CubeSat Data Analysis
Revision -

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Signature Page

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<table>
<thead>
<tr>
<th>REV LEVEL</th>
<th>DESCRIPTION OF CHANGE</th>
<th>DATE APPROVED</th>
</tr>
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<tbody>
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<td>-</td>
<td>Baseline Release</td>
<td></td>
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</table>
Table of Contents

1 Introduction ................................................................. 4
2 Statement of Work ....................................................... 5
3 Database ........................................................................ 5
4 Distributions by Satellite Classes, Users, Mass, and Volume 7
   4.1 Distribution by satellite classes ............................... 7
   4.2 Distribution by satellite users ................................. 8
   4.3 CubeSat Distribution by mass ............................... 8
   4.4 CubeSat Distribution by volume ........................... 8
5 Annual Number of CubeSats Launched ....................... 9
6 Reliability Data Analysis ........................................... 10
   6.1 Introducing “Time to Event” variable ....................... 10
   6.2 Probability of a Successful Launch ........................ 10
      6.3.1 Kaplan-Meier Estimate .................................... 10
      6.3.2 Weibull Distribution Estimation ....................... 11
   6.4 Estimation of Probability of mission success after successful launch as a function of time and satellite mass using Weibull Regression 13
      6.4.1 Weibull Regression .......................................... 13
      6.4.2 Data used for estimation of the model parameters 13
      6.4.3 Comparison of the Kaplan-Meier estimates of the Reliability function and the estimates based on the Weibull regression 16
7 Conclusion ....................................................................... 17
8 Acknowledgement .......................................................... 18
9 References ...................................................................... 18
10 Appendix ....................................................................... 19

Table of Figures

Figure 4-1 CubeSats distribution by mass ................................................................. 8
Figure 4-2 CubeSat distribution by volume ................................................................. 9
Figure 6-1 Kaplan-Meier Reliability (Survival) function of the CubeSats after successful launch .......... 11
Figure 6-2 The Weibull Reliability (Survival) function of the CubeSats after successful launch. The time axis units are days ......................................................... 12
Figure 6-3 Weibull regression Reliability function ..................................................... 17

Table of Tables

Table 4-1 ........................................................................... 7
Table 4-2 ........................................................................... 8
Table 5-1 Annual number of CubeSats launched ....................................................... 8
Table 6-1 Kaplan-Meier Reliability estimate S(t) and its standard deviation (STD) ................. 11
Table 6-2 Data used for fitting Weibull Regression Model ......................................... 14
Table 6-3 Kaplan-Meier S(t) estimates for different satellite masses ............................ 15
Table 6-4 Regression summary for dependent variable: Ln(-Ln(S(t))) .......................... 15
Table 6-5 Kaplan-Meier estimates of Reliability Function and Estimates Based on Weibull Regression 16
I Introduction

“In November 2013, a single Minotaur rocket carried 29 satellites into orbit, setting a new record for the most satellites deployed in a single launch. Less than two days later, a single Dnepr beat that record, lifting 32 satellites into orbit. Such launch rates—inconceivable just a few years ago—are rendered all the more remarkable considering that many of these satellites were not sponsored by well-funded government agencies but by universities and small private entities.

Evidently, the space industry is starting to realize the potential of small satellites. Indeed, the last decade has seen a substantial boom in their development, both domestically and internationally. Much of this growth can be attributed to the popularity of CubeSats, a well-known subclass of small satellites. However, CubeSats are only part of this rapidly expanding picture. Furthermore, it appears that small satellites are starting to move beyond the demonstration phase to provide the performance and reliability needed for commercial ventures and governmental applications”[1].

The purpose of the CubeSats project is to provide a standard for design of picosatellites to reduce cost and development time, increase accessibility to space, and sustain frequent launches. CubeSat Project is an international collaboration of over 100 universities, high schools, and private firms developing picosatellites containing scientific, private, and government payload.

