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Reliability Measurement For Operational Avionics Software

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RELIABILITY MEASUREMENT
FOR OPERATIONAL AVIONICS SOFTWARE

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Hampton, Virginia

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ABSTRACT

This study was conducted to determine quantitative measures of reliability for operational software in embedded avionics computer systems. Analysis was carried out on data collected during flight testing and from both static and dynamic simulation testing. Failure rate was found to be a useful statistic for estimating software quality and recognizing reliability trends during the operational phase of software development. The scope of the analysis was limited due to insufficient environment where adequate maintenance and service records for avionics systems are kept.

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I. INTRODUCTION

This is the final report of the third phase of the Measurement of Software Reliability Study conducted for the NASA Langley Research Center, under contract NASI-14392.

The purpose of this study was to develop quantitative measures of reliability for operational avionics software systems. Previous studies (References 1 and 2) analyzed measures of software reliability using data acquired during the development phase of a data base software product, which was designed to operate in a typical batch environment. Failure rate and failure ratio were found to be statistically valid measures for predicting software reliability during the development phase.

During this study, an attempt was made to further examine the statistical attributes of these two measures as quantities for estimating and predicting software reliability during the operational phase of a software product. However, availability of adequate data to conduct reliability measurement analysis has been a very limiting element in this study. In order to support this study, data reporting was required on error frequency, cause of error, and time required to isolate and correct errors and recertify the software. Unfortunately the data sources contacted during the study were software development and maintenance groups that retain software error data primarily for diagnostic purposes.

Much of the burden of collecting and assembling the data rested upon the development groups because of the distributed nature of the data. Every attempt was made to select data that were collected during the final test and verification stages of the development cycle; thus, the code maturity would be near that of an initial operational release. The trouble report data were correlated with CPU time data to establish analytic data sets. These data sets consist of composed data, collected during static simulation testing, dynamic simulation testing, and actual flight testing.

II. OVERVIEW

Prior to detailed discussion of the operational software measures studied, it is important to consider what is meant by software reliability. To a great extent this is dependent upon the software application intended.

To a group responsible for the design of advanced computer systems, the issue of reliability is of central concern. The ability of the software to operate correctly as the system environment changes, such as in the fault tolerant technology, is a major element affecting the overall system performance.

To a group responsible for design, implementation, and validation of software products, the issue of reliability is commonly replaced by the issue of quality. Any large or sophisticated operational software product contains an unidentifiable number of errors. Although these errors may be due to coding, formulation, or design, the central problem facing the development group is the identification and correction of as many of these errors as possible prior to release. Clearly the fewer the errors remaining in the product, the higher the quality. In this environment a "software failure" is hardly applicable. The software never fails to operate - it always operates, either correctly or incorrectly. Correct operation however, is not always formally specified and generally includes implied requirements.

It is apparent that given identical specifications, two different software development groups will each produce a product of different quality. Similarly, differing specifications for the same product submitted to a single development group will result in products of different quality. The functions of specification and implementation each directly contribute to software quality.

The central issue facing a software development group is that of determining when the product is "ready" for operational release. Established practices include extensive laboratory testing in both static and dynamically controlled environments, testing by an independent software group, flight testing, and acceptance testing by the eventual user. A typical procedure used for identifying and correcting errors consists of trouble reporting. Each report is fully investigated by a software systems engineer and corrective action, if any, is recommended. At this point the report and recommended action are reviewed and an action decision is made. Any code corrections are entered into the next modification and testing continues.

This system provides tight control over the identification and correction of software errors. Also, it provides formal documentation on detected software errors. Generally however, the accumulated data resulting from this procedure does not include CPU time or the number of times the software has been executed in a given time period. Hence, it is difficult to quantitatively establish software quality or reliability at the time the code is released for operational service.

Such quantitative measures could be readily used by the development group, the program management group, and the operations group to aid in planning, costing, and decision making tasks. These applications should be pursued for their inherent value; however, quantitative measures have yet another application. Quantitative measures of software quality or reliability can assist the systems designer in analyzing software/hardware interactions and in quantitatively specifying the overall system performance.

Previous studies (References 1 and 2) have assessed the various merits and properties of several reliability measures.

The failure ratio, U, is defined as

$$U = F/N$$

where F is the number of failures or software errors observed in N runs in a given calendar period, usually one month. The failure rate, FR, is defined as

$$FR = f/t$$

where f is the number of software errors observed during the total CPU time accumulated over a given calendar period. Additionally, the indicator MTBF is defined as

$$MTBF = 1/FR$$

which is an important quantity because it is analogous to commonly used hardware reliability expressions.

The principle indicator derived and analyzed from this study was the failure rate, with MTBF presented for comparative and illustrative purposes. The form in which the data was available, in effect dictated the use of failure rate. During avionic software development, CPU time has been demonstrated to be more easily collectable than the number of initial program loads (IPL), regardless of the type of testing, i.e., flight testing or dynamic simulation testing. Additionally, flight time and ground time are traditionally well maintained statistics for aircraft, and hence for their avionics systems.

III. DATA RESOURCES

The operational environment selected for this study was an embedded avionics computer system. An attempt was made to obtain error data from several different avionics systems. The two contractually designated data sources were the A-7 Avionics Development Program, Naval Weapons Center, China Lake, California, and the F-111 Operational Flight Program, Sacramento Air Logistics Center at McCellan Air Force Base, Sacramento, California. In addition, the Aerospace Corporation identified four other potential data sources: the F-14 avionics computer program office at the Pacific Missile Test Center, Point Magu, California, the Naval Air Development Center, Warmister, Pennsylvania, the Air Force Avionics Laboratory, Wright Patterson Air Force Base, Dayton, Ohio, and the Jet Propulsion Laboratory, Pasadena, California. A preliminary investigation was conducted at these facilities to determine the availability of data suitable for a reliability measurement study.

