mode of the computer. These tableaus of the index mode contain a variety of alphanumeric information pertinent to the ASW operation. The TACO may view these tableaus on his situation display by depressing the appropriate function switches. He also may modify or enter information into these tableaus via his keyset, thereby inputting information to the computer.

The Loran tableau, in addition to containing the Loran position, also contains the dead-reckoned latitude and longitude of the aircraft. The Loran position does not automatically correct the dead-reckoned position. However, the TACO may do a manual correct based on his assessment of the overall navigation pattern.

Lat-long correct

A "lat-long correct" function is incorporated to allow the TACO to correct manually to positions obtained other than by Loran, for example, by tactical air navigation (TACAN). The navigator communicates to the TACO the range and bearing from a TACAN station. The TACO then depresses the lat-long correct switch and enters, via his keyboard, the lat-longs of the TACAN station and the range and bearing from the aircraft to the station. The computer will, on receipt of this data, compute a new long-range position for the aircraft. The amount of correction applied to obtain the new long-range position also will be applied to the tactical position.

Summary

The foregoing discussion has outlined all the navigation functions that are related to the computer. Practical experience has shown that a computer-integrated system of this type offers significant gains in the ASW environment, in both the long and short range modes. Calculation errors have been minimized by the man being taken out of the "mathematical loop"; navigation relative to surface and subsurface objects has been improved greatly by the use of the various biasing techniques and, finally, the tactical crew has been given breathing space on which to arrive at rational tactical decisions.

Future Developments

Curently, an ASW simulation system is being developed at the Naval Air Development Center, Johnsville, Pa. This system, designated MOD 2, is a follow-up to MOD 1 and reflects the knowledge gained in developing MOD 1. The MOD 2 system will be used to develop new techniques in automated ASW exercises. The MOD 2 system is being followed by an airborne MOD 3 system that will be a third-generation A-NEW system, reflecting the developments of both MOD 1 and MOD 2. The MOD 3 system will be installed in an Orion aircraft. The navigation system will incorporate an OMEGA receiver, and the computer will provide astro-data to a periscopic sextant, mechanized to provide heading monitoring and correction.

Reference

[1] "Automatic Loran data processing for VS aircraft," Bureau of Naval Weapons, U.S. Navy, VS Data Processing Memo. RUDC—48020-3 (February 7, 1961).

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Tactical Avionics Maintenance Simulation

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This paper describes analytic and simulation techniques for the study of maintenance characteristics of tactical avionic systems and their ground support equipment. The techniques have been used to define tactical avionics and ground support equipment features required to assure avionic maintainability in the use environment and have been applied to a variety of avionics systems from the preliminary design phase through field use. Although much remains to be done, the experience to date shows that the techniques can translate operational support and maintainability requirements into design requirements when applied in a practical engineering environment. The brief summary presented here illustrates the approach by summarizing the techniques and presenting some typical results. It is believed that this data should be of interest both to maintenance and support specialists and to aerospace management personnel concerned with the problem of developing an integrated approach to maintenance and support engineering within their organizations. An analytical model and two simulation models are described. These models use avionic design parameter estimates as inputs (such as system reliability, test thoroughness, and maintenance task times), allow for various field and operational factors (such as flight schedule and logistics delays), and yield predicted operational characteristics as output (such as undetected fault probability and in-commission rate).

Introduction

THE avionic system designer and military user of avionic systems face a growing problem. The annual costs of maintaining avionic systems are approaching system purchase costs. The demand for skilled electronic technicians threatens to exceed the supply potentially available. With maintenance resources and personnel available, the in-commission rate and operational reliability in the field often are less than desired.

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As part of the effort to solve this problem, analytic and simulation models of squadron-level maintenance have been developed and tested against field data available for systems in operational use. The models then have been applied to a spectrum of avionic systems for present and advanced aircraft including Air Force tactical fighters, interceptors, and strategic bombers, and Navy attack and defense aircraft. The models have been used for various purposes, including setting quantitative maintainability requirements at the system and unit levels, planning field support for systems under development, and evaluating field maintenance practices for systems in operational use.

