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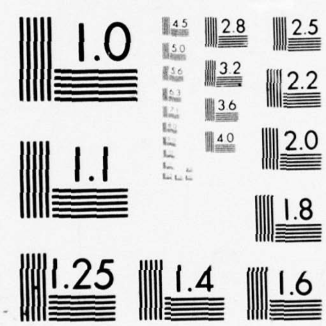

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A Review of the Mission Success of Communications Satellites and Related Spacecraft

Advanced Communications Systems
Satellite Systems Division
Systems Engineering Operations

October 1977

Final Report

Prepared for
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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The mission successes of a number of satellites designed for long operational lifetimes are presented. Based on this compilation, a number of statistical correlations are made in an attempt to determine those attributes of a program which, if emphasized during the program design development phase, will maximize the probability of mission success. Mission success, as used here, is the attainment of long operational life for each satellite.

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A spacecraft utility function is statistically derived from actual on-orbit life data. The paper analyzes this utility function in a further attempt to draw some conclusions concerning achievable satellite operational life. Finally, some comparisons are drawn between military and commercial spacecraft.

PREFACE

A number of people in The Aerospace Corporation aided in the preparation of this paper. In addition, Mr. Donald Bane, of the Jet Propulsion Laboratory, and Dr. Pier Bargellini, of Comsat Laboratories, provided much of the interplanetary spacecraft and commercial communications satellite information used in the data base for the longevity analyses. The cooperation of all of these people is greatly appreciated.

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I. INTRODUCTION

In 1975, a satellite longevity study was conducted by The Aerospace Corporation for the Military Satellite Communications Systems Office of the Defense Communications Agency (Ref. 1) The main purpose of this study was to identify the primary factors that influence the on-orbit operational lifetimes of communications satellites. This study also attempted to determine what changes in these factors would tend to increase the on-orbit reliability of such spacecraft. The factors investigated in this study spanned programmatic as well as technical design and manufacturing issues. For ease of presentation, this particular study for the Military Satellite Communications Systems Office shall hereinafter be referred to as "the MSO study."

Thirty-one satellite programs were investigated in the MSO study. The only requirement concerning the programs investigated was that the individual spacecraft be communications satellites, or be functionally related to communications satellites.

Table 1 provides a list of the programs involved in the MSO study. As indicated in the third column of this table, not all of these programs were included in the longevity analysis, or operational life survey. The cutoff date for the on-orbit operational life analysis of the MSO study was set at May 1, 1975.

Subsequent to the MSO study, an additional on-orbit longevity analysis was made for a somewhat different set of programs. This second set, which dealt only with synchronous altitude and higher spacecraft, including all present communications satellites and interplanetary spacecraft, is listed in

[1] Buehl, F. W. and Hammerand, R. E., A Review of Communications Satellites and Related Spacecraft for Factors Influencing Mission Success, Volume I: Analyses, TOR-0076(6792)-1, Vol.-1, The Aerospace Corp., El Segundo, Calif. (17 November 1975).

Table 1. Satellite Programs Reviewed

PROGRAM	MSO STUDY		
	1975 PROGRAM ANALYSES	1975 OPERATIONAL LIFE SURVEY	1977 OPERATIONAL LIFE SURVEY
MILITARY:			
TRANSIT	X	X	
AGENA	X		
VELA	X	X	X
DMSP	X	X	
IDCSP	X	X	X
TACSAT	X	X	X
SKYNET I & II	X	X	X
NATO II & III	X	NATO II ONLY	X
PROJECT A	X	X	X
DSCS II	X	X	X
FLTSATCOM	X		
LES PROGRAMS	X	LES 1 TO 6 ONLY	X
SOLRAD II			X
COMMERCIAL:			
INTELSAT I TO IVA	X	I TO IV ONLY	X
ANIK	X	X	X
WESTAR	X	X	X
MARISAT	X		X
COMSTAR	X		X
JAPANESE CS	X		
RCA SATCOM	X		X
JAPANESE BROADCAST SATELLITE (BSE)	X		
PALAPA			X
NASA - EXPERIMENTAL			
ATS	X	X	X
NIMBUS	X	X	
SMS(GOES)	X	X	X
ITOS	X	X	
ERTS/LANDSAT	X	X	
STP 71-2	X	X	
MARINER 2 TO 10			X
PIONEER 6, 10, 11			X
VIKING			X
HELIOS			X
CTS			X
SYMPHONIE			X

the last column of Table 1. The cutoff date for the on-orbit experience for this latest compilation was set at July 1, 1977.

