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LEM GUIDANCE AND NAVIGATION

VALIDATION STUDY

[U]

November 6, 1963

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ABSTRACT

The Office of Manned Space Flight has requested Bellcomm, Inc., to perform a study which would either:

- a) validate the proposed configuration of the LEM Guidance and Navigation System; or
- b) recommend changes to improve the configuration if the proposal is not validated.

The proposed configuration uses the MIT primary system with major components essentially the same as those planned for the CM guidance system and an abort system with an attitude reference and a pitch programmer.

As a result of the study, it is recommended that:

- a) The MIT system be the primary LEM Guidance and Navigation System.

This recommendation does not include an endorsement of the MIT computer. (There are arguments for using the same guidance computer in the LEM and CM.)

- b) The configuration of the primary and abort system be such as to permit adding backup capability to the degree permissible by overall LEM weight constraints.

This recommendation recognizes that additional study is required before a complete LEM Guidance and Navigation System can be defined.

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LEM GUIDANCE AND NAVIGATION VALIDATION STUDY*

1.0 INTRODUCTION

The Office of Manned Space Flight has requested Bellcomm, Inc., to perform a study which would either:

- a) validate the proposed configuration of the LEM Guidance and Navigation System; or
- b) recommend changes to improve the configuration if the proposal is not validated.

As presently planned, the LEM Guidance and Navigation System consists of a primary system and an abort system. The primary system provides the guidance functions required in a normal mission plus those required in the abort maneuvers should some other system fail. The abort system is intended for crew safety and would be used only if the primary system failed. The abort system provides the guidance functions required to attain an orbit with a clear pericyynthion when boosting from any point along the powered descent trajectory (down to hover) and from the lunar surface.

The ASPO Guidance and Control Systems Office of MSC has proposed a configuration for the LEM Guidance and Navigation System. The configuration uses a single primary

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* This report is a written record of a presentation made by Bellcomm, Inc., to an MSC meeting on the LEM Guidance and Navigation System on October 9, 1963.

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system with major components essentially the same as those planned for the CM guidance system and an abort system with an attitude reference and a pitch programmer. It is this configuration which Bellcomm has been asked to validate.

The main technical issue is centered about the reliability achievable with the proposed configuration. Under present ground rules, if either the primary or abort system fails, the mission must be aborted. This requirement that both systems be operating normally to attempt a lunar landing places stringent demands on the reliability of the primary and the abort systems in order to achieve a high probability of mission success.

2.0 BACKGROUND

Current LEM Guidance and Navigation development activities on the primary system are being conducted by the MIT Instrumentation Laboratory. MIT plans to use major components such as the three gimbal platform and the computer already under development for the CM guidance system in the LEM system. The major planning effort for the abort guidance system is being carried out at the Grumman Aircraft Engineering Corporation (GAEC). As yet, no hardware is under development for the abort system. There is, however, an RFP for a four gimbal platform for use in the abort system which has not yet been released.

The computer in the MIT system has been examined in detail in an earlier Bellcomm study. Although this study evaluated the use of the MIT computer in the CM guidance system, the results are pertinent to the present situation. The recommendation of the study was that

consideration be given to replacing the MIT computer in the CM by the computer being developed for the Saturn IB and Saturn V vehicles. This latter computer, which is variously called the Saturn TMR (Triple Modular Redundancy) computer or the IBM-TMR computer, is being developed by IBM under the direction of MSFC.

It is claimed that state-of-the-art advances in the inertial hardware field will permit a system to be built which is functionally equivalent to the MIT primary system with a significant saving in weight. The statement is made that two primary systems which use the newly developed equipment would weigh no more than the MIT system. Two primary systems properly connected would greatly improve the system reliability. Furthermore, the new lightweight systems considered use four gimbal platforms and therefore, remove the attitude restrictions now present with the MIT system.

3.0 STUDY GROUND RULES

The ground rules for the study are taken from the Apollo System Specification. These ground rules identify, among other items, the requirement for an abort system and the design goal of providing a backup capability so that the system may survive a single failure without necessitating abort.

