A Satellite Mortality Study to Support Space Systems Lifetime Prediction

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4 authors, including:

Gregory F. Dubos
California Institute of Technology

Ronald P. Salazar
NASA

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George Fox
818-354-1278
George.Fox@jpl.nasa.gov

Ronald Salazar
818-354-6173
Ronald.P.Salazar@jpl.nasa.gov

Hamid Habib-Agahi
818-354-1063
Hamid.Habib-Agahi@jpl.nasa.gov

Gregory Dubos
818-354-0318
Gregory.F.Dubos@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109

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).

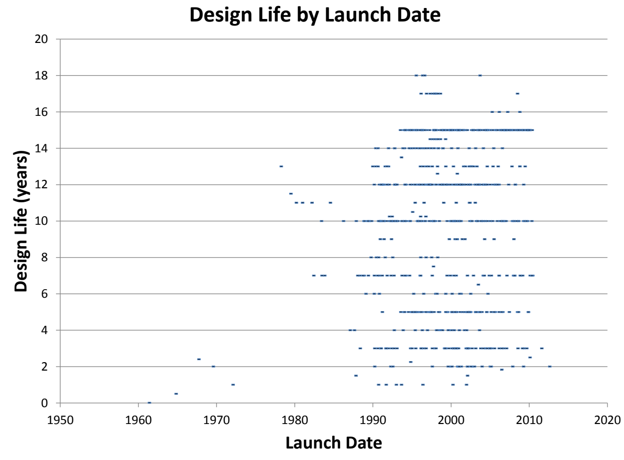

Figure 1 – Design Life at Launch Date

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.

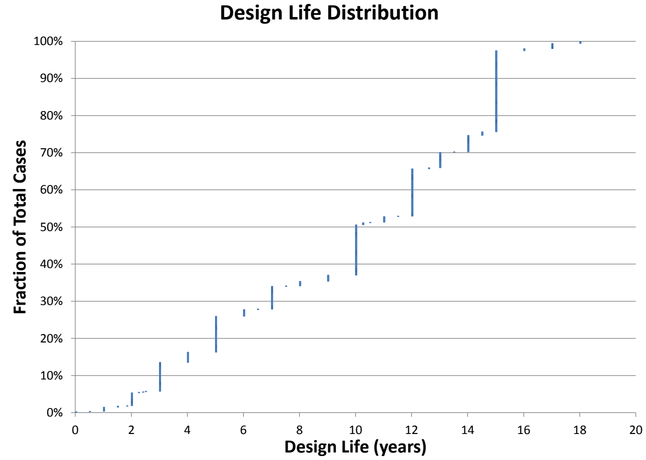

Figure 2 – Design Life as a Fraction of Total Cases

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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 (Ref. 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 Ref.6 and Ref. 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 publically 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* (Ref. 5), containing 310 satellites, and the 2010 *Compendium of Satellites and Satellite Launch Vehicles* (Ref. 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.