The history of the CubeSats began in 1999, and initial specifications were developed by Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University. A *CubeSat* is a small satellite usually having a volume of exactly one liter (10 cm cube) and the mass of up to 1.33 kg., intended to use in low Earth orbit (LEO) to perform scientific research and explore new space technologies. The first CubeSats were launched in June 2003 on a Russian Eurockot, and approximately 75 CubeSats had been placed into orbit by 2012 [2].

In this paper, the CubeSat data collected by the Saint Luis University (SLU) are analyzed. The data records begin with 02/06/2000. The latest record is dated by 06/28/2015. There are 370 CubeSat records in total in this database.

According to the satellite classification based on mass, the satellites considered below belong to the class of nanosatellites\(^1\) (see Section 4). It should be noted that in our study the CubeSat data are analyzed mainly from Reliability/Risk analysis standpoint.

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\(^1\) By definition, nanosatellite mass belong to the interval \((1 – 10) \text{ kg}\)
2 Statement of Work

Saint Louis University (SLU) has compiled a database of all CubeSats that have flown or have firm manifests. It includes mission status and functional status for each satellite. Part 3 will analyze the database and perform reliability/risk analysis, which includes the following subtasks:

- Review the existing database to identify any fields that may need to be added; request additional data and review
- Determine what useful knowledge can be gained from analysis of the data, i.e., determine the objectives of the analysis to be performed
- Identify the types of analyses that should be performed to meet the objectives.
- Perform statistical reliability/risk analyses
- Deliver a draft report to Task Monitor and NASA Headquarters customer with objectives and preliminary statistical analysis
- Deliver final report

3 Database

The SLU database consists of the records of 370 CubeSats. The database’s 25 variables (V1 – V25) as specified by the database are:

V1. NORAD ID
V2. Name
V3. COSPAR name
V4. Launch Country
V5. Launch Date
V6 Launch Site

1. AFETR Cape Canaveral, USA
2. AFWTR Vandenberg (Air Force Western Test Range), USA
3. Brazil Alcantara, Brazil
4. FRGUI Europe's Spaceport, Kourou, French Guiana, Europe
5. ISS International Space Station Deployed, ISS
6. JSC Jiuquan Space Center, China
7. KAUAIP Barking Sands, USA
8. KODAK Kodiak Alaska, USA
9. KSCUT Uchinoura Space Center (nee Kagoshima), Japan
10. KWAJ Kwajalein Atoll, USA
11. KYMTR Kapustin Yar, Russia
12. OREN  Dnepr Bunker Site, Russia  
13. PKMTR  Plesetsk Missile and Space Complex, Russia  
14. SRI  Satish Dhawan Space Centre (nee Sriharikota), India  
15. TNSTA  Tanegashima Space Center, Japan  
16. TSC  Taiyuan Space Center, China  
17. TTMTR  Baikonur Cosmodrome, Russia (although in Kazakhstan)  
18. WLPIS  Wallops Island, USA  
19. WRAS  Western Range Airspace, USA  
20. XSC  Xichang Launch Facility, China  

V7. Class  
V7.1 Civ  
V7.2 Com  
V7.3 Mil  
V7.4 Uni  

V8. Type (Cube, or Pocket Cube (5 records only))  

V9. Sub-type (in U: U1, U2, etc., U1 has one liter volume, U2 has two liter volume, etc.)  

V10. Ejector (16 names)  

V11. Mission Type  

“Mission Type is based on primary mission (the one paying the bills, if such a mission exists):  

T - Technology demonstration  
S - Science  
C - Communications  
M - Military (some military comm./tracking missions don't fit any other category)  
I - Commercial Earth imaging; I count this separately from S-class to distinguish the commercial aspect, and because it keeps Planet Labs from taking over one of the other categories.  
E - education/training” [3]  

V12. Mission Status  
0 - prelaunch  
1 - launch (the rocket lifted off the ground, but the CubeSat is still inside)  
2 - release (the CubeSat is free-flying)  
3 - initial operations/checkout (confirmed uplink and downlink)  
4 - preliminary mission operations  
5 - primary mission accomplished (though it may continue to be in main operations)  

V13. Decay Date - is the UTC date of reentry, taken directly from Jonathan's Space Report [3]  

V14. Mass (kg)  

V15. Ops End (Date)  

