 + \frac{K_{ox}}{D}tox\right)} - JE\varphi$$

tox: Thickness of oxide layer/cm

φ:Flux of oxygen atoms/at cm^{-2} s^{-1}

K_{ox}: Oxidation Rate constant/ cm s^{-1}

M:Number of oxygen atoms incorporated per cm^3 of AgO/at cm^{-3}

D: Diffusion coefficient/cm^{2}s^{-1}

J:Erosion yield

E:Energy of oxygen atoms

We simulated the erosion of the silver plating over a course of 20 years at different LEO orbital altitudes (300km, 400km, 500km and 600km) as the atomic oxygen concentration varies with altitude. To validate the model, comparisons between our final erosion depth and that calculated by SPENVIS were made. Inclination and variation in flux and temperature[3] was not taken into account in our estimations.

III. Results

<u>Satellite natural decay (atmospheric drag)</u>

We fitted some parameters to the data for both TeLEOS-1 and Galassia and we predicted their resultant trajectories as shown in the figure below.

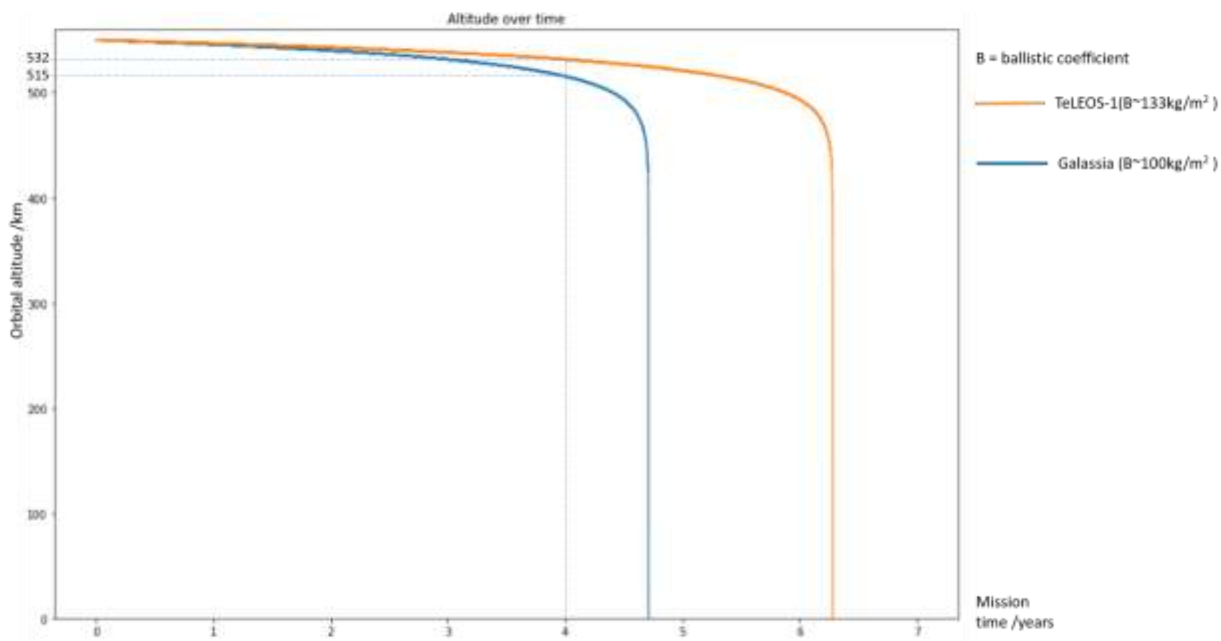

Fig. 1: Graph of TeLEOS-1 and Galassia's altitude over time.

[3] Inclination causes the exposure of the satellite to the solar heat to vary and hence the rate of oxidation of the surface, while flux is proportional to the rate of erosion by atomic oxygen.

