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Relative Impact of Spacecraft Payload Mass Fraction on Spacecraft Operations and Lifespan

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Abstract: Spacecraft payloads are the sensing components that remain active over time and ensure Spacecraft's capability to perform multiple operations. It determines the rate of mission extension and the amount of scientific return based on extended performance. But it degrades over time due to the continuous process of operation and several space environmental factors. This paper has estimated payload mass fraction using the Spacecraft's data to relate it to the lifetime of orbital Spacecraft. Our prime intent is to check whether the spacecraft payload mass fraction affects the Spacecraft's lifetime concerning the initial hypothesis that the spacecraft mass greatly influences spacecraft lifetime. We derive some mathematical relation and establish a relationship between spacecraft payload mass fraction and lifetime. Finally, to verify our relation, we employ spacecraft data to investigate and interpret reliability behavior based on payload fraction and lifetime relation.

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1. Acronyms and Subscripts

m_G	-	Gross mass of the spacecraft (kilograms)
m_D	-	Dry mass of the spacecraft (kilograms)
m_{PP}	-	Propellant mass (kilograms)
m_{PL}	-	Payload mass (kilograms)
δ	-	Spacecraft payload mass fraction
δ_G	-	Spacecraft payload mass fraction concerning gross mass
δ_D	-	Spacecraft payload mass fraction concerning dry mass
t	-	Mission lifetime of the spacecraft (years)
k	-	Inverse proportionality constant

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2. Introduction

Spacecraft payloads and their numbers are determined based on their target of exploration, where their number of instruments reflects their multiple capabilities to accomplish numerous objectives. So, the number of payloads proportionate to the spacecraft mass also has a significant contribution to the spacecraft's lifetime. Concerning our preceding paper and literature analysis on spacecraft reliability based on mass category [1-5], we investigate how the payload mass fraction has a significant contribution to the spacecraft's lifetime. We use spacecraft data such as spacecraft payload mass, dry mass, and gross mass to estimate and introduce a novel spacecraft parameter called "spacecraft payload mass fraction." We then relate it to the lifetime of the orbital Spacecraft. Finally, we derive and verify the payload fraction-lifetime relation using the spacecraft data gathered from SpaceTrak.

3. Research Methodology

- The first phase of our study reviews the significance of reliability and spacecraft lifetime based on earlier analysis and investigation reports **[1-5]**.
- We define and introduce a novel spacecraft parameter called "Spacecraft's Payload Mass Fraction", based on the spacecraft reliability analysis over various mass categories and mass fractions.
- Then, we gather spacecraft data from **[6,7]** in terms of Spacecraft's gross mass, dry mass, propellant mass, maximum payload mass, elapsed lifespan, and design lifetime.
- Overall, we gathered a data sample of 9000+ inactive, retired, and active Spacecraft from the International registered database "SpaceTrak," as of 1st May 2021. Out of 9000+ data. We have sorted out 236 data samples that are complete with full data descriptions.
- Then using the gathered data, the spacecraft payload mass fraction (δ_D, δ_G) were estimated using the introduced mass fraction relation defined in equation (1-2).
- Further, the estimated data were plotted against the Spacecraft's lifetime, followed by the execution of the linear curve fitting algorithm.
- We established a relation between the Spacecraft's payload mass fraction and its lifetime employing the curve fitting results.
- Based on the resultant graphs, we estimated the slope parameter (Δ) whose inverse gives the ratio of payload mass fraction and lifetime.
- Furthermore, we have defined the Spacecraft's lifetime equation (t) concerning distinct mass category (δ). We then plot the lifetime equation to discuss how the spacecraft mass fraction affects the spacecraft lifetime (t).
- Finally, we discuss the possible causes responsible for the difference in lifetime behavior characteristics and have recommended some effective countermeasures for enhancing lifetime.