Naval Weapons Center (NWC)

Software error data from the embedded avionics computer system on the A-7 aircraft was available for this study from the Naval Weapons Center. The data came from two major software releases. The NWC-2 software package provided actual operational flight time data and the NWC-3 release provided data from the final test and evaluation phase of the software system, including more than 5000 hours of flight time and simulation time.

During the operational lifetime of a software release, errors are isolated by a full investigation of all trouble reports. There is a formal mechanism for reporting system computer errors; however, many reports are verbal and complete documentation for all reported errors does not exist. When it was available, information on the frequency of error occurrences existed only in narrative form. After an actual software error is catalogued, an operational fix is generated and the code is corrected in the next release. The time and effort required to investigate each report was not documented, but it was estimated that a fix takes about one month.

Before the NWC-2 avionics software package was released in May, 1977 for operational use, through testing and evaluation phases were performed to detect many of the errors in the software. An additional period of verification and validation was used so that by the end of the examinations the software was essentially error free. The data was collected from various aircraft flights over a period of thirteen months from May, 1977 through May, 1978. It was acquired during a visit to the Naval Weapons Center on January 22, 1979.

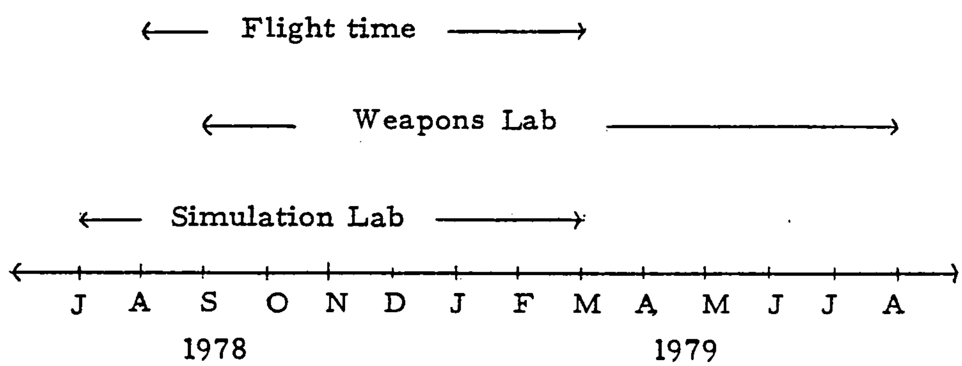
Three errors were detected following the release of the NWC-2 software. One was detected by the fleet almost immediately after the release, and two by the Naval Weapons Center early in the release. Although the exact time of the error detections is not known, the data included the total number of flight hours for each month, the number of errors detected, the type of error (fatal, critical, or non-critical), and the month the error was corrected. The monthly flight hours and the number of planes in the fleet are classified information; however, the total monthly flight hours are unclassified and have been used in the data analysis.

The NWC-3 was released during the test and evaluation phase in January, 1979. NWC collected error data during the verification and validation phase which began at the end of February and continued until the end of April. During this period of acquisition, nine codes were released, denoted here 6B, 6D, 6F, 7A, 8A, 8B, 8C, and 8D. The period of operation for each of the codes is given in Table 1. Note that the codes

TABLE 1

NWC-3 CODE RELEASE DATES

Code	Operational Dates
6B	15 Aug 78 - 26 Sep 78
6D	13 Sep 78 - 23 Oct 78
6E	28 Sep 78 - 20 Nov 78
7A	29 Nov 78 - 9 Jan 79
8A	3 Jan 79 - 24 Jan 79
8B	24 Jan 79 - 16 Mar 79
8C	8 Mar 79
8D	14 Mar 79 - 27 Mar 79



7A and 8A, and codes 8B and 8C have overlapping flight dates as shown in the time table. The data came from three sources: actual test flights, the weapons laboratory and the simulation laboratory. This data included CPU time, number of errors encountered, and detailed trouble reports about the types of errors found, with a brief description of each. Naval Weapons Center personnel maintained time logs during test flights and dynamic simulation tests, and it was thought that it would be possible to correlate computer time and errors from this data.

Sacramento Air Logistics Center

The F-111 avionics system consists of three computers: the Guidance and Navigation Computer (GNC) for general navigation tasks, the Weapons Defense Computer (WDC) for weapons deliverance tasks, and the Navigation Computer Unit (NCU) for navigation and control tasks. The original software was developed by the General Dynamics Corporation. The F-111 software section at McClellan is responsible for the development, integration, and test and evaluation of the software.

The F-111 software management is based on an 18-month life-cycle. User requirements, and changes in mission requirements that affect the overall system and cost are thoroughly reviewed, resulting in a coordinated block of modifications. These undergo full-scale static and dynamic testing during the development phase and are then installed and implemented in the system. There is an independent test and evaluation (IT&E) of the code which is usually performed by a contractor test team. The IT&E phase is conducted, for the most part, on a dynamic simulator. The trouble reports generated during the IT&E phase are the source of the software error records. The software section also maintains accounting records from which mean time to repair (MTTR) may be calculated. The next phase is engineering flight testing, which is performed on an instrumented aircraft. Finally, user flight testing is conducted on non-instrumented aircraft.

Although this facility was designated as a good data source prior to study execution, further investigation revealed that no logs were kept of flight time or CPU time. Because it was determined that several man months would have been required in order to extract any relevant data, it was decided not to pursue this source further.

