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Reliability of CubeSats – Statistical Data, Developers’ Beliefs and the Way Forward

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ABSTRACT

In this paper we investigate the data on 178 launched CubeSats and conduct a nonparametric and parametric analysis, where the dead-on-arrival (DOA) cases as well as the subsystem contribution to failure are specifically addressed. Using Maximum Likelihood Estimation, a Single Weibull and a 2-Weibull mixture parametric model are fitted to the non-parametric data. Furthermore, by combining developers’ beliefs on several reliability aspects from a survey conducted in late 2014 with data from past missions, we make a first attempt to correlate space engineering “best guesses” and intuition to actual data. Finally, the probabilistic CubeSat reliability estimation tool is introduced as a method to reduce the infant mortality of CubeSats: CubeSat developers should be able to estimate their required functional testing time on subsystem and system level at an early project stage, while targeting a desired reliability goal on their CubeSat.

INTRODUCTION

Since the beginning of the space age, satellite design philosophy was dominated by highly reliable components and conservative designs built for durability under extreme environmental conditions of space, featuring redundancies and extensive qualification and performance testing at part, subsystem and integrated system levels. The dawn of the CubeSats changed this philosophy in favor of utilizing state-of the art, commercial-off-the shelf products, potentially yielding, if successful, an increased performance per mass figure of merit for those small vessels. CubeSats seemed to promise universities and companies to be faster, better and cheaper than larger traditional missions – once more in history. But at what price? In this paper, we try to assess the on-orbit failure rate and time-dependent root causes of past CubeSat missions up to a launch date of 30/06/2014. In total, 178 individual CubeSats were assessed, merging publicly available data, data from other databases and data from a survey conducted in late 2014 into the CubeSat Failure Database (CFD). The failure data was analyzed using non-parametric Kaplan-Meier estimation, both on system and subsystem levels. By quantifying the relative contribution of each subsystem to the failure and by fitting a parametric model to the data, we derive data-driven answers to demanding questions of CubeSat development, such as: What is the average reliability of past CubeSat missions over time? Is

any specific subsystem a major contributor to reduced reliability of CubeSats? Does this change over time? Specifically, the Dead on Arrival cases are addressed in the parametric model, being a large contributing factor to the overall failure rate in past CubeSat missions. Furthermore, by combining developers’ beliefs on several reliability aspects from the survey with data from past missions, we make a first attempt to correlate space engineering “best guesses” and intuition to actual data. Our analysis techniques, based on empirical data, provide the means to assess the realistic mission design lifetime, necessary testing, and create input for reliability growth plans during testing. The ‘flood’ of recent CubeSats has both commercialized and liberated the satellite market to some extent, and many universities contributed to and benefited from this revolution in its first phase. However, to now evolve CubeSats into reliable and accepted platforms for scientific payloads and commercial applications, more work is needed regarding system reliability and testing, without losing the spirit and opportunity of CubeSat missions to use novel, state-of-the-art technologies, by fine tuning the paradigm shift in satellite design and manufacturing with adequate testing.

THE CUBESAT FAILURE DATABASE (CFD)

Although several studies analyzed the on-orbit failure rate of satellites in different mass classes [1,2] there is no dedicated analysis known to the authors specifically

Table 1: The CubeSat failure database (CFD)

Satellite Name	Class	Sub-type	Launch	Time of Failure	Cause	Censored Time (no failure occurred)
CubeSat 1	uni	1U	30.06.2003	22.09.2003	XYZ	-
CubeSat 2	uni	2U	30.06.2003	-	-	30.09.2013
....
CubeSat 178	uni	3U	30.06.2014	-	-	31.12.2014

addressing the CubeSat failure rate over time. Excellent research carried out by Swartwout [3,4] shows the causes and the success and failure rates of past CubeSat missions, the time dependence of both parameters remains unknown. To fill this gap, the CubeSat Failure Database (CFD) (Table 1) was built in late 2014. It is comprised of 178 individual CubeSats up to a launch date of 30/06/2014 and was created with the aim to collect time of failure and root cause data of all CubeSats launched so far. For this purpose, information was collected from publicly available sources [5-10] as well as from work from Klofas [11,12] and publications on the individual spacecraft. Furthermore, information was gathered within a survey, which was sent out in late 2014 to 987 individuals affiliated with CubeSat programs worldwide. Finally, through personal communication during conferences or via E-Mail, unpublished information was also added to the database. The first version of the database was completed by the end of 2015, containing the class, the sub-type, the launch date, the time of failure and the root cause of 70 failures within 178 missions, not including launch failures. Furthermore, in the case of initial successful on-orbit arrival, the censored time of the CubeSats (i.e. when they are retired

