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Statistical Reliability Analysis of Interplanetary Spacecraft Operating at Different Interplanetary Extremity

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Abstract: The success of spacecraft depends on their reliability which is influenced by the space environment complexity. This study examines the reliability of interplanetary spacecraft in different regions. We focused on spacecraft in interplanetary space, specifically within the interplanetary boundary. Our analysis excluded planetary landers, probes, and satellites in Earth orbit. 131 spacecraft were studied, with data on launch mass and lifespan recorded. Non-parametric analysis was initially conducted, followed by parametric analysis using the Weibull Distribution. Results showed higher reliability for spacecraft beyond Earth and Mars extremities. Analyses were also done based on spacecraft mass categories to validate reliability effects. Various factors affecting reliability were discussed, including design, integration processes, testing methodologies, and mass constraints.

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Nomenclature

$\overline{R}$ = Mean Reliability of the Spacecraft
$\hat{R}(t)$ = Reliability function (Kaplan-Meier)
$S_f(t)$ = Weibull Distribution function for the spacecraft
EH = Earth-Heliopause
LCL = Lower Confidence Level
R(t) = Weibull Reliability function
SE = Sun-Earth
t = Lifespan (Years)
AU = Astronomical Unit

Var = Variance
Γ = Gamma function
λ (t) = Hazard function / Hazard rate
β = Shape parameter
UCL = Upper Confidence Level
η = Scale parameter
σ = Standard Deviation
τ = Mean life of the spacecraft
ESA = European Space Agency

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Interplanetary Boundary Conditions

- ***SE-Extremity:*** This refers to the region of interplanetary space extending from the proximity of the Sun to the vicinity of the Earth.
- ***EH-Extremity:*** This denotes the region of interplanetary space extending from the proximity of the Earth to the farthest point of the Solar System, often referred to as the Heliopause.

1. Introduction

Reliability of spacecraft stands as a pivotal parameter dictating the extent of mission accomplishment, as any lapse in reliability can lead to mission failure. While scientists and data analysts have extensively studied the reliability of earthbound satellites and on-orbit spacecraft failures, little attention has been given to spacecraft operating in different interplanetary boundary and space environments [1-6]. No statistical analyses have been identified in past technical literature regarding this perspective. In order to further the study of reliability analysis and validate the reliability effect proposed by Dubos in 2010, we have gathered spacecraft data, including gross mass at launch and lifespan in years, from sources spanning the period from 1960 to 2020. Our data collection encompasses various sources, including [7-9] and relevant online resources of space agencies. This dataset enabled us to conduct both non-parametric and parametric estimations. Our analysis revealed that spacecraft operating beyond the extremity of Earth and Mars demonstrate the highest reliability compared to any other interplanetary extremity. Finally, we present graphical representations of our findings and discuss potential causes contributing to the substantial increase in reliability observed at the EH-Extremity, along with the reduced reliability at the SE-Extremity.

2. Research Methodology and Data Description

2.1. Research Methodology

- Our analysis utilizes spacecraft data classified into categories of success, partial success, failed (with lifespan estimated until its last active state), and ongoing active spacecraft (with lifespan estimated based on the elapsed time as of October 2020) situated in interplanetary space. The dataset includes information on each spacecraft's gross mass in kilograms and lifespan in years.
- The data were organized into two main categories: SE extremity and EH extremity. This categorization excludes data from planetary landers, sample return and atmospheric probes, impactors, and rovers. We conducted statistical analyses employing both non-parametric (Kaplan-Meier estimation) and parametric (Weibull probability) estimation methods over the spacecraft data. This analysis was carried out in two iterations: iteration-1 for the SE extremity and iteration-2 for the EH extremity.
- Subsequently, we repeated the reliability analysis procedure using spacecraft data categorized into various mass categories: Small (0-500kg), Medium (500-2500 kg), and Large (>2500kg). This comparison aimed to validate and elucidate the reliability effects identified by G.F. Dubos.
- Finally, based on the results obtained, we discuss potential causes responsible for the variance in reliability behavior observed among spacecraft operating in different interplanetary environments.

2.2. Data Description and Categorization

For our analysis, spacecraft data were collected from sources [7-9], comprising information on each spacecraft's gross mass in kilograms and lifespan in years spanning the period from 1960 to 2020. The data collection template is depicted in Table-1. Our database encompasses a total of 131 spacecraft, including successful, partially successful, failed, and active missions. To ensure homogeneity, sister spacecraft with similar lifespans were grouped together. Additionally, en-route space missions were excluded from our database for further analysis. For instance, missions such as the Emirates Mars Mission and the Mars 2020 Rover were eliminated. Finally, the overall dataset was categorized based on extremity conditions, with 82 spacecraft falling under the SE-Extremity category and 49 under the EH-Extremity category.