This paper deals with some of the major findings from the MSO study, and with the historical records of communications satellites and related spacecraft, in terms of achieved on-orbit operational life, as perceived in the 1975 and 1977 longevity analyses. A precautionary note concerning the utility of statistical analyses of this type will be made. Some of the differences between military and nonmilitary communications satellites and their implications vis-a-vis operational life will also be discussed.

II. HISTORICAL REVIEW

Figure 1 provides a chronology of communications satellites. Of the 108 active communications satellites launched by the United States between January 1963 and July 1977, 89 were placed into operational orbits.

Figure 2 indicates the trends towards increased satellite weight, prime power requirements, and number of piece parts (not counting solar cells) that have characterized communications satellites over the past fifteen years. The upper limits on weight and power have been set by booster lift capabilities. Factors related to booster growth capability are the plateaus in launch cost. Significant cost increases are imposed going from one booster type to another to obtain more lift capability. To keep pace with the increasing demands for more communications satellite capability, the low- and medium-priced booster systems have gradually improved with time. The most dramatic example of this growth is the Thor-Delta class of boosters, whose lift capability to a synchronous transfer orbit has grown from about 100 lb in 1962 to 2000 lb in 1976. With the advent of the shuttle, the influence of booster lift capability on spacecraft weight and power is expected to diminish.

Complexity in terms of design sophistication and number of functions performed on a communications satellite has increased rapidly with time. The number of piece parts comprising a communications satellite has also increased, although not as rapidly as weight, power, and complexity. Whatever relationship may have existed between piece parts and complexity is also diminishing sharply with the advent of integrated circuitry. The onset of this disparity surfaced in the MSO study and was the major factor in not being able to correlate parts count with complexity.

The growth in weight and power as shown in Fig. 2 is indicative of the increasing demands for communications satellite service at reasonable cost. The increasing spread in these factors with time is indicative of the growing diversity among the users of satellite communications systems.

