Survival Analysis for Nanosatellites and Picosatellites

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ABSTRACT

The nascent field of fractionated satellite architectures provides an opportunity to improve spacecraft modularity and afford greater flexibility, adaptability, and upgradeability to spacecraft constellations. Satellite modules within a coherent formation can be replaced without facing the challenges of manufacturing, assembly, or disassembly in the harsh space environment (e.g., satellite modules conducting electromagnetic formation flight (EMFF) are not physically connected such that one module may be replaced with potentially less risk of damaging or degrading the performance of the other modules). Conventionally, the depot for constellation replenishment is located on Earth, however, minor augmentations to spacecraft formations cannot be conducted economically under such a framework. The present research proposes the utilization of proactively launched supply depots to replenish geostationary formations from ultrageostationary orbit (i.e., that volume of space encompassed between the altitude of geostationary orbit and the altitude of the L1 Lagrange point). This work explores reliability factors associated with such a concept by conducting a survival analysis for nanosatellites and picosatellites. Time to failure data is collected for 85 spacecraft in the nano- (1.01 – 10 kg wet mass) and pico- (0.11 – 1 kg wet mass) classes without data censoring. These spacecraft were launched between 2010 and 2019, inclusive, having an internationally diverse set of owners from the sectors of military, government, commercial, and academia. This data is used to build a distribution for the survival analysis of satellites in these classes. JMP Pro 13 is used to conduct a goodness-of-fit test for multiple distributions. Analysis (using a standard alpha value of 0.05) indicates that the data is from a two-parameter Weibull distribution wherein the spacecraft experience beneficial aging.

INTRODUCTION

The U.S. Air Force 2030 Science and Technology Strategy characterizes five transformational strategic capabilities as integral to the airpower and spacepower of the U.S. including [1]:

- global persistent awareness
- resilient information sharing
- rapid, effective decision-making
- complexity, unpredictability, and mass
- speed and reach of disruption and lethality

The strategy explicitly ties “global persistent awareness” to the technological opportunity of “small satellites and low-cost launch.” The strategy also explicitly ties “complexity, unpredictability, and mass” to the technological opportunity of “low-cost air and space platforms.” These national security technological opportunities provided an impetus for the development of the Kinetically-Aggregated Infrastructure Revitalization of Spacecraft (KAIROS) concept. KAIROS exists as the replenishment or enhancement of a fractionated spacecraft by a supply depot also located in space. [2] This current work focuses on the reliability aspects of KAIROS.

In understanding the KAIROS concept, one may consider a simplified use case wherein several spheres flying in formation along the geostationary belt constitute the functional capability of a communications satellite. Approximately homogeneous in mass, these spheres present inertia tensors with no cross-coupling and equal angular inertia values for each axis. A control moment gyroscope mounted internally on each axis provides satellite attitude control and rings embedded along the outer shell of each sphere surge current to create an electromagnetic field in order to generate the force necessary to conduct intra-formation position maneuvers. The spheres can aggregate and use thrusters to perform conventional orbital maneuvers. Power can be distributed wirelessly and computing power can be disaggregated to the different spheres. Supply depots located at higher altitudes in ultrageostationary orbit can send individual spheres to designated formations for the replenishment or enhancement of a particular constellation.

Exploring the reliability factors associated with KAIROS enables an understanding of the failure times for future operational systems. Such knowledge improves the Planning Programming Budgeting and Execution (PPBE) process and affords a more accurate Program Objective Memorandum (POM) for the Future Year Defense Program (FYDP). The subsequent improvements to acquisitions performance in terms of cost, risk, schedule, and system capability ultimately promote the security and prosperity of the U.S..

This article seeks to advance the national security posture of the U.S. through the presentation of research on the reliability factors of an advanced technology conceptual framework. Motivation for the research is contextualized to the acquisitions processes within the U.S. Air Force (USAF) and U.S. Space Force (USSF). Descriptive statistics and data collection of the reliability of 85 satellites is discussed. Finally, analysis and distribution building for the time to failure of these spacecraft is conducted.

LITERATURE REVIEW

Kong et al. proposed the use of electromagnetic formation flight (EMFF) as a propellant-free alternative to satellite formation flight. [3] Hilton, Alvisio, and many others of the Massachusetts Institute of Technology (MIT) Space Systems Laboratory (SSL) advanced EMFF technology with their work on the Synchronized Position Hold Engage and Reorient Experimental Satellites Resonant Inductive Near-field Generation System (SPHERES-RINGS). [4, 5] The reconstitution of an operational version of such a fractionated spacecraft by a supply depot in space provides an excellent example of the KAIROS concept.