Pacific Missile Test Center (PMTC)

The Pacific Missile Test Center's formal system for cataloging all avionics computer system errors is called the Airborne Weapons Corrective Action Program (AWCAP). Software errors are found by a full investigation of the trouble reports collected during the development and operational lifetime of the software release. Each reported problem is entered into the computer data base and updated whenever more information is received. The trouble report contains the following items:

System component identification
Problem brief
Occurrences (including date and source of the report)
Problem description
Configuration
Corrective action
Action summary
References

The reliability data are embedded in the problem description, the corrective action taken, and the action summary, all of which are in narrative form. AWCAP provides considerable sorting and reporting capabilities; however, this system provided no established procedure for flagging timing information, so it was decided that this data source could not be utilized.

Naval Air Development Center (NADC)

The NADC software development cycle is similar to that of the A-7 office at NWC and to that of the F-14 office at the Pacific Missile Test Center. Computer logs were kept during the test and evaluation phases that could be used to calculate the run time of the software over each day. From these it might have been possible to correlate data from the trouble reports. It was decided that no data would be collected from the Naval Air Development Center because the P-3 software data was quite similar in form and type to that of the Naval Weapons Center, and personnel at this facility maintained that approximately three man-months would have been necessary in order to extract the required data.

Air Force Avionics Laboratory (AFAL)

AFAL was chosen to perform the independent verification and validation testing on the F-16 avionics software developed by the General Dynamics Corporation. Testing had been completed on six versions of the flight tape by January, 1979. AFAL was using the production tape to train fleet pilots in the Pilot Training Operation (PTO). A total of 48 hours of flight time was logged on two separate dates by various training pilots, 17 hours in January, 1979 and 31 hours in February, 1979. They collected software reliability data during this time, including CPU time, and number and type of errors.

Delivery of the data was made by Major John Weber of AFAL in March, 1979. It consisted of two months of data which were very similar to the operational data from the NWC-2 software. Although an agreement was made to supply as much data as needed for statistical analysis, the final shipment of data was never received, and the data supplied was too limited to be statistically significant.

Jet Propulsion Laboratory (JPL)

The Development Section of JPL's Mission Control Computer Center (MC^3) has for three years collected software error data from the Voyager ground base real-time software computer system. It was thought that this large data base could be used to validate the statistical approach to the A-7 and F-16 analysis, even though it came from a ground based system rather than an airborne system.

During the three years the Voyager has flown, there have been only two errors involving the on-board computer. One was a memory hardware failure and the other was the transmittal and loading of an incorrect set of commands. In contrast, the software on the real-time ground based computer system has had between two and three thousand reported failures during the last three years. The records of these errors included the time of error occurrence and level of severity. This data was provided on a weekly basis from the 48th week of 1978 through the 20th week of 1979, covering a total of 9756.138 hours of operation.

IV. DATA ANALYSIS

The data base consisted of two sets of data: (1) from the Naval Weapons Center, error data from the A-7 avionics software package, consisting of the NWC-2 utilization code and the NWC-3 release, and (2) from the Jet Propulsion Laboratory, error data from the Voyager's ground based computer system. The principal statistical analyses performed on this data were the calculation of the failure rate (FR), number of failures divided by the CPU time accumulated over a given calendar period, and the mean time between failures (MTBF). Evaluation of the data was determined from simple linear regression analysis of the failure rate on the successive codes and/or the release date.

Other statistics were investigated, including the cumulative mean time between failures (total number of CPU time divided by the accumulative number of errors) and an exponential model for relating failure rates from one calendar period to the next, but these statistics did not yield any significant findings. Due to the lack of information on the number of runs in the data, the failure ratio (number of failures per calendar interval divided by the total number of runs) could not be calculated.

Naval Weapons Center (NWC)

Error severity was established for all the errors which were reported to have occurred during a software release. Severity ranged from critical to non-critical. A fatal error caused the system to fail completely; a critical error indicated that one part of the system failed, but the system continued to function with, perhaps, the wrong information; and a non-critical error was an annoyance type, such as a misnamed variable or a pilot preference for certain mechanisms or ways.

Table 2 shows the NWC-2 error data ordered by flight date. Fatal, critical and non-critical errors were assigned a 1, 2 or

TABLE 2

NWC-2 FLIGHT DATES

Flight Date	No. of Flight hours	No. of Errors	Type of Error
May 77	11829	1	3
June 77	13338	1	3
July 77	11536	1	3
Aug 77	13697	0	
Sep 77	12639	0	
Oct 77	12353	0	
Nov 77	12393	0	
Dec 77	10485	0	
Jan 78	11129	0	
Feb 78	12663	0	
Mar 78	14586	0	
Apr 78	12329	0	
May 78	9613	0	

3, respectively. Only three non-critical errors occurred in this software. Since the exact time of the occurrences is not known, it is assumed that one error occurred each month for the first three months. Figure 1 is a plot of the failure rates for these three months. Since the correlation coefficient is zero, nothing can be concluded about the relationship of failure rate and software reliability from this data. In fact, this is really an ideal case, because the errors detected were correctly fixed and the software has been operating successfully ever since. The remarkable MTBF of 4062 hours and FR of .0002, can partly be explained by the fact that the diversity of aircraft this software was run on, tended to isolate errors not captured by the final test and evaluation phase of the development cycle.

The NWC-3 data required some organization before analysis could be initiated. The 87 discrepancy reports were divided into three groups depending on whether they were from actual test flights, the weapons laboratory, or from the simulation laboratory. A total of 62 errors occurred during the period of 5753 hours of data made available. Table 3 shows the breakdown of error types for the three data sets. Note that non-critical errors occurred most frequently, followed by critical and finally by fatal errors.