A higher ballistic coefficient (calculated by dividing the mass of the satellite over the effective surface area of the satellite) would enhance the lifetime of the satellite as the effects of drag on the satellite is reduced as seen from the equation(1). However, the reference height(*H*) actually increases with altitude[7]. Thus, by using the fitted value for the reference height at 550km to model the trajectory of the satellites until their end of lifetime has probably caused us to underestimate their lifetime, i.e. the satellites' lifetime should decrease gradually instead of the sharp decline shown in Figure 1.

Radiation exposure

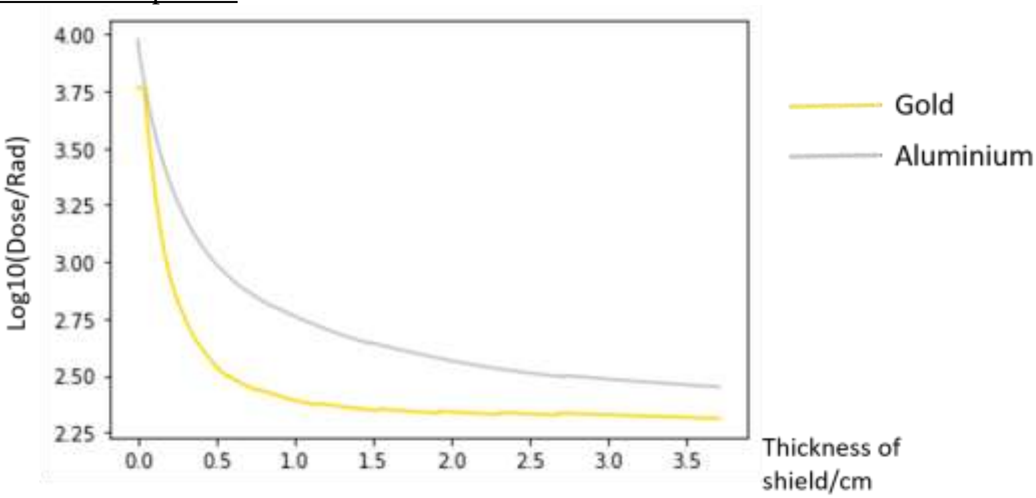

Fig. 2: Graph of total dose/rad against thickness of shield/cm for gold and aluminium shielding

We have found that gold is a more effective material than aluminium than stopping protons. This is probably due to the fact that gold atoms have a higher nuclear charge than aluminium, causing gold to have a higher proton stopping power than aluminium. Furthermore, gold has a larger nucleus, causing the probability of the protons to collide into the nucleus and lose energy drastically to be much higher. However, we also note that gold is an expensive and heavier material and hence it is not feasible to construct the shield entirely out of gold.

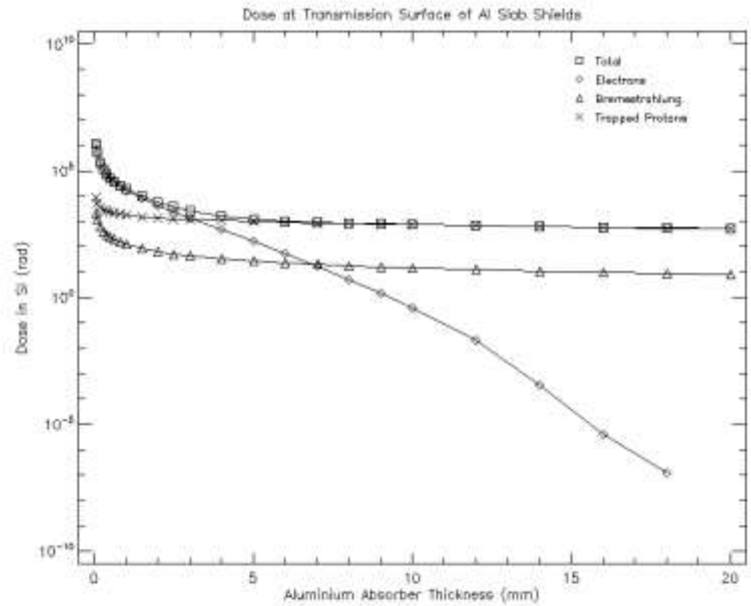

Fig. 3: SPENVIS graph of dose in silicon/rad against aluminium shield thickness/mm.