Saleh discussed the application of the Weibull distribution (a more generalized form of the exponential distribution) to spacecraft reliability. [6] The U.S. Air Force discussed the potential benefit of using disaggregation to improve the resiliency of spacecraft architectures. [7] Cristini, Mathieu, Daniels, and Brown also discussed the benefits of fractionated satellite architectures. [8, 9, 10, 11]

ANALYSIS

Convenience sampling was used to collect time to failure data for 85 spacecraft in the nano- (1.01 – 10 kg wet mass) and pico- (0.11 – 1 kg wet mass) classes with no censoring. Consistent with an ultraquality framework, reliability was considered only at the system level. [12] These spacecraft were launched between 2010 and 2019, inclusive, having an internationally diverse set of owners from the sectors of military, government, commercial, and academia. These 85 spacecraft had a mean survival time of 0.513 years (median survival time of 0.186 years) with a standard deviation of 0.961 years and range of 0.003 years to 7.351 years. The failure times for the satellites are plotted in Figure 1. These failure times were used to build a distribution for the survival analysis of satellites in these classes.

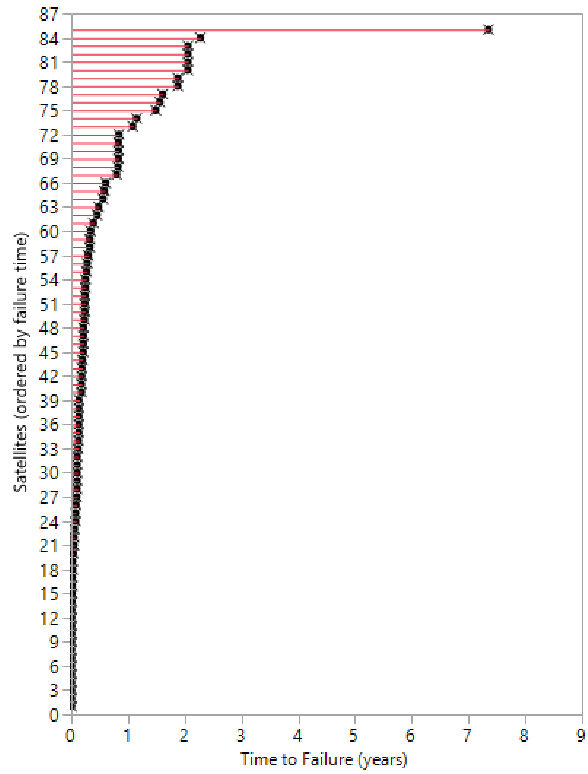

Figure 1: Satellite Failure Times

The time to failure data in Figure 1 was used to find a probability distribution that could be used to model spacecraft survivability (time until system failure). Spacecraft reliability is sometimes modeled with the exponential distribution, however, the exponential distribution is known to have a memoryless property, which, in this application, would imply that failure at any given time is not dependent on how long the spacecraft has survived already. This is a property in contrast to the beneficial aging that is theorized for this set of satellites. Therefore, two different reliability distributions were considered to model the time until failure: the exponential distribution due to its common application and potential usefulness given the shape of the distribution in Figure 1 and the Weibull distribution which is related to the exponential distribution through a transform of the exponentially distributed random variable yet does not maintain the memoryless property of the exponential distribution (and thus, may better fit the concept of beneficial aging). Specifically, let the time to failure be denoted as random variable X. Then, the exponential distribution for X is expressed as:

$$f(x) = \frac{e^{-\frac{x}{\beta}}}{\beta} \qquad (1)$$

with the support of x ranging from zero to infinity. The Weibull distribution is related to the exponential distribution through the random variable transformation:

$$X_{Weibull} = X_{Exponential}^{\frac{1}{\gamma}} \qquad (2)$$

to yield a Weibull-distributed random variable Z whose probability density is defined as:

$$f(z) = \frac{e^{-\frac{z^{\gamma}}{\beta}}}{\beta} \gamma z^{\gamma-1} \qquad (3)$$

and whose support ranges from zero to infinity. β is the scale parameter (characteristic life span) while γ is the shape parameter.

The Weibull distribution accounts for beneficial or deleterious aging, through its additional parameter, γ, in which $\gamma < 1$ indicates beneficial aging and $\gamma > 1$ indicates deleterious aging. To determine the best distribution for this satellite data, JMP Pro 13 was used to conduct goodness-of-fit testing for both the exponential and Weibull distributions. The Cramer-von Mises W goodness-of-fit test and the Kolmogorov's D goodness-of-fit test were used to formally determine whether or not the Weibull and exponential distributions fit the data, respectively. The Akaike Information Criterion (AIC) goodness-of-fit for the likelihoods of both the exponential and Weibull distribution were compared. Formal statistical testing was conducted using a standard alpha value of 0.05.