Table 3 also shows that MTBF is lowest for actual flight time and highest for the simulation laboratory. When arranged by code, Table 4 shows that the software was more reliable as each code was released. Note that codes run on all three systems, again show the highest reliability at the simulation laboratory. This probably indicates that simulation tests do not detect as many errors as actually flying the software, and that failure rate for all NWC-3 data combined is not a meaningful statistic.

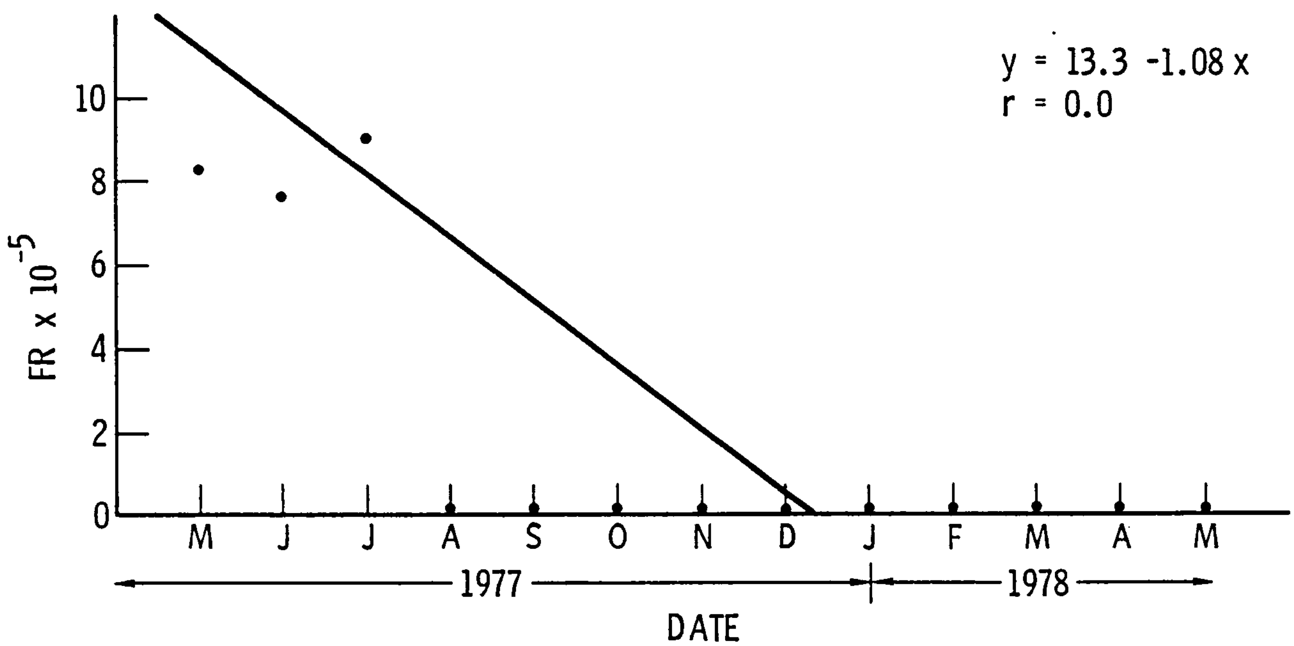


Figure 1. NWC-2 Failure Rate vs Flight Date

TABLE 3

NWC-3 ERROR TYPES

ACTUAL FLIGHT TIME

Type of Error	No. of Errors	MTBF	FR
1	1	388.0	0.0026
2	3	129.33	0.0077
3	15	25.87	0.0387
Total	19	20.42	0.0490

WEAPONS LABORATORY

Type of Error	No. of Errors	MTBF	FR
2	7	172.43	0.0058
3	26	46.42	0.0215
Total	33	36.58	0.0303

SIMULATION LABORATORY

Type of Error	No. of Errors	MTBF	FR
2	2	2080.0	0.0005
3	8	520.0	0.0019
Total	10	410.0	0.0002

TABLE 4

NWC-3 ERROR DATA BY CODE

ACTUAL FLIGHT TIME

Code	FR	MTBF	FAILURE RATE Type 1	Type 2	Type 3
6B	0.25	4.0			0.25
6D	0.375	2.667		0.125	0.25
6E	0.1429	7.0		0.0476	0.0952
6F	0.12	8.333			0.12
7A	0.125	8.0		0.0416	0.0833
8A					
8B	0.0174	57.47	0.0058		0.0116
8C	0.025	40.0			0.025
8D	0.0252	39.68			0.0252

WEAPONS LABORATORY

Code	FR	MTBF	Type 1	Type 2	Type 3
6B	0.04	25.0		0.0081	0.0324
6D	0.025	40.0		0.003	0.0240
6F	0.083	12.005			0.0833
7A	0.02	50.0		0.0042	0.0167
8A	0.041	24.39		0.0167	0.0250
8B	0.018	55.55		0.0042	0.0042

SIMULATION LABORATORY

Code	FR	MTBF	Type 1	Type 2	Type 3
6B	0.0031	322.58		0.0016	0.0016
6D	0.0063	158.73			0.0063
6E	0.0031	322.58		0.0014	0.0014
7A	0.0028	357.14			0.0028
8A	0.0007	1428.57			0.0007

Table 5 is a summary of the data by month. For example, one software failure was detected during 7/78, zero during 8/78, six during 9/78 etc. In addition, it can be seen that the numbers of errors decreases in each successive release and that those that occurred were non-critical. Figures 2-4 are plots of the failure rate for each code run on the three systems. The correlation coefficient for the actual flight time data shows a strong negative correlation of failure rate with time. Any correlation between failure rate and time is negligible for the weapons laboratory. The simulation laboratory shows the highest correlation, although as mentioned earlier, it is not clear that this is valid data for predicting software reliability. The same conclusions emerge when failure rate is plotted by month, as seen in Figures 5-7. No additional information was yielded when failure rate was plotted for each error type separately.