Table 1 Sample Template of Data Collection

Spacecraft Name	Launch Date	Failure/Decay Date	Launch Mass (kg)	Lifespan (Years)
Pioneer 5	11 Mar 1960	26 Jun 1960	63	0.30
Pioneer 6A	16 Dec 1965	08 Dec 2000	63	34.94
….	….	….	….	….
New Horizons	19 Jan 2006	XX Oct 2020*	401	14.66

***lifespan estimated for ongoing missions as of October 2020**

3. Formulations

3.1. Kaplan-Meier Estimation

Kaplan-Meier is indeed a non-parametric statistical estimation method commonly used to analyze survival data, such as spacecraft lifespans. To adapt the Kaplan-Meier equation for estimating spacecraft reliability at different interplanetary boundaries based on their lifespan data, we can modify the expression as follows.

$$\widehat{R}(t)=\prod_{t_i\leq t}\left(1-\frac{s_i}{n_i}\right) \tag{1}$$

s_i - number of spacecraft operating or accomplished its mission intent
n_i - number of spacecraft failed at time t
t_i - initial time after leaving low earth orbit
t - time elapsed for the spacecraft to accomplish its intent/ time elapsed at the current operating state.

3.2. Weibull Distribution

Similar to Kaplan-Meier estimation, Weibull probability distribution (parametric function) is used to estimate the reliability analysis for electronic components and spacecraft subsystems. Here, we define the Weibull distribution function for the spacecraft at appropriate extremity as

$$S_f(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

where β is the shape parameter, η is the scale parameter, and t is the lifespan of spacecraft in years.

Relation of Failure rate with $\boldsymbol{\beta}$: (i) for $\beta<1$ defines that the failure rate decreases with time (lifespan), (ii) for $\beta\simeq1$ the spacecraft has a fairly constant failure rate, and (iii) for $\beta>1$ the failure rate of the spacecraft increases with time(lifespan).

Reliability of the Spacecraft

Weibull Reliability expression for the spacecraft from parametric estimation can be defined as

$$R(t)=e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

where the reliability is the exponential function of scale parameter η and shape parameter β.

Hazard Function of the Spacecraft

The hazard function or hazard rate $\lambda(t)$ of the spacecraft can be defined as the ratio of Weibull distribution function to Weibull reliability that can be mathematically written as

$$\lambda(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{4}$$

Mean Reliability and Median life of the Spacecraft

The expression for the mean and median life of the spacecraft can be defined from the Weibull distribution function that can be written as

$$\text{Mean Reliability } \overline{R}=\eta\,\Gamma\left(\frac{1}{\beta}+1\right) \tag{5}$$

$$\text{where } \Gamma \text{ is the gamma function } \Gamma(n)=\int_0^{\infty} e^{-t}\, t^{n-1}\, dt \tag{6}$$

$$\text{Median Life} \qquad \tau=\eta(\ln(2))^{\frac{1}{\beta}} \tag{7}$$

Variance from Weibull Distribution Function

$$\textbf{Variance}=\eta^2\left[\Gamma\left(1+\frac{2}{\beta}\right)-\left(\Gamma\left(1+\frac{1}{\beta}\right)\right)^2\right] \tag{8}$$

4. Non-Parametric and Parametric Analysis of Spacecraft Reliability

4.1. Non-Parametric Kaplan-Meier Estimation

Our database holds three types of data samples 1) time to the successful mission accomplishment, 2) time to the failure of spacecraft, and 3) time to the ongoing/active missions. This study intends to understand the reliability behaviour of the spacecraft when exposed to the distinct interplanetary environment. So, we have performed a powerful Kaplan-Meier estimation with random data censoring. The lifespan of the spacecraft in years was inputted as time range with random data censoring.

4.2. Parametric Weibull Probability Distribution

To understand the analogy of reliability behaviour exhibited by interplanetary spacecraft by the Kaplan-Meier method, we perform the Weibull probability distribution function over the spacecraft data. The procedure follows random data censoring and Weibull analysis over the lifespan (in years) of spacecraft by maximum likelihood estimation of single Weibull fit. Relevant equations and formulations are shown in equation (1-8).

5. Results

5.1. Non-Parametric Results for SE-Extremity

The Kaplan-Meier estimation reveals that spacecraft operating within the boundary of the Sun and Earth demonstrate 48% reliability after 2 years of operation, with the potential to maintain approximately 30% reliability after 6 years. Additionally, at this extremity, spacecraft experience a hazard rate of 10% after 4 years and 20% after 15 years of operation. Figure 1 illustrates the reliability behavior of spacecraft at the SE-Extremity.