This paper describes the analytic and simulation models and presents typical results. Emphasis is placed on 1) tactical fighter avionics and 2) radar subsystems for advanced Navy Carrier based attack aircraft.

Approach

Three models have been found most useful. The first model is an analytic system test thoroughness model, which estimates the probability that an avionics system is free of uncorrected mission-essential failures at takeoff. This model is used to determine the built-in and external test requirements for avionic systems, subsystems, and units. The second and third models are simulations that encompass the factors determining the judged in-commission rate (a system classified in-commission may not be failure free) of avionic systems, such as elapsed time for maintenance tasks, spares delays, flying schedule, etc. Flightline simulation represents operational and maintenance events for a squadron of aircraft and emphasizes at-aircraft maintenance. It is used to derive system level maintainability requirements. Shop simulation represents checkout and repair of line replaceable units (LRU's) removed from a squadron's aircraft and is used to derive unit-level maintainability requirements, and to set requirements on shop equipment design. All of the models use inputs from reliability analysis, which take account of part failure rates, redundancy, and usage during a mission.

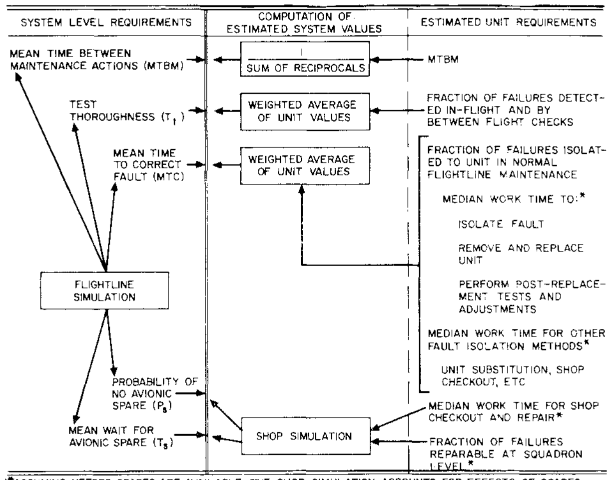
Table 1 illustrates major factors considered in the models. Column 1 lists operational characteristics of the system closely associated with maintenance and reliability. These characteristics often are specified as requirements by the customer. Columns 2 and 3 list factors that determine the operational characteristics. Those listed in column 2 are controlled primarily by the user, those in column 3 by the system designer.

The major outputs of the models are the operational characteristics. The inputs are the field factors and the system characteristics and may be varied to determine combinations that meet requirements. During preliminary design, variations in system characteristics will be of most interest. During later development and operational use, greater emphasis will be placed on field factors. As a separate step (not included in the models), combinations of field factors and system characteristics which meet requirements can be costed to determine a least-cost solution.

Table 1 Avionics maintenance factors

OPERATIONAL CHARACTERISTICS	FIELD FACTORS	SYSTEM CHARACTERISTICS
• JUDGED IN COMMISSION PROBABILITY • ALERT COMMITMENT • OPERATIONAL RELIABILITY MISSION RELIABILITY (FAILURES GENERATED DURING MISSION) UNCORRECTED FAULT PROBABILITY (FAILURES PRESENT BEFORE TAKEOFF) UNDETECTED DETECTED BUT NOT CORRECTED	• NUMBER OF AIRCRAFT • FLIGHT RATE AND SCHEDULE • NON-AVIONIC SYSTEMS PRIORITY MAINTENANCE • MAINTENANCE PERSONNEL NUMBERS SKILLS • SUPPLY SYSTEM • AMOUNTS OF SUPPORT EQUIPMENT • SPARES BUY • MAINTENANCE WORK SCHEDULE	• FAILURE RATE OR MEAN TIME BETWEEN FAILURES • THOROUGHNESS OF TEST: BUILT-IN OR EXTERNAL FAULT DETECTION FAULT ISOLATION • ELAPSED WORKING TIME FOR TESTS AND REPAIR AT AIRCRAFT IN SHOP • FIELD REPAIRABILITY

Table 2 Deriving unit maintainability requirements



*ASSUMING NEEDED SPARES ARE AVAILABLE. THE SHOP SIMULATION ACCOUNTS FOR EFFECTS OF SPARES SHORTAGES. BOTH SIMULATIONS ACCOUNT FOR OTHER DELAYS (WAITING FOR MAINTENANCE RESOURCES, WAIT OVER NON-WORKING HOURS, ETC.)