Following are statements taken from the Apollo System Specification which are pertinent to the LEM G&N study.

2.2 System Design Policy

2.2.2 Where the nature of any element of the system is such that its reliability cannot be assessed with the proper confidence,

then the design of the system shall be such that a failure of the element, as a goal, shall not cause loss of any crew member.

2.2.3.where reliability demonstration is impractical.....the system shall be designed to include back-up or alternate modes of operation wherever possible, rather than place sole reliance on simple parallel redundancy of elements whose reliability cannot be demonstrated. The net result shall be, as a goal, to preclude any single component failure from necessitating abort or seriously degrading the probability of successful abort in the event of a second component failure in the same area.

2.2.4 If the preceding reliability provisions cannot be met, then in-flight maintenance and/or parts replacement shall be provided, where practicable.

2.2.5 In those areas where requirements (performance, reliability, etc.) can be met by the existing state-of-the-art, the design of the system shall not be made dependent on the development of new components or techniques. Where a new development is required to accomplish design of the system, and is considered to involve high risk, steps shall be taken to insure a suitable back-up capability in the event the new development effort is unsuccessful.

2.2.6 The design of all flight equipment shall be such as to accommodate the various flight

tests and vehicle configurations which are planned with minimum variation of the equipment from flight test to flight test and flight test to lunar mission.

4.4 Navigation, Guidance and Control

4.4.3.17 The design of the guidance and control system for the LEM shall be such that it is possible to abort the mission at any point in the descent of the LEM and return the LEM to lunar orbit for rescue.

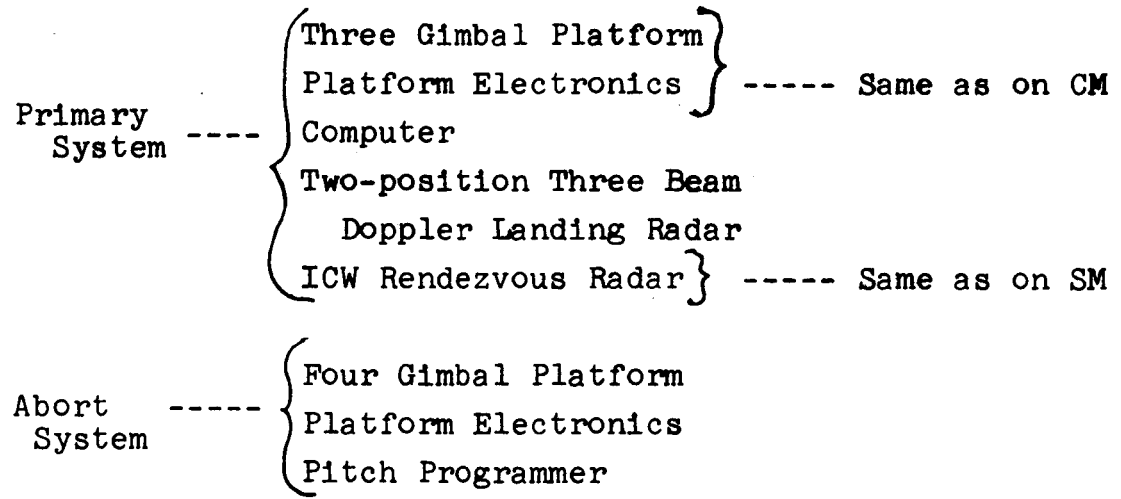
4.4.3.18 An alternate, simple and self-contained means of LEM guidance shall be provided in event of failure of the LEM primary guidance system at any time subsequent to landing. This shall not preclude the use of a CM-LEM launch signal command or CM-LEM voice links.

4.4.3.19 As a design objective, the mechanization of the CM and the LEM shall be such that the CM can signal the time of launch to the LEM and subsequently range and track the LEM for the purpose of relative CM-LEM position determination and as an aid to rendezvous.