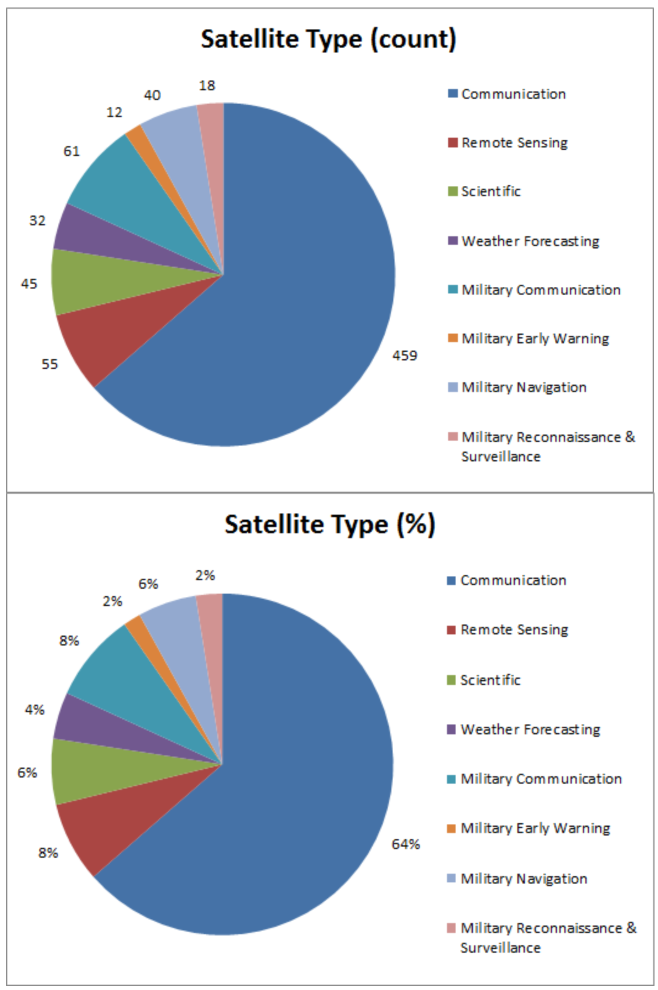

Figure 3 – Satellite Type by Count and Percentage

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 1 - Satellite Deaths by Type

Type	Count	%	No. of Deaths	% Dead
Communication	459	64%	21	4.6%
Remote Sensing	55	8%	7	12.7%
Scientific	45	6%	7	15.6%
Weather Forecasting	32	4%	6	18.8%
Military Communication	61	8%	2	3.3%
Military Early Warning	12	2%	0	0.0%
Military Navigation	40	6%	0	0.0%
Military Reconnaissance & Surveillance	18	2%	0	0.0%
Total	722			

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.

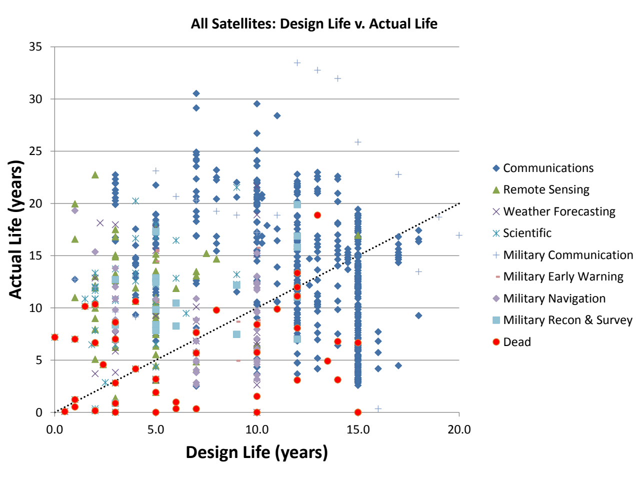

Figure 4 – Actual versus Design Life – All Satellites

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.

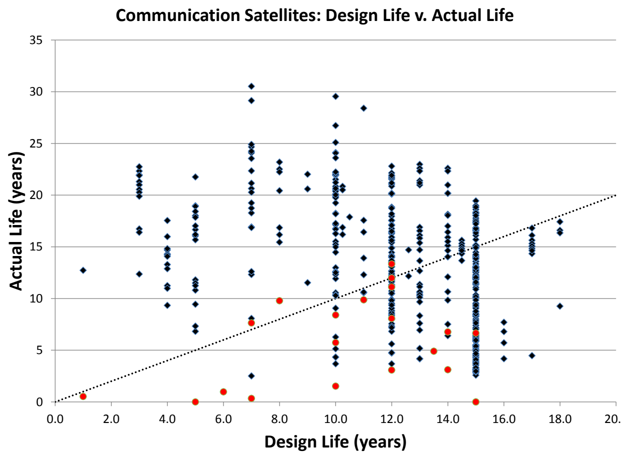

Figure 5 – Actual versus Design Life Communication Satellites

Figure 6 plots Actual Life (vertical axis) versus Design Life (horizontal axis) 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.