Our results are somewhat inaccurate compared to SPENVIS-generated results. This may be due to the fact that we used a limited proton spectrum, and thus, we do not have data that accounts for protons of energies higher than >40MeV. These high energy protons may have a lower flux, but their high energy results in a significant amount of radiation damage to the silicon chip, contributing to total dose. Furthermore, SPENVIS does not take into account the proton scattering cross section of the target material, leading to a possible overestimation on their part as they assume that all ions that pass through will effectively transfer all their energy to the target material.

Atomic Oxygen

We have found a strong linear dependence of the erosion depth after 20 years on the average atomic oxygen flux as shown by Fig. 3:

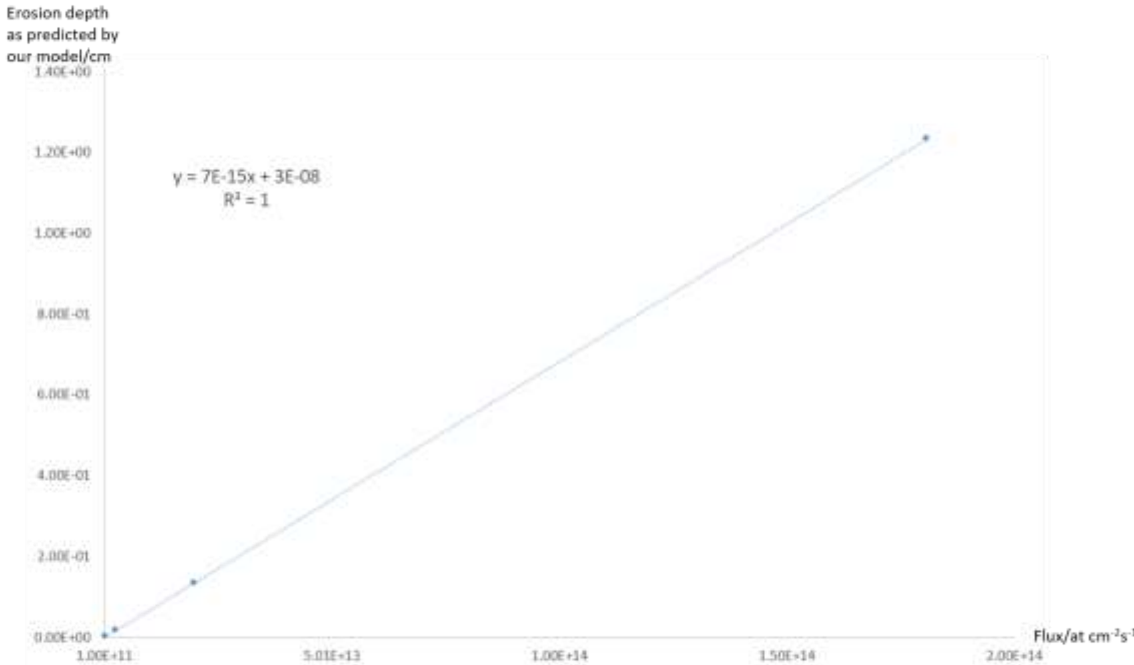

Fig. 4: Graph of erosion depth/cm after 20 years against average atomic oxygen flux/at cm^{-2} s^{-1}

This is expected since the rate of change of the oxide layer as shown in formula (8) is directly proportional to the average atomic oxygen flux. More surprisingly, the growth of the oxide layer overtime does not follow the typical shape predicted by the Deal-Grove model which was used in our model:

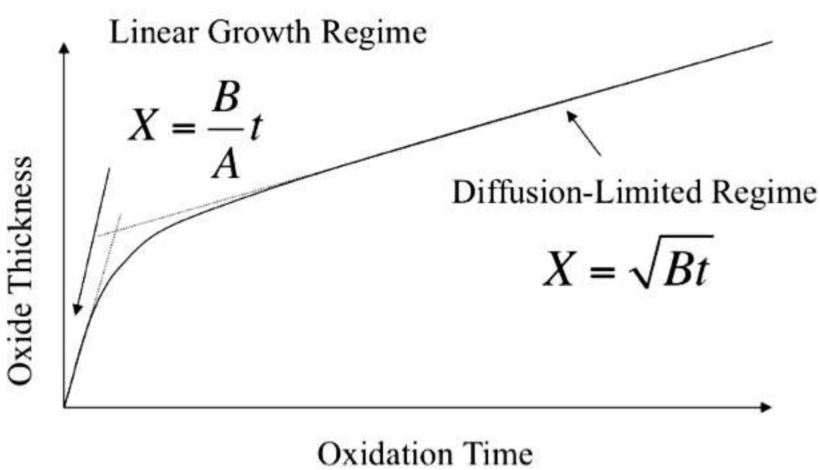

Fig. 5: Typical Deal-Grove model behaviour

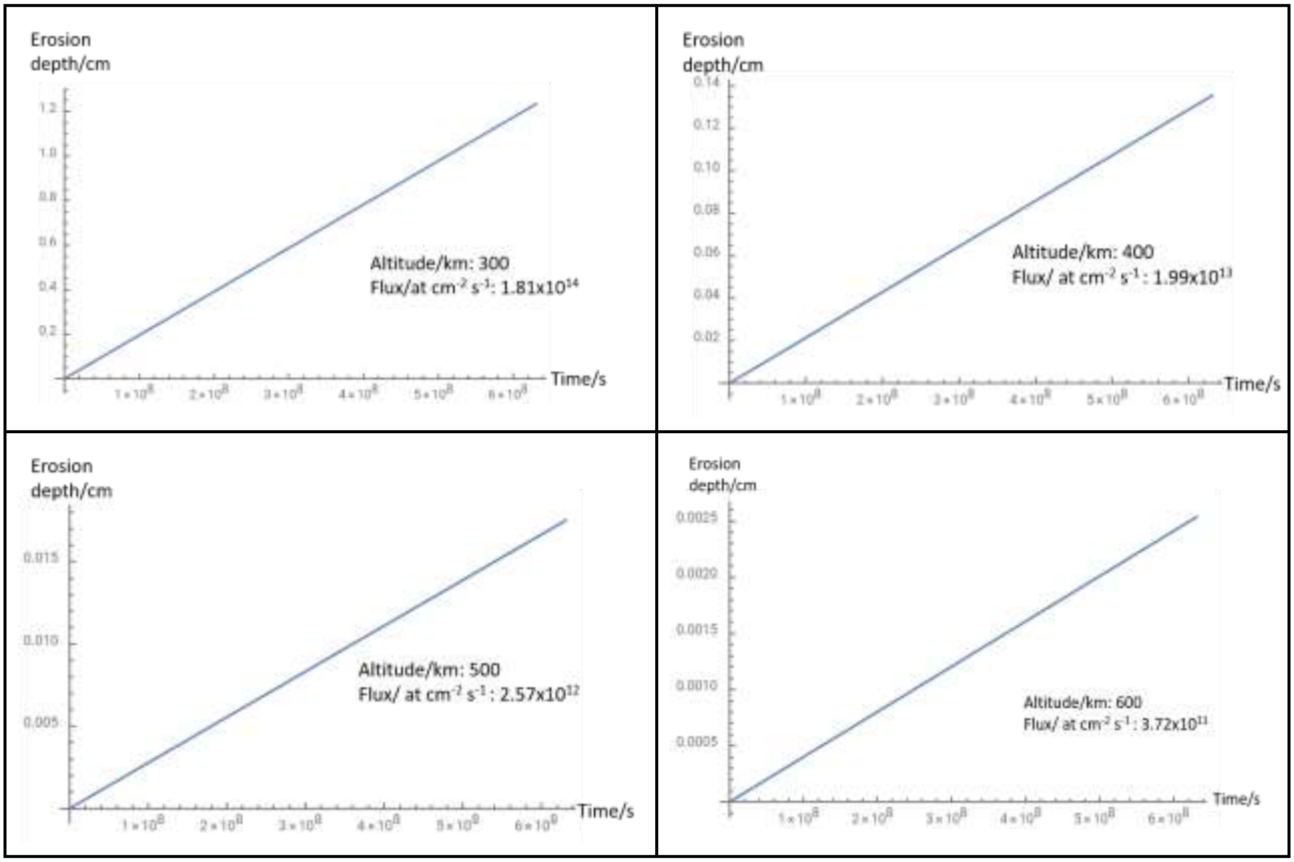

Fig. 6: Erosion depth over time for various altitudes.

This is due to the fact that the ratio of the reaction rate constant to the diffusion constant is rather small and hence($\frac{K_{ox}}{D} tox$)which is inversely related to the rate of growth is rather small and the oxide layer would need to grow to a considerable thickness before the oxidation process becomes limited by diffusion and hence slows down. However, the continual removal of the oxide layer which is accounted for in the last term ($-JE\varphi$) ensures that the oxide thickness continually decreases due to flaking and hence, the erosion depth will continue to grow at a relatively constant rate for a long period of time (< 20 years).

