THE STATUS OF RELIABILITY ASSESSMENT FOR UNMANNED SATELLITES*

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Summary

Reliability Assessment techniques applied to Goddard's unmanned space systems now have been in effect for about five years and it is useful to review the methodology used, its effectiveness and usefulness. Such a review encompasses not only the approach and methodology which has been used but also a comparison of the assessment results prior to space flight with actual flight results. Major problem areas are the development of adequate mathematical models, the availability of information to estimate system, subsystem, component and part failure rates, the use of "correction" factors to compensate for the space environment and the proper interpretation of assessment results.

The performance of assessments before actual flight is discussed from the viewpoint of establishing a plausible hypothesis which is subject to acceptance or rejection by the flight program. The question of interpreting a situation where assessment results show a relatively unreliable system but later flight results show success or the opposite is examined in the framework of scientific and rational models.

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Introduction

The Goddard Space Flight Center of the National Aeronautics and Space Administration has managed thirty-four unmanned earth orbiting satellites which have accumulated in excess of twenty-five years of orbit life as of September, 1964. Included among these are scientific satellites such as Vanguard III and the Explorer series, weather satellites TIROS and Nimbus, international satellites Alouette and the United Kingdom (UK) series, observatories OSO and OGO, and passive and active communications systems such as Echo, Telstar, Relay, and Syncom. All these satellites, with perhaps two exceptions, have provided us with varying degrees of useful scientific and engineering information and knowledge. Individual lifetimes of satellites have varied from a few hours to 2 and 4 years of life. No two satellites launched were identical although the eight TIROS satellites launched were certainly similar -- complexity in terms of number of parts ranged from two thousand for Explorer VII to a 5000 part magnitude for TIROS, and IMP (Explorer XVIII) with about 12,000 onto 30,000 - 40,000 for OGO and Nimbus types.

The purpose of my remarks is not to discuss any formal engineering and scientific information which has been gained but rather to talk about reliability assessment with particular emphasis on Goddard's space experience. As you all know, we are dealing with a new discipline, one which does not have any extensive history of

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over 10 years. There exist today some half dozen books on the subject and to mention a few, they include Lloyd and Lipow, (1), Bazovsky, (2), Pieruschka, (3), and ARINC's "Reliability Engineering", (4), handbook. As far as applications are concerned for the aerospace systems, the Proceedings of the National Symposium on Reliability and Quality Control represent the best available source of information. My remarks are expository in nature and represent my personal views on the subject and should not necessarily be taken as Goddard or NASA doctrine.

A Rational Framework

One of the first points I would like to discuss is the role of reliability assessment as part of a rational scientific framework of inference. By reliability assessment I am referring to the analytical processes which include the block or functional diagrams of a system, the mathematical model, the data used to estimate the parameters of the model, and the inferences made regarding the reliability of the system based on the results obtained. Reference (5) gives a more detailed discussion of different types of reliability assessments and an example of a general mathematical model. Frequently, assessments for reliability are performed before a system is operated in its intended environment. For example, consider Goddard's Orbiting Astronomical Observatory (OAO), prior to any space flight, it is desired to determine as much as possible about the reliability of the system on the basis of such factors as the design, parts information and test results.