V16. Mission End (Date)
V17. Functional Status

- D - Deorbited (pre-launch or disposal)
- N - Nonoperational
- S - Semioperational
- A – active

V18. Inc.
V.19 Apogee
V20. Perigee
V21. Users (e.g., Aerospace Corporation or University of Tokyo)

V22. Failures -- are grouped by subsystem, if a leading cause could be identified

- NC – not categorized
- Comm – loss of communication
- Power -- something in the electrical power subsystem
- Mech – structural/mechanical failure (including binding/sticking of deployment mechanisms)
- CPU -- hardware or software failures in on-board computing/command
- ADC – attitude determination & control
- Software -- usually an unrecovered system crash
- Debris – on-orbit collision
- LF – launcher failure

V23. Contractor (it can coincide with Users)
V24. Orbit Vehicle
V25. Summary (comments)

The data records begin with 02/06/2000 (the launch date). The latest record is dated 06/28/2015. It should be noted that many of the 370 records have missing data of some of the above listed variables. The information about the design satellite life is missing, which makes reliability estimation difficult.

4 Distributions by Satellite Classes, Users, Mass, and Volume

4.1 Distribution by satellite classes
The database divides the 370 satellites into the following 4 classes shown in Table 4-1:

<table>
<thead>
<tr>
<th>Class</th>
<th>Notation in Database</th>
<th>Number of records (satellites)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Communication</td>
<td>Com</td>
</tr>
<tr>
<td>2</td>
<td>University</td>
<td>Uni</td>
</tr>
<tr>
<td>3</td>
<td>Military</td>
<td>Mil</td>
</tr>
<tr>
<td>4</td>
<td>Civilian</td>
<td>Civ</td>
</tr>
</tbody>
</table>

2 Mission Status and Functional Status are quasi-independent; the Spirit Mars Rover would be classified as 5N, while Curiosity is 4A (or maybe 5A, depending on who you talk to) [3].
4.2 Distribution by satellite users
The major CubeSats users are shown in Table 4-2 below.

<table>
<thead>
<tr>
<th>User</th>
<th>Number of CubeSats in database</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Planet Labs</td>
<td>110</td>
</tr>
<tr>
<td>2 NASA (Ames and JPL)</td>
<td>14</td>
</tr>
<tr>
<td>3 Cal Poly</td>
<td>11</td>
</tr>
<tr>
<td>4 Aerospace Corporation</td>
<td>9</td>
</tr>
<tr>
<td>5 All others that have ≤ 4 satellites</td>
<td>226</td>
</tr>
</tbody>
</table>

Table 4-2

The other CubeSats users have 4 or less than 4 satellites. It is obvious that the telecommunication and academic (university) communities are the two major classes of the CubeSat users, and among these users, the Planet Labs is the major one.

4.3 CubeSat Distribution by mass
The satellite distribution by mass is shown in Figure 4-1 below. The figure reveals that the prevalent masses of the CubeSats are 1 kg and 5 kg (34% and 42% of the population, correspondingly).

4.4 CubeSat Distribution by volume
The CubeSat volume is defined by its sub-type. For example, the subtype U1 has the volume of 1 liter, the sub-type U2 has the volume of 2 liters, etc. The satellite distribution by volume is shown in Figure 4-2

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3 Founded in 2010, Planet Labs, Inc. (formerly Cosmogia, Inc.) is an American private company that aims to create an Earth observation satellite constellation with open data access
below. The figure reveals that the most common volumes are 1 liter and 3 liters (35% and 52% respectively).