5.2. Non-Parametric Results for EH-Extremity

Similarly, spacecraft operating between the bounds of Earth and the farthest point of the Solar System (i.e., the Heliopause) demonstrate 60% reliability after 2 years of operation, with the potential to maintain approximately 40% reliability after 6 years. Within this extremity, spacecraft are subject to a hazard rate of 10% after 6 years and 20% after 18 years of operation. These reliability trends are depicted in Figure 2.

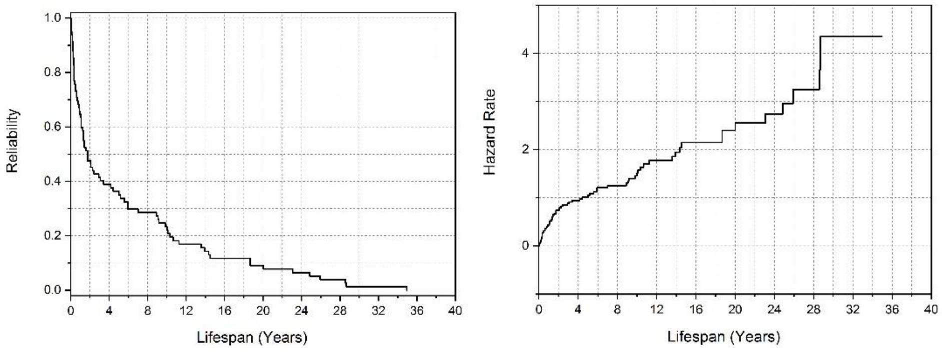

Figure-1 Kaplan-Meier Curve for Reliability and Hazard Rate of Interplanetary Spacecraft at SE-Extremity

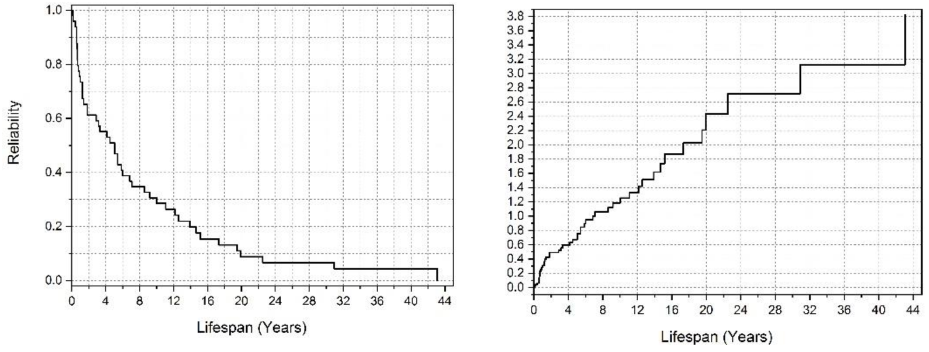

Figure 2 Kaplan-Meier Curve for Reliability and Hazard Rate of Interplanetary Spacecraft at EH-Extremity

5.3. Parametric Results for SE-Extremity

Parametric estimation using the Weibull Distribution indicates that spacecraft operating within the boundary of the SE-Extremity exhibit 35% reliability after 4 years of operation, with a 95% upper confidence level of 48% and a lower confidence level of 30%. These spacecraft can function for a maximum duration ranging from 36 to 38 years. At this extremity, spacecraft encounter a 20% hazard rate after 2.5 years, which gradually decreases as the lifespan of space probes increases. Refer to Figure 3 for visualization of these trends.

5.4. Parametric Results for EH-Extremity

In contrast to the SE-Extremity, spacecraft operating between the boundary of Earth and the outer limits of the Solar System demonstrate 52% reliability after 4 years of operation, with a 95% upper confidence level of 70% and a lower confidence level of 48%. These spacecraft experience a 10% hazard rate after 12.5 years of operation, which diminishes relative to an increase in lifespan. This trend is illustrated in Figure 4. Furthermore, spacecraft at this boundary can endure for a maximum of 48 years of operation.

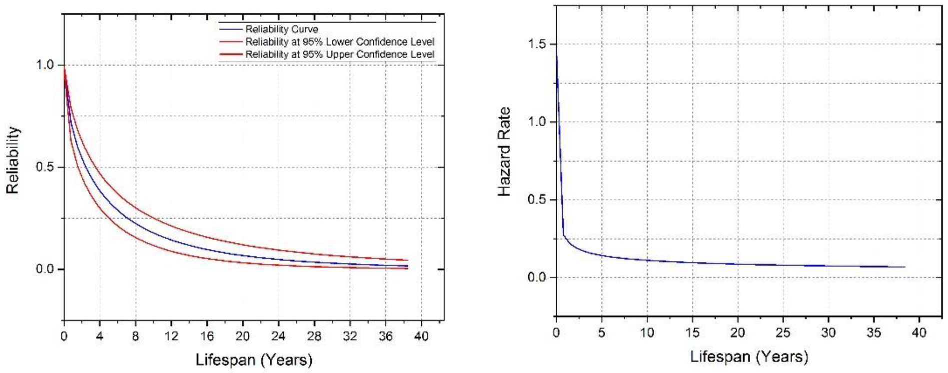

Figure-3 Weibull Curve for Reliability and Hazard Rate of Interplanetary Spacecraft at SE-Extremity