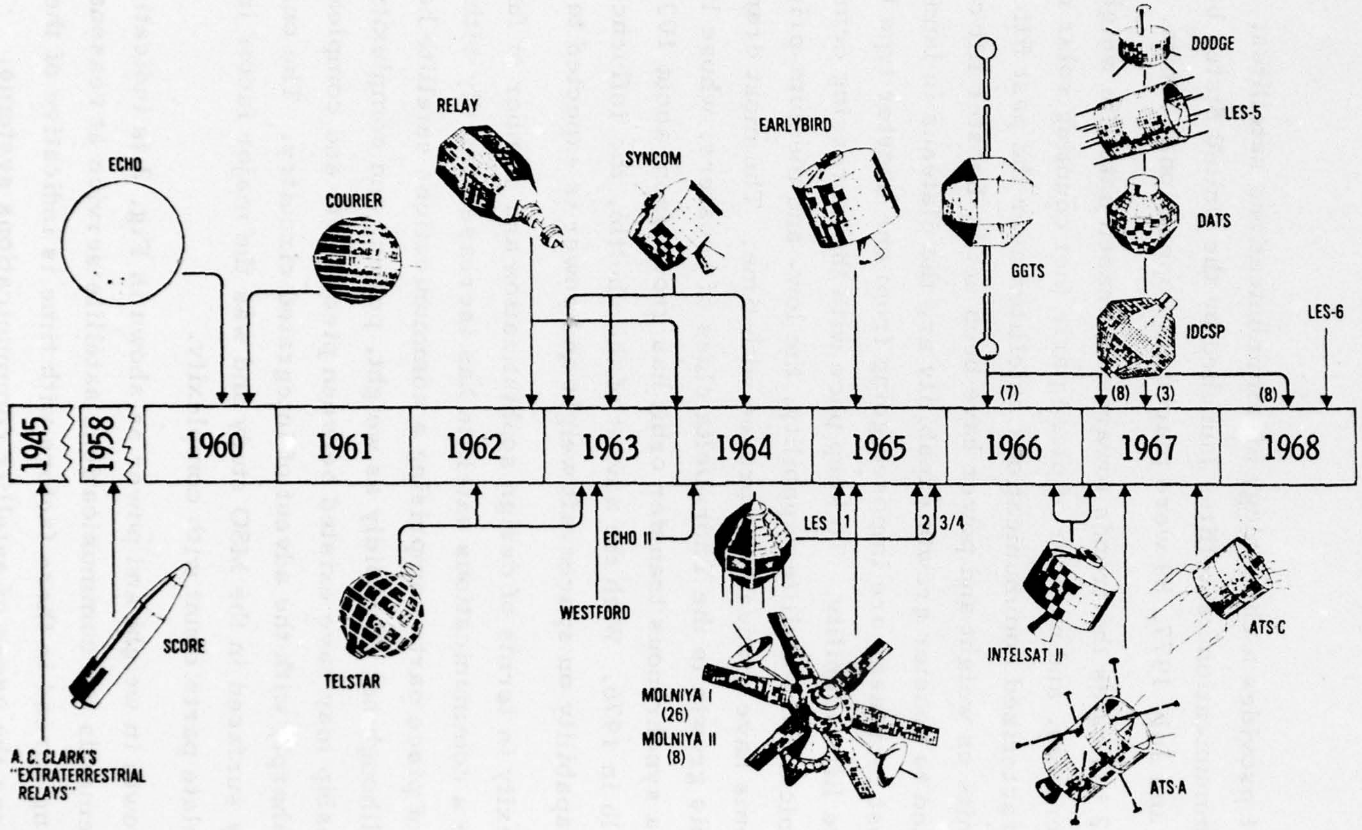

Fig. 1. Communications Satellites - History

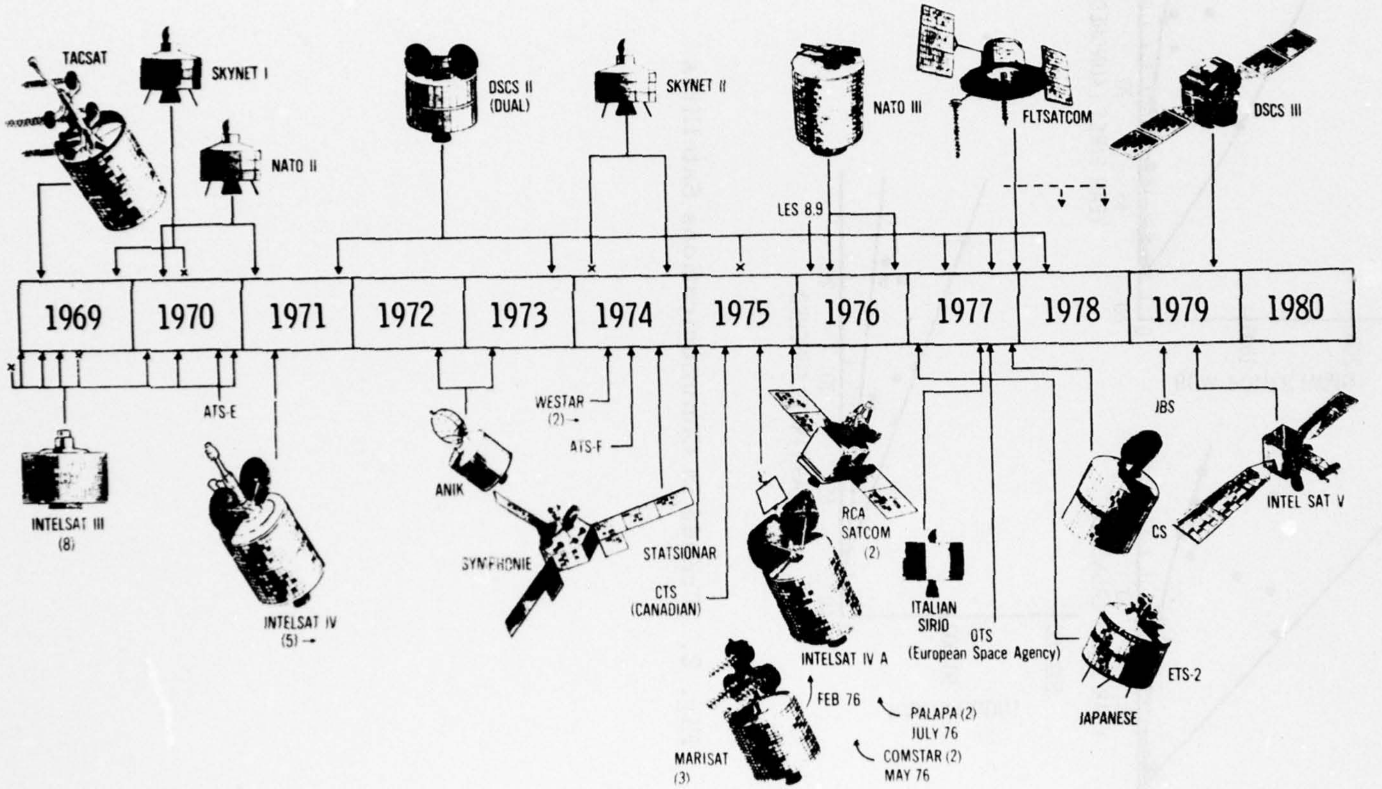

Fig. 1. Communications Satellites - History (Cont'd.)