The models represent a combination of analytic and simulation approaches. The test thoroughness model is at present analytic, because solvable equations could be developed, whereas the Flightline and Shop maintenance models take advantage of simulation's flexibility in representing a complex problem with a savings in computation time.

Unit Maintainability Requirements

If maintenance is to be thoroughly considered in design, unit-level maintainability requirements must be furnished to design areas. The system test thoroughness model is applicable at the system, subsystem, and unit level. However, the flightline simulation is applied at the system level, whereas the shop simulation is applied at the unit level. Table 2 shows how the two simulations are used to derive unit maintain ability requirements. The area to the left of the double line represents use of the flightline simulation to derive system-level maintainability requirements. The area to the right of the double line represents derivation of unit maintainability requirements. The far right column represents the estimation of unit maintainability characteristics by design areas and maintenance analysts using design data and relevant field data. In the middle column, estimated system values are shown calculated from the unit estimates. At the double line, the estimated system values are compared with the required values, and discrepancies are resolved. The resolution of discrepancies may involve another iteration of the process, because maintenance requirements must be compatible with other requirements (such as performance, weight, volume, and power) and constraints (cost, state of the art, schedule, etc.).

System Test Thoroughness Model

The analytical model used to evaluate the probability of an uncorrected mission-essential avionic failure is illustrated in Fig. 1. The horizontal axis is the number of missions flown by a particular aircraft. The vertical axis is the probability of an uncorrected mission-essential avionic failure. In this brief description, the aircraft is considered as it flies its 21st mission. The probability of a failure present before takeoff is represented by P_2, P_{3_1}, and P_{3_2}.

One type of such fault (probability P_2) is detectable by the in-flight and between-flight tests, but may be present before takeoff because it occurred on a prior mission but was not corrected by maintenance. Another (probability P_3) is detectable only by thorough test. If it occurred before the thorough test shown after mission 3 but was not corrected by this test, it would still be present (P_{31}). If this type of fault

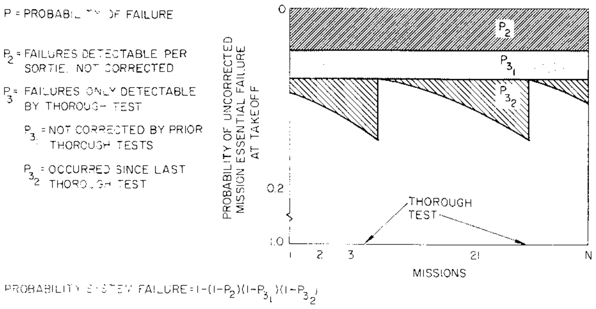


Fig. 1 Avionic system test thoroughness model.

occurred after mission 3, it will remain in the system at least until the next thorough test (probability P_{3_2}).

The probability of an uncorrected system failure P_{uc} is the combination of the probabilities as shown in the equation at the bottom of the chart. To obtain values for the probabilities requires analysis at least at the subsystem level for each type of mission; unit level analysis is desirable.

Major inputs for the test thoroughness model for a particular mission include subsystem mean time between mission-essential failures, subsystem operating time per prior sortie, test thoroughness per sortie (proportion of failure rate evaluated by the in-flight and ground tests applied every flight), probability that a detected fault is corrected in unscheduled maintenance, number of missions between scheduled thorough tests, and fault detection and correction probabilities for the thorough test.

System Test Thoroughness Model Results

Figure 2 shows how the probability of no uncorrected mission-essential failure at takeoff (P_{uc}) for an advanced tactical fighter radar is determined by 1) thoroughness of in-flight test, 2) hands-off or scheduled thorough test maintenance policy (under a hands-off maintenance policy no thorough tests are scheduled and units receive a thorough test only when taken to the shop for unscheduled maintenance), 3) the number of LRU's into which the system is packaged, and 4) system reliability.

