

# Satellite Reliability: Statistical Data Analysis and Modeling

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The technical literature has long recognized the importance of satellite reliability, but a statistical analysis of expansive on-orbit failure data is still lacking. As a result, inconsistencies persist in the literature due to the absence of an empirical basis for settling the issues, for example, regarding the existence or absence of satellite infant mortality. Weibull distributions with a shape parameter larger than one are commonly used to model satellite reliability. This choice for the shape parameter fails to capture infant mortality and is shown here to be flawed. The present work fills a gap in the technical literature by 1) conducting a thorough nonparametric statistical analysis of recent on-orbit failure data, 2) fitting a parametric model to the actual/observed spacecraft reliability, and 3) quantifying the relative contribution of each subsystem to satellite failure and identifying the subsystems that drive spacecraft unreliability. The sample analyzed in this study consists of 1584 Earth-orbiting satellites successfully launched between January 1990 and October 2008. The results presented here should prove useful for the space industry, for example, in redesigning satellite (and subsystem) test and screening programs and in providing an empirical basis for subsystem redundancy allocation and reliability growth plans.

## Nomenclature

$D(t)$	= dispersion of the 95% confidence interval around $\hat{R}(t)$
$m_i$	= multiplicity of ties at time $t_{(i)}$
$n_i$	= number of items functioning right before $t_{(i)}$
$\hat{P}_{\text{sat}}$	= probability of satellite failure
$\hat{P}_{\text{sub},j}$	= probability of satellite failure due to subsystem $j$
$\hat{p}_i$	= conditional probability of surviving $t_{(i)} + \delta t$
$R(t)$	= reliability function, also known as the survivor function
$R_n(t)$	= reliability estimate from a complete data set with $n$ units
$\hat{R}(t)$	= Kaplan–Meier estimator of the reliability function from a censored data set
$R^2$	= coefficient of determination in a regression analysis
$r_j$	= percent contribution of subsystem $j$ to the probability of satellite failure
$T_F$	= random variable time to failure
$t_{(i)}$	= $i$ th failure time, arranged in ascending order
$\hat{\text{var}}$	= estimated asymptotic variance of $\hat{R}$
$\beta$	= Weibull shape parameter, dimensionless parameter
$\delta t$	= arbitrary small time interval in which no failure or censoring occurs
$\theta$	= Weibull scale parameter, years
$\lambda(t)$	= failure rate, also known as the hazard function
$\sigma$	= estimated asymptotic standard deviation of $\hat{R}$

## I. Introduction

**R**ELIABILITY is a critical design attribute for systems operating in remote or inhospitable environments. Consider, for example, satellites or subsea installations: because physical access to these high-value assets is difficult or impossible, maintenance cannot be relied upon to compensate for substandard reliability [1]. As a result,

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designing high-reliability into these systems is an essential engineering and financial imperative.

For space systems, statistical analysis of flight data, in particular of actual on-orbit reliability and multistate failures, would provide particularly useful feedback to spacecraft designers. In particular, it would help guide satellite test and screening programs and provide an empirical basis for subsystem redundancy and reliability growth plans. Unfortunately, limited empirical data and statistical analysis of satellite reliability exist in the technical literature. In the following, we highlight three limitations with this state of affairs, namely that of 1) data obsolescence, 2) missing prerequisite/absence of realistic inputs, and 3) reliability specification/absence of model validation.

Before discussing these three points, it is worth addressing a common argument, which is that competitive sensitivity is one reason for the lack of published data and statistical analysis of on-orbit reliability. Although this might be true for satellite manufacturers, it is not the case for satellite operators (private or government agencies) whose interests are better served by transparent reliability analysis of different spacecraft buses. Furthermore, satellite manufacturers could also benefit, in the long-term, in having satellite reliability analyzed and published. For example, such studies would constitute a transparent benchmark against which satellite manufacturers can compete and hence improve their products' reliability. They can also constitute a strong motivation for satellite manufacturers to (re-)design their reliability improvement programs.

We start with the data obsolescence problem in satellite reliability studies. Binckes [2] provides one of the early references on satellite reliability. The author analyses communication satellite reliability and identifies mission-critical subsystems. This work, however, presents a mathematical model based on the Intelsat IV series of communications satellites of the 1970s. Given the significant technological changes in spacecraft design since the 1970s, the data on satellite reliability presented in [2] is obsolete and of limited relevance for today's spacecraft. Krasich [3] uses flight data from the Voyager, Magellan, and several of the Mariner probes to demonstrate a decreasing failure rate and infant mortality and concludes that an exponential lifetime distribution cannot match data from flight experience. Krasich [3] adds, "reliability predictions with MIL-HDBK 217 constant failures rates are unrealistic." Krasich's contribution is significant, but it is confined to interplanetary spacecraft "and other orbiters" (which are not identified). As a result, the range of applicability of that analysis is uncertain, and the data used, although more recent than that in [2], is two decades old or more, and thus suffers similar obsolescence and validity (or lack of) concerns.