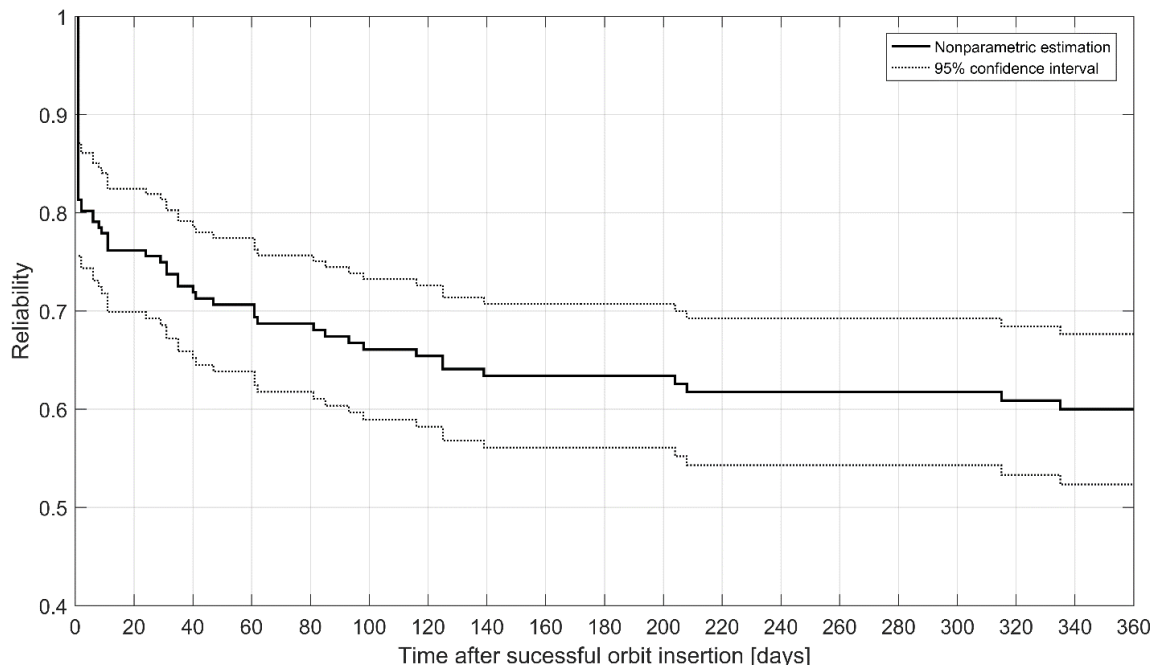
or the observation window ends) can be accessed. Since the publicly available information on satellites of the Flock Constellation of Planet Labs [13] was scarce, those satellites were also not included in the database. Ongoing work is carried out to further expand the database to satellites launched since the end of 2014, and to also include class II anomalies (major non-repairable failure that affects operation of a satellite or its subsystems on a permanent basis [14]) in the future.

NONPARAMETRIC AND PARAMETRIC RELIABILITY OF CUBESATS

Nonparametric Reliability Assessment

As shown in other work [15,2] the Kaplan-Meier estimator [16] for reliability $R(t)$ is best suited for nonparametric analysis and samples with the type of censoring occurring in our database. The Kaplan-Meier estimator for reliability $R(t)$ (equation 1) for censored data used in this study is adapted from [15]:

$$R(t) = \prod_{\text{all } i \text{ such that } t_{(i)} \leq t} \frac{n_i - 1}{n_i} \quad (1)$$

**Figure 1: CubeSat reliability with 95% confidence interval – first year in orbit**

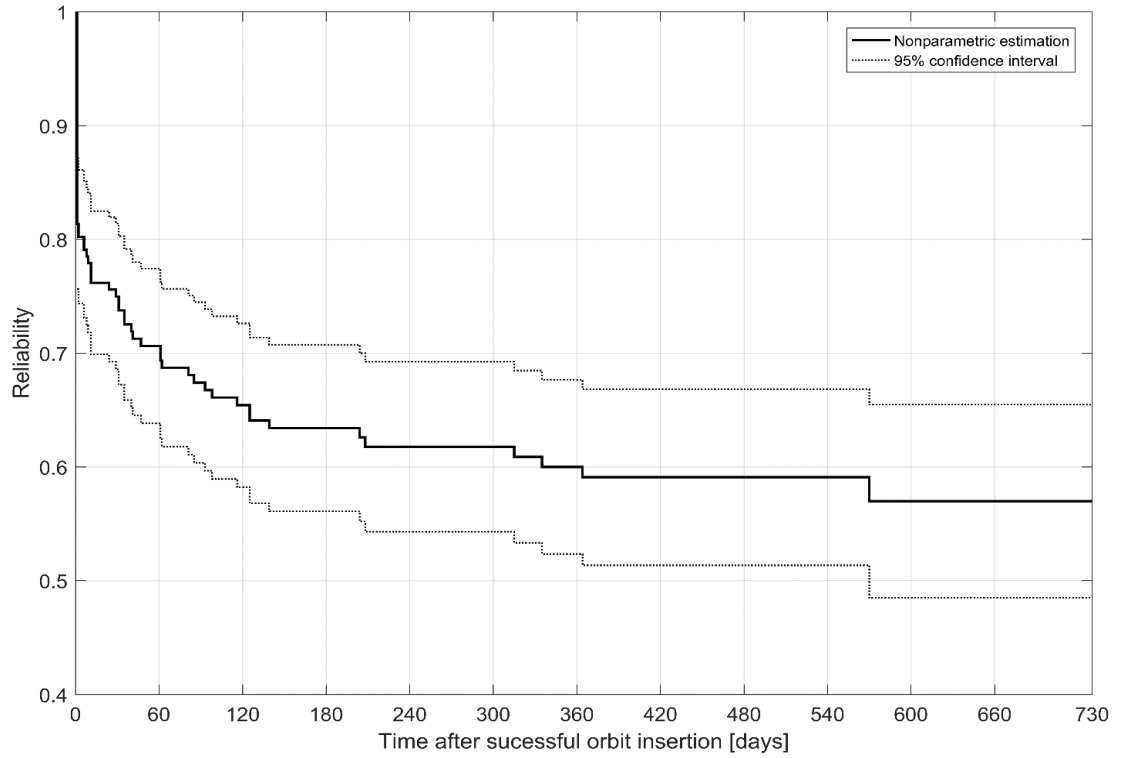


Figure 2: CubeSat reliability with 95% confidence interval – 2 years in orbit

with $t_{(i)}$ as the time to i^{th} failure, and n_i the number of operational units right before $t_{(i)}$. More details on the background of nonparametric analysis for satellite reliability data can be found in [15]. Figure 1 shows the results of the nonparametric reliability estimation with 95% confidence intervals for 1 year in orbit. The overall reliability of CubeSats is strongly dominated by so-called dead-on-arrival (DOA) cases, where the satellite was ejected from its deployer and subsequently never achieved a detectable functional state. Due to these DOA cases after a successful deployment, the overall reliability thus drops instantly to a value between 87.09% and 75.62% (95% confidence interval). With a reliability value between 73.24% and 58.94% (95% confidence interval) after 100 days in orbit, infant mortality is the dominant effect. Although the data indicates that CubeSats in low earth orbit (LEO) are not as susceptible to wear out as geostationary satellites, the effect might will emerge with longer lifetimes and higher reliability in early phases. The 2-year reliability estimation (Figure 2) ranges from 65.49% on the upper end of the confidence interval to 48.49% on the lower one after two years in orbit. Due to scarcity of on-orbit failure data late in the mission, prognostics must be treated very carefully. In Figure 4, the nonparametric reliability estimation with 95% confidence intervals for 2 years in orbit are depicted.

