REPORT ON A TECHNICAL COMPARISON OF THE APOLLO SPACECRAFT GUIDANCE COMPUTER WITH A PROPOSED NEW DESIGN

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Introduction

The Apollo guidance system presently uses a computer being designed by MIT and manufactured by Raytheon. As a result of a recent Guidance and Navigation review, the Office of Systems had recommended to MSC that consideration be given to replacing the MIT computer by the computer presently being developed for the S-IB and S-V vehicles. This computer, which is called the Saturn TMR (Triple Modular Redundancy) computer, is being developed by IBM under the direction of MSFC. This recommendation has been jointly studied by MSC and the Office of Systems.

The major technical point at issue is reliability. The MIT computer is a single channel machine with an MTBF of approximately 1500 hours. It is anticipated that high reliability can be achieved by the use of in-flight maintenance using spare parts carried in the spacecraft to supplement the basic reliability of the machine design. The IBM TMR computer is a three channel machine, each channel having an MTBF approximately equal to that of the MIT machine. It is anticipated that high reliability can be achieved in the TMR machine by the use of automatic electronic switching to switch out failed modules.

This document presents the status of a technical evaluation and comparison of the two computers being conducted by the Office of Systems and the Apollo Spacecraft Project Office.

Reliability Objective

MIT has established a reliability apportionment of .9987 for the guidance computer. This is based on an overall apportionment of .994 for the navigation and guidance subsystem established by the spacecraft contractor (NAA). The N & G apportionment for the LEM is .992 so that the computer apportionment will not change significantly. In either case, however, the basic MIT computer reliability is such that it will not, by itself, meet the reliability goals established. The present approach is to carry 100% spares (three trays) and replace these during the mission if a failure occurs. The approach recommended by Office of Systems is to use built-in triple modular redundancy with automatic switching logic.

Reliability, Weight, Volume, and Power Comparison

Comparison data for the two computers are shown in Table 1. All of the weight, volume, and power data are identified as to source. All of the reliability data were generated as a part of this study with one exception for the IBM computer which is discussed below.

On the basis of the mission profile given in the MSC Lunar Landing Mission Design Plan, the following two computer operating time budgets were used in this comparison.

a. Computer, continuous and standby modes.

1.	On-the-pad just preceding launch.	4 hours
2.	Launch through translunar injection.	3.5 hours
3.	Translunar coast.	3 hours
4.	Lunar orbit insertion.	0.5 hours
5.	Lunar parking orbit.	12.5 hours
6.	Transearth injection.	0.5 hours
7.	Transearth coast.	3 hours
8.	Re-entry.	3 hours
		30.0 hours on
		160.0 hours standby
		90 on-off cycles

b. Computer, continuous mode only.

1. 190 hours on.
2. 1 on-off cycle.

These two budgets represent the extremal operating time philosophies. The problems associated with 14 days on-the-pad testing prior to launch are not considered here. Neither are aborts.

The reliability of the MIT computer was derived from data supplied by MIT which identified failure rates on a per-tray and a per-module basis. These data indicate an MTBF of 1440 hours for the MIT computer. Some of the MIT component failure rates were adjusted to be consistent with corresponding component failure rates used in the IBM reliability estimates. The net result of these changes was to cause the MTBF of the MIT computer to change from 1440 to 1476 hours.

Two maintenance disciplines were evaluated for the MIT computer. Both of them assume that three complete spare trays are carried, one spare tray for each of the functioning trays of the computer. If a malfunction occurs, the spare trays are inserted into the computer on a cut-and-try basis until the fault is cleared. For the calculations of the "tray sparing" reliability, the maintenance actions stop at this point. For the calculations of the "module sparing" reliability, it is assumed that the malfunctioning module is identified by cut-and-try substitution of modules from the "bad" tray into the tray of the now functioning computer. There are 40 modules in the logic tray, 23 modules in the rope tray, and 12 modules in the power supply and core tray.

The reliability of the MIT computer was calculated with "tray sparing" and "module sparing" by making the following assumptions:

a. The repair time is ignored.

b. All spares are good.

c. When the computer is in the standby condition, only those circuits with power on (the clock) can fail.

d. There are no turn-on or turn-off stresses in the computer.

e. The semiconductor junction temperature is 70°C.

The reliability of the IBM computer was derived from an IBM report on the advanced Saturn computer. This report breaks the computer into five parts. They are:

1. Oscillator
2. Timing Generator and Computer Logic
3. Memory Modules
4. Power Supplies
5. Data Adapter

For each of these parts the reliability has been calculated by IBM for 100 hour, 250 hour, and 500 hour missions, and for semiconductor junction temperatures of 60°C, 75°C and 100°C. (The present advanced Saturn integral cooling design results in a junction temperature of 60°C.)

For the purposes of this comparison, the data adapter of interest is not the data adapter of the Saturn instrument unit but a data adapter with input-output capabilities equivalent to the input-output of the MIT computer. Estimates of the weight, volume, power, and reliability of this I/O capability were obtained from IBM.