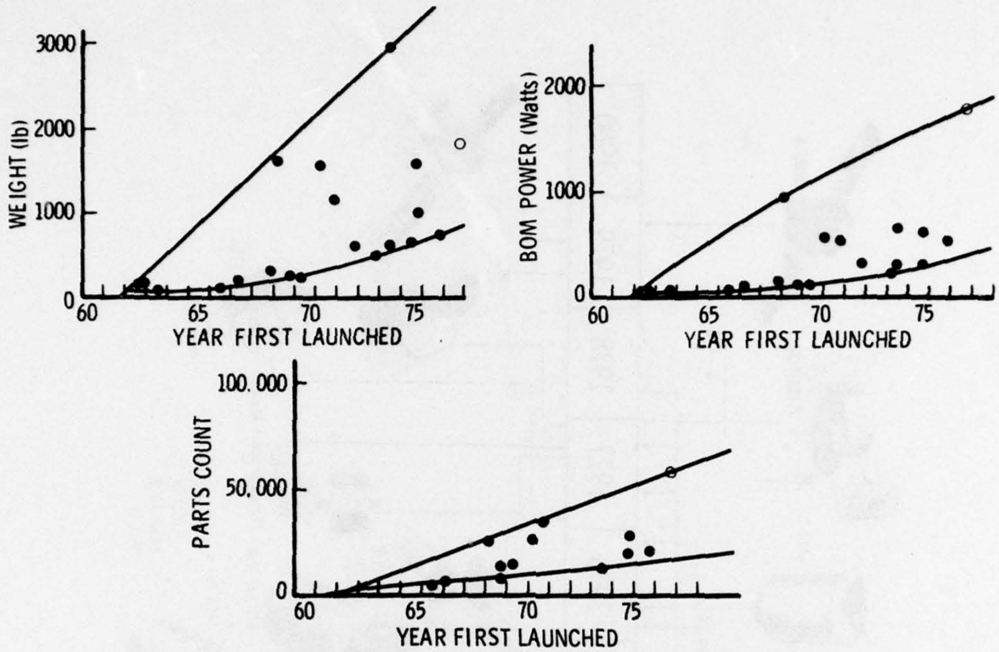

Fig. 2. Trends in Communications Satellites

III. USEFUL OPERATIONAL LIFE

Useful on-orbit life was defined for the MSO study as beginning at the insertion of a spacecraft on-orbit and ending when that spacecraft no longer performed its mission. In many cases, however (e.g., some of the Intelsat and Vela spacecraft), satellites have been deactivated or assigned as on-orbit spares when upgraded satellites were orbited.

No way was found to normalize the operational life data of the different spacecraft. Because of the many factors involved and the subjective nature of the data, it is believed that there is no universally acceptable way for this data to be normalized. Two attempts that failed are illustrated in Fig. 3; neither the calculated mean mission duration nor the spacecraft weight could be correlated with achieved operational life. This inability to normalize the life data was again borne out in a NASA study by The Aerospace Corporation in which attempts were made to relate both program costs and spacecraft complexity to mission success (Ref. 2). (The measure of spacecraft complexity employed in this NASA study was itself a complex function of some eight spacecraft parameters.)

Because the operational life data could not be normalized, all spacecraft were treated as a single population, and the longevity analysis was made on a nonparametric basis. This same philosophy was carried over to the longevity analysis of 1977 where, again, a variety of spacecraft were included in the population.

Figure 4 is a graph of the statistically inferred probability of useful service, or utility, functions of the spacecraft included in the 1975 MSO study. Each curve shows the cumulative percent of the spacecraft population remaining operational versus time after launch. Note that in the longevity

[2] Standardization and Program Practice Analysis (Study 2.4) Final Report, Volume I: Executive Summary, ATR-77(7375-01)-1, Vol. 1, The Aerospace Corp., El Segundo, Calif. (15 March 1977).