Hence, in a general way, we can consider an assessment as an analysis which is performed prior to the performance of the actual experiment of interest, namely, the space flight. For reliability assessments in the manner discussed, we are not dealing with any of the classical notions of statistical inference such as estimation or testing of hypothesis. The former of which deals with the estimation of parameters which are of interest on the basis of experimental results -- for example, on the basis of several TIROS flights, considered as a sample from a conceptual population, we can estimate the percent success, or the mean life of such a system. For hypothesis testing, first let us consider the classical concept. Webster defines a hypothesis as "A tentative theory or supposition provisionally adopted to explain certain facts and to guide in the investigation of others." A statistical hypothesis is a tentative statement regarding parameters, usually of an assumed distribution function. A hypothesis is either accepted or rejected on the basis of an experiment or sampling procedure. As an example, consider a sample from a manufacturing lot, we either accept or reject the lot for a stated quality level after observing the quality characteristics in the sample. The basic question is, therefore, how to relate a pre-experiment procedure such as reliability assessment to statistical inference concepts and procedures. There is one point which I would like to clarify. The data used to determine the reliability of components, parts and subsystems, which are used as inputs in the reliability model for a system being assessed usually come from experimental sources, namely, laboratory or ground testing. However, the origin, test and environmental conditions of such data are usually not known in sufficient detail and hence the "failure rates" can only be viewed as the best available parametric values rather than random variables obeying statistical laws. The assessed reliability of a system is not a statistical quantity but a fixed number obtained through an analytical process which is not of known experimental origin. Hence, an assessment of the type outlined above serves most often only for the establishment of a plausible reliability hypothesis which is tested by a space flight program.

Reliability Assessment and Statistical Inference

A reliability assessment may be considered from the following viewpoint. In order to be more concrete let us assume that a reliability assessment for a satellite yields a value of .97 for a defined mission of assumed duration. Let us assume it is correct. Before the mission takes place, we are dealing with a "pre-data predictive" situation, in the sense discussed by Dempster, (6), before the event occurs, namely, predictively .97 can be considered as a measure of the degree of certainty about an event, in this case the mission. After the mission has been completed, we are dealing with a "post-data predictive" situation which has resulted in one of two outcomes:

(1) If the mission was successful: "An event with probability .97 has occurred" or

(2) If it were unsuccessful: "An event with probability .03 has occurred" and we are surprised.

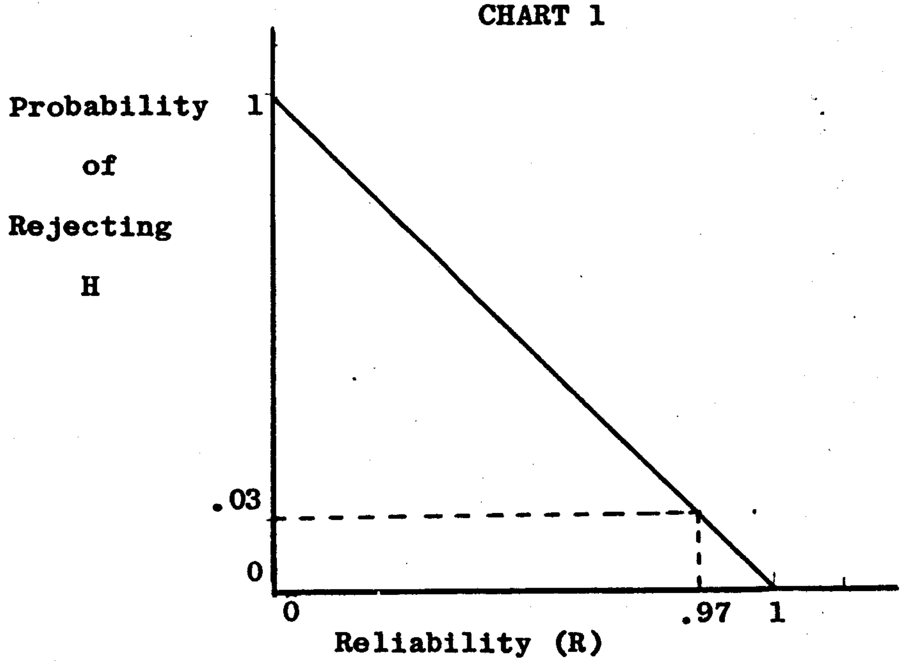
It is important to realize that neither outcome "proves" or "disproves" the accuracy of the assessment.

In more classical statistical inference theory we first establish the hypothesis (H):

$$H: \quad R = .97$$

namely, the reliability (R) of the system is hypothesized to be .97. Under case (1) above, "success", we accept H and under case (2) we reject H. The single test would therefore have a power function as shown on Chart 1.