The reliability of the oscillator, memory modules, power supplies, and data adapter for the IBM computer can be calculated by analytical means. This was done for 30 hours on, 160 hours off, and for 190 hours on. The assumptions were:

a. When the computer is in the standby condition, only those circuits with power on (the clock) can fail.

b. There are no turn-on or turn-off stresses in the computer.

c. The semiconductor junction temperature is 75°C.

The reliability of the TMR computer logic was evaluated by IBM by means of Monte Carlo techniques on a 7090 computer. This simulation is assumed to be correct but this has not been verified. The reliability of the TMR computer logic for the 30 hour on, 160 hour off and 190 hour on conditions was obtained by linear interpolation from the reliability figures in the IBM report.

TABLE 1

COMPARISON OF COMPUTER CHARACTERISTICS

	MIT - RAYTHEON			IBM
	No Spares	Tray Sparing	Module Sparing	Triple Modular Redundancy
Reliability				
30 hours on 160 standby	0.9689	0.9998	0.99999	0.9991
190 hours on	0.8837	0.9965	0.99989	0.9941
Weight	Basic Computer 68 pounds Three Spare Trays 55 pounds Cold Plate 6 pounds Total 129 pounds (MIT)			*113 pounds (IBM) 133 pounds (R/C) 130 pounds (MSC)
Volume	Basic Computer 1.6 cu. ft. Three Spare Trays 1.1 cu. ft. Cold Plate .1 cu. ft. 2.8 cu. ft. (MIT)			* 2.7 cu. ft. (IBM)
Power	100 watts on 20 watts standby (MIT)			** 300 watts on 30 watts standby (IBM)

*The three weights are three independent estimates by the organizations shown in parenthesis. It could be expected that independent volume estimates would follow approximately the same trend.

*For 190 hours of operation, the 200 watts difference in the two machines converts to 30 pounds of reactant weight. For 30 hours on, and 160 hours standby, the difference is 6 pounds of reactant.

In-Flight Maintenance Versus Redundancy

Some concern has been expressed by the Office of Systems over the basic approach of in-flight maintenance for a digital computer. Maintenance experience four to five years ago would dictate against such an approach since modules were not interchangeable even though identical in manufacture. Considerable re-adjustment was required after each replacement. The trouble was that circuit designs were too marginal in terms of component tolerances and component tolerances were not held closely. Better circuit designs and better components have made these problems unnecessary. Raytheon was required to demonstrate this to the Navy for the Polaris MK-2 guidance computer by interchanging modules in three computers. No adjustments were allowed or necessary. All three computers operated satisfactorily with any combination of modules. Module or stick replacement is now standard Navy maintenance procedure in the factory, in the field, and on board submarines. No adjustment is required and no special training is needed. Maintenance data for Polaris MK-1 and MK-2 systems was recently checked by MSC to verify this situation. Similar response was obtained recently by Major R. Henry of OMSF from SAC headquarters. The SAC staff feels that the secret to meeting mission requirements is in-flight maintenance on the B-52 Airborne Alert Fleet (20 to 30 hour missions) and on-site maintenance for the ballistic missile force.

The magnitude of the total in-flight maintenance task needs further study to evaluate it quantitatively. A quick look by MSC is not particularly alarming since the four critical powered flight periods are only a few minutes each in duration, leaving most of the mission time available for performing maintenance between non-time critical crew tasks. The three main systems being considered for in-flight maintenance are the N&G, stabilization and control, and communications. With existing equipment reliabilities, the probability of there being a failure during the mission that can be fixed with in-flight maintenance is approximately one part in five. The probability of two of these occuring at the same time within, say the same hour just prior to a critical flight phase, which would cause a peak maintenance task, is negligibly small for a 190 hour mission. The process of replacing complete trays of modules makes possible a quick fix without isolating the fault to a particular module in a critical time period. Subsequently the fault can be traced to the particular module in a less critical phase of the mission. A major advantage of the redundant system is that it permits operation in the presence of a failure at any time during the mission.

The problem of isolating the fault beyond the tray level in the MIT computer requires trial and error replacement of modules. This can take up to 1.5 hours but can undoubtedly

be improved as operating experience with the computer is acquired. There are approximately 80 modules in the MIT computer but many are identical. The trial and error approach at the module level, however, does exercise the module connectors and results in concern about the possibility of inducing connector failures. The solution is primarily a matter of good mechanical design and has received close attention. It results in some additional weight in the mechanical construction of the modules in the MIT computer. In any event, the tray sparing approach is adequate to meet the reliability objective without going to the module replacement level.

There is another kind of computer malfunction besides the hard failures considered in the rest of the report. This is transient failures, where noise or some other mechanism causes a bit to be dropped or created. The data that exists on the frequency of occurrence of transients indicates that transient failures are a factor of from 5 to 10 more frequent than hard failures. For a simplex computer, transient failures constitute a risk that cannot be avoided. A TMR computer contains the mechanisms for automatically correcting transient failures.