4. Formulations

4.1. Spacecraft Payload Fraction

Technically, in aerospace engineering, the payload fraction is estimated for launch vehicles with respect to payload mass. It is the measure of payload mass to the mass of the launch vehicle. Similarly, we can extend this approach to estimate payload fraction for Spacecraft because it gives satisfactory results in terms of spacecraft lifetime (t). To extend this approach, we use the same convention as a payload fraction to introduce "Spacecraft payload fraction," which is the measure of the ratio of payload mass (i.e., the total mass of onboard instruments) to either gross mass and dry mass. Mathematically, we can write the ratio as,

$$\boldsymbol{\delta_G = \frac{m_{PL}}{m_G}} \qquad \text{Eq(1)}$$

(and)

$$\boldsymbol{\delta_D = \frac{m_{PL}}{m_D}} \qquad \text{Eq(2)}$$

5. Relating the Spacecraft's Payload Fraction with Lifetime

5.1. Spacecraft's Payload Fraction with Lifetime Relative to Gross Mass

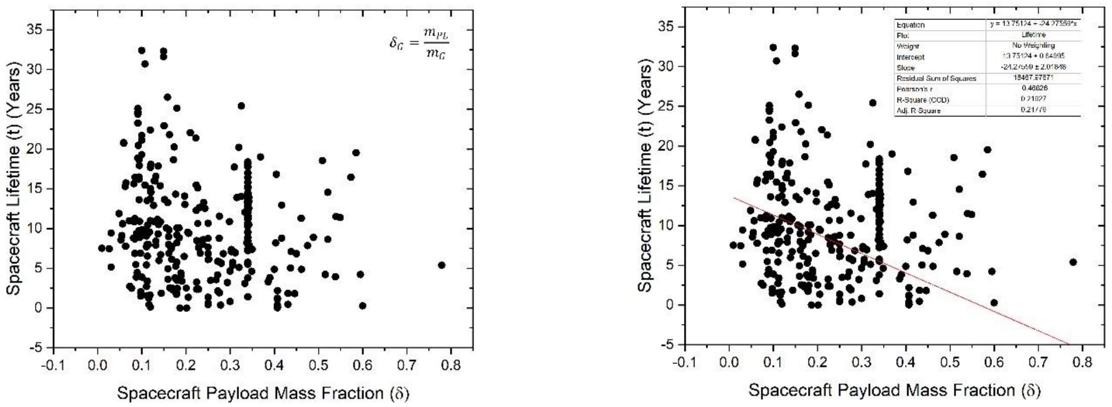

Figure 1 Linear Curve Fit for the Spacecraft Payload Mass Fraction (δ_G) and Lifetime (t)

Our gathered data samples have only 130 rows with complete data, and it is not sufficient to interpret the results. Hence, we collected data of active Spacecraft's data as of 1 May 2021, and we gathered 236 data samples of all Spacecraft. Linear fit over spacecraft payload mass fraction showed the following results. It reflects that the Spacecraft's payload fraction is inversely proportional to the lifetime of orbital Spacecraft. Hence,

$$\boldsymbol{\delta} \propto \frac{\mathbf{1}}{\boldsymbol{t}} \qquad \text{Eq(3)}$$

$$\delta = k\,\frac{1}{t}$$

$$t = \frac{k}{\delta} \qquad \text{Eq(4)}$$

$$k = \delta t \qquad \text{Eq(5)}$$

Where,
k – Inverse proportionality constant
$\boldsymbol{\delta}$ - Spacecraft's Payload Mass Fraction
t - Spacecraft's lifetime (years)

Equation (4) establishes the relationship between spacecraft payload mass fraction and lifetime.

5.2. Spacecraft's Payload Mass Fraction with Lifetime Relative to Gross Mass (Fueled & Unfueled)

Rewriting the equation (4) for Spacecraft's payload mass fraction concerning gross mass

Spacecraft payload fraction for gross mass (with fuel)

$$\boldsymbol{k = \delta_G(t)} \qquad \text{Eq(6)}$$

$$t = \frac{k}{\left(\frac{m_{PL}}{m_G}\right)}$$

$$t = k\left(\frac{m_G}{m_{PL}}\right) \qquad \text{Eq(7)}$$

The above equation gives the lifetime of Spacecraft concerning payload mass fraction against gross mass (δ_G).

5.3. Estimating the Slope Parameter from Graph

From figure 1, the slope gives the ratio of a lifetime and the Spacecraft's payload mass fraction.

$$\boldsymbol{Slope}\ (\Delta) = \frac{\boldsymbol{t}}{\boldsymbol{\delta_G}} \qquad \text{Eq(8)}$$

Then the inverse of the slope gives the ratio of Spacecraft's payload mass fraction and lifetime. The slope parameters are found to be (**Δ= -24.27559±2.01848),** and its inverse gives

$$\frac{\mathbf{1}}{\boldsymbol{Slope}\ (\Delta)} = \frac{\boldsymbol{\delta_G}}{\boldsymbol{t}} = \mathbf{-0.04119} \qquad \text{Eq(9)}$$