CHART 1



We are dealing with a binomial sampling situation with a sample size of $n = 1$, and under success we accept H and under failure we reject H. Again, nothing can be proven regarding the absolute value of the reliability of the system tested. Furthermore, if we should reject H, i.e. $R = .97$, then we reject the assessment value and not the general methodology underlying the assessment. In fact, we are rejecting some aspect of the particular assessment application. Going one step further, we can say that under rejection, the particular model implied by the assessment value is not consistent with observed fact. This situation is not uncommon in scientific investigations. Naturally, if we continually reject H as additional systems are flight tested, the more we would question the assessment model. This is because, as more experimental evidence is accumulated, the larger becomes the statistical power of the inference procedure, and the more confidence we would have in the results indicated.

I would like to conclude this aspect of my discussion with two quotations. One is from a paper by a British medical researcher, (7), which is particularly pertinent and is as follows: "We have, however, underlined how misleading, and potentially disastrous, it can be if a mathematical model is applied to a real situation which it does not truly represent. All mathematical models must simplify: that is their strength. They may, in over-simplifying, distort: that is their danger." The other quotation is made by two mathematical physicists, (8), "One often sees a statement that some result has been vigorously proved, unaccompanied by any verification that the conditions postulated in the proof are satisfied in the actual problem -- and very often they are not. This misuse of mathematics is to be found in most branches of Science," and if I may add in many reliability assessment studies.

Goddard Reliability Assessments

Reliability assessment techniques have been used extensively on Goddard managed programs. There have been essentially two types of assessment operations. One of these stems from the policy by NASA to employ independent assessment contractors for major systems. These contractors are non-hardware organizations, which under NASA direction perform reliability assessments on specified systems. Reliability contractors are selected on a competitive basis from a list of qualified bidders. The list on the following page represents the contractors which have or are performing reliability assessments for Goddard managed systems.

In addition to performing reliability assessments, the contractors have supported the Goddard project managers, and in the case of CNES, the French project manager, in the performance of other reliability tasks such as failure mode analyses, test monitoring, and parts application analyses. The role of the reliability

SUMMARY OF RELIABILITY CONTRACTS FOR GODDARD PROJECTS

Space System	Independent Reliability Contractor
OAO	Booz-Allen Applied Research
OGO	Planning Research Corporation
Nimbus	Operations Research, Inc.
Advanced Syncom & ATS	Planning Research Corporation
AOSO	Operations Research, Inc.
IMP D&E	Bird Engineering Associates
FR-1	ARINC Research Corporation*

* This is a French contract administered and directed by CNES, Centre National D'Etudes Spatiales, Bretigny, France, the French space agency.

contractors is advisory in nature and they act as consultants to the NASA project manager. The use of independent assessment contractors has usually been restricted to major projects which have prime or major subsystem contractors. Reliability assessments of a more minor nature on subsystems and assemblies are sometimes handled on a Goddard in-house basis.

The other type of reliability assessment used on Goddard managed systems is that which is performed by the contractors themselves. I think that it is accurate to state that there has been some reliability assessment performed by virtually every space system contractor involved in Goddard managed projects. Some of these are performed by contractor design organizations, others by reliability organizations, and others on a subcontract basis.

Reliability assessments are also a requirement of most proposals for space hardware systems. Let me add that reliability assessments made for the same system concept by different organizations are most difficult to compare as far as the absolute numbers are concerned, not only because the design approach may differ, but the mathematical models differ, failure rates differ and such factors as derating methods and "K-factors" are also not comparable. The main basis for an evaluation must therefore rest on the approach taken and the concepts used to demonstrate capability and ingenuity rather than absolute values. I recall several instances where numerical reliability requirements were very ambitious, however, I recall no instance where a proposal did not meet these requirements -- that is, on paper.