Parametric Reliability Assessment

Since parametric models can be used in a broader range of applications, it was decided to create a parametric function resembling the nonparametric reliability estimation. The Weibull distribution was chosen for this purpose, as it has been used before in other reliability studies on larger satellites [1,2,15,17]. To determine the parameters of the Weibull function, the Maximum Likelihood Estimation (MLE) Method is used. While the traditional Single Weibull function and the 2-Weibull mixture function were sufficient for the analysis of larger satellites [17], the reliability of CubeSats, with their large fraction of DOAs, cannot be parametrized in a proper way by those function types. To address the DOA cases, the Percent Non-Zero (PNZ) calculation [18] was chosen, as it can handle out-of-the-box failures. Within the PNZ method, the traditional Weibull function is multiplied by the ratio of non-zero failure items, called PNZ (equation 2):

$$R(t) = \text{PNZ} \exp \left[- \left(\frac{t}{\theta} \right)^\beta \right] \text{ for } t \geq 0 \quad (2)$$

Using MLE, the parameters of the Weibull function can be estimated as $\beta = 0.4797$, $\text{PNZ} = 0.8146$ and $\theta = 4661.7975$.

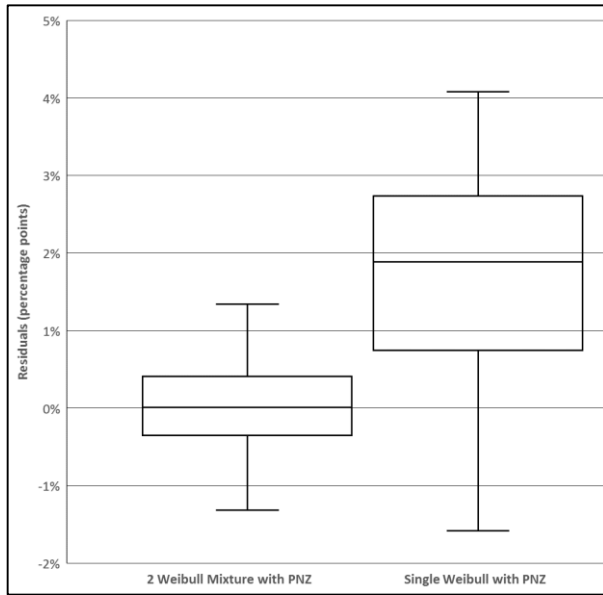


Figure 3: Box plots of the residuals between the Weibull fits and the nonparametric estimation over 1 year.

For the 2-Weibull mixture function, the PNZ value was multiplied by the Weibull function with the shape parameter $\beta \leq 1$, since this element captures the infant mortality failures in the overall reliability model.

$$R(t) = PNZ \left[\alpha_1 \exp \left[- \left(\frac{t}{\theta_1} \right)^{\beta_1} \right] + \alpha_2 \exp \left[- \left(\frac{t}{\theta_2} \right)^{\beta_2} \right] \right] \text{ for } t \geq 0$$

Hence, the parameters of the 2-Weibull mixture function are: $\beta_1 = 0.9017$, $PNZ = 0.8146$, $\theta_1 = 57.9715$, $\alpha_1 = 0.2115$, $\beta_2 = 1.0710$ and $\theta_2 = 4837.3947$.

Figure shows a box plot of the residuals between the 2 different Weibull PNZ fits and the nonparametric model during the first year, while Figure depicts the resulting parametric best fit, the PNZ 2-Weibull mixture function. In conclusion, the data out of the CFD and the subsequent nonparametric and parametric modelling yielded in a PNZ enhanced 2-Weibull mixture general reliability function for CubeSats. Using parametric data from other research [1,2] the parametric CubeSat model is shown in Figure 14 with respect to other spacecraft classes.

RELIABILITY OF SUBSYSTEMS

After assessing the overall system reliability of CubeSats, the nonparametric and parametric reliability of the involved subsystems was studied using data from the CFD. Therefore, the following 6 subsystems (plus an “unknown” category for failures, where no specific subsystem was identified as a root cause) were defined:

- Electrical Power System (EPS)
- On-Board Computer (OBC)
- Communication System, incl. antennas (COM)
- Attitude Determination and Control System (ADCS)
- Payload (PL)
- Structure & Deployables (other than antennas) (STR)
- Unknown