Finally, the equation for the lifetime of the Spacecraft is

$$\boldsymbol{t} = \frac{\boldsymbol{k}}{\boldsymbol{\delta_G}}\ (\boldsymbol{Years}) \qquad \text{Eq(10)}$$

Plotting the resultant equation shows the following results

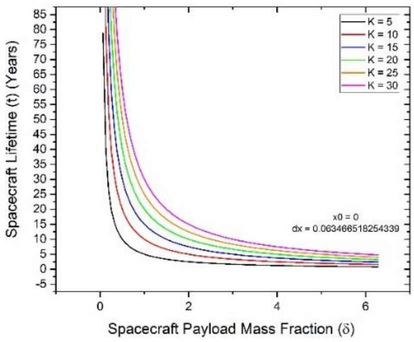

Figure 2 Resultant Equation Plot for Spacecraft Payload Mass Fraction and Lifetime ($\boldsymbol{\delta_G}$)

6. Spacecraft's Payload Fraction with Lifetime Relative to Dry Mass

6.1. Formulations

Employing equation (2), we estimated payload mass fraction against dry spacecraft mass using 236 data samples. Then the data were plotted against Spacecraft's lifetime to perform a linear curve fit. The fitting function showed the following results.

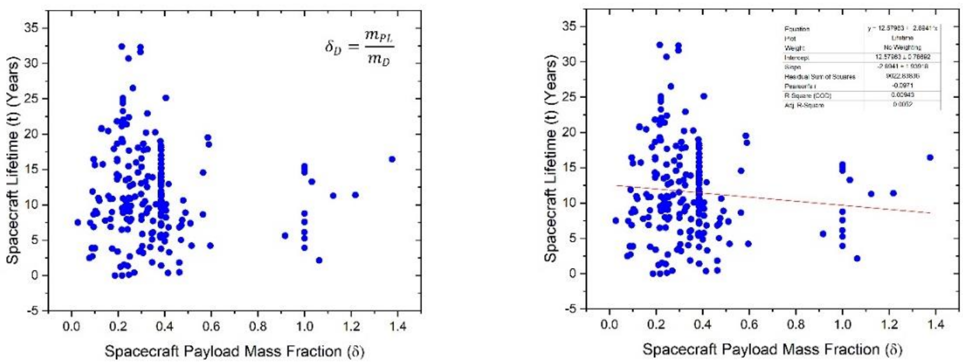

Figure 3 Linear Curve Fit for the Spacecraft Payload Fraction (δ_D) and Lifetime (t)

The results show that the spacecraft payload mass fraction concerning dry mass is inversely proportional to the lifetime of the Spacecraft.

$$\boldsymbol{\delta_D} \propto \frac{\mathbf{1}}{\boldsymbol{t}} \qquad \text{Eq(11)}$$

$$\delta_D = k\,\frac{1}{t}$$

$$t = \frac{k}{\delta_D} \qquad \text{Eq(12)}$$

$$k = \delta_D t \qquad \text{Eq(13)}$$

Where,

$\boldsymbol{k}$ – Inverse proportionality constant

$\boldsymbol{\delta_D}$ - Spacecraft's Payload Mass Fraction

$\boldsymbol{t}$ - Spacecraft's lifetime (years)

The equation (4) establishes the relationship between spacecraft payload mass fraction ($\boldsymbol{\delta_D}$) and lifetime.

Rewriting the equation (13) for spacecraft's payload mass fraction ($\boldsymbol{\delta_D}$)

Spacecraft payload fraction for dry mass (without fuel)

$$\boldsymbol{k = \delta_D(t)} \quad \text{Eq(14)}$$

$$t = \frac{k}{\left(\frac{m_{PL}}{m_D}\right)}$$

$$t = k\left(\frac{m_D}{m_{PL}}\right) \quad \text{Eq(15)}$$

The above equation gives the lifetime of Spacecraft concerning payload mass fraction against dry mass.