![Number of Satellites by Volume](image)

*Figure 4-2 CubeSat distribution by volume*

## 5 Annual Number of CubeSats Launched

Table 5-1 below shows the annual number of CubeSats launched from 2000 through 2015.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of CubeSats</th>
<th>Year</th>
<th>Number of CubeSats</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>5</td>
<td>2008</td>
<td>8</td>
</tr>
<tr>
<td>2001</td>
<td>1</td>
<td>2009</td>
<td>11</td>
</tr>
<tr>
<td>2002</td>
<td>1</td>
<td>2010</td>
<td>15</td>
</tr>
<tr>
<td>2003</td>
<td>6</td>
<td>2011</td>
<td>12</td>
</tr>
<tr>
<td>2004</td>
<td>0</td>
<td>2012</td>
<td>23</td>
</tr>
<tr>
<td>2005</td>
<td>3</td>
<td>2013</td>
<td>84</td>
</tr>
<tr>
<td>2006</td>
<td>20</td>
<td>2014</td>
<td>118</td>
</tr>
<tr>
<td>2007</td>
<td>7</td>
<td>2015</td>
<td>56^4</td>
</tr>
</tbody>
</table>

It should be noted that annual number of CubeSats launched increased about ten times in 2014 compared to the number CubeSats launched in 2011.

^4 The data are truncated on 07/17/2015
6  Reliability Data Analysis

6.1  Introducing “Time to Event” variable
In order to estimate the CubeSats reliability, a variable similar to the time to failure should be introduced. We will use “Time to Event” for this purpose. An event might be failure (due to all failure modes, or due to a given failure mode) or it can be censoring, in which case it is an event when observations were terminated for any reason except for a failure.

6.2  Probability of a Successful Launch
The database provides information on 370 CubeSats (370 records). To estimate the probability of a successful launch, the following variable is introduced:

\[ \text{Var1} = \text{“Mission End Date” – “Launch Date”} \]

The launch date is available for all 370 records, but there are only 96 records having the mission end date. Thus, there are only 96 records, for which the Var1 is available.

Out of these 96 records, in 34 cases Var1 takes on zero value (Var1 = 0), which corresponds to the respective launch failure. Based on these data, the probability of a successful launch can be estimated as follows:

Point Estimate: \( (96 – 34)/96 = 0.646 \)

The corresponding 60% lower confidence limit: 0.628

Out of these 96 records, in 39 cases Var1 takes on the value of zero or one (Var1 ≤ 1), which also might be considered as a launch failure (a launch failure or a failure on the first day). Based on this definition, the probability of a successful launch can be estimated as follows:

Point Estimate: \( (96 – 39)/96 = 0.594 \)

The corresponding 60% lower confidence limit: 0.575


6.3.1  Kaplan-Meier Estimate
The data available for CubeSats reliability estimation are given in Appendix Table A1.

The results of the Kaplan-Meier (K-M) estimation are shown in Table 6-1, and illustrated by Figure 6-1 below. The figure reveals that the CubeSat Reliability function is difficult to fit parametrically. The Kaplan-Meier (non-parametric) estimate of the median life is 110 days.
6.3.2 Weibull Distribution Estimation

The results of the Weibull distribution estimation using the Weibull++ are as follows: the scale parameter $\alpha = 200.25$ days, and the shape parameter $\beta = 0.54$. The value of the shape parameter indicates the decreasing failure rate (rejuvenation) distribution. The $R^2$ is 0.92 that shows that the goodness of the distribution fit is not very good, which is seen in the Figure 6-2.

Table 6-1 Kaplan-Meier Reliability estimate $S(t)$ and its standard deviation (STD)