Jet Propulsion Laboratory (JPL)

The best error information JPL could provide was the total number of each type of error and the type of fix taken. These are listed in Table 6. Since the time of occurrence of most of the 154 errors was not transmitted, very little analysis was possible. Failure rate was determined for all errors occurring during a given week and plotted on Figure 8. The MTBF was calculated to be 63.35 hours and the FR 0.0158. Although Figure 8 shows a slight positive correlation between failure rate and time, more information on the type of errors that occurred would have been required in order to draw conclusions regarding the quality of the software.

TABLE 5

NWC-3 ERROR DATA SUMMARY

Date	No. of Software Failures	Flight Time (Hours)	No. of Errors Type 1	No. of Errors Type 2	No. of Errors Type 3	FR	MTBF	FAILURE RATE Type 1	FAILURE RATE Type 2	FAILURE RATE Type 3
ACTUAL FLIGHT TIME										
7/78	1	4.0			1	0.25	4.0			0.25
9/78	6	29.0		2	4	0.2069	4.833		0.069	0.1379
10/78	3	25.0			3	0.12	8.333			0.12
11/78	2	9.0		1	1	0.222	4.5		0.111	0.111
12/78	1	15.0			1	0.0667	15.0			0.0667
1/79	3	189.5	1		2	0.0158	63.167	0.005		0.0102
3/79	3	114.5			3	0.0262	38.167			0.0262
WEAPONS LABORATORY										
7/78	10	247.0		2	8	0.0405	24.7		0.008	0.0324
9/78	9	336.0		1	8	0.0268	37.3		0.003	0.0283
10/78	2	24.0			2	0.0833	12.0			0.0833
11/78	5	240.0		1	4	0.0208	48.0		0.004	0.0167
1/79	7	360.0		3	4	0.0194	51.429		0.008	0.0111
SIMULATION LABORATORY										
7/78	2	320.0		1	1	0.0063	160.0		0.003	0.0031
8/78	1	320.0			1	0.0031	320.0			
9/78	2	640.0			2	0.0031	360.0			0.0031
10/78	2	720.0		1	1	0.0031	360.0		0.001	0.0014
12/78	2	720.0			2	0.0031	360.0			0.0031
1/79	1	1440.0			1	0.0007	1440.0			0.0007

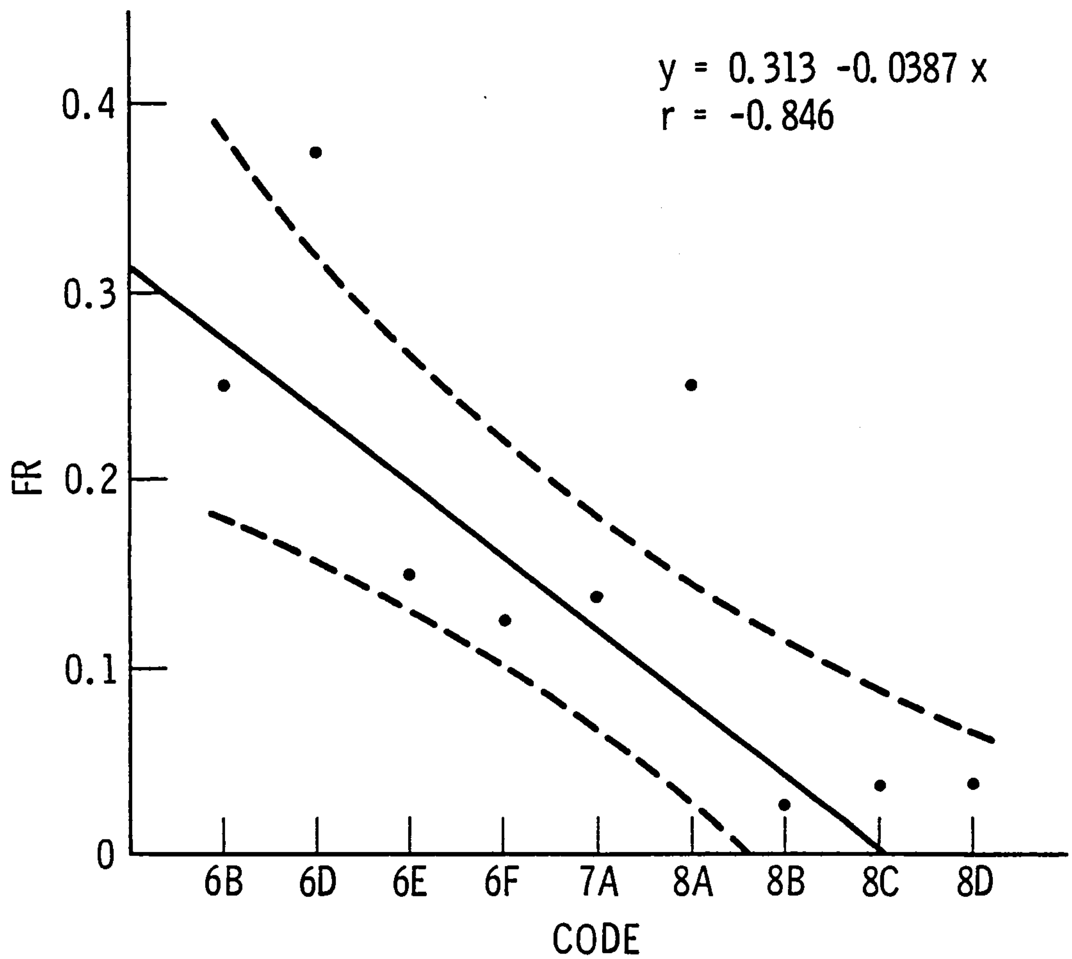


Figure 2. NWC-3 Actual Flight Time (all errors)