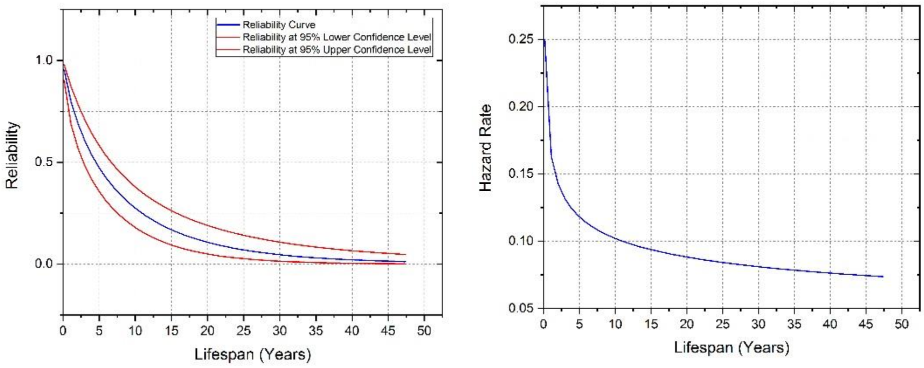

Figure-4 Weibull Curve for Reliability and Hazard Rate of Interplanetary Spacecraft at EH-Extremity

6. Comparison of Results

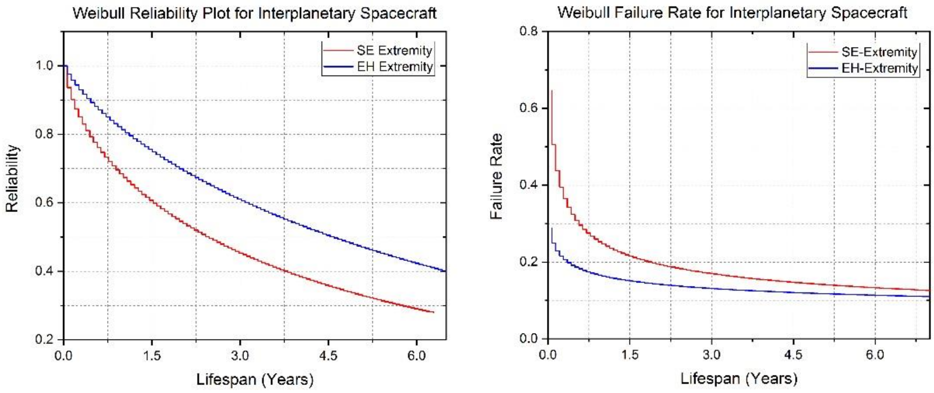

Figure-5 Weibull Reliability and Failure Rate Plot for Interplanetary Spacecraft at SE & EH-Extremity

Comparing both parametric and non-parametric results in terms of reliability behaviour and hazard rate of interplanetary spacecraft inhered in two interplanetary boundaries, we have found that the boundary limit from the Earth to the Heliopause renders a promising environment for substantial reliability than the Sun-Earth boundary. Our analysis shows that the approximate mean reliability of spacecraft at SE-Extremity is 58% which is smaller than 74% at EH-Extremity with a variance of Var_{SE}=0.0238 to Var_{EH}=0.0145 shown in table 4. More precisely the reliability behaviour can be understood from the equations

$$\mathrm{R(t)_{SE}}=\mathrm{e}^{-\left(\frac{\mathrm{t}}{4.29271}\right)^{0.64439}} \quad \text{and} \quad \mathrm{R(t)_{EH}}=\mathrm{e}^{-\left(\frac{\mathrm{t}}{7.23227}\right)^{0.79025}} \qquad \text{(9) and (10)}$$

Similarly, both extremity shows a shape parameter (β=0.644 at SE-Extremity) and (β=0.790 at EH-Extremity) shown in table 4. And overall shape parameter is found to be less than unity (i.e. β<1). The parameter β<1 depicts the failure rate or the hazard rate decreases with an increase in lifespan that can be precisely understood from the expressions,

$$\lambda\mathrm{(t)_{SE}}=0.150\left(\frac{\mathrm{t}}{4.29271}\right)^{0.64439\text{-}1} \quad \text{and} \quad \lambda\mathrm{(t)_{SE}}=0.109\left(\frac{\mathrm{t}}{7.23227}\right)^{0.79205\text{-}1} \qquad \text{(11) and (12)}$$

Further, the results and estimates from the non-parametric and parametric analyses are shown in the table-2. Estimated values calculated from equation (5, 7,8) are shown in table 4.