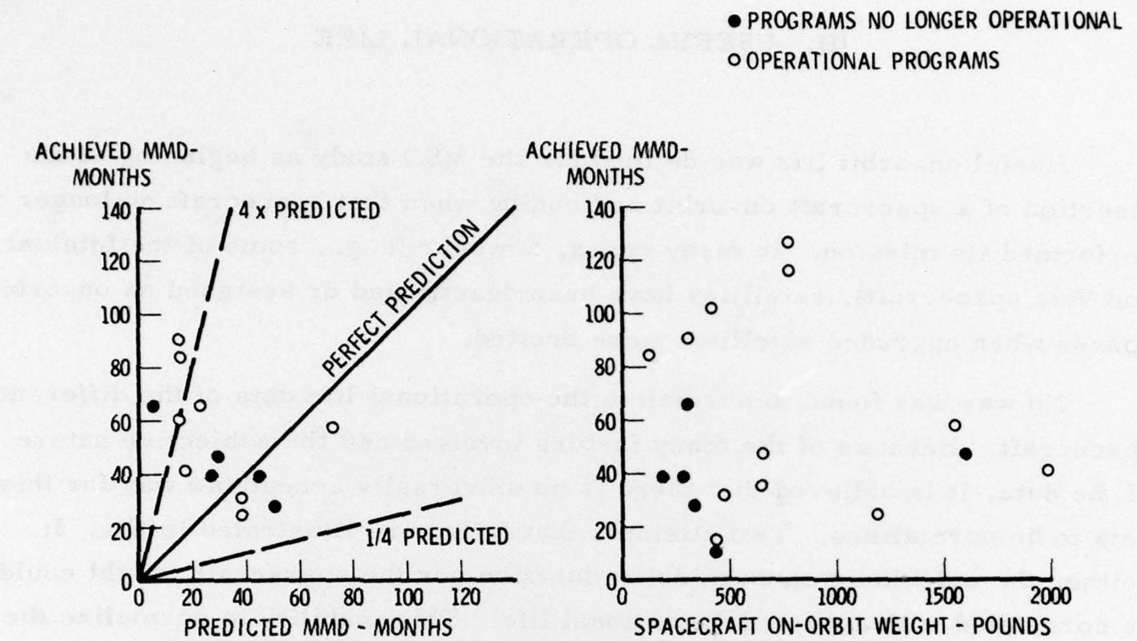

Fig. 3. Achieved Mean Mission Duration (MMD) versus Predicted MMD and Spacecraft Weight

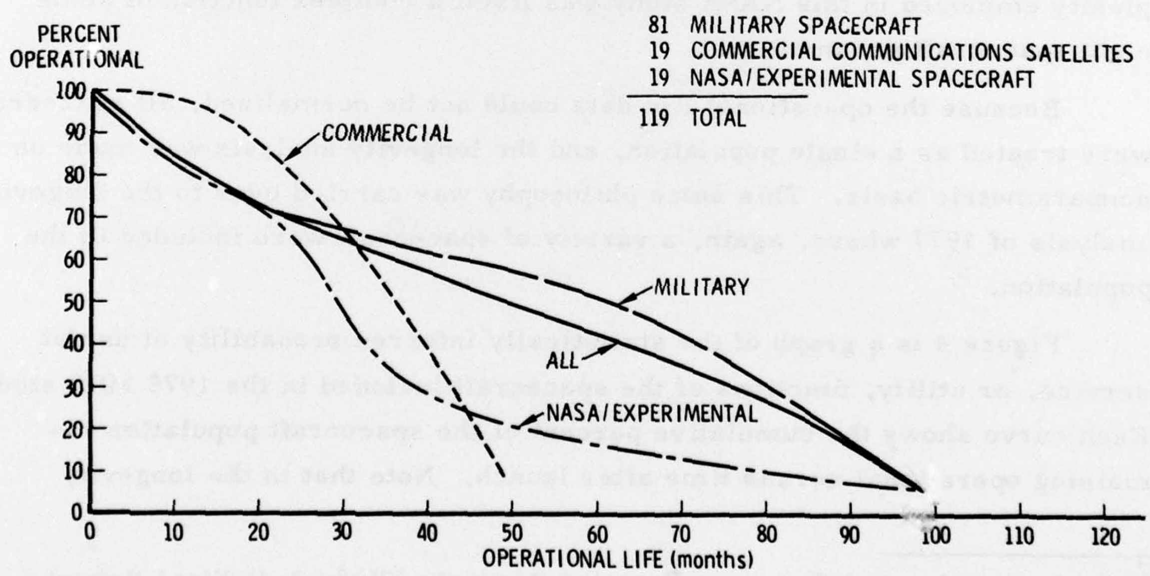

Fig. 4. Orbital Experience: 1963 to 1975

analysis of Fig. 4, approximately 20 percent of the military and experimental spacecraft considered in the May 1975 study had failed or were decommissioned during their first year on-orbit. On the other hand, the commercial communications satellites were not evidencing this infant mortality in their first year on-orbit. As will be shown, the high infant mortality of the military and NASA/experimental spacecraft was due to the inclusion of a number of early experimental programs in the population of the 1975 longevity analysis. None of these programs were specifically designed for long operational life and none were communications satellites. Note also, that after about two and a half years on-orbit, the probability of a spacecraft being operational is apparently higher for military spacecraft than for the commercial communications satellites. The seemingly poor longevity of the NASA and experimental spacecraft was again due to the sample of spacecraft used in the MSO study of 1975. Few of the NASA and experimental spacecraft included in this study had been specifically designed for long life.