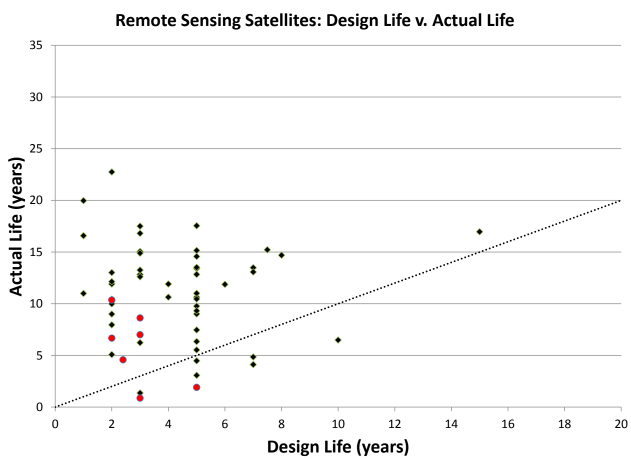

Figure 6 – Actual versus Design Life Remote Sensing Satellites

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

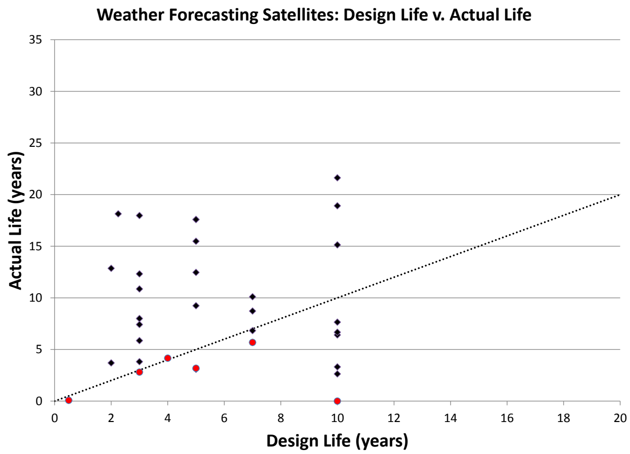

Figure 7 – Actual versus Design Life
Weather Forecasting Satellites

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.

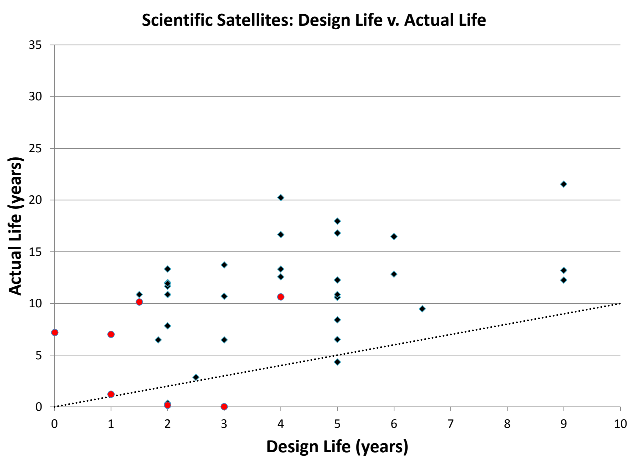

Figure 8 – Actual versus Design Life
Scientific Satellites

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.

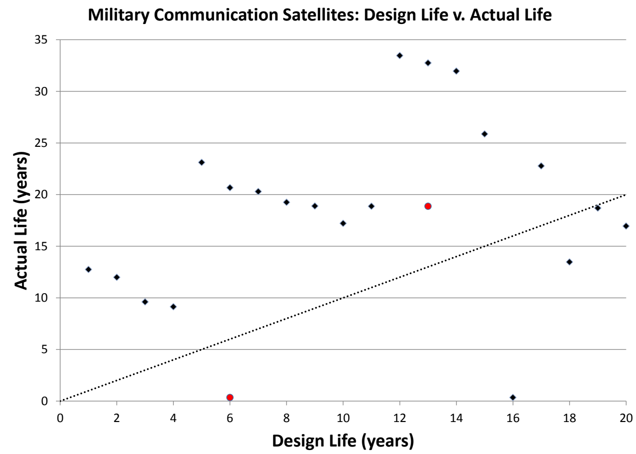

Figure 9 – Actual versus Design Life
Military Communication Satellites

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.

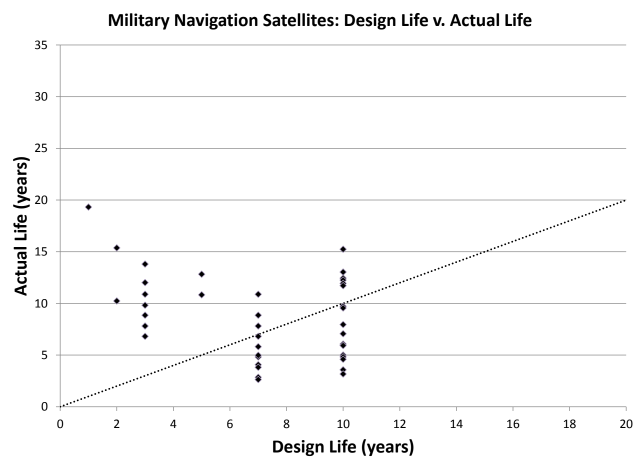

Figure 10 – Actual versus Design Life
Military Navigation Satellites

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.

