Abstract— Estimating the operational lifetime of satellites and spacecraft is a complex process. Operational lifetime can differ from mission design lifetime for a variety of reasons. Unexpected mortality can occur due to human errors in design and fabrication, to human errors in launch and operations, to random anomalies of hardware and software or even satellite function degradation or technology change, leading to unrealized economic or mission return. This study focuses on data collection of public information using, for the first time, a large, publically available dataset, and preliminary analysis of satellite lifetimes, both operational lifetime and design lifetime. The objective of this study is the illustration of the relationship of design life to actual lifetime for some representative classes of satellites and spacecraft. First, a Weibull and Exponential lifetime analysis comparison is performed on the ratio of mission operating lifetime to design life, accounting for terminated and ongoing missions. Next a Kaplan-Meier survivor function, standard practice for clinical trials analysis, is estimated from operating lifetime. Bootstrap resampling is used to provide uncertainty estimates of selected survival probabilities. This study highlights the need for more detailed databases and engineering reliability models of satellite lifetime that include satellite systems and subsystems, operations procedures and environmental characteristics to support the design of complex, multi-generation, long-lived space systems in Earth orbit.

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1. INTRODUCTION
From the earliest days of the space age, satellites and spacecraft have been designed to fulfill desired mission durations with high reliability. Figure 1 displays the history of mission design life for the 722 satellites and spacecraft comprising the dataset considered for this study (details on the data collection process are provided in section 2).

Figure 1 – Design Life at Launch Date

Starting in the late 1980’s a virtual avalanche of launches occurred with desired design lifetimes varying essentially uniformly from a few weeks to 20 years. Figure 2 shows the percent of total cases for each design life.

Figure 2 – Design Life as a Fraction of Total Cases
In roughly equal proportions, design lives of 0 to 7 years are 34% of all cases, 8 years to 12 years are 32% and 13 years to 20 years are 34%. The largest single design life is 15 years comprising 22% of all cases.

A number of questions arise. Based on the observation that there is a full range of design lifetimes, how close are the lifetimes that are observed when the spacecraft are in operations to the intended design lifetimes? How relevant to the analysis is the “one-hoss shay” model [9] in which the system deterministically fails precisely at the end of its design lifetime?

Several studies have analyzed spacecraft failure data and formulated models of spacecraft reliability [1, 2, 3, 4]. Issues surrounding design lifetime have been discussed in [6] and [8]. This paper describes the initial analysis of the largest known set of publicly available data to date on spacecraft operations termination (excluding launch failures) along with the corresponding design lifetimes to investigate the extent to which actual operating lifetimes differ from design lifetimes. The large data set of publicly available data makes possible, for the first time, statistically relevant conclusions on the current state of satellite lifetimes, taken as a whole, and also separated into different satellite types. Other studies have attempted to extract “Design for Reliability” rules. The present study focuses on the statistical analysis of actual experience. It may be possible to extract further information on the ‘secrets of long satellite life,’ however the current study focuses on the first step, which is to assess the current state, more than a half century into the history of satellites and spacecraft. The paper is organized as follows. First, in Section 2 the data collection effort is described as background for the veracity of the selected lifetime information. Next, Section 3 provides some simple sample statistics on both design lifetime and actual operating lifetime, presented for the entire sample of satellites as well as for the distinct subcategories related to satellite type—Communication, Remote Sensing, Scientific, Weather Forecasting, Military Communication, Military Early Warning, Military Navigation, and Military Reconnaissance and Surveillance. Next, two data analysis models are described in Section 4. Given the paucity of failure/termination information we consider only two groups for quantitative analysis, communication satellites and the combined group of all satellites and spacecraft. First, a standard Weibull and Exponential maximum likelihood analysis comparison of probability distribution fits to the ratio of operating to design lifetime is described for both groups. This analysis considers failures as distinct from currently operating satellites (i.e. right censored lifetimes). Second, a Kaplan-Meier survival distribution is constructed from operating lifetimes for both groups. Section 5 describes the uncertainty estimation for the Kaplan-Meier survival distributions using bootstrap sampling from the original dataset. Finally, Section 6 ties together the data and models to suggest future avenues of research.