<table>
<thead>
<tr>
<th>#</th>
<th>Time, days</th>
<th>S(t)</th>
<th>STD</th>
<th>#</th>
<th>Time, days</th>
<th>S(t)</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.983871</td>
<td>0.015998</td>
<td>43</td>
<td>505</td>
<td>0.306452</td>
<td>0.058550</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.967742</td>
<td>0.022439</td>
<td>44</td>
<td>506</td>
<td>0.290323</td>
<td>0.057647</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.951613</td>
<td>0.027252</td>
<td>45</td>
<td>581</td>
<td>0.274194</td>
<td>0.056656</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.935484</td>
<td>0.031200</td>
<td>46</td>
<td>622</td>
<td>0.258065</td>
<td>0.055571</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.919355</td>
<td>0.034581</td>
<td>47</td>
<td>635</td>
<td>0.241936</td>
<td>0.054388</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>0.903226</td>
<td>0.037548</td>
<td>48</td>
<td>731</td>
<td>0.225806</td>
<td>0.053100</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>0.887097</td>
<td>0.040192</td>
<td>49</td>
<td>742</td>
<td>0.209677</td>
<td>0.051699</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>0.870968</td>
<td>0.042575</td>
<td>50</td>
<td>830</td>
<td>0.193548</td>
<td>0.050175</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>0.854839</td>
<td>0.044738</td>
<td>51</td>
<td>833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>0.838710</td>
<td>0.046710</td>
<td>52</td>
<td>833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>0.822581</td>
<td>0.048517</td>
<td>53</td>
<td>833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>0.806452</td>
<td>0.050175</td>
<td>54</td>
<td>886</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>0.790323</td>
<td>0.051699</td>
<td>55</td>
<td>1051</td>
<td>0.169355</td>
<td>0.049393</td>
</tr>
<tr>
<td>14</td>
<td>7</td>
<td>0.774194</td>
<td>0.053100</td>
<td>56</td>
<td>1051</td>
<td>0.145161</td>
<td>0.047897</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>0.758065</td>
<td>0.054388</td>
<td>57</td>
<td>1051</td>
<td>0.120968</td>
<td>0.045617</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>0.741936</td>
<td>0.055571</td>
<td>58</td>
<td>1051</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>18</td>
<td>0.725807</td>
<td>0.056656</td>
<td>59</td>
<td>1071</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>21</td>
<td>0.709677</td>
<td>0.057647</td>
<td>60</td>
<td>1101</td>
<td>0.080645</td>
<td>0.044819</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>0.693548</td>
<td>0.058550</td>
<td>61</td>
<td>1405</td>
<td>0.040323</td>
<td>0.036265</td>
</tr>
</tbody>
</table>
Figure 6-2 The Weibull Reliability (Survival) function of the CubeSats after successful launch. The time axis units are days.
6.4 *Estimation of Probability of mission success after successful launch as a function of time and satellite mass using Weibull Regression*

6.4.1 Weibull Regression

The Weibull regression in its general form is given by [4]:

\[ S(t, x) = \exp \left[-\left(\frac{t}{\eta(x)}\right)^{\beta}\right] \] \hspace{1cm} (1)

where \( S(t, x) \) is Reliability function, \( \eta(x) = f(a, x) \) is a function of a vector of explanatory variables \( x \), having a vector of parameters \( a \).

At this point, we are going to consider a simple case, in which the only explanatory variable is the satellite mass \( x \), and the function \( f(a, x) \) is the power law model:

\[ \eta(x) = ax^{-b} \] \hspace{1cm} (2)

where \( a > 0 \), and \( b > 0 \).

Taking logarithm of Equation (1) twice, one gets

\[ \ln(-\ln[S(t, x)]) = \beta \ln(t) - \beta \ln[\eta(x)] \]
\[ = A_0 + A_1 X_1 + A_2 X_2 \] \hspace{1cm} (3)

where \( X_1 = \ln(t) \), \( X_2 = \ln(x) \), \( A_0 = -\beta \ln(a) \), \( A_1 = \beta \), and \( A_2 = \beta b \).

Equation (3) is the two variable linear regression.

6.4.2 Data used for estimation of the model parameters

In the following analysis, the time to failure (TTF) is defined as “Mission End Date” (with the Functional Status D, N, or S) minus “Launch Date”. Respectively, the time to censoring (TTC) is defined as “Mission End Date” (with the Functional Status A) minus “Launch Date”. There are only 62 records, for which TTF/TTC can be evaluated.