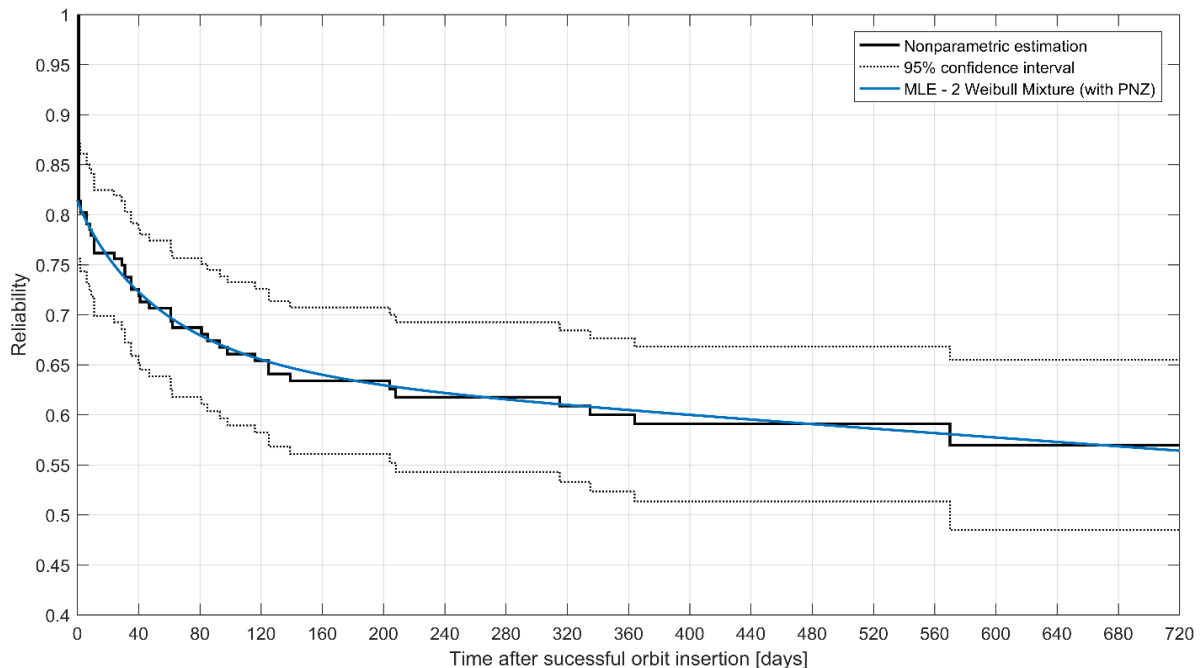


Figure 4: MLE 2-Weibull mixture parametric fit.

The contributions of each subsystem to the satellite failures are depicted in Figure 5. Looking at data from larger satellites [19], the “unknown” category clearly strikes as they major source of error in early stages for CubeSats. While communication could not be established for many of the DOA satellites, interviews with CubeSat developers indicate that approximately half of the DOA cases are caused by the “unknown” category, while the developer has some indication of like causes of DOA for the remainder. The second largest contributor in the early

phases and the largest one in later stages is the EPS, with more than 40% of all failures caused after 30 days (Figure 5). After 90 days, the communication subsystem accounts for nearly 30% of the failures. ADCS, PL and STR are contributing altogether less than 10% to the failure of the satellite. The three main subsystems causing CubeSat failures (OBC, EPS and COM) and the “unknown” category are modelled using nonparametric Kaplan-Meier estimation and parametric Single Weibull PNZ fits as shown in Figure 6 and Figure 7.

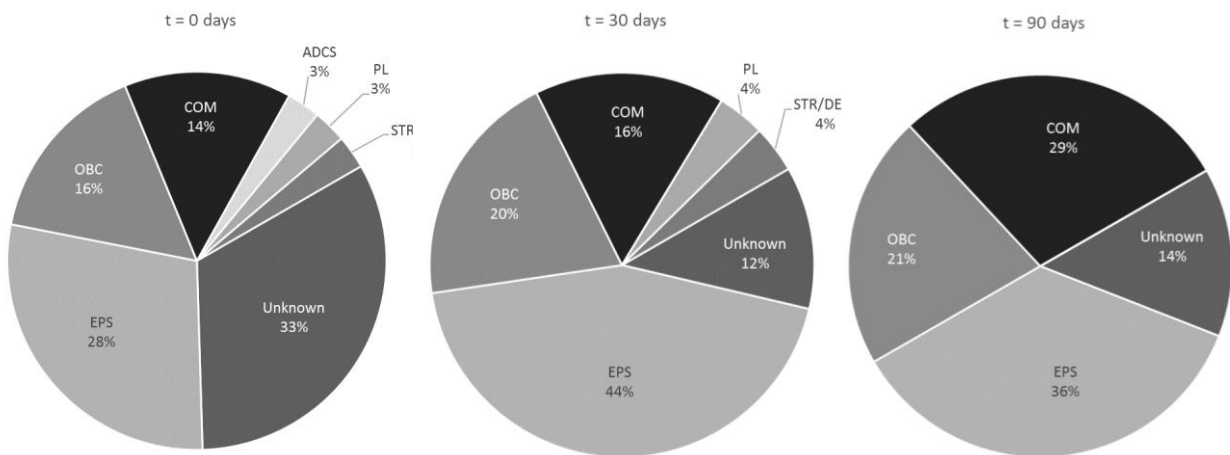


Figure 5: Subsystem contributions to CubeSat failure after ejection (incl. DOA), 30 days and 90 days

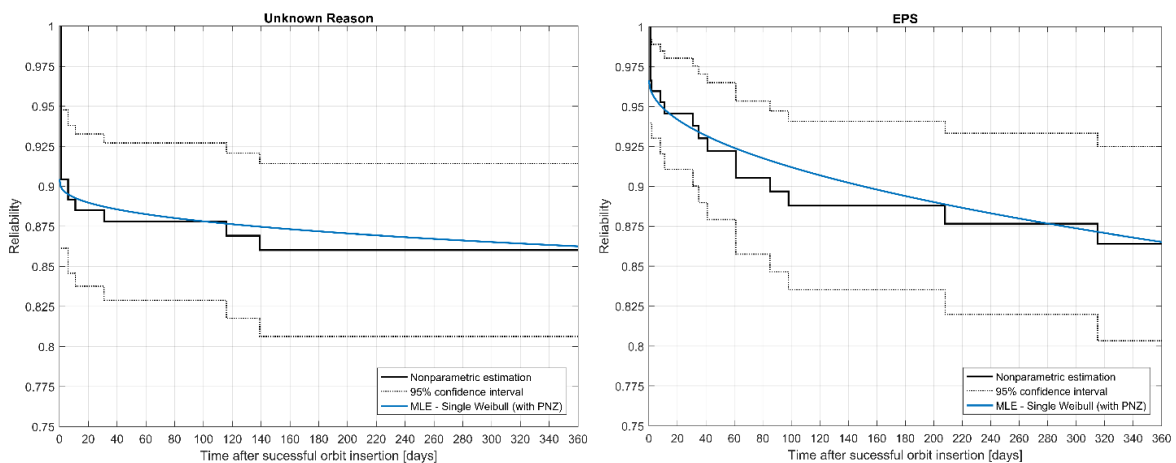


Figure 6: Nonparametric and Parametric Modelling of the “unknown” section and the EPS subsystem for a CubeSat failure during the first year in orbit.