2. DATA COLLECTION

The mortality dataset was extracted from two extensive public data sets, The 2001 Edition Communications Satellite Databases [5], containing 310 satellites, and the 2010 Compendium of Satellites and Satellite Launch Vehicles [7], containing 649 satellites for which launch date, end date and design life information was available. The combined data yielded 722 unique satellites with Design Life, Launch Date and End Date. Descriptive variables identifying the satellites include satellite type: Communication, Remote Sensing, Scientific, Weather Forecasting, Military Communication, Military Early Warning, Military Navigation, and Military Reconnaissance and Surveillance. The data sets were combined and duplicate items were removed. A large sample of satellite data was missing and/or needed to be checked. Searching was done on the internet to identify primary sources and other on-line databases. Conflicts were resolved by using the most reliable source. No launch failures are included in the final dataset, although some satellites in the dataset have failed unrelated to launch shortly after attaining an orbit.

Figure 3 shows the constitution of the sample resulting from the data collection. The majority of satellites are commercial
communications satellites (65%). Military satellites make up 18% of the total, but with only 2 failures (that we know of!), they provide little statistical power in estimating failure rates at that disaggregated level. Analysis has only been performed on Communication Satellites and All Satellites considered as a group.

3. SAMPLE STATISTICS

Satellite mortality statistics by satellite type are displayed in Table 1. Preliminary analysis shows that about 60% of satellites in the database have exceeded their design life. Among those that have not, many operating are recent launches or satellites in the early years of a predicted long design life. The following figures add quantitative support to these observations.

<table>
<thead>
<tr>
<th>Type</th>
<th>Count</th>
<th>%</th>
<th>No. of Deaths</th>
<th>% Dead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>49</td>
<td>6%</td>
<td>4</td>
<td>4.0%</td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>19</td>
<td>2%</td>
<td>7</td>
<td>12.7%</td>
</tr>
<tr>
<td>Scientific</td>
<td>18</td>
<td>2%</td>
<td>6</td>
<td>18.8%</td>
</tr>
<tr>
<td>Weather Forecasting</td>
<td>10</td>
<td>1%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Military Communication</td>
<td>10</td>
<td>2%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Military Early Warning</td>
<td>10</td>
<td>2%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Military Reconnaissance &amp; Surveillance</td>
<td>10</td>
<td>2%</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Total</td>
<td>722</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 plots Actual Life (vertical axis) versus Design Life (horizontal axis) for all satellites. Points above the 45-degree upward sloping light dotted line are satellites that have exceeded their design life. Red circles denote satellites that have either died due to technical failures of components, depletion of station keeping fuel, or loss of service/mission demand.

Figure 5 plots Actual Life versus Design Life for Communication Satellites. This group displays a good dispersion of design lives, especially for the older design lives of 10, 12 and 15 years.

Figure 6 plots Actual Life versus Design Life for Remote Sensing satellites. In these cases the planned lifetimes are generally 5 years or less. The data indicate actual lifetimes many times longer than required.

Figure 7 plots Actual Life versus Design Life for Weather Forecasting satellites. Like the Remote Sensing Satellites, these in general have much longer actual lives than planned.
Weather Forecasting Satellites: Design Life v. Actual Life

Figure 8 plots Actual Life (vertical axis) versus Design Life (horizontal axis) for Scientific Satellites. Except for two early failures, these missions have far exceeded expectations in terms of durability.

Military Communication Satellites: Design Life v. Actual Life

Figure 9 plots Actual Life (vertical axis) versus Design Life (horizontal axis) for Military Communications Satellites. Except for one early failure with a 6-year design life, these missions have far exceeded expectations in terms of durability. The regularities of the points with actual life declining as design life increases seem to suggest families of satellites with early launches having shorter design lives. The longer ongoing lives and higher design lives of older operating satellites suggests a trend to shorter design lives for more recently launched military communication satellites.

Military Navigation Satellites: Design Life v. Actual Life

Figure 10 plots Actual Life (vertical axis) versus Design Life (horizontal axis) for Military Navigation satellites. No failures are evident in the data. The majority of these satellites are of recent vintage, currently 7 and 10 year design lives with a large group of 3 years all exceeding their planned life.