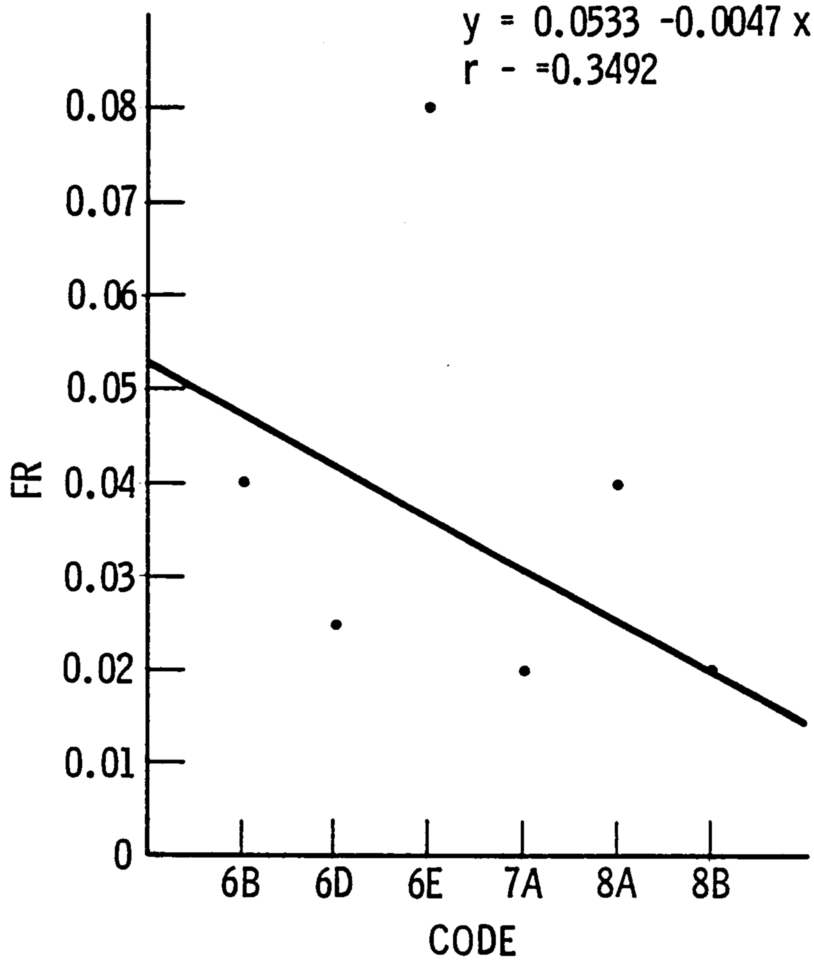


Figure 3. NWC-3 Weapons Laboratory (all errors)

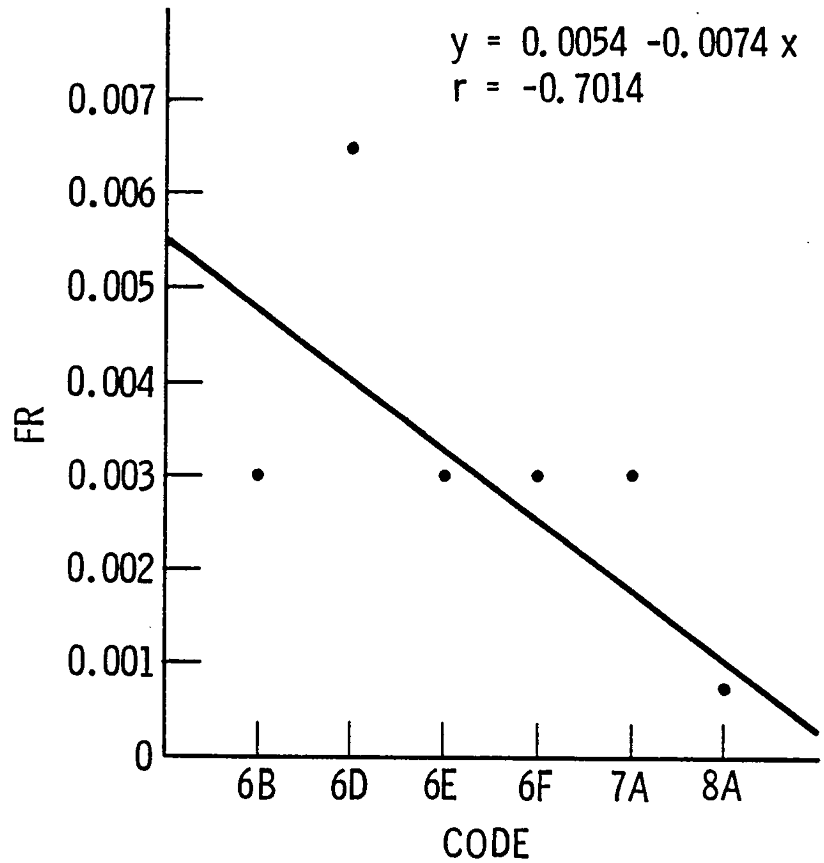


Figure 4. NWC-3 Simulation Laboratory (all errors)