Figure 2 shows the cumulative distribution function for spacecraft failure with the aforementioned fitted exponential and includes a 95% confidence interval. Ideally, if the data was exponentially distributed, it would follow along the solid line and lie within the 95% confidence bounds. The time to failure data does not follow the expected probability well in Figure 2 and via formal testing, failed the Kolmogorov's D goodness-of-fit test, indicating that the data was not from an exponential distribution. Specifically, this test yielded a Kolmogorov's D of 0.250270 and a p-value of 0.01. The AIC value for the best fitting exponential distribution was 58.514460.

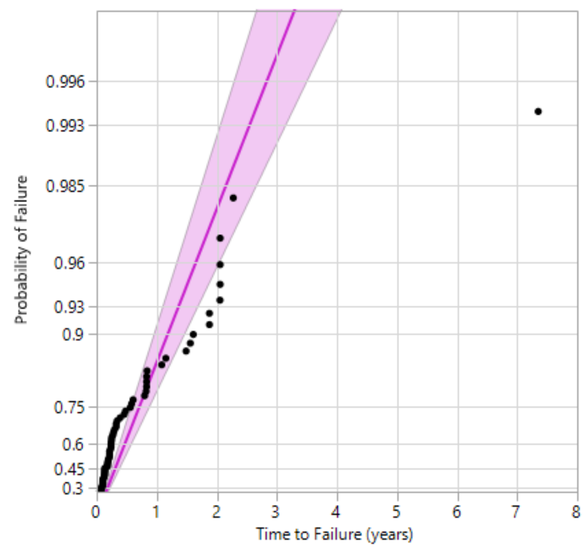

Figure 2: Probability of Failure vs. Time to Failure with Fitted Exponential Distribution

The Cramer-von Mises W goodness-of-fit test for a fitted Weibull yielded a Cramer-von Mises W of 0.103840 and a p-value of 0.0907 indicating that the Weibull distribution may be an adequate fit for the data. Fitting the two-parameter Weibull yielded parameter estimates of $\beta = 0.3306607$ and $\gamma = 0.5922925$ which indicates beneficial aging – the expected result in spacecraft reliability. The 95% confidence intervals for these parameter estimates are as follows:

$$0.2240266 \leq \beta \leq 0.4820571 \qquad (4)$$

$$0.4987221 \leq \gamma \leq 0.693607 \qquad (5)$$

The AIC value for this best fitting Weibull was 8.831280, indicating a better fit for the Weibull distribution than the exponential distribution (lower AIC value is better).

Figure 3 shows the cumulative distribution function for spacecraft failure with the aforementioned fitted Weibull. Figure 3 also encompasses a 95% confidence interval for the Weibull distribution. In general, the data better fits the Weibull distribution as shown in Figure 3.

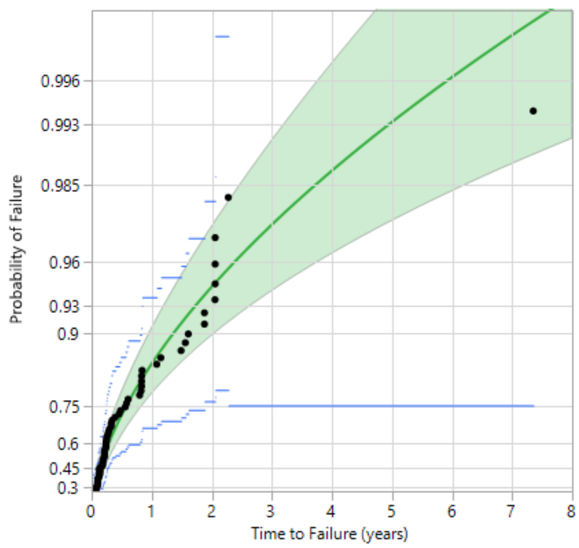

Figure 3: Probability of Failure vs. Time to Failure with Fitted Weibull Distribution

CONCLUSION

This article created a parametric distribution for a data set encompassing nano- and pico- class satellites to characterize the survival analysis of satellites in these classes. The analysis determined a Weibull distribution parameterized to represent beneficial aging constituted a representation of the data which was both accurate and tractable. Understanding the reliability characteristics of satellites in these classes affords the U.S. Department of Defense the opportunity to increase the efficacy of its acquisition programs. Ultimately, this work strives for the enhancement of the security and prosperity of the U.S. through the advancement of strategic thinking within the space domain.

Future work will integrate this knowledge into a framework which will help guide the acquisition and operational decisions of the USSF. This future framework will integrate parametric distributions such as those discussed in this article with game theoretic models as well as population models including Lanchester, Lotka-Volterra, and Brackney.

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