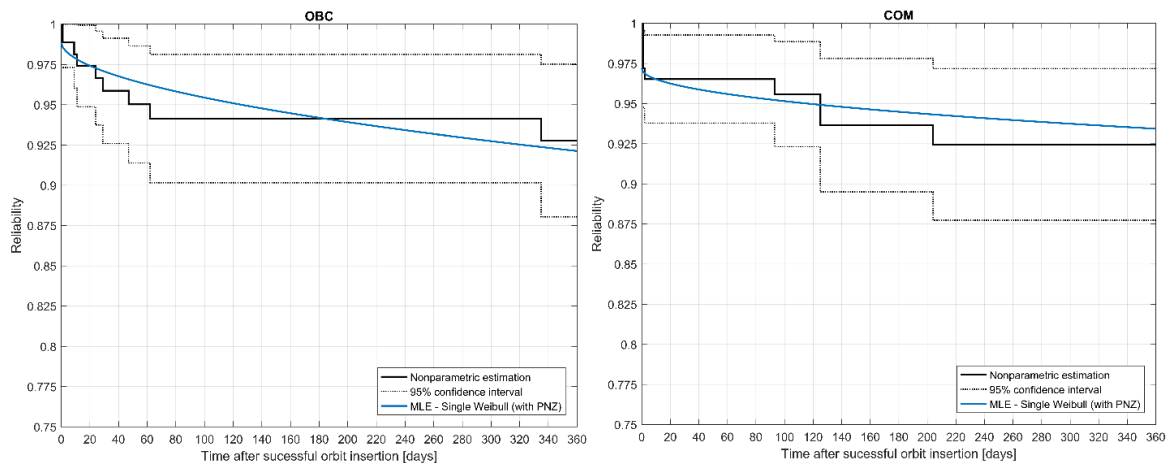


Figure 7: Nonparametric and Parametric Modelling of the OBC and the EPS subsystem for a CubeSat failure during the first year in orbit.

DEVELOPERS' BELIEFS

In addition to statistical data gathered for the CubeSat Failure Database, the survey conducted at the end of 2014 was also used to gain information on the developers' beliefs on the general reliability and specific reasons for failure of their respective CubeSats. Of the surveys sent out to 987 individuals, 113 were returned fully completed.

Firstly, the likelihood of failure for a university-built CubeSat within the first 6 months was estimated on average to be slightly below 50%. A normal distribution was used to fit the expert elicitation data. Figure 8 shows the experts' judgement and the fitted normal distribution, with fitted parameters being $\mu = 48.98$ and $\sigma = 19.29$. For the first use, the normal distribution seemed a sufficient fit – nevertheless future work will be needed to estimate if there is a better fit on the experts' judgement. A second question was dealing with the expected likelihood of failure of the planned own CubeSat, if the expert was a team member of the to-be-launched CubeSat. A normal distribution was also used as a fit to the elicitation data. Out of $n = 88$ participants answering that part of the questionnaire, the normal distribution was fitted with $\mu = 16.53$ and $\sigma = 21.27$. Figure 9 shows the expert elicitation and the fitted normal distribution, while Figure depicts both, the judgement on the own CubeSat (blue) as well as the experts' opinion on a general, university built CubeSat (red). The difference between the means of both normal fits is more than 23%, meaning that the estimation for the likelihood of failure of the own mission is rather optimistic or the judgement of other missions is very conservative. In conclusion, the data out of the CFD and the subsequent nonparametric and parametric

modelling yielded in a PNZ enhanced 2-Weibull mixture general reliability function for CubeSats.

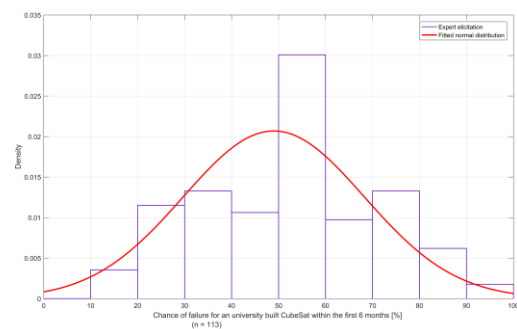


Figure 8: Developers' beliefs on the likelihood of failure for a university built CubeSat within the first 6 months. Fitted normal distribution. (n = 113)

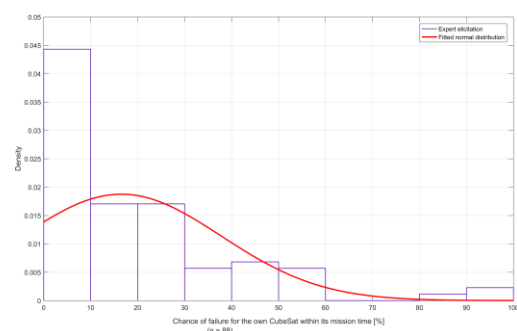


Figure 9: Developers' beliefs on the likelihood of failure for their own mission in its projected lifetime. (n = 88)

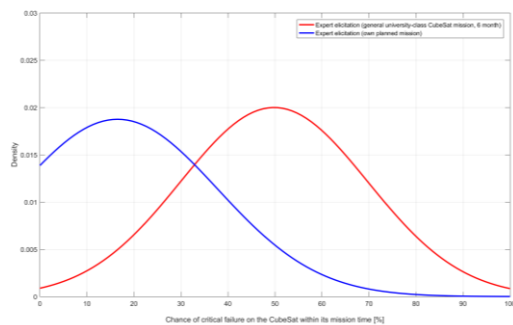


Figure 10: Developers' beliefs on the likelihood of failure for their own mission (blue) and on a general university-built CubeSat in its projected lifetime. (n = 86)

Expert Opinions – Suspected Failed Subsystem

To gather developer's beliefs on failure susceptibility of different subsystems, a "betting game" was carried out within the survey. All participants were asked to judge whether a specific subsystem could have been the reason for a critical failure on a generic university-built CubeSat, within an assumed mission time of 6 months. Figure 15 to Figure 20 (Appendix) depict the analysis of the survey data gathered from the experts, where normal distributions were used again for fitting.