It was expected that the inferred utility functions (Fig. 4) would change with time. The precursors for these changes were the large number of spacecraft in the total population that were still operational as of the May 1975 cutoff date. Figure 5 presents one of the results of the July 1977 longevity analysis, which includes spacecraft launched between 1962 and 1977. Each curve again shows the percent of spacecraft remaining operational versus time after launch.

The similarities between the results of the May 1975 and the July 1977 longevity analyses are striking. As expected, both the military and commercial spacecraft exhibit much longer average lifetimes than noted in the 1975 study. A major difference, however, was the seeming improvement in early orbit lifetimes of both the NASA and the military spacecraft. As indicated previously, this difference was due to the elimination of a number of early experimental spacecraft from the population analyzed. Also note that the military spacecraft, after approximately a year on-orbit, apparently have

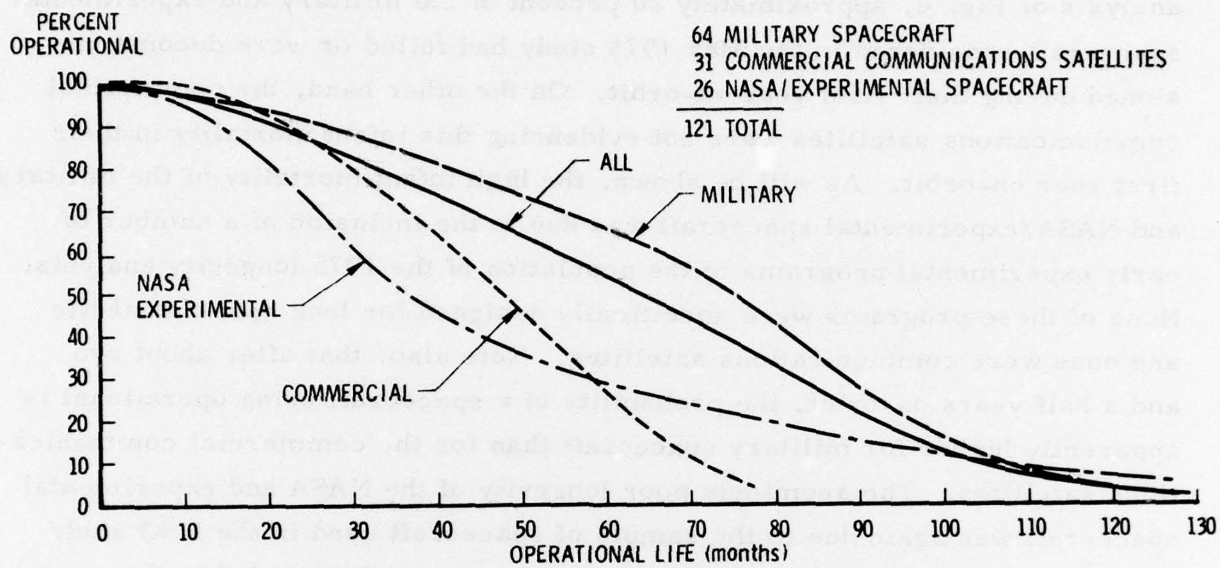

Fig. 5. Orbital Experience: 1962 to 1977

a higher probability of being operational than the commercial communications satellites. These apparent improvements in the military spacecraft over commercial communications satellites are due primarily to the differences in the populations analyzed in the two analyses rather than to any specific improvements in military satellites in the intervening two years. The 1977 longevity analysis included only spacecraft specifically designed for long operational life; whereas the 1975 longevity analysis included many experimental spacecraft whose operational life goals were only a few months to a year.

As another illustration of the dependence of the shape of the probability of useful service curves on the spacecraft comprising the population of a longevity analysis, a second analysis was made of the 1977 data using spacecraft launched after September 1968 (beginning with the LES 6 and Intelsat III spacecraft). The result of this analysis is provided in Fig. 6. By eliminating the early programs, the probability of the military spacecraft being operational now appears to be less than that of the commercial spacecraft for the first four and a half years. The point to be made is this: Statistical data can be selected to support almost any argument desired in comparing different families of spacecraft.