Table 2 Mean and Quartile Estimate from Kaplan-Meier Analysis

Quartile Estimate	SE-Extremity			EH- Extremity			Mean Estimate	SE-Extremity	EH-Extremity
Percent Failures	25	50	75	25	50	75	Estimate	5.9393	8.2871
Estimate	0.49	1.74	9.16	1.00	5.05	12.16	Standard Error	0.9128	1.4950
95% LCL	0.31	1.08	5.00	0.66	1.83	6.83	95% LCL	4.1501	5.3568
95% UCL	0.92	3.41	13.58	1.83	7.08	17.33	95% UCL	7.7284	11.2174

Table 3 Estimate from Weibull Probability Distribution Function

Weibull Parameters	SE-Extremity				EH-Extremity			
DF	1	1	1	1	1	1	1	1
Estimate	1.4569	1.5518	4.2927	0.6443	1.9785	1.2654	7.2322	0.7902
Standard Error	0.1820	0.1356	0.7816	0.0563	0.1918	0.1422	1.3875	0.0888
95% LCL	1.1000	1.3075	3.0043	0.5429	1.6025	0.0152	4.9656	0.6340
95% UCL	1.8137	1.8417	0.5429	0.7647	2.3545	1.5772	10.5336	0.9849

Table 4 Parametric Results of Spacecraft Reliability

Results	Notation	SE-Extremity	EH-Extremity
Shape Parameter	β	0.64439	0.79025
Scale Parameter	η	4.29271	7.23227
Variance	Var	0.0238	0.0145
Mean Reliability	$\bar{R}$	0.586	0.740
Mean Life	τ	2.4316	4.5413
Standard Deviation	σ	0.154330	0.120698

7. Hypothesis on Possible Causes Responsible for Distinct Reliability Behaviour

7.1. Distribution of Cosmic Radiation over Interplanetary Space

High-energy particles from cosmic rays and galactic cosmic rays pose significant risks to spacecraft electronics. Incidents such as the damage of electronic chips aboard the Fobos-Grunt mission highlight these dangers. Galactic cosmic rays, solar cosmic rays, and solar particle events are natural phenomena in space that can damage onboard circuitry and electronic components. Notable instances include the electrical system damage experienced by the Nozomi and Phobos spacecraft during their interplanetary transit to Mars. Spacecraft operating within the SE-Extremity, close to the Sun (0.4 - 1.0 AU), are particularly vulnerable to solar particle events and flares due to their proximity. Conversely, spacecraft operating within the EH-Extremity experience reduced vulnerability to solar events and cosmic radiation intensity. Observations from radiation measurements on Pioneer and Voyager spacecraft demonstrate a gradual decrease in cosmic radiation intensity away from the SE-Extremity. Solar events play a significant role in radiation distribution throughout the solar system environment. Therefore, the EH-Extremity offers a more promising environment for interplanetary spacecraft operation with increased reliability **[20-34]**.

7.2. Power Source of the Spacecraft

Spacecraft power is a critical component affecting reliability. Spacecraft operating at both extremities face challenges in power generation. Solar panels on spacecraft at the SE-Extremity degrade over time due to extreme temperatures and collision with particles during solar events, leading to power loss and decreased reliability. Similarly, spacecraft operating at the EH-Extremity face challenges in solar power generation due to decreased solar irradiance compared to the SE-Extremity and unavailability during solar conjunctions. However, spacecraft at the EH-Extremity may benefit from increased reliability due to the use of nuclear thermoelectric generators, as seen in probes like Voyager 1 and 2, and New Horizons, providing uninterrupted power throughout their missions **[20-34]**.

7.3. Space Environment and Temperature

The interplanetary space between the Sun and the Heliopause poses challenges to spacecraft operation and reliability. The SE-Extremity experiences extreme temperatures that affect spacecraft internal temperature stabilization. This temperature also influences fuel storage and electronic component efficiency or lifetime, impacting spacecraft reliability. In contrast, the EH-Extremity experiences lower temperatures due to reduced solar irradiance, providing a more stable environment for nuclear-powered spacecraft to maintain thermal stability and enhance reliability **[20-34]**.

7.4. Impact of Spacecraft Mass

Spacecraft mass, particularly fuel mass, significantly influences reliability. Fuel depletion can lead to failure of orientation and attitude control systems, resulting in spacecraft disposal despite functioning subsystems. Challenges in fuel management and cryogenic storage exist in both extremities, potentially leading to malfunction of attitude thrusters and decreased reliability. Therefore, spacecraft with a considerable fuel mass within the range of 500-2500 kg are desirable for reliable missions **[20-34]**.