To perform validation, we did a comparison with SPENVIS results, as shown in Fig. 6:

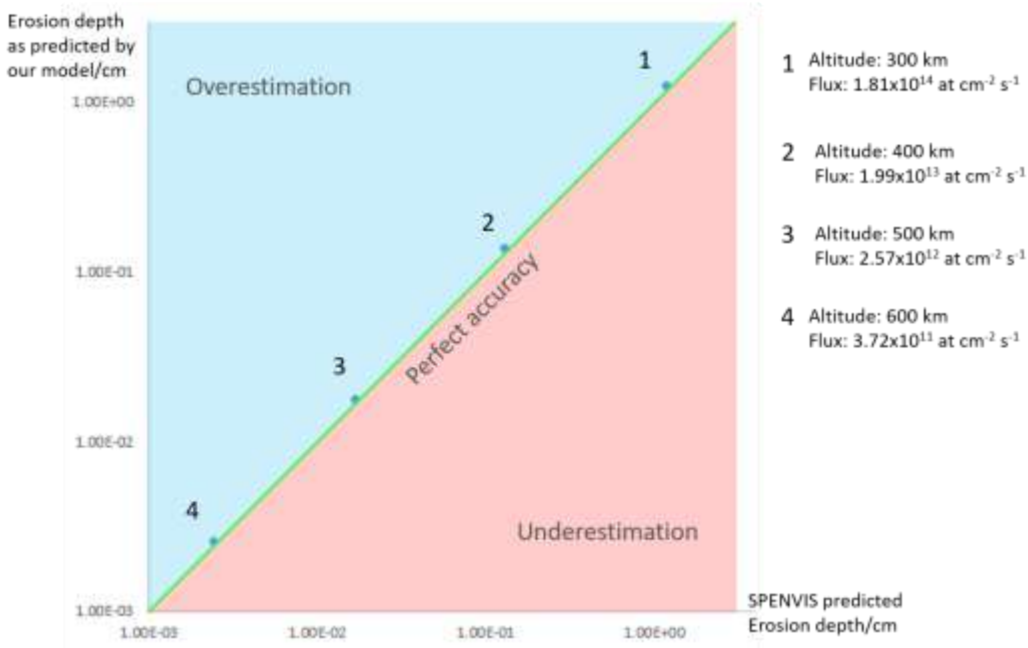

Fig. 7: Comparison between SPENVIS results and our model's predictions

All of our predictions fall very closely along the green line which has a gradient of 1 and represents a complete match between SPENVIS's results and our model. This proves that although simplistic in nature, our model is rather accurate (using SPENVIS data as the standard), thus being a potential model which can reduce computational power while not compromising on the accuracy of the predictions made on the erosion depth.