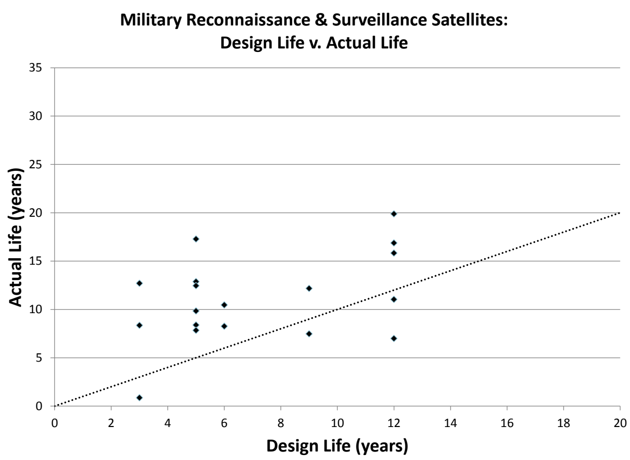

Figure 11 – Actual versus Design Life
Military Reconnaissance & Surveillance Satellites

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 20^{th} century satellites are highly reliable! (Note: No launch failures are in the database.)

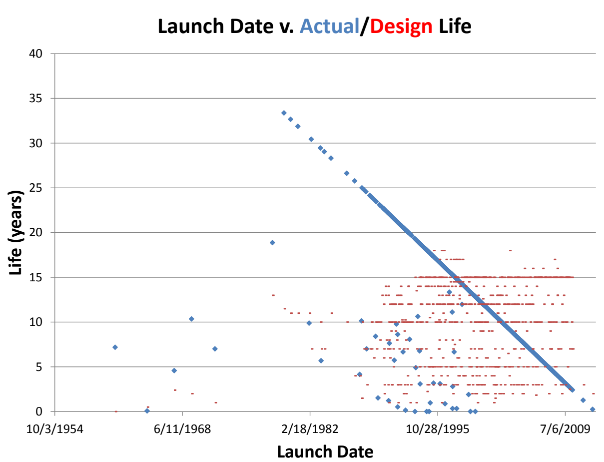

Figure 12 – Launch Date versus Actual/Design Life
All Satellites

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

$$S(t) = \exp(-(t/\eta)^{\beta}) \tag{1}$$

$$f(t) = \beta/\eta\ (t/\eta)^{\beta-1} \exp(-(t/\eta)^{\beta}) \tag{2}$$

$$L = \Pi_i^{\text{Failures}} f(t_i)\ \Pi_j^{\text{Censored}} S(t_j) \tag{3}$$

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. β 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. η 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 β 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. For all satellites, the Weibull has 96% of satellites that are left operating after 1 design life compared with 98% for the Exponential. At two design life times, the values are over 94% for the Weibull and 97% for the Exponential. This illustrates that the early infant failures for the Weibull distribution, β = 0.65, are more prevalent than under the Exponential distribution (i.e. constant failure rate). The scale parameter, η = 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.

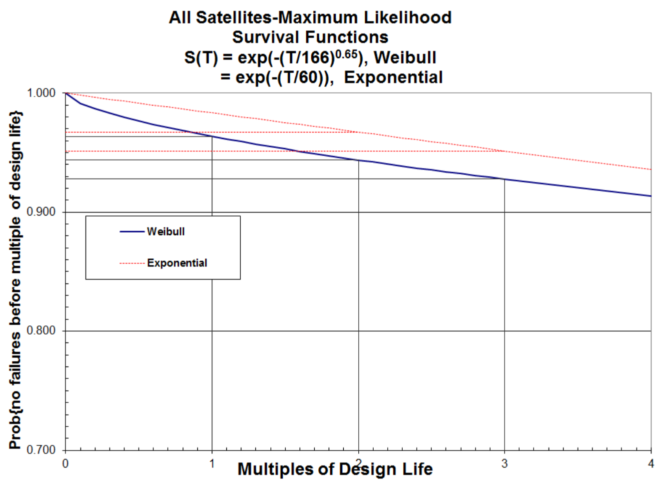

**Figure 13 – Weibull Analysis
Failure & Censored Data
All Satellites**

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, $\beta = 0.78$, 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.