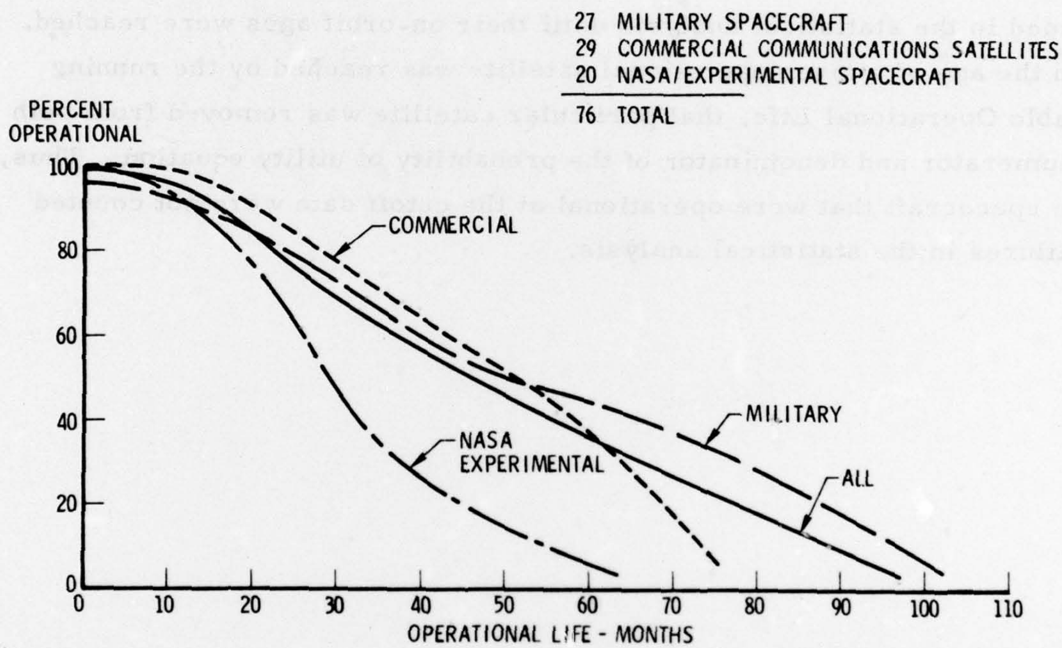

Fig. 6. Orbital Experience: 1968 to 1977

This is not to say that the statistical analyses illustrated in Figs. 4, 5, and 6 are not useful for measuring the attained mission success of a given type of spacecraft. The user of statistical analyses of this type must take care, however, to fully understand the subjective quality of the data and the method of selection of spacecraft to be included in the population under study. First, the data should include all applicable spacecraft (beware of errors of omission). Second, the data should not include spacecraft that are not members of the family under study (beware of errors of commission). Third, the data should be checked for consistency (are all failures and/or retirements defined and treated alike in the data and the analysis?).

Some explanation is in order about the derivation of the probability of utility functions of Figs. 4, 5, and 6. Through the use of the equation given in Table 2, operational spacecraft (at the time of the cutoff date) were included in the statistical analysis until their on-orbit ages were reached. When the age of a given operational satellite was reached by the running variable Operational Life, that particular satellite was removed from both the numerator and denominator of the probability of utility equation. Thus, those spacecraft that were operational at the cutoff date were not counted as failures in the statistical analysis.

Table 2. Calculation of Statistically Inferred Probability of Utility

$$P_u(T) = \frac{N_o(T)}{N_p - N_o(A \le T)}$$

Where

T = Time on-orbit

$N_o(T)$ = Number of spacecraft still operational at time T

N_p = Number of spacecraft in population

$N_o(A \le T)$ = Number of operational spacecraft (at cutoff date) whose ages on-orbit $\le T$

For example, for all spacecraft in the 1975 MSO study:

N_p = 119 spacecraft

T = 20 *months*

$N_o(20)$ = 79 spacecraft still operational

$N_o(A \le 20)$ = 16 spacecraft on-orbit $\le$ 20 months and still operational as of May 1975.

Therefore, the inferred probability that a spacecraft is still operational after 20 months on-orbit is

$$P_u(20) = \frac{79}{119-16} = 76.7\%$$

IV. RELIABILITY ANALYSIS AND TESTING

Some of the major findings of the 1975 MSO study were that the degree of reliability analysis and testing implemented in a program affected the operational life attained by that program's spacecraft. Of particular importance was the use of the failure modes and effects analysis (FMEA). This type of reliability analysis can identify the major effects caused by the failure of each component. With this knowledge, the designer can reduce the probability of occurrence of a catastrophic failure by providing alternate paths or redundant components and thus maximize mission success. FMEA was found to be most effective when conducted early in the design phase of a program and was a combined effort of design and reliability engineering.