IV. Discussion/Applications

For a satellite's natural decay due to atmospheric drag, there is little one can do to stop its decay assuming that the spacecraft's station-keeping capabilities are compromised. Knowledge of how the satellite's orbit will decay over time can help influence design decisions such as the amount of propellant to carry on the spacecraft in order to perform station-keeping, allowing us to perform a cost-benefit analysis based on the amount needed to station-keep versus the weight (and thus, cost) that would be added to the spacecraft.

Shielding can drastically reduce the radiation dose and therefore reduce the damage to the sensitive electronics in the spacecraft. High nuclear charge and atomic weight materials such as gold are more effective at shielding against protons than lighter materials such as aluminium. However, the high cost of using such materials is problematic. Thus, a combination of shielding materials could be used such as gold coated aluminium foil. Cheaper dense materials such as bismuth could also be explored.

For atomic oxygen, the erosion depth of the oxygen will allow us to calculate the damage done to the material in question and reverse-engineer the satellite such that even at the end of the prospective mission lifetime, the satellite would still have enough power/shielding to function as per normal. The engineers can then decide whether it is necessary to apply a protective layer above the silver connectors.

In summary, to estimate the mission lifetime of any given satellite, one way is to estimate the time it takes for the satellite (and mission) to fail due to all possible individual factors, compare these values for the shortest one in order to gain a rough estimation of its lifetime.

V. Acknowledgements

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VI. References

[1] Jerold, E. 2009. Space Basics: Orbital Mechanics: p72. In: Handbook of Space Engineering, Archaeology, and Heritage. Ann, G.D. Beth L.O. CRC Press, U.S.A.
[2] Tsoline, M. 2001. Spacecraft Charging and Hazards to Electronics in Space. Physics of the Space Environment: 21.
[3] Tsoline, M. 2001. Spacecraft Charging and Hazards to Electronics in Space. Physics of the Space Environment: 22.
[4] Elena, M.D. 2017. Energy-Dependent Proton Damage In Silicon: 43-62.
[5] S.R. Messenger, M.A. Xapsos, E.A. Burke, R.J. Walters, and G.P. Summers. 1997. Proton Displacement Damage and Ionizing Dose for Shielded Devices in Space. IEEE Transactions On Nuclear Science, Vol. 44, No. 6: 2169-2173.
[6] A.., & Rooij, D. (1999). Product Assurance and Safety Department , ESTEC , Noordwijk , The Netherlands The Oxidation of Silver by Atomic Oxygen.ESA Journal 1989, Vol. 13, 364-366
[7] John K. 1999. Satellite Orbital Decay Calculations: 1-11.
[8] M. Torky, A. E. Hassanein, A. H. El Fiky and Y. Alsbou. 2019. Analyzing Space Debris Flux and Predicting Satellites Collision Probability in LEO Orbits Based on Petri Nets. IEEE Access, vol. 7: 83461-83473.
[9] George, G., James, A., Dale, A., Walter, F., Nicholas, J., Donald, K., Stephen, K., Dietrich, R., Susumu, T. and Stanislav, V. 1995. Hazards to Space Operations from Debris, p79-99. In: Orbital Debris: A Technical Assessment. National Academy Press. Washington, D.C.
[10] Kanevskii, L.S. & Dubasova, V.S. 2005. Degradation of lithium-ion batteries and how to fight it: A review. Russian Journal of Electrochemistry, vol. 41: 1-16.
[11] Martin, O.B. 1964. The Calculation Of Proton Penetration And Dose Rates: p1-5. In: Nasa Technical. Memorandum. George C. Marshall Space Flight Center Huntsville, Alabama.
[12] Michael, F.L. 2012. Radiation Physics and Radionuclide Decay: Stopping power and Linear energy transfer:p133-135. In:Handbook of Radioactivity Analysis (Third Edition). Academic Press
[13] Amable, Anthony & Godsway, Banini & Nyaaba, Rudolf & Manson, Eric. (2017). Theoretical Study of Stopping Power and Range For Low Energy (<3.0mev) Protons In Aluminium, Germanium, Lead, Gold and Copper Solid Materials.p5-7. DOI:10.13140/RG.2.2.13069.18404.