Expert Opinions – Suspected Reason of Failure

Without knowing any further details, the experts also had to subjectively assess what reason might have caused the assumed critical failure of the satellite. Results are shown in Figure 21 to Figure 26 (Appendix), compiled from the survey answers of the reporting experts.

THE WAY FORWARD

Many of the CubeSats launched and built today are lost during their first phase of operations. The large percentage of DOAs and early failures is not acceptable if CubeSats should evolve into reliable and accepted platforms for scientific payloads and commercial applications. To stay attractive, CubeSats have to be launched and built fast, using appropriately selected COTS electronics and, due to budgetary and time constraints, reducing, appropriately selected, many of the standardized test procedures the space agencies are using for their high-reliability, expensive and large spacecraft. The solution to improve overall reliability cannot be, in our opinion, to try solve everything with processes already used in the traditional space industry (like space-grade components or lot testing). As Swartwout pointed out, many of the early failures are due to poor system-level functional testing, i.e. the spacecraft was not operated (or not long enough operated) in a flight-equivalent state before launch [3]. Thus, many of the

early failures could be resolved by a certain time of functional testing, rather than adding more and more complicated traditional acceptance and qualification tests.

Our survey also tried to gather information if the participants used failure or risk analysis on their satellite. As depicted in Figure 11, 73% of the participants considered themselves not as a beginner or as without knowledge in risk and failure analysis.

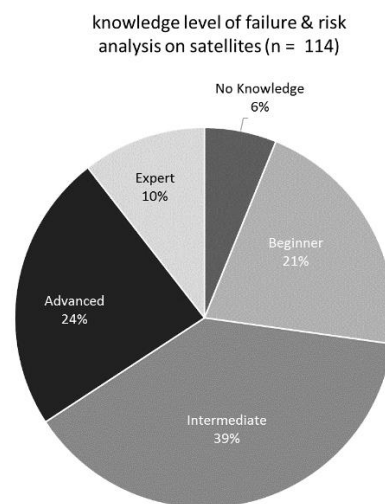


Figure 11: Survey results on knowledge level on risk & failure analysis on satellites

Nevertheless, 34% of the group didn't use any method to quantify risk or reliability in the mission (Figure 12). For those who didn't use such methods, lack of time and lack of knowledge are the two biggest reasons not to implement them.

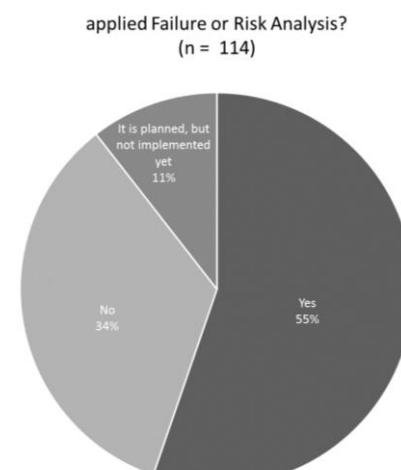


Figure 12: Survey results on the implementation of risk or failure analysis within their CubeSat program

With the statistical data in the first chapter and the developers' belief in the second one, it is the goal of the authors to create an easy-to-use reliability estimation model for CubeSats. Inspired by work from Cho [20,21] and Babuscia [22], a probabilistic CubeSat reliability estimation tool (Figure 13) is currently being built, using Bayesian methods [23-25], to provide meaningful data for all developers on the reliability and necessary functional testing time of their CubeSats.

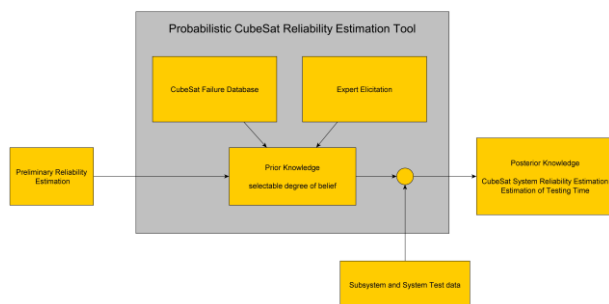


Figure 13: The Probabilistic CubeSat Reliability Estimation Tool

With the probabilistic tool, CubeSat developers should be able to estimate their required functional testing time on subsystem and system level beforehand, while targeting a desired reliability goal on their CubeSat with a certain percentage. Thus, CubeSat developers should be able to estimate the necessary time for full functional testing on the system in an early phase of the project, potentially reducing the DOA and infant mortality rate of CubeSats in the future.

The probabilistic CubeSat reliability estimation tool will be tested for the first time during subsystem functional tests of the MOVE-II [26] satellite in late 2016.

CONCLUSION

Despite their high rate of early failures, CubeSats changed the way how satellites are being built and how commercial and scientific missions can be carried out in the last decade. Their performance per mass figure of merit and fast delivery enables business models unthinkable of before their dawn. To further enhance their potential range of applications, the high rate of infant mortality has to be reduced in the near future. By combining statistical data from past missions and developer's beliefs with specific test data of system and subsystems via a Bayesian framework, we hope to decrease the rate of early failures.

Acknowledgments

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APPENDIX A1 – PARAMETRIC CUBESAT RELIABILITY MODEL WITH RESPECT TO OTHER PARAMETRIC MODELS AND SPACECRAFT CLASSES.