4.0 RELIABILITY ARGUMENTS

4.1 Introduction

The proposed configuration based on the MIT primary system and the GAEC abort system is as follows (major components only):



GAEC's plans for the abort system are still in the formative stage. For example, they have indicated a possible need for three body-mounted accelerometers to implement their present guidance scheme.

This section of the report considers the main issue of the study: -the reliability of the proposed configuration and the changes, if any, needed to increase its reliability. The approach used is to discuss first a reliability model for the proposed configurations. Next, with this model as a background, various configurations are examined with a view toward their possible reliability advantages.

This approach is used rather than a numerical analysis because lacking firmly established failure rates it is impossible to prove that a system can or cannot meet a reliability apportionment.

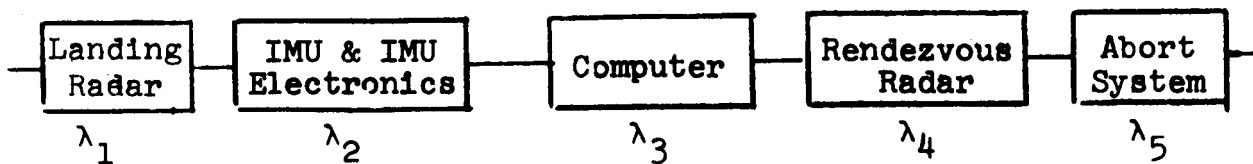
4.2 Reliability Model

From the previously stated ground rules the following statement can be derived: "To continue the

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RELIABILITY MODELS

DESCENT



ASCENT

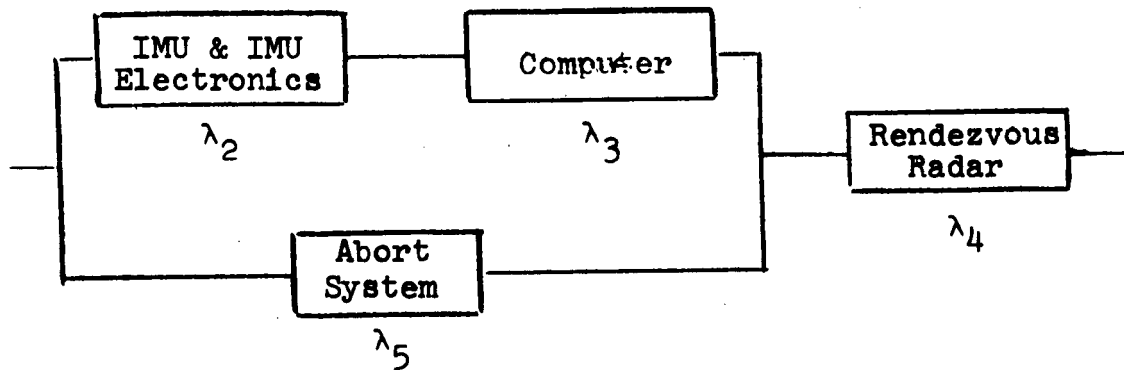


Figure 1

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mission after a single failure in the G&N system, the system must be able to survive a second failure and still have the capability of aborting the mission." This ground rule can be applied to the proposed configuration to establish a reliability model.