One major result is that P_{uc} increases directly, with in-flight test thoroughness over a wide range of LRU's and MTBF's for either maintenance policy. The result emphasizes the importance of in-flight test thoroughness.

Results at a particular in-flight test thoroughness are also of interest. For example, assuming that a 0.98 test thoroughness can be obtained within the airborne weight allowed for

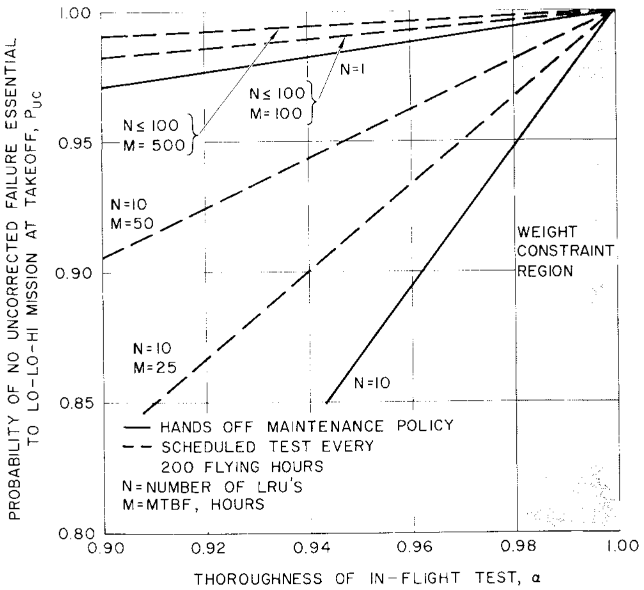


Fig. 2 Tactical fighter radar test thoroughness results.

built-in test, the hands-off maintenance policy provides P_{uc} between 0.95 and 0.985, depending on the number of LRU's. The fewer the LRU's, the higher P_{uc}, because a bigger fraction of the subsystem is taken to the shop when unscheduled maintenance occurs. Comparable values can be obtained with a scheduled thorough test policy, and, with more freedom to package into a larger number of LRU's for radar subsystem mean time between failures (MTBF's) from 25 to 500 hr.

For a tactical application, where personnel and support equipment are airlifted to overseas theatres, the penalty of added flightline labor to perform the scheduled thorough test must be evaluated against the reduction in uncorrected faults provided.

Flightline Simulation

The basic element of flightline simulation is an aircraft consisting of an avionic system and a simplified representation of all nonavionic systems (powerplant, hydraulics, etc.) as a single system. During the simulation, the aircraft move through the states shown in Fig. 3. A squadron of up to 25 aircraft may be handled at one time.

A desired flight schedule is an input. If needed aircraft are not available at the time of a schedule flight, unmet flight(s) are recorded. After a flight, aircraft enter postmission servicing, represented as a fixed delay. The flight may generate no requests for unscheduled maintenance (USM) or requests for nonavionic USM, for avionic USM, or for both. Nonavionic USM may precede avionic maintenance or be parallel with it. The probability of USM is determined from the mission length and mean operating time between unscheduled maintenance actions (MTBM).

Elapsed time until the completion of USM on an aircraft includes the following time elements: 1) delays waiting for maintenance personnel and equipment, 2) delays over nonworking hours, and 3) active working time. Channels are used to calculate the first type of delay. A channel is the collection of personnel and support equipment needed to perform maintenance on one aircraft. Up to 10 channels are provided for each type of USM. The delay over nonworking hours is determined from the maintenance work schedule. Active working times are distributed log-normally.

The delay for avionic spares represents waiting for a needed LRU. The probability that no avionic spare will be available and the mean wait for a spare are calculated through shop simulation. Avionic scheduled inspection is entered after the system accumulates a specified amount of calendar time or in-flight hours and is represented as a fixed delay.

An allowance is made for aircraft not available for routine daily flying (on alert, in nonavionic scheduled maintenance, waiting for nonavionic part, or undergoing modification) by eliminating these aircraft from the runs but considering them in reducing the output data.