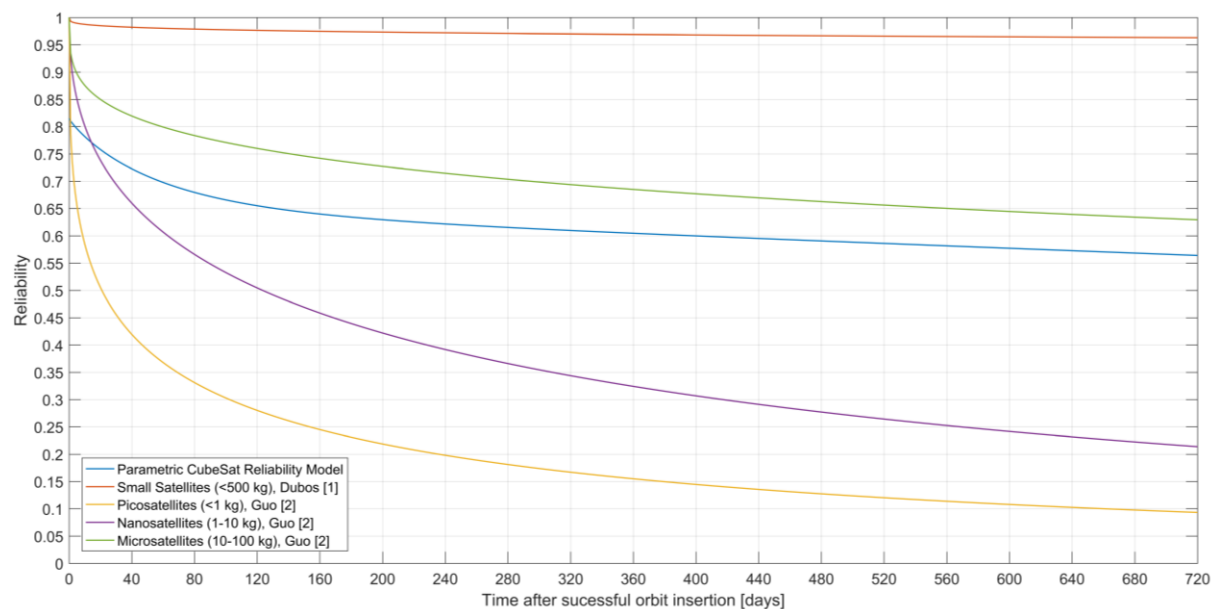


Figure 14: Parametric CubeSat reliability model (blue) with respect to other spacecraft classes.

APPENDIX A2 – DEVELOPERS’ BELIEFS ON FAILED SUBSYSTEMS

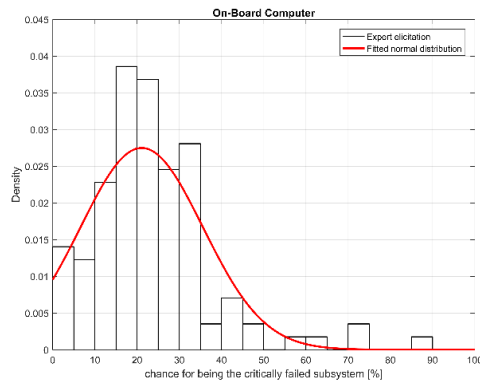


Figure 15: Developers’ beliefs on the likelihood of the on-board computer being the critically failed subsystem within the first 6 months of operation. (n = 114)

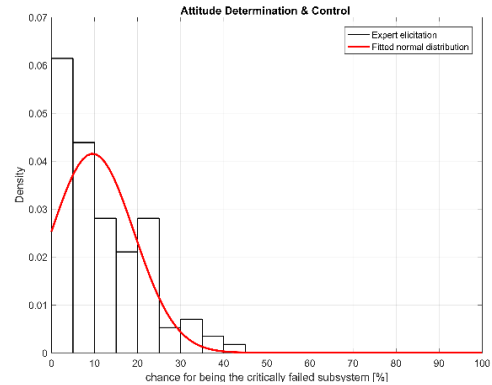


Figure 18: Developers’ beliefs on the likelihood of the attitude determination & control subsystem being the critically failed subsystem within the first 6 months of operation. (n = 114)

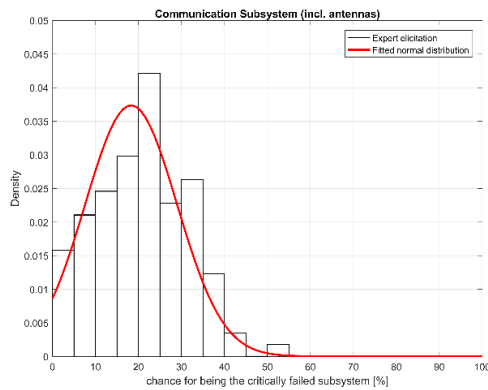


Figure 16: Developers’ beliefs on the likelihood of the communication subsystem being the critically failed subsystem within the first 6 months of operation. (n = 114)

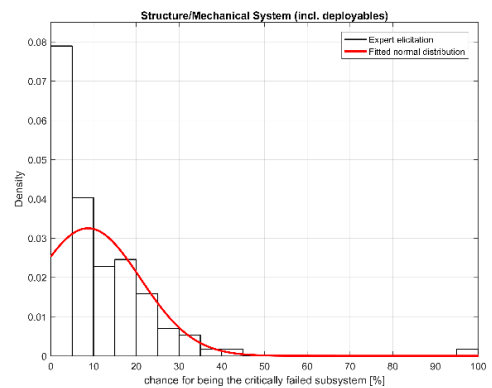


Figure 19: Developers’ beliefs on the likelihood of the structure & mechanical subsystem being the critically failed subsystem within the first 6 months of operation. (n = 114)

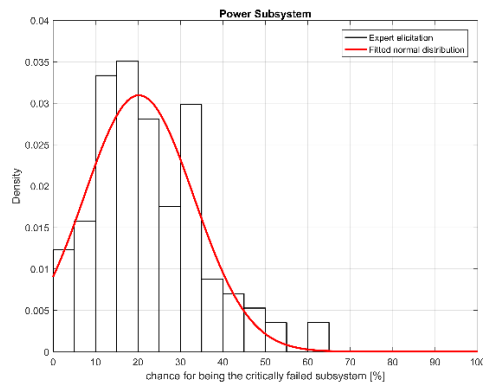


Figure 17: Developers’ beliefs on the likelihood of the power subsystem being the critically failed subsystem within the first 6 months of operation. (n = 114)