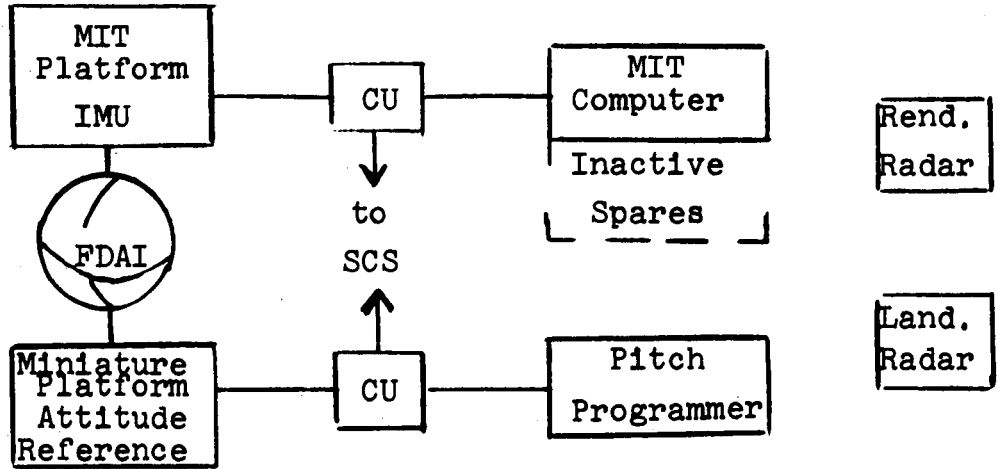
In the proposed configuration, the primary system has the capability of guiding both descent and ascent maneuvers; the abort system only on ascent maneuver. For crew safety, both systems must be functioning properly during the LEM descent to the lunar surface. Therefore, the primary and abort systems are "in series" from a reliability or mission success point of view during the descent phase. Since during ascent both systems are capable of supplying the guidance function, they are "in parallel" from a mission success point of view. This reliability model is illustrated in Figure 1. It is evident from the model that the descent phase where all elements are in series limits the LEM reliability. To increase the reliability it is necessary to parallel some or all of the series elements in the descent model.

The failure rates, (λ 's in Figure 1), associated with the various elements in the reliability model are not firmly established. There has been some analysis, however, which indicates that the λ 's do not differ one from another by any large amount. Basically, therefore, the overall reliability is not greatly increased by making any single element redundant.

4.3 Configuration Modifications

Various configurations are examined now with a view toward their reliability advantages. A reliability model is not presented with each configuration. The

INITIAL LEM G&N SYSTEM



FIRST MODIFICATION

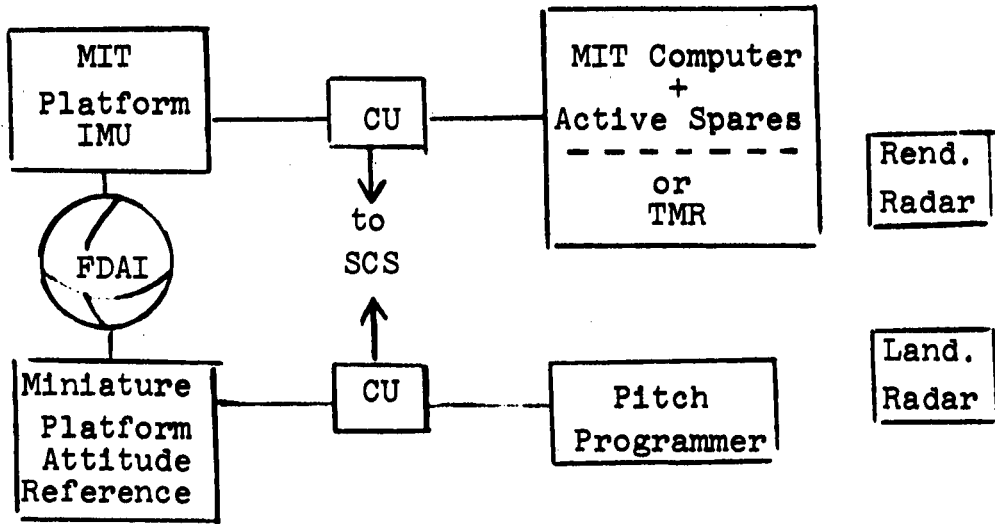


Figure 2

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discussion of the effects of failures on the capability of a configuration, however, does imply the use of a reliability model derived from the ground rule stated in the previous section.

The configurations discussed are illustrated with simple block diagrams indicating major components only. Readers familiar with Apollo guidance plans or inertial guidance systems in general should have little difficulty visualizing the complete system. Furthermore, the intent is to evolve new configurations from the proposed configuration rather than strive for completeness by indicating all possible combinations of elements.