An advanced flightline simulation (not shown here) also has been developed, and is being applied to tactical avionics currently. Among the improvements in this model are repre-

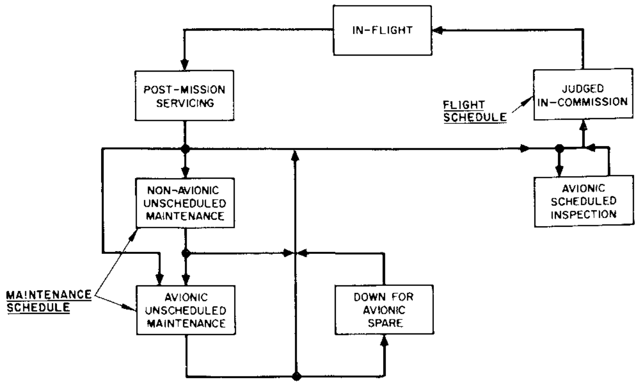


Fig. 3 Flightline simulation flow diagram.

sentation of squadron aircraft at dispersed bases; separate representation of each of several avionic subsystems; distinction between "up" faults (faults not affecting mission essential functions, whose correction may be deferred) and "down" faults (faults that affect mission essential functions, and whose correction may not be deferred); maintenance resources simulated in terms of personnel, support equipment, and other required facilities, rather than as a collection of maintenance channels; separate alert state; and more flexible representation of flight schedules.

Test on Operational System

The simulation was tested for the F-106 aircraft that utilizes the MA-1 radar weapon control system. Inputs were based on data obtained from MA-1 Systems Engineering and reported by using squadrons. The simulation outputs were then compared with reported in-commission and flight rates. The use of field data was highly desirable for such inputs as flight schedule and maintenance work schedule. It was necessary for other inputs, such as mean active working time to correct fault mean time correction (MTC) and the ratio of maintenance actions to system failures, which are not accurately given in the design data.

The reported in-commission and the flight rates were obtained from squadron monthly summaries. Avionic input data were obtained from Hughes Field Service and Support, which has field representatives at using squadrons, from squadron monthly summaries, AFM 66-1 reports and forms, and MA-1 Systems Engineering. Detailed nonavionic input data were not available to Hughes. Estimates were made based on squadron data and published F-106 Category III test reports.

Results are presented in Table 3. Absolute differences between simulation predictions and field-observed results generally are slight. Any bias is in favor of nonavionic systems. Relative differences (not shown in the table) range from 5 to 15%, the greatest differences applying to nonavionic quantities.

One hundred 1-month segments of squadron operation were simultated in 3 minutes of IBM 7090 computer time. The 100 months of simulated operation provided a stable estimate of the mean avionic judged in-commission probability. The standard deviation of this mean (σ_M) was 0.003.

Results

Squadron flight rate

The results illustrated in Fig. 4 indicate that avionic system maintainability requirements closely depend on the type of aircraft, the operational situation, and avionic reliability.

Figure 4 applies to the avionics of a fighter operated at maximum flight rate (a wartime case). Aircraft with two types of nonavionic maintainability, that typical of current aircraft (Level I) and that typical of requirements for future aircraft (Level II), are considered. With Level I aircraft, flight rate ceases to increase once avionic MTBF is beyond about 20 hr. At this point nonavionics become the main factor influencing flight rate. With Level II aircraft, avionic

Table 3 F-106/MA-1 study-simulation predictions vs field data (November 1961)

Parameter	Absolute difference[a]
Weapon system out-of-commission probability	−0.02
Nonavionic out-of-commission probability	−0.06
Avionic judged out-of-commission probability	+0.02
Flight rate (flight hours per month per aircraft)	−1.0
Simulation characteristics	
Running time for 100 months of simulated squadron operations: 3 min; Standard deviation (σ_M), avionic out-of-commission: 0.003	

[a] + indicates higher value predicted by simulation than observed in field.

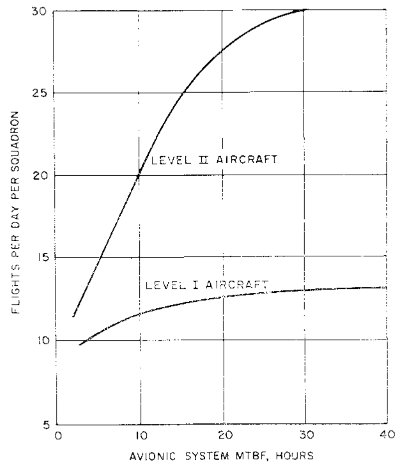


Fig. 4 Tactical fighter maximum flight rate results.