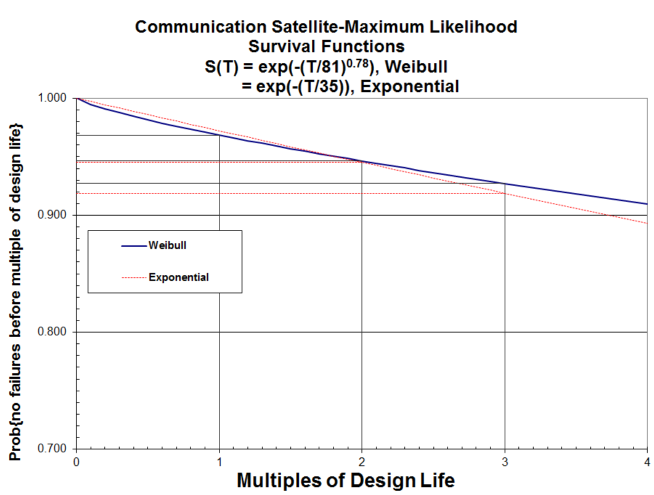

**Figure 14 – Weibull Analysis
Failure & Censored Data
Communication Satellites**

Kaplan-Meier Estimator

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. The exponential curve on the graph displayed in red has a lifetime of 190 years (not the Life/Design Life ratio used in the Weibull analysis), roughly tracking with the Kaplan-Meier function's shape at failures. The exponential curve is for comparison only and not derived from any fitting or optimization procedure.

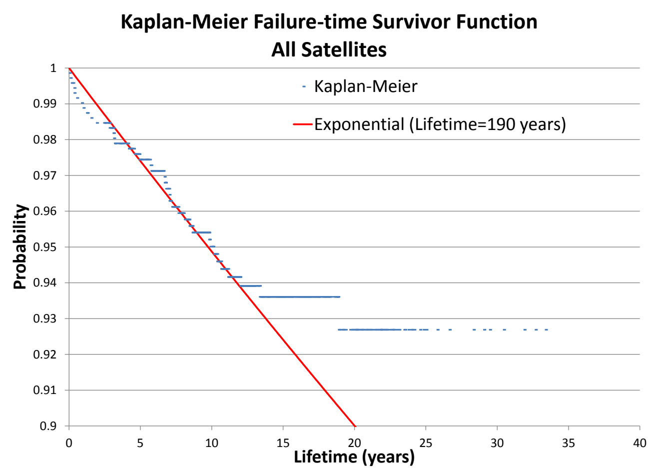

**Figure 15 – Kaplan-Meier Failure-time
Survivor Function
All Satellites**

Figure 16 displays the Kaplan-Meier Survivor Function for the Communication satellites. Here 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.

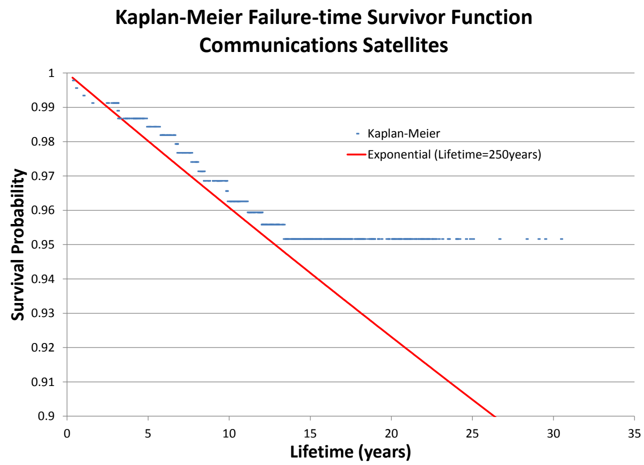

Figure 16 – Kaplan-Meier Failure-time Survivor Function Communication Satellites

5. UNCERTAINTY BY BOOTSTRAP

Bootstrap sampling from the dataset of 722 satellites was utilized to derive uncertainty estimates for the 5 year, 10 year, 15 year and 20 year survival probabilities. One thousand bootstrap samples were constructed from the original dataset. Each sample is a mix of 722 random satellites drawn from the original dataset. The Kaplan-Meier failure-time survivor function is calculated and the 5, 10, 15 and 20 year survival probabilities are summed for all of the one thousand bootstrap samples. Table 2 presents the results for the case of all satellites. The uncertainties on the survival probabilities range from a standard deviation of 0.6% on the 5 year probability of 97% to 1.4% for that on the 20 year survival probability of almost 93%. The equivalent exponential lifetimes show a similar consistency for 5 and 10 year lifetime, rising slightly for the 15 and 20 year values. This is consistent with greater uncertainty and lower failure rates for long surviving satellites: this is a justification for using the Weibull instead of the Exponential distribution for all satellites as highlighted in the earlier Weibull-Exponential comparison.