Figure 2 shows the proposed LEM G&N configuration together with the "first modification." The "first modification" uses the TMR Computer or two MIT Computers (active spares). Both configurations can survive a single computer failure without aborting. With the TMR computer, or two MIT computers with some type of automatic switching, the "first modification" can survive a computer failure during powered flight. With "inactive spares", as in the proposed system, the configuration can survive a failure only during a period when repair is possible.

Both of the configurations in Figure 2 show a miniature platform used as an attitude reference. When two computers are used, as in the "first modification", it is a simple and natural change to tie the platform to one of the computers, use the information from the accelerometers on the platform, and use the platform and accelerometers as an IMU. Figure 3 illustrates this

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SECOND MODIFICATION

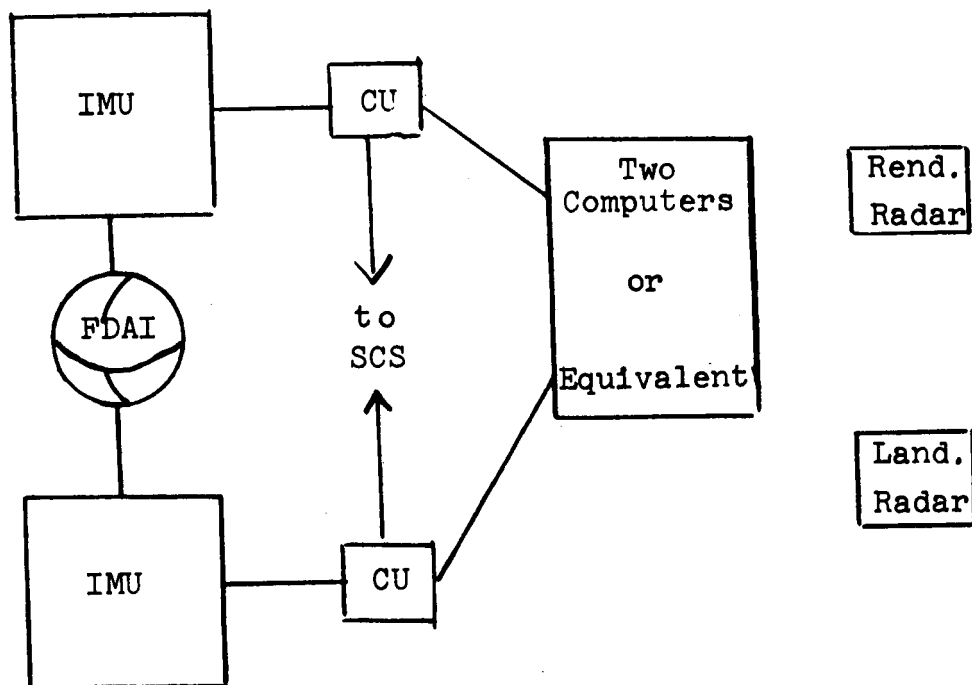


Figure 3

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"second modification" which is a generalized configuration that results when the attitude reference is changed to an IMU, connected to one of the computers, and the pitch programmer is eliminated.

The "second modification" represents two complete G&N systems, both with the ability to land on the moon as well as ascend. As the configuration stands, a single failure requires an abort. The utility of the configuration can be improved, however, if an astronaut-controlled abort scheme (suggested by FCOD) proves feasible.

The suggested abort scheme requires the astronaut to execute the ascent maneuver, which is a simple pitch program, and insert the LEM into lunar orbit, using only the attitude control stick and the "eight ball" attitude indicator. After orbit insertion, the astronaut circularizes the orbit using information generated by the landing radar.*