MTBF's greater than 30 hr are needed to prevent the avionics from constraining flight rate.

Avionic judged in-commission probability

The results for in-commission probability (Fig. 5) show that MTBF and unscheduled maintenance are key factors in determining the judged in-commission probability.

Figure 5 applies to a naval carrier aircraft tactical radar and associated displays and data processor. The design makes extensive use of microcircuitry. The judged in-commission rate is lower in wartime because of higher flight rates and less dependable logistics. Once the radar subsystem MTBF is beyond about 100 hr, further increases in MTBF have little effect on in-commission probability. Time to correct a fault does not have a marked effect on in-commission probability over the spectrum of MTBF's studied.

Shop Simulation

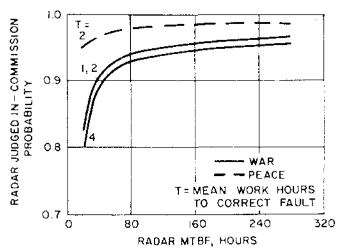
The shop simulation calculates two factors used in flight-line simulation: the probability of no avionic spare and the mean wait for a spare. It has been used in determining unit maintainability requirements, shop equipment concepts, and spares estimates. The basic element is an avionic unit removed from an aircraft-installed system. Up to 100 types of units may be represented.

Judged faulty units arrive at the shop from aircraft landing at scheduled times (Fig. 6). The number and type of judged faulty units from each aircraft are determined by Monte Carlo techniques from unit MTBM's and on-times per mission. An arriving unit is routed to its assigned test stand(s). A variety of test stand assignments is possible; one possible arrangement is shown in the insert in Fig. 6. Units are served in the order of their arrival and must wait their turn if a backlog has developed.

Each time a unit arrives at the shop, a unit of the same type is withdrawn from the spares bank to replace the arriving unit. If there is no unit of this type in the spares bank, a unit shortage occurs. The duration of the shortage is the time elapsed until a unit of this type enters the spares bank from a test stand or the depot. Demands for a unit are filled on a first-come, first-served basis.

Checkout on the test stand determines if the unit is good or faulty and, if faulty, whether it can be repaired in the shop.

Fig. 5 Carrier aircraft radar judged in-commission rate.



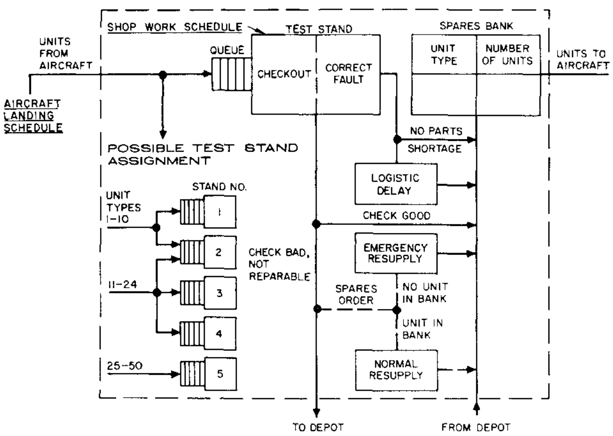


Fig. 6 Avionic shop simulation flow diagram.

For faulty reparable units, the active work time for fault correction is drawn from a log-normal distribution. Repair is delayed if a nonworking hour interval is encountered or if a needed part is not available (logistic delay). Good units go directly to the spares bank. Faulty nonreparable units are sent to a depot, and a replacement unit is ordered. The replacement arrives at the spares bank after a resupply time. An emergency resupply time is used if an aircraft is waiting for the unit.

Results

The results given in Table 4 illustrate the use of shop simulation to evaluate proposed shop test stand configurations and squadron initial spares provisioning. The table shows results for a carrier-based attack aircraft microcircuited radar. In this study interest is centered on the spares mix, since the shop load could be handled without saturation by one test stand. The results indicate that a spares mix intermediate between II and III is adequate. The blank indicates that in the runs evaluating spares mix III, no unit shortages occurred.