Table 2. All Satellites' Validation Statistics

All Satellites Kaplan-Meier Failure-Time Survivor Function Bootstrap Cross-Validation	5 year survival probability	10 year survival probability	15 year survival probability	20 year survival probability
Average	97.43%	94.98%	93.62%	92.73%
Standard Deviation	0.62%	0.89%	1.06%	1.36%
Exponential Lifetime	191.7	194.0	227.5	264.9
Failure Rate (per year)	0.00522	0.00515	0.00440	0.00377

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 is less clear for communication satellites as mentioned in the earlier Weibull-Exponential comparison study.

Table 3. Communication Satellites' Validation Statistics

Communication Satellites Kaplan-Meier Failure-Time Survivor Function Bootstrap Cross-Validation	5 year survival probability	10 year survival probability	15 year survival probability	20 year survival probability
Average	98.52%	96.47%	95.45%	95.45%
Standard Deviation	0.57%	0.88%	1.05%	1.05%
Exponential Lifetime	334.5	278.3	322.2	429.6
Failure Rate (per year)	0.00299	0.00359	0.00310	0.00233

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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BIOGRAPHIES

***George Fox**: Engineers used slide rules when George entered Caltech as a freshman in 1965. After certification as a quantum mechanic & micro economist (Caltech PhD, Applied Physics and Economics, 1979) George joined JPL to determine the value of solar-cell-supplied power for the national PV solar energy program. As the program diminished, George changed sides, doing military acquisition policy analysis & war-gaming modeling for the highly successful JESS, validated during Gulf War (One!). As an original co-developer of the Space Station System Design Tradeoff Model and a founding analyst for JPL's Project Design Center, George has been informing NASA and JPL about cost-performance-risk tradeoffs. He has developed reliability-based design models of complex systems (JPL's Space Interferometry Mission and NSF's NEPTUNE Project). Recently, he entered the quagmire of joint cost and schedule risk modeling to try to convince others that it cannot be done without relevant historical data and appropriate statistical models. George is currently the statistical analyst for NICM, the NASA Instrument Cost Model.*

***Hamid Habib-Agahi**: Hamid Habib-Agahi has a Bachelor Degree in Electrical Engineering, M.S in Industrial Economics and a Ph.D. in Mathematical Economics from Purdue University. He has been on the faculty of the University of Waterloo and the University of Pennsylvania and has published numerous articles in leading economics, statistics and management science journals and has co-authored two books. He is currently a principal systems engineer, the manager of the Systems Analysis & Model Development Group at JPL and the manager of NASA Instrument Cost Model (NICM) development. He has been working for over 30 years in the area of risk analysis, probabilistic cost model development, systems analysis, and resource optimization in support of NASA flight missions as well as NASA's Deep Space Network ground system.*

***Ronald P. Salazar**: Ronald P. Salazar has a B.S. in Aerospace Engineering from the University of Southern California and a M.S. and Ph.D. in Mechanical Engineering from the University of California, Santa Barbara. At JPL he has performed Thermal and System Engineering on a number of flight projects, from concept design through extended mission operations. He has been a manager of Advanced Concept and Mission and System Architecture development. He has led several dozen studies with Team X, JPL's Advanced Concepts Concurrent Engineering Team. Most recently he has been on assignment to the Missile Defense Agency, first as the Associate Director of the Space Knowledge Center, which sponsored this work, and currently as the Space System Engineer of the Precision Tracking Space System.*

***Greg Dubos**: Greg Dubos is a Systems Engineer in the Mission Systems Concept Section at the Jet Propulsion Laboratory (JPL). He received his Bachelor and M.S degrees in Aeronautics from SUPAERO, Toulouse, France, and his M.S and Ph.D. in Aerospace Engineering from the Georgia Institute of Technology in Atlanta, GA. His current work at JPL focuses on the infusion of Model-Based Systems Engineering (MBSE) and simulation during mission formulation activities. For DARPA's F6 project, he developed discrete-event simulation models that capture technical risks such as launch failures, spacecraft failures, and orbital debris. He also regularly serves as the Risk and Programmatics Chair for Team X, JPL's concurrent engineering environment. He was a contributing author for the "Encyclopedia of Aerospace Engineering" (Wiley&Sons) and "Spacecraft Reliability and Multi-State Failures, A Statistical Approach" (Wiley&Sons).*