Military Reconnaissance and Surveillance Satellites: Design Life v. Actual Life

Figure 11 plots Actual Life (vertical axis) versus Design Life (horizontal axis) for Military Reconnaissance and Surveillance satellites. No failures are evident in the data. The majority of these satellites are of past vintage, currently 5 and 12 year design lives with a majority of planned lifetimes exceeded.
Figure 12 displays all satellites actual and design lives in a single chart. The red dots represent the design life, the blue diamonds are the actual life as of 2012. The downward sloping 45-degree line represents all currently operating satellites, representing 95% of database satellites. The diagonal, downward sloping line of currently operating satellites extends back to launches from the early 1980’s. There is a dearth of failed (on-orbit) satellites in the decade from the year 2000 on. This highlights that modern, post 20th century satellites are highly reliable! (Note: No launch failures are in the database.)

Figure 11 – Actual versus Design Life
Military Reconnaissance & Surveillance Satellites

Launch Date v. Actual/Design Life

Figure 12 – Launch Date versus Actual/Design Life All Satellites
4. MODEL ANALYSIS

This section describes two data analysis models evaluated using the collected data for both groups, the first of all satellites and spacecraft and the second of communication satellites. The term “failure” is used here to denote both technical failures as well as other terminations of life.

The maximum likelihood Weibull failure distribution with right censored data, i.e. ongoing surviving satellite lifetimes, is given by

\[
S(t) = \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right) \quad (1)
\]

\[
f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp\left(-\left(\frac{t}{\eta}\right)^\beta\right) \quad (2)
\]

\[
L = \prod_{i}^{\text{Failures}} f(t_i) \prod_{i}^{\text{Censored}} S(t_i) \quad (3)
\]

Equation (1) is the Survival Function, which indicates the fraction of satellites remaining at time \( t \), where \( t \) is the lifetime calculated from launch to the failure date or to the censored date (i.e. the present.) For the purposes of the first study, the time \( t \) is divided by the design life. The Weibull and Exponential analysis fits are done using this ratio for each satellite. \( \beta \) is the dimensionless shape parameter; when less than one, it models infant failures in excess of an exponential distribution, i.e. a constant failure rate; when greater than one, it models more late failures relative to the exponential. \( \eta \) is the dimensionless scale parameter providing uniform variation of the ratio of lifetime to design life. Equation (2) is the Weibull probability density function for failure at time \( t \). Equation (3) is the likelihood, \( L \), to be maximized by an iterative parameter variation in this study, a product of the distributions of failures and censored survival functions. The Exponential distribution is in the Weibull family of distributions with the value of \( \beta \) set to 1.

**Weibull and Exponential Analysis Comparison**

For the Weibull and Exponential analysis, satellite lifetime is scaled by design life, i.e. survival lifetime is divided by design life for each satellite. A simple numerical iteration is used to maximize the Weibull and Exponential likelihood functions, a product of failed satellite probability density functions and operating satellite survival functions.

Figure 13 compares the maximum likelihood survival function of the Weibull with the maximum likelihood Exponential survival distribution for all satellites. The Weibull has nearly 97% of satellites left operating after 1 design life compared with a little over 97% for the Exponential. At two design life times, both values are roughly even at 94.5%. This illustrates the lower incidence of infant failures for communication satellites for the Weibull distribution, \( \beta = 0.78 \), relative to the Exponential. The scale parameter, \( \eta = 81 \), greater than the exponential lifetime ratio of 35, means the Weibull survival function exceeds the Exponential for multiples greater than about 2 design lives.

Figure 14 compares the maximum likelihood survival function of the Weibull with the maximum likelihood Exponential survival distribution for communication satellites. The Weibull has nearly 97% of satellites left operating after 1 design life compared with a little over 97% for the Exponential. At two design life times, both values are roughly even at 94.5%. This illustrates the lower incidence of infant failures for communication satellites for the Weibull distribution, \( \beta = 0.65 \), are more prevalent than under the Exponential distribution (i.e. constant failure rate). The scale parameter, \( \eta = 166 \), much greater than the exponential lifetime ratio of 60, means the Weibull catches up in survivors for larger multiples (>6) of the design life.
The Kaplan-Meier failure-time survivor function estimator is the standard tool for clinical trials where participants, for various reasons, leave the trial (i.e., are right censored) without either success or failure of the treatment. The failure lifetimes and censored lifetimes (for ongoing missions) are sorted from low to high values. In the use for satellite mortality estimation, failures result in a “drop down” of the survivor function and ongoing and censored satellites result in the function continuing horizontally. Figure 15 displays the results of including all satellites in the study. Early failures result in the rapid drop for the first 3 years of the function. Censored data is then mixed in with failures until about 10 to 12 years out, after which ongoing satellites dominate. For reference, three different exponential distribution curves are displayed on the graph in red. These distributions have a lifetime of 150, 200, and 250 years respectively (not the Life/Design Life ratio used in the Weibull analysis), with the 200-year exponential curve roughly tracking with the Kaplan-Meier function’s shape at failures. Note that these curves are for comparison only and not derived from any fitting or optimization procedure.