7.5. Spacecraft Components, Design, Testing, and Integration

The quality of electronic components, spacecraft dimensions, integration, and testing procedures profoundly impact reliability. Electronic components used in older spacecraft like Pioneer and Voyager have demonstrated longevity beyond their estimated mission lifetimes, whereas modern components pose uncertainties in reliability. Large spacecraft are associated with complex hardware and wiring configurations, increasing the risk of human error during integration. Inadequate shielding, design flaws, and negligent fabrication also contribute to spacecraft reliability issues **[20-34]**.

8. Testification of Reliability Effect Interpreted by G.F.Dubos in 2010

Data Categorization and Censoring

In this section, the spacecraft data were sorted in ascending order concerning the gross mass. Then the overall data were distributed to the mass column of distinct mass category shown in table 5.

Table-5 Spacecraft Categorization

Spacecraft's Mass Category	Mass Range	Example at SE-Extremity	Example at EH-Extremity
Small	0-500 kg	Helios A & B, Genesis	Mariner 4, New Horizons
Medium	500-2500 kg	Venera 11 & 12, Messenger	Solar Orbiter, Voyager 1 & 2
Large	>2500 kg	Venera 14 and 15	Tianwen-1

There were 50 spacecraft in the small category, 55 spacecraft in the medium-sized category, and 26 spacecraft in the large category. These sorted data were analyzed over powerful Kaplan-Meier estimation and then with Weibull probability fit with random data censoring. Our analysis executed here is to address the question of whether the spacecraft's mass affects reliability. And to assert the reliability effect interpreted by Duboset.al.2010 employing Castet and Saleh spacecraft's reliability model **[1, 6]**.

9. Non-Parametric and Parametric Results for Mass Category

9.1. Non-Parametric Results (Kaplan-Meier)

Small Category: Our analysis indicates that spacecraft in this category achieve approximately 50% reliability after 2.5 years of operation in interplanetary space, extending up to 10 years with 20% reliability. These spacecraft can operate for a maximum lifespan of 20-25 years.

Medium Category: Spacecraft in this category demonstrate superior reliability compared to the other mass categories. Our analysis reveals that these spacecraft operate with 60% reliability after 2.5 years of continuous operation, extending up to 5 years with 55% reliability. Subsequently, they maintain 20% reliability for 13 years in interplanetary space. The maximum estimated lifespan for spacecraft in this category is 25-30 years.

Large Category: Spacecraft in this category exhibit approximately 30% reliability after 2.5 years of operation, with a hazard rate of 15%. Reliability decreases to 10% after 7 years, with a hazard rate of 25% at 7.5 years. Space probes within this mass limit are expected to function for a maximum lifespan of 10-13 years. Figure 6 illustrates the reliability and hazard rate estimated from the parametric analysis.

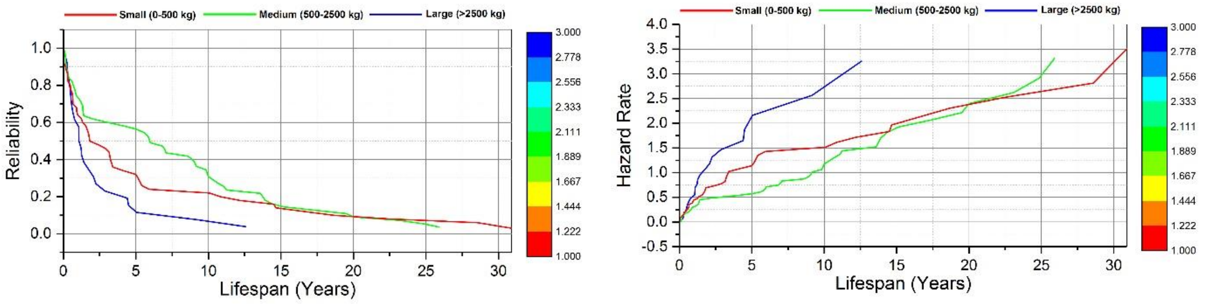

Figure-6 Kaplan-Meier Estimation: Reliability and Hazard Rate Plot for Various Mass Category

9.2. Parametric Results (Weibull Fit)

Small Category: The Weibull analysis indicates that spacecraft in this category achieve approximately 30% reliability after 7 years of operation, with a 95% upper confidence level of 40% reliability and a lower confidence level of 20%. The overall hazard rate experienced by these probes during their operational period ranges from 1% between 10-20 years.

Medium Category: Medium-sized spacecraft exhibit approximately 48% reliability after 5 years of operation, with a 95% upper confidence level of 60% reliability and a lower confidence level of 30%. These spacecraft have an overall hazard rate of 1% after 10 years of operation, which decreases relative to an increase in lifespan.