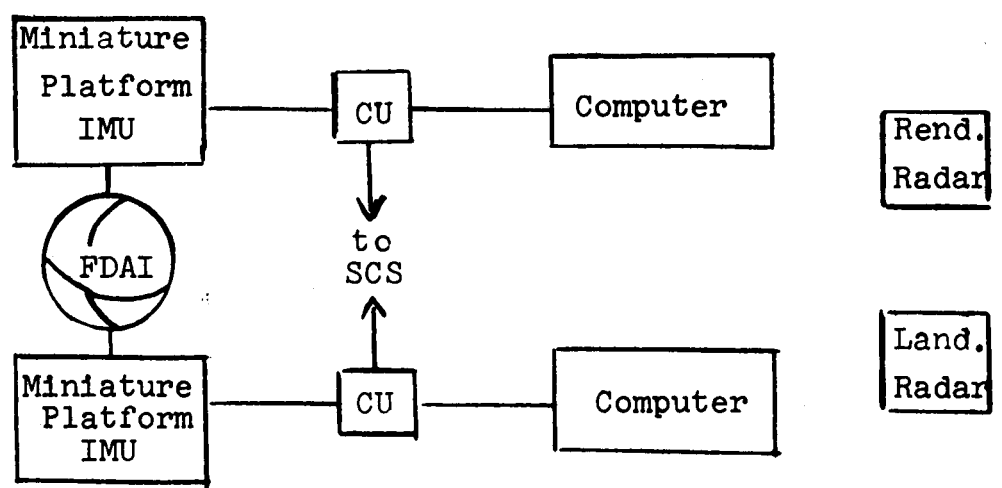
If the aforementioned abort scheme is feasible, the configuration in Figure 3 can survive several failures and continue the mission. Specifically, it can withstand the failure of a computer or the failure of the accelerometers associated with one of the IMU's. The platform with the defective accelerometers can still function as an attitude reference.

Two plans for implementing the configuration in Figure 3 are shown in Figure 4. One plan would use two miniature platforms of the type suggested for the attitude reference in the proposed configuration, and two computers,

* Moving the landing radar from the descent stage to the ascent stage as required for this scheme would increase the LEM separation weight between 100 and 200 pounds, (GAEC estimate).

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MINIATURE PLATFORM - TWO COMPUTER MODIFICATION



STRAPPED DOWN - TMR MODIFICATION

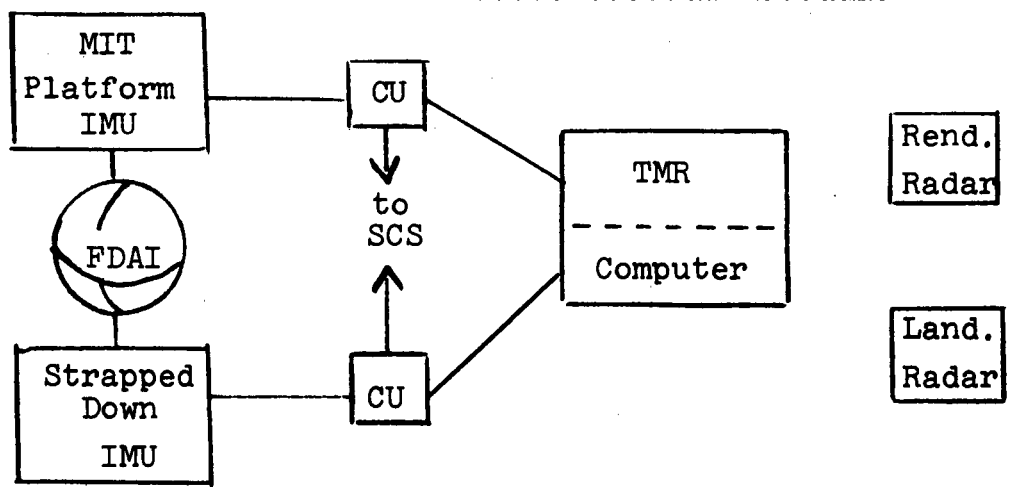


Figure 4

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(perhaps two MIT computers). The other plan uses the MIT platform and a strapped-down system with the TMR computer (or two MIT computers).

The strapped-down system consists of a set of three gyros arranged with axes orthogonal, and mounted to the body of the spacecraft, and a similar set of three accelerometers. The electronics associated with the inertial instruments consists of pulse torque rebalancing circuits, coordinate converters, and means of driving the FDAI (eight ball). With the present state-of-the-art, the strapped down system is less accurate than a platform, but on the other hand, represents less mechanical complexity.