Figure 16 displays the Kaplan-Meier Survivor Function for the Communication satellites, along with three reference exponential curves. The displayed exponential curve lifetime of 250 years is 25% higher than that for all satellites combined.

Given the nature of these functions, it is useful to ask: how precisely are the survivor functions known? What are the uncertainties associated with survival after 5 years? 10 years? 15 years? 20 years? The concluding section presents the results of bootstrap resampling of the original satellite survival data to estimate the uncertainty in the Kaplan-Meier functions.

Table 2. All Satellites’ Validation Statistics

<table>
<thead>
<tr>
<th>All Satellites</th>
<th>Kaplan-Meier Failure-time Survivor Function</th>
<th>Bootstrap Cross-Validation</th>
<th>5 year survival probability</th>
<th>10 year survival probability</th>
<th>15 year survival probability</th>
<th>20 year survival probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.9745%</td>
<td>0.9582%</td>
<td>0.9265%</td>
<td>0.902%</td>
<td>0.872%</td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.025%</td>
<td>0.010%</td>
<td>0.010%</td>
<td>0.010%</td>
<td>0.010%</td>
<td></td>
</tr>
<tr>
<td>Exponential Lifetime</td>
<td>191.7</td>
<td>191.7</td>
<td>227.5</td>
<td>265.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure Rate (per year)</td>
<td>0.00626%</td>
<td>0.00615%</td>
<td>0.00649%</td>
<td>0.00627%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 presents the results for communication satellites. The uncertainties on the survival probabilities range from 0.6% on the 5 year probability of 98.5% to 1.1% for that on the 20 year survival probability of almost 95.5%. The equivalent exponential lifetimes show a decline at 10 years relative to 5 year and 15 year survival times, rising by 1/3 for 20 year survival values. A justification for using the Weibull instead of the Exponential distribution for all satellites as highlighted in the earlier Weibull-Exponential comparison.
for communication satellites as mentioned in the earlier Weibull-Exponential comparison study.

### Table 3. Communication Satellites’ Validation Statistics

<table>
<thead>
<tr>
<th>Communication Satellites</th>
<th>Kaplan-Meier Failure-Time Survival Function Bootstrap Cross-Validation</th>
<th>5 year survival probability</th>
<th>10 year survival probability</th>
<th>15 year survival probability</th>
<th>20 year survival probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>88.62%</td>
<td>86.47%</td>
<td>86.45%</td>
<td>86.44%</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.97%</td>
<td>0.81%</td>
<td>1.07%</td>
<td>1.05%</td>
</tr>
<tr>
<td></td>
<td>Exponential Lifetime</td>
<td>333.5</td>
<td>279.3</td>
<td>322.2</td>
<td>429.8</td>
</tr>
<tr>
<td></td>
<td>Failure Rate (per year)</td>
<td>0.0025</td>
<td>0.0035</td>
<td>0.0031</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

6. SUMMARY AND CONCLUSIONS

This study is but a preliminary step in understanding the basic outline of satellite mortality using publicly available data. Simple statistical tools, based on Weibull-Exponential distribution comparisons and Kaplan-Meier function estimation with resampling techniques, provide robust, consistent summary information about satellite mortality, both unintended failures and conscious operation terminations. Considering all satellites as a group suggests an early failure excess of the Weibull over Exponential fits (equivalently, late failures are less prevalent, implying longer survival lifetimes.) The case of communications satellites suggests that an Exponential distribution captures the essential life cycle effects. These effects seem to hold true whether we are using actual lifetimes in a Kaplan-Meier analysis or in a Weibull-Exponential analysis lifetimes modified by design life. In the future, more detailed functional, hardware, environmental and operations information will be required to derive refined lifetime models that should incorporate economic along with technical considerations. This database of design life and actual lifetime and its analysis was a needed first step, suggestive of collecting more extensive data and developing more detailed models of design, development and testing options for targeting precise reliability distribution moments around a given design life, commensurate with economic and programmatic risk considerations.

7. ACKNOWLEDGEMENT

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### REFERENCES


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