6.2. Estimating the Slope Parameter from Graph

From figure 3, the slope gives the ratio of a lifetime and the Spacecraft's payload mass fraction.

$$\boldsymbol{Slope}\ (\Delta) = \frac{\boldsymbol{t}}{\boldsymbol{\delta_D}} \quad \text{Eq(16)}$$

Then the inverse of the slope gives the ratio of Spacecraft's payload mass fraction and lifetime. The slope parameters are found to be (Δ**= 12.57963±0.78692),** and its inverse gives

$$\frac{\boldsymbol{1}}{\boldsymbol{Slope}\ (\Delta)} = \frac{\boldsymbol{\delta_D}}{\boldsymbol{t}} = \boldsymbol{0.0795} \quad \text{Eq(17)}$$

Finally, the equation for the lifetime of the Spacecraft is

$$\boldsymbol{t} = \frac{\boldsymbol{k}}{\boldsymbol{\delta_D}}\ (\boldsymbol{Years}) \quad \text{Eq(18)}$$

Plotting the resultant equation shows the following results

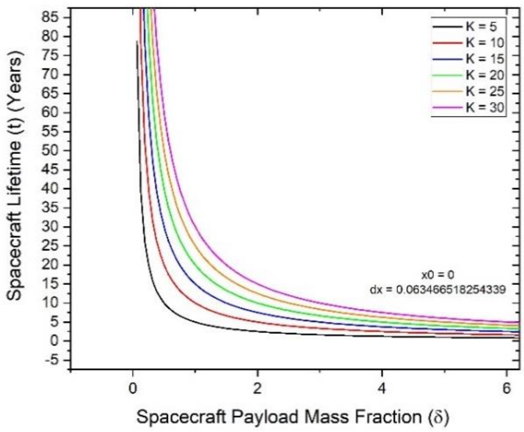

Figure 4 Resultant Equation for the lifetime of the Spacecraft concerning payload mass fraction ($\boldsymbol{\delta_D}$)

7. Results and Conclusion

This paper has established a relationship between the spacecraft payload mass fraction and its lifetime concerning our previous technical reports **[3, 4]**. The novelty of this paper is the introduction of "Spacecraft Payload Mass Fraction," which measures the ratio of payload and dry or gross mass. In addition to this, we have also derived the lifetime equation of space probes based on payload mass fraction. Further, we intend to perform reliability analysis over Spacecraft of distinct payload mass fraction parallel to other reliability analysis over spacecraft mass and propellant mass fraction. Furthermore, we are currently under study to perform reliability analysis over inactive and retired Spacecraft concerning propellant mass and gross mass category **[7-11]**.

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9. Biography

Malaya Kumar Biswal, the Founder & CEO of Acceleron Aerospace in Bangalore, India, is a pioneering entrepreneur and esteemed scientist in the field of aerospace engineering. With a strong background in aerospace engineering and a passion for space exploration, Biswal has made significant contributions to the industry. After completing his bachelor's degree in Aerospace Engineering, Biswal joined Grahaa Space as a Senior Research Scientist. During his time there, he focused on satellite reliability, aerospace design and structures, and research and development for space science and applications. His expertise and innovative mindset led him to publish over 35 papers in prestigious conferences, including AIAA, IAA, IAC, and LPSC.

Driven by his entrepreneurial spirit, Biswal founded Acceleron Aerospace, where he currently serves as the CEO. Under his visionary leadership, the company is at the forefront of revolutionizing the aerospace industry. Biswal's research interests lie in human Mars exploration, and he envisions ambitious missions to Mars and even the celestial body Ceres. Biswal's remarkable achievements and expertise have earned him recognition and respect within the scientific community. He is considered a thought leader in aerospace engineering, with a relentless dedication to pushing the boundaries of human space exploration.

Beyond his professional pursuits, Biswal actively promotes the popularization of space science and technology. He mentors aspiring scientists and enthusiasts, inspiring them to pursue their own journeys of discovery and innovation. Malaya Kumar Biswal's unwavering dedication, combined with his exceptional expertise, continues to shape the field of aerospace engineering. His legacy serves as an inspiration to those who strive for advancements in space science and technology, paving the way for future generations of space pioneers.

10. Acknowledgements

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11. Funding Resources

No external funding was received to support this study.

12. Conflict of Interest

The authors have no conflict of interest to report

13. Data Availability

The data to support this study was supported by Seradata's SpaceTrak Database and Tim Fuller, CEO on premium basis.

14. Supplementary Resources

Theory and Modelling of Various Spacecraft Mass Fractions and their Influence over Spacecraft Lifespan and Reliability. In ASCEND 2021. https://arc.aiaa.org/doi/abs/10.2514/6.2021-4220

Spacecraft Reliability and Lifetime Modelling: Impact of Spacecraft Mass and Mass Fractions on Spacecraft Lifespan and Reliability. In AIAA Science and Technology Forum and Exposition 2022 Forum. https://arc.aiaa.org/doi/abs/10.2514/6.2022-1140