In this study a year of flight operations was simulated in about 2 minutes of computer time. Although a detailed, unit-by-unit test against an operational system has not been made, results are in general agreement with field-observed values.

Reliability and Field Support Cost Estimates

Although the simulations do not explicitly include cost factors, the results can be coupled with cost data to arrive at least-cost solutions. Unfortunately, accurate data on the dollar costs of system and unit maintainability and reliability features often are not available.

Reliability and field support cost estimates are shown in Fig. 7 for a mid-1960 attack radar design. Field support costs include personnel, spares, and test equipment and are calculated

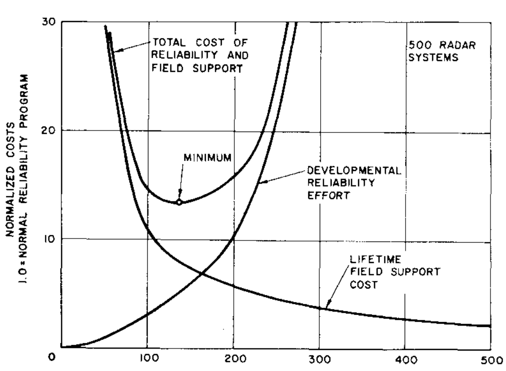


Fig. 7 Attack radar reliability and field support cost function.

Table 4 Carrier-based attack aircraft radar soph

Spares mix	Number of spares: Antenna-receiver	Data processor	Other units	Probability aircraft is waiting for spare
I	0	0	1 each	0.02
II	1	1	1 each	0.01
III	4	4	1 each	...

from a detailed set of equations not presented here. Reliability costs are based on engineering change proposal (ECP) cost data for an earlier radar weapon control system adjusted for two factors: 1) greater economy when effort is concentrated early in design to reduce ECPs and 2) lower failure rates available from component technology. Naturally, great uncertainty exists about the accuracy of the reliability costs. Total cost is simply the sum of the two costs. A minimum total cost to the user is shown at about 130 hr MTBF, at a reliability expenditure at least an order of magnitude above current practices. The results shown on the graph remain only illustrative until they are based on cost data of much improved accuracy. The equation used to generate the reliability cost curve is

$$C_R = k\{1/(\lambda - \lambda_L) - 1/(\lambda_0 - \lambda_L)\}^{1.2}$$

where λ_L is the inherent failure rate limit of design, λ_0 is the failure rate with limited reliability program, λ is the desired failure rate, and k is the cost factor.

Conclusions

The major conclusions drawn from the tactical avionics studies performed are the following:

1) The central variable in the maintenance problem is the reliability of the equipment. The reliabilities that would minimize total life time field support and reliability costs lie in the region where reliability costs during development exceed normal practices.

2) In the reliability region for typical attack avionics, the most stringent design requirement imposed by maintenance considerations is thoroughness of per sortie testing, typically mechanized by built-in test. High test thoroughnesses are needed to minimize the probability of no uncorrected mission-essential faults at takeoff. To attain required values within usual airborne weight constraints implies a rigorous built-in test effort closely integrated with prime equipment design from program inception.

3) At typical test thoroughness values and reliabilities, a hands-off maintenance policy of no scheduled inspection implies system packaging into relatively few LRU's and a very thorough shop check-out of units. Addition of scheduled inspection can ease packaging restrictions and provide higher probabilities of no uncorrected fault at takeoff, but at the penalty of added manpower and support equipment.

4) Elapsed times for maintenance typically are a less critical variable. In the shop, an adequate spares bank can buffer the weapon system from shop repair delays. Although at-aircraft maintenance does contribute directly to weapon system down-time, it also is buffered by administrative delays. A typical finding is that small increases in judged in-commission rate are realized from even large decreases in repair time.

5) Much further work needs to be done to analyze maintenance requirements in terms that influence equipment design. However, the models described here have proven useful in support of avionic preliminary design and the early phases of system development efforts.

A word of caution: appropriate use of the models requires good input data and expertise in their application to the timely eva,uation of design decisions. Poor decisions could result from inappropriate application of the techniques.