Out of these 62 records, there are only 21 records that have 3 or more satellites with equal mass. Thus, we have only 21 records that can be used for fitting the Weibull regression model. These data are displayed in Table 6-2 below.
Table 6-2 Data used for fitting Weibull Regression Model

<table>
<thead>
<tr>
<th>NORAD ID</th>
<th>Name</th>
<th>TTE Mission End Date - Launch Date</th>
<th>Censoring Indicator = 0 if Failure (D, N, S)<em>, = 1 if Censoring (A)</em></th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CUTE-1 (CO-55)</td>
<td>1825</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>AAU CUBESAT 1</td>
<td>84</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>UWE-1</td>
<td>21</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>LIBERTAD 1</td>
<td>30</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>CAPE 1</td>
<td>120</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>CP4</td>
<td>425</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>COMPASS 1</td>
<td>1405</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>UWE-2</td>
<td>3</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>9</td>
<td>NEGAI-STAR (Negai-Boshi)</td>
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<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>e-st@r</td>
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<td>0</td>
<td>1.00</td>
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<td>Goliat</td>
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<td>1.00</td>
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<td>833</td>
<td>1</td>
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<td>0</td>
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<td>0</td>
<td>4.00</td>
</tr>
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* D – Deorbited (pre-launch or disposal)  
N - Nonoperational  
S - Semioperational  
A – active

For the mass values of 1, 3, and 4 kg, the Reliability function was estimated using the Kaplan-Meier method as shown in Table 6-3 below.
Table 6-3 Kaplan-Meier $S(t)$ estimates for different satellite masses

<table>
<thead>
<tr>
<th>Order #</th>
<th>Time, days</th>
<th>Reliability Function</th>
<th>Std. Error</th>
<th>Mass, kg</th>
</tr>
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<tbody>
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<td>1</td>
<td>3</td>
<td>0.928571</td>
<td>0.068830</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.857143</td>
<td>0.093522</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.785714</td>
<td>0.109664</td>
<td>1.00</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>0.714286</td>
<td>0.120736</td>
<td>1.00</td>
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<tr>
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<td>0.132260</td>
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<tr>
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<td>84</td>
<td>0.500000</td>
<td>0.133631</td>
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</tr>
<tr>
<td>8</td>
<td>120</td>
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<td>0.132260</td>
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<td>120</td>
<td>0.357143</td>
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<td>1.00</td>
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<tr>
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<td>314</td>
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<td>0.120736</td>
<td>1.00</td>
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<td>0.000000</td>
<td>1.00</td>
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<tr>
<td>15</td>
<td>21</td>
<td>0.666667</td>
<td>0.272166</td>
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</tr>
<tr>
<td>16</td>
<td>60</td>
<td>0.333333</td>
<td>0.272166</td>
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<td>0.000000</td>
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<td>0.216506</td>
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<td>0.250000</td>
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<td>90</td>
<td>0.250000</td>
<td>0.216506</td>
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<td>506</td>
<td>0.000000</td>
<td>0.000000</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Table 6-4 below shows the regression analysis results. It is clear that all the model parameters are statistically significant, and the Reliability function is dependent not only on time but also on the satellite mass.

Table 6-4 Regression summary for dependent variable: $\ln(-\ln(S(t)))$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Std.Err.</th>
<th>t-ratio</th>
<th>p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>$A_0 = -2.56056$</td>
<td>0.162441</td>
<td>-15.7631</td>
<td>0.000000</td>
</tr>
<tr>
<td>Ln(Time)</td>
<td>$A_1 = 0.49830$</td>
<td>0.037129</td>
<td>13.4210</td>
<td>0.000000</td>
</tr>
<tr>
<td>LN(Mass)</td>
<td>$A_2 = 0.40691$</td>
<td>0.107772</td>
<td>3.7757</td>
<td>0.002047</td>
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</table>

The estimates of the parameters of the Weibull regression model given by Equations (1) and (2) are:

$$\beta = A_1 = 0.4983, \quad b = A_2/\beta = 0.8166, \quad a = \exp \left( -\frac{A_0}{\beta} \right) = 170.4754$$

The respective squared correlation coefficient $R^2 = 0.971$, which reveals a good adequacy of the obtained model.
6.4.3 **Comparison of the Kaplan-Meier estimates of the Reliability function and the estimates based on the Weibull regression**

The Kaplan-Meier estimates of the Reliability function and the estimates based on the above Weibull regression are displayed in **Table 6-5** below.