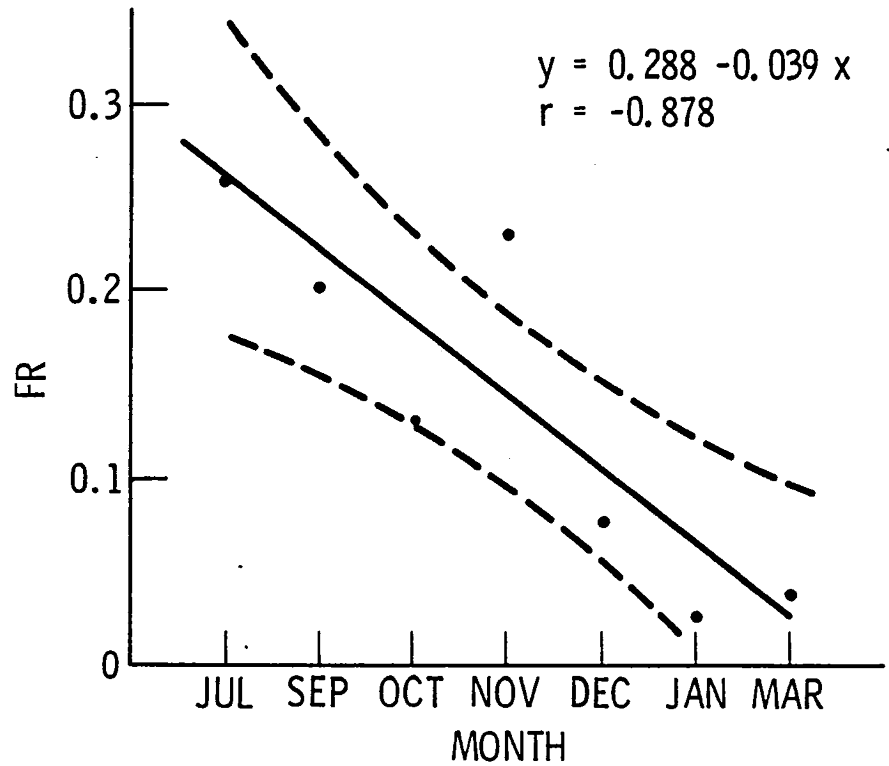


Figure 5. NWC-3 Actual Flight Time (all errors)

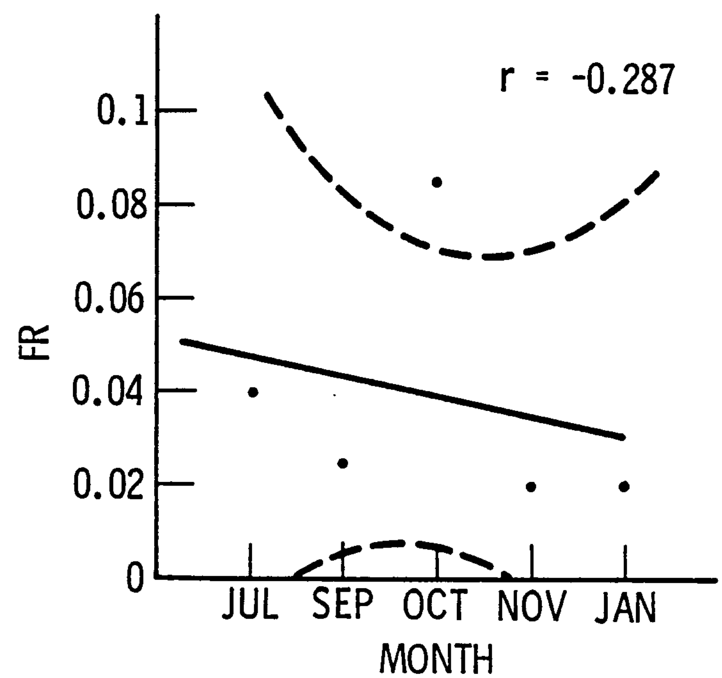


Figure 6. NWC-3 Weapons Laboratory (all errors)

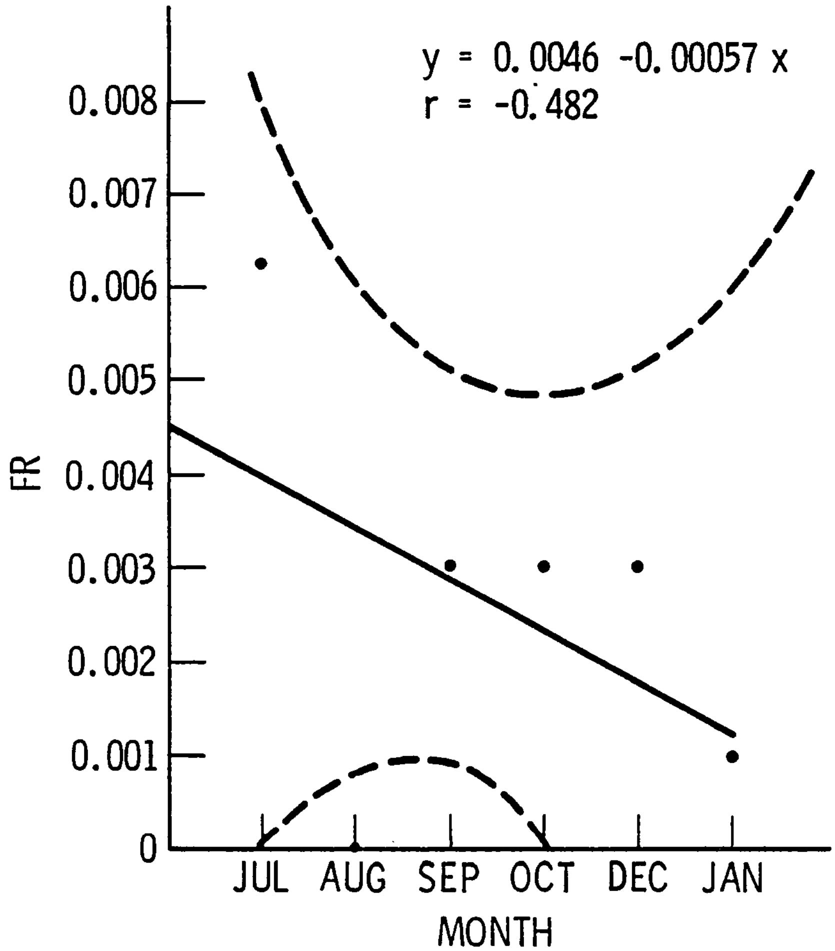


Figure 7. NWC-3 Simulation Laboratory (all errors)