Large Category: Large-sized spacecraft with a mass exceeding 2500 kg demonstrate approximately 20% reliability after 5 years of operation, with a 95% upper confidence level of 50% reliability and a lower confidence level of 10%. These spacecraft have a maximum hazard rate of 3% after 5 years of operation and a minimum of 2% after 10 years. The reliability behavior of spacecraft across various mass categories and their hazard rates is depicted in Figures 7-8.

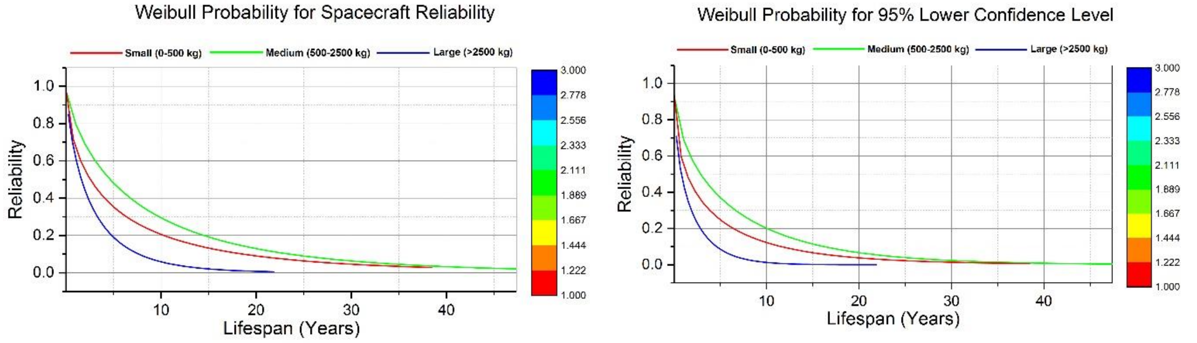

Figure-7 Weibull Analysis: Reliability and 95% LCL Reliability Plot for Various Mass Category

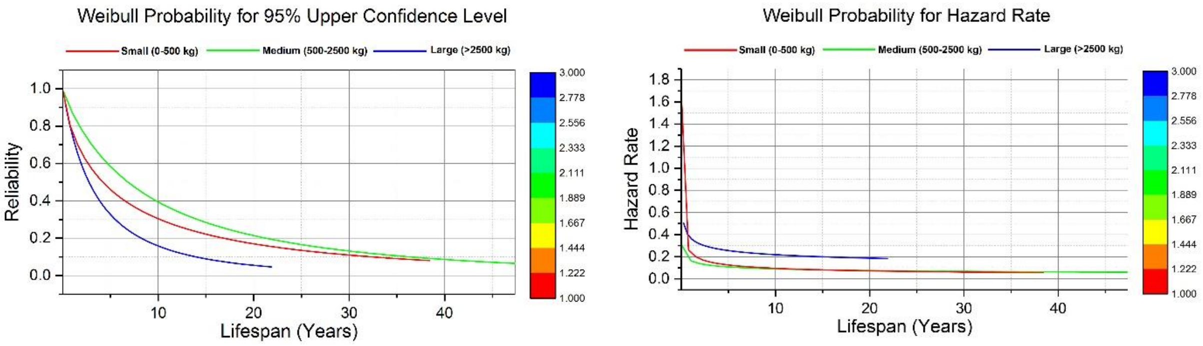

Figure-8 Weibull Analysis: 95% UCL Reliability and Hazard Rate Plot for Various Mass Category

9.3. Comparison of Results

In contrast to the results, medium-sized spacecraft exhibits superior reliability than the other two mass categories with the least hazard rate of 1%. It can be realized from the expression below

$$\text{Reliability, } R(t)_{\text{Medium}} = e^{-\left(\frac{t}{7.63407}\right)^{0.74117}} \tag{13}$$

$$\text{Hazard Rate, } \lambda(t)_{\text{Medium}} = 0.097\left(\frac{t}{7.63407}\right)^{0.74118-1} \tag{14}$$

where $\lambda(t)_{Medium}$ is the hazard function that decreases with an increase in the lifespan of medium-sized spacecraft.

The resultant plot for the Reliability and Hazard rate of the spacecraft from scale and shape parameter of various mass categories is shown in Fig 9. Further, Mean and Quartile estimate from Kaplan-Meier estimation and Weibull probability distribution is shown in table 6-8.