A comprehensive test program was also found to be very valuable in achieving long operational life satellites. The test programs should encompass all levels of components and subsystems from the lowest level of assembly to the whole spacecraft. Power-on environmental testing of both subsystems and the complete spacecraft proved to be exceptionally useful in culling out marginally designed or manufactured components and assemblies. It was also found that the use of an automated system level test at the launch base, especially of critical functions, was worthwhile in verifying the flight readiness of a spacecraft. However, all testing, to be useful, must be completely reviewed prior to the commitment to follow-on tests or to launch.

To maintain the same degree of comprehensiveness from program to program, the more complex a spacecraft, the more testing and reliability analyses required in the program. Both factors imply longer schedules and higher costs for complex spacecraft over those required for less complex spacecraft.

V. MILITARY AND COMMERCIAL COMMUNICATIONS SATELLITES

The fundamental differences between military communications satellites and those designed for nonmilitary use stem from the need for operational versatility and the need to protect the military mission from deliberate disruption and, in some cases, interception. The unique military requirements placed on military communications satellites are:

- Physical Survivability
- Electronic Survivability:
  - Command Antijam and Security
  - Communications Antijam and Security
- Flexibility

The increasing emphasis now being placed on these additional demands is causing the newer military spacecraft designs to become more sharply separated from commercial communications satellites. As a result, the next generation of military communications satellites will evidence much greater on-board processing than the commercial satellites. This on-board processing is used for diverse message handling and to meet the increase in demands for antijam and antispoof protection. Thus, for the same capacity and a given set of terminal sizes, the military communications satellite systems operate in a different manner from the commercial systems. Programmatically, the multiple mixture of services provided by the military communications satellites, from supporting strategic to tactical situations, from interfacing with small mobile terminals to large powerful terminals, demands more combinations and permutations of testing prior to launch. This increased testing results in longer development times.

Variations in success between military and commercial communications satellites has been a function of development maturity. Both the military and the commercial programs have experienced on-orbit difficulties when new designs are used - (e.g., Intelsat III with new traveling wave tube amplifiers

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and a despun antenna). Success records shift between the military and commercial programs when the contractor can take advantage of proven hardware to satisfy the requirements of a new program. The growing requirements of the military communications satellite systems, however, tend to generate needs for upgraded designs.

The MSO study found that the first few flight models of most programs employing advanced technology experienced more anomalies than later vehicles of the same program. The study also found that, in general, new programs whose spacecraft had evolved from a previous successful program had a higher success rate and achieved longer operational lifetimes than programs employing spacecraft of radically new design.

Commercial spacecraft that experienced long on-orbit operational lifetimes were often based on similar vehicles sponsored by the military or by earlier commercial interests. Thus, the overriding factor in achieving long on-orbit operational life is probably the experience and capability of the contractor rather than whether the spacecraft is a commercial or military communications satellite. Whenever a contractor must take a large step forward from his existing designs for a new spacecraft, the likelihood of problems increases.

The Department of Defense policy is to maintain a flexible military posture. This flexibility is reflected in the requirements for military communications satellite systems. The need for flexibility results in the requirement to include small mobile terminals along with large fixed terminals within the user communities of its communications satellite systems. The military systems must also be able to operate in both benign electronic environments in peacetime and hostile environments under stressed conditions. Additionally, the military systems must be designed to meet the demands of physical survivability. These requirements warrant the use of state-of-the-art designs. Commercial communications satellites enjoy the freedom to operate with standardized terminals and must overcome only the natural and unintentional electronic environments. Commercial programs add new technology when it is proven, the requirements seek it, and the risk is commensurate with the profit. Because the military spacecraft usually lead the way in technology, the probability of on-orbit anomalies are higher, and longivity will probably be shorter.

A final note concerning U. S. military and U. S. commercial communications satellite contractors: <u>They are one and the same.</u>

VI. CONCLUSIONS

The conclusions that can be drawn from the MSO study and the longevity analyses are summarized below:

- The mean attained operational life of communications satellites and related spacecraft is about five years.
- Operational life attainment is independent of spacecraft size and complexity:
  - More complex spacecraft require more reliability analyses and testing to assure long operational life.
- Present reliability modeling is incapable of predicting operational life.
- To maximize the probability of long operational lifetimes:
  - Maximize use of proven techniques and hardware.
  - Maximize capability and experience of contractor.
  - Employ comprehensive failure modes and effects analysis to minimize probability of catastrophic failure.
  - Employ a comprehensive test program to prove flight readiness.
- Statistical analysis is a useful tool for indicating achievable operational life, but:
  - Scrutinize data for
    - * Consistency.
    - * Completeness.
    - * Applicability.