**Table 6-5 Kaplan-Meier estimates of Reliability Function and Estimates Based on Weibull Regression**

<table>
<thead>
<tr>
<th>Mass, kg</th>
<th>Time, Days</th>
<th>S(t), Kaplan-Meier</th>
<th>S(t), Weibull Regression</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>0.929</td>
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</tr>
<tr>
<td>1</td>
<td>3</td>
<td>0.857</td>
<td>0.875</td>
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<tr>
<td>1</td>
<td>5</td>
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<td>0.842</td>
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<td>0.703</td>
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<tr>
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<td>30</td>
<td>0.643</td>
<td>0.657</td>
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<td>30</td>
<td>0.571</td>
<td>0.657</td>
</tr>
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<td>84</td>
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<td>0.495</td>
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<td>0.432</td>
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<td>314</td>
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<td>425</td>
<td>0.214</td>
<td>0.207</td>
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<td>1405</td>
<td>0.107</td>
<td>0.057</td>
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<td>1825</td>
<td>0.000</td>
<td>0.038</td>
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<td>0.056</td>
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<td>4</td>
<td>7</td>
<td>0.750</td>
<td>0.699</td>
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<td>90</td>
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<td>0.049</td>
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</table>

**Figure 6-3** below illustrates the fitted Weibull regression Reliability function.
Using the Weibull regression Reliability model, a CubeSat Reliability can be estimated not only as a function of time, but also as a function of the satellites mass. For example, the median life of a 1 kg CubeSat is estimated as 85 days. In contrast, the median life of a 4 kg CubeSat is about 22 days only.

7 Conclusion

- The SLU database consists of the records of 370 CubeSats, most of which are the nanosatellites. Each record has up to 25 variables, but many of these records are incomplete. The information on the satellite design life are not available (i.e., missing), which makes practical reliability estimation difficult.
- Telecommunication and academic (university) communities are the two major classes of the CubeSat users, and among these users, the Planet Labs is major one (more than 75% of the satellites in the database are from Planet Labs).
- The satellite distributions by mass and by volume are bi-modal. The most popular volumes of the CubeSats are 1 liter and 3 liters (35% and 52% respectively). The most common masses are 1 kg and 5 kg (34% and 42% correspondingly).
- Annual number of CubeSats launched increased about ten times in 2015 compared to the number CubeSats launched in 2011.
- Based on 96 available records, the probability of a successful CubeSat launch can be estimated as follows:
  Point Estimate: 0.65, and the corresponding 60% Lower Confidence Limit as 0.63
• The CubeSat time to failure (after successful launch) distribution is difficult to estimate parametrically. The Kaplan-Meier (non-parametric) estimate of the median life is 110 days.

• The results of the Weibull distribution estimation yield the scale parameter $\alpha = 200.25$ days, and the shape parameter $\beta = 0.54$. The value of the shape parameter indicates the decreasing failure rate (rejuvenation) distribution. The $R^2$ is 0.92 that shows that the goodness of the distribution fit is not very good.

• In order to get better reliability estimation, the Weibull Regression with the satellite mass as an explanatory variable was applied. The fitted model provides a better goodness-of-fit ($R^2 = 0.97$). Based on the model, the median life of a 1 kg CubeSat is estimated as 85 days. In contrast, the median life of a 4 kg CubeSat is about 22 days only.

8 Acknowledgement
We are most grateful to Professor Michael Swartwout from SLU for sharing with us the SLU CubeSats database, as well as for providing the new variables as a response to our request.

9 References
3. Michael Swartwout, SLU, Private Communication
\section*{10 Appendix}

Table A1. Data available for CubeSats reliability estimation

<table>
<thead>
<tr>
<th>NORAD ID</th>
<th>Name</th>
<th>Mission End Date - Launch Date</th>
<th>Censoring Indicator = 0, if Failure (D, N, S), = 1 if Censoring</th>
</tr>
</thead>
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<td>26904 PICOSAT 7&amp;8 (TETHERED)</td>
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<td>0</td>
</tr>
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<td>3</td>
<td>27562 MEPSI</td>
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<td>0</td>
</tr>
<tr>
<td>4</td>
<td>27844 CUTE-1 (CO-55)</td>
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<tr>
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<td>27845 QAKESAT 1</td>
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