A Comparison With Flight Results

The most effective means of evaluating the adequacy of a reliability assessment is to compare assessment results with the actual operation of a space system in its intended environment. This is usually most difficult to do for space systems because experience to date, although substantial in terms of total accumulated orbit life, is not based on like systems. I would like to relate briefly a comparison between assessment and space operation which was performed for the first six TIROS meteorological satellites.

TABLE 1

SUMMARY OF AVERAGE LIFE TIROS I THROUGH VI

Function	Observed (Days)	Assessed Without "K" Factors (Days)	Observed ÷ Assessed	Assessed With "K" Factors (Days)	Observed ÷ Assessed
Direct TV					
At least one TV	217	230	.94	160	1.36
One specific TV	140	152	.92	105	1.33
Both TV	64	90	.71	60	1.07
Remote TV					
At least one TV	215	80	2.69	70	3.07
One specific TV	131	60	2.18	52	2.52
Both TV	48	43	1.12	35	1.37

A reliability contractor performed the reliability assessment and Goddard's TIROS project office furnished flight histories for TIROS I through VI. It should be pointed out that the TIROS satellites were not identical in design or manufacture. However, overall differences were not considered of such a gross nature as to make summary statements meaningless.

Table 1 summarizes the comparison between observed and assessed orbit life. The observed mean life figures in the table are based on averaging over the six TIROS flights. Twelve TV camera chains were used for "one specific TV" data as each TIROS contained two cameras. The assessed values are given without and with "K-factors" and are based on "graphical integration" from curves and data in the reliability contractor's report. We can relate mean life to the area under a reliability curve with the following formula:

$$\text{Mean life} = \int_0^\infty R(t)dt,$$

where R(t) is the reliability or probability of exceeding mission time "t". Conclusions are that observed and assessed values are closer in one direction for the "Direct TV" than for the "Remote TV" and also that the comparison is better without "K-factors". It is also interesting to note that for the observed life figures, the life for the redundant system, namely, "at least one TV" is not too much different from the expected 3/2 mean life theoretical value for one specific TV which is based on exponential theory. The above represents one specific comparison and does show that assessment results, using essentially standard techniques, are not grossly inconsistent with actual operation. In general, based on our limited experience to date, it can be concluded that carefully performed assessments can yield results which are not inconsistent with later experimental verification. I hasten to add though, that especially on individual flights, the discussion in the first part of these remarks is applicable, and that present assessment techniques are inadequate to predict operational results with sufficient confidence.

Conclusions and Recommendations

The following conclusions and recommendations can be made:

1. Reliability Assessment is a useful technique especially in the evaluation of alternative design approaches, the pinpointing of areas of unreliability, and to give management an order of magnitude of the reliability of a system.

2. Assessment results should be used very cautiously to predict operational reliability before flight history has been obtained.

3. Much remains to be done in developing techniques for the analytical representation of complex systems as mathematical models.

4. Data inputs such as part failure rates used in system assessments are often inadequate due to lack of test knowledge, effect of interaction and unknown environment. The same can be said for "K-factors".

Summary Remarks and Acknowledgments

My remarks should not be construed as an indictment of reliability assessment, on the contrary let me repeat as I have stated previously, (9), namely, there exists at present no other means of evaluating the reliability of a highly complex system before end use by using a rational approach and a quantitative basis than by using an approach at least similar in concept to that used for reliability assessment. History has shown that scientific and emotional factors are sometimes difficult to separate, one only has to review the work and life of Galileo and Copernicus and their problems with the science of astronomy. I am not making technical comparisons between the astronomer's woes and those of reliability analysts, however, reliability assessments seem to bring out strong feelings pro and con, and these are often more concerned with the possible consequences of assessment interpretations rather than the technology involved in assessments per se.

I would like to acknowledge the work of my colleague, Mr. Eugene Hixson, for his contributions in the TIROS study and for accumulating life history data for Goddard managed satellites. In addition, for the help of my other colleagues at Goddard, and numerous industry and government personnel who enabled me to make the above remarks, I wish to express my appreciation.

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