Common Computers

Computationally, there is no need for more than one basic computer in the lunar mission. If the TMR computer were used in CM and LEM, all of the spaceborne computers used

in a lunar mission would be basically alike. There would be differences in the input-output and memory size requirements, but the basic logic and memory arrays would be identical. This would enhance the chances of actually achieving the required reliability since more identical units would be manufactured, tested, and used. In addition, the launch people at the Cape would have to contend with basically one type of device. This reasoning has already resulted in the LEM and CM computers being basically the same in the MIT version. Whether these advantages could be maintained through the development period of both the launch vehicle and spacecraft is open to speculation.

APPENDIX A

The Apollo Guidance Computer (AGC), as being designed and developed by MIT and supported industrially by the Raytheon Company, has the following characteristics:

Memory:	Core Rope Memory	24,576 words.
	Erasable Memory (coincident current ferrite)	1,008 words.
Word Length:	16 bits (15 bits + parity).	
Speed of Computation:		
	Memory Cycle Time	11.7 μ sec.
	Add Instruction Time	23.4 μ sec.
	Multiply Instruction Time	98 μ sec.
	Double Precision Add Subroutine	234 μ sec.
	Double Precision Multiply Subroutine	780 μ sec.
Number of Instructions:		
	Normal Order Code	11 sec.
	Involunary Instructions (Interrupt, Increment, Load, Start)	8
Input-Output:		
	Counters	20 counters
	Discrete Input Lines (one input bit per line)	60 lines
	Discrete outputs (for displays)	18 lines
	Pulsed Outputs Under Program Control	25 lines
	Telemetry:	Single Error Correcting Pulse Train. Output Asynchronous to AGC Timing.
	Up Link:	Serial Input to One Register. Rates up to 5 Words per Second Asynchronous.
Interrupt Options:		5 options

The construction of the MIT machine is divided into three trays. Each tray can be independently removed and inserted into an end connector on the back of the panel. Precaution has been taken in the design of the trays such that end connector pins will not be bent when inserting the tray into the back panel. Two of the trays weigh 20 lbs. and the third weighs 15 lbs. They are of ruggedized construction suited for In-Flight Maintenance. Each tray contains modules which can be replaced. Errors in replacement of modules are prevented by six holes on each side of the bottom of the module. When a module is inserted into a tray no connections are made until the code as defined by the 12 holes is ascertained by proper mating of pins in the tray structure. Further screwing down of the module is required before connectors are made. In addition, a module can be put on a flat surface and rotated in any direction, without the connector touching the surface.

The core rope memory (24,576 words) is a permanent wired-in memory. This memory insures against a loss of memory during the flight.

APPENDIX B

The Saturn V guidance computer evaluated in this report (see Note on page 2) contains:

1. Timing - simplex oscillator, TMR electronics.
2. Control and Arithmetic - TMR.
3. 12 K Erasable Memory (24 K instructions) - duplex.
4. Power - duplex.
5. Interrupt (5 options) - TMR.
6. Input-Output (equivalent to AGC4) - TMR.

The machine is organized as a hybrid parallel-serial computer -- parallel data to the control and serial to the arithmetic sections. The memory word length is 28 bits. Each word accommodates two 13-bit instructions, plus two parity check bits. A signed, binary number (25 bits plus sign) with parity check would occupy one work. There are 16 instructions in the repertoire. Typical arithmetic speeds are:

Add - 84 μ sec.
Multiply - 336 μsec.
Divide - 672 μ sec.

} 25 bit accuracy (1:32 million)

The machine may be interrupted from external sources (5 wired-in options). Its input-output capabilities are:

46 input lines
18 discrete outputs
25 pulsed outputs
Telemetry down-link
Timing register (module = 10 hours)

All circuits in the logic portions of the computer are triple modular redundant, using majority voting at the outputs. The inputs to the voters are monitored for disagreement, thereby identifying a malfunction to a trio of modules (7 modules/simplex channel). Provisions are included for switching power individually to the three channels to allow simplex operation. The parallel operation of the memory, parity-check and comparison circuits is designed to correct automatically single, transient errors.

The device technology used in the Saturn V computer relies principally on components and integrated circuit fabrication techniques (Unit Logic Device) developed at IBM. The computer is packaged in a single structure that includes integral liquid cooling.

NOTE: The Saturn V computer evaluted in this report is configured to make it functionally equivalent to the AGC4. The machine actually under contract to MSFC differs from that discussed here mainly in the packaging arrangement. In the actual system the computer is packaged in two separate enclosures (each using integral liquid cooling), which contain:

Enclosure A - Timing, Control and Arithmetic, Memory (8 K duplex, with spare volume to double the capacity to 16 K duplex).

Enclosure B - Power, Interrupt Logic, Input-Output Digital and Analog Circuits.