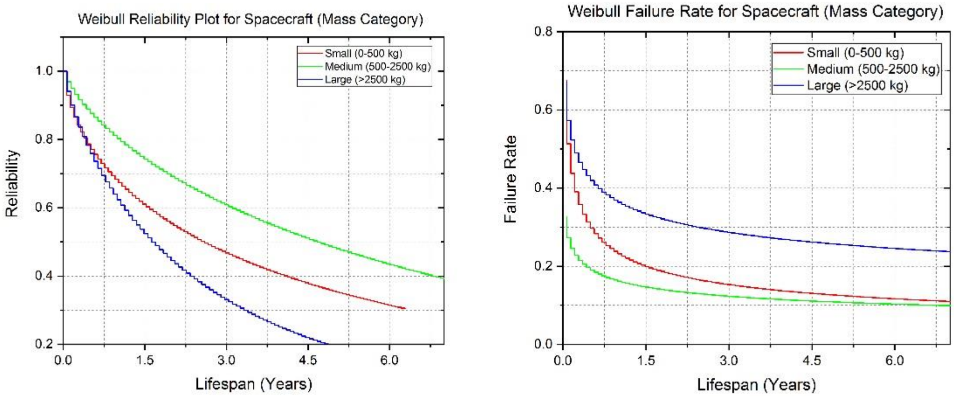

Figure-9 Weibull Probability: Reliability and Hazard Rate Plot for Various Mass Category

Table 6 Mean Estimate from Kaplan-Meier Analysis

Mean Estimate	Small Category	Medium Category	Large Category
Estimate	6.4262	8.5254	2.9407
Standard Error	1.3071	1.2933	0.8692
95% LCL	3.8642	5.9905	1.2371
95% UCL	8.9881	11.0603	4.6444

Table 7 Quartile Estimate from Kaplan-Meier Analysis

Quartile Estimate	Small Category			Medium Category			Large Category		
Percent Failures	25	50	75	25	50	75	25	50	75
Estimate	0.65	1.83	5.93	0.9	6	11.25	0.58	1.08	2.87
95% LCL	0.31	1.25	3.33	0.42	2.08	9.16	0.33	0.66	1.26
95% UCL	1.33	3.41	14.66	2.08	9.16	15.16	1.08	2.08	5.05

Table 8 Estimate from Weibull Probability Distribution

Parameters	Small Category				Medium Category				Large Category			
DF	1	1	1	1	1	1	1	1	1	1	1	1
Estimate	1.5467	1.6517	4.6960	0.6054	2.0326	1.3492	7.6340	0.7411	0.9586	1.2916	2.6082	0.7742
Standard Error	0.2478	0.1885	1.1637	0.0691	0.1924	0.1511	1.4693	0.0830	0.2704	0.1887	0.7054	0.1131
95% LCL	1.0610	1.3206	2.8893	7.6326	1.6553	1.0831	5.2351	0.5950	0.4285	0.9700	1.5350	0.5814
95% UCL	2.0324	2.0658	7.6326	0.7572	2.4098	1.6805	11.1322	0.9232	1.4887	1.7198	4.4315	1.0309

Table 9 Parametric Results of Spacecraft Reliability (Mass Category)

Results	Notation	Small Category	Medium Category	Large Category
Shape Parameter	β	0.6054	0.7411	0.7742
Scale Parameter	η	4.6960	7.6340	2.6082
Variance	Var	0.0180	0.0116	0.0802
Mean Reliability	$\bar{R}$	0.5538	0.6964	0.6877
Mean Life	τ	2.5614	4.6518	1.6216
Standard Deviation	σ	0.1343	0.1079	0.2833

9.4. Possible Causes Accountable for Reliability Behavior of Spacecraft of Various Mass Categories

We have refrained from delving extensively into the possible causes behind the reliability behavior of spacecraft across distinct mass categories, as these aspects were comprehensively addressed in [6]. Nonetheless, the significance and potential causes were clearly elucidated in that source. However, the role of spacecraft reliability concerning mass categories in interplanetary space was discussed in Section 7, "Impact of Spacecraft Mass."

10. Conclusion

The reliability of spacecraft stands as a significant parameter in determining mission proficiency and success. Various factors in the space environment can either enhance or diminish reliability. To investigate whether spacecraft at different interplanetary extremities exhibit differing reliability, we conducted statistical analyses using Kaplan-Meier and Weibull Probability distribution over spacecraft data. Our analysis revealed that the region between Earth and the outer limits of the solar system provides a protective and favorable environment for sustainable and reliable missions. Furthermore, reliability analysis of interplanetary spacecraft across different mass categories, employing the Castet-Saleh model, demonstrated that spacecraft in the medium category (with a mass range of 500-2500 kg) exhibit more robust reliability compared to those in the small and large categories. We also discussed potential causes contributing to differences in reliability behavior among spacecraft operating at distinct interplanetary boundaries. In conclusion, we believe that our work offers a valuable framework for space agencies and spacecraft manufacturers to consider when designing and integrating spacecraft, as well as selecting interplanetary boundaries for future missions.

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12. Biography

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The author have no conflict of interest to report.

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