TABLE 6

JPL ERROR CLASSIFICATION

Type	Description	No. of Errors
1	Not a problem	10
2	Not worth fixing	15
3	Source code fix	48
4	Critical-make patch	34
5	Under investigation	6

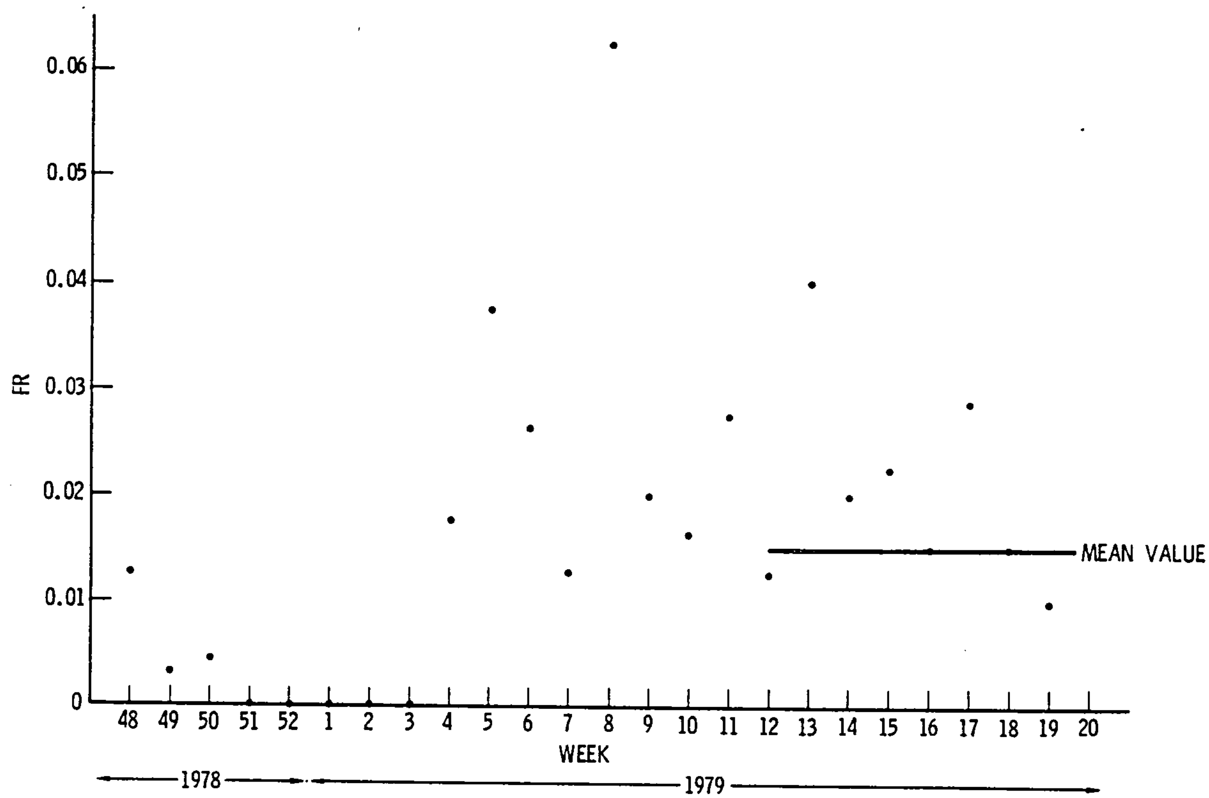


Figure 8. Jet Propulsion Laboratory Failure Rate vs Date

V. CONCLUSIONS

Failure rate appears to be a useful statistic for estimating software quality and recognizing trends in the reliability of operational avionics software. Although the NWC-2 data is summary type data for a large sample of aircraft, and thorough reliability measurement analysis requires data by individual aircraft, a figure of merit may be associated with the software at the time of its release to operational units since the failure rate is decreasing with increasing development time. While the Naval Weapons Center provided excellent statistical data during the final test and evalution phase of the NWC-3 code, diagnostic efforts continued throughout the operational acceptance testing and use, so that a true operational figure of merit would not be available until several months after the operational release. Because failure rate decreases with each successive code release, there is an implication that the code is continually maturing. Preliminary results on the ground base computer system for the Voyager would tend to indicate somewhat inferior software quality, yet the system is highly functional. The degree of software quality a system needs, is a question that must be answered in the future.

The data available for this study was clearly insufficient for any detailed reliability measurement analysis. Collection of data would ideally come from an operational environment where continuous maintenance and service records were kept. Such an opportunity may well exist within the military, provided an agreeable data collection and transmission protocol can be established, and security conflicts resolved.

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15. Supplementary Notes

16. Abstract This study was conducted to determine quantitative measures of reliability for operational software in embedded avionics computer systems. Analysis was carried out on data collected during actual flight testing and from both static and dynamic simulation testing. Failure rate was found to be a useful statistic for estimating software quality and recognizing reliability trends during the operational phase of software development. The scope of the analysis was limited due to insufficient environment where adequate maintenance and service records for avionics systems are kept.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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