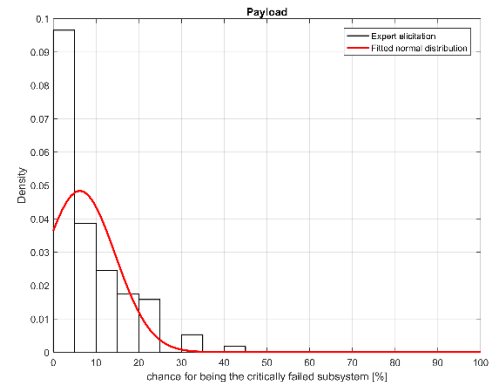


Figure 20: Developers’ beliefs on the likelihood of the Payload being the critically failed subsystem within the first 6 months of operation. (n = 114)

APPENDIX A2 – DEVELOPERS’ BELIEFS ON REASONS FOR CRITICAL FAILURE

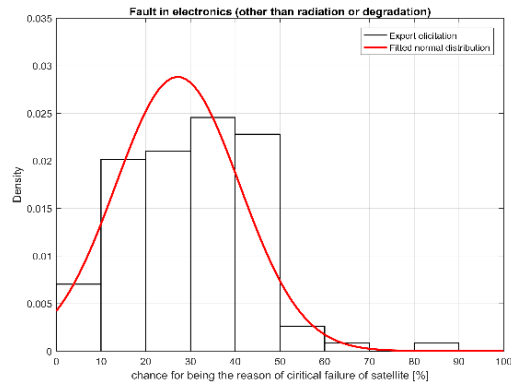


Figure 21: Developers’ beliefs on the chance that a fault in the electronics (other than radiation or degradation) is the reason for the critical failure within the first 6 months of operation (n = 114)

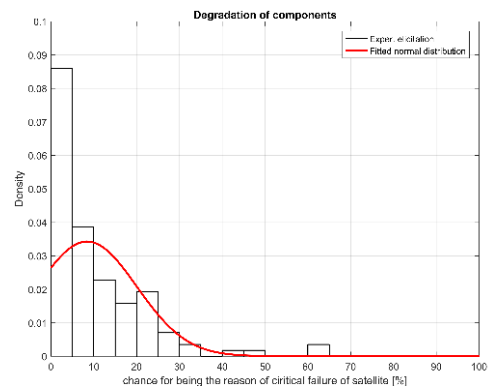


Figure 24: Developers’ Beliefs on the chance that degradation of components are the reason for the critical failure within the first 6 months of operation (n = 114)

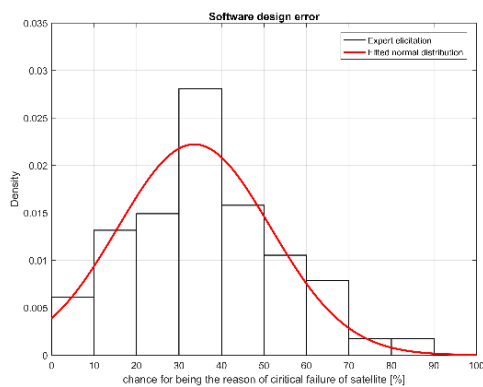


Figure 22: Developers’ beliefs on the chance that a software design error is the reason for the critical failure within the first 6 months of operation (n = 114)

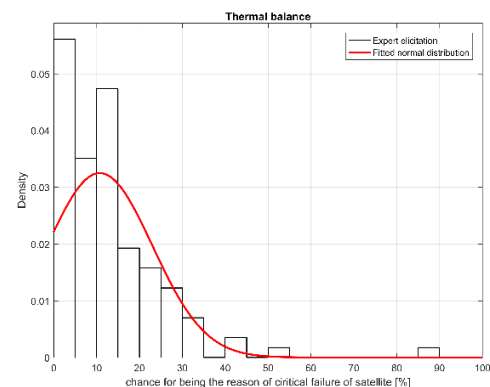


Figure 25: Developers’ beliefs on the chance that thermal balance is the reason for the critical failure within the first 6 months of operation (n = 114)

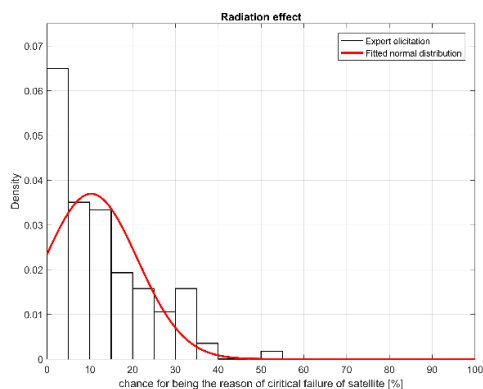


Figure 23: Developers’ beliefs on the chance that high energy radiation effects are the reason for the critical failure within the first 6 months of operation (n = 114)

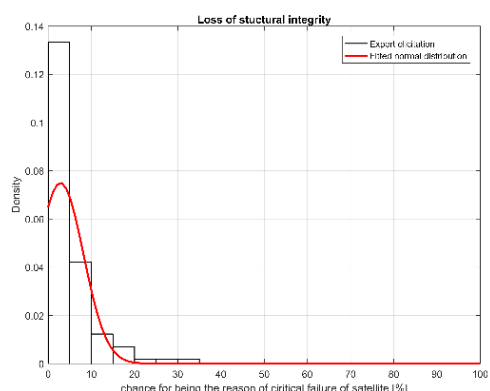


Figure 26: Developers’ beliefs on the chance that loss of structural integrity is the reason for the critical failure within the first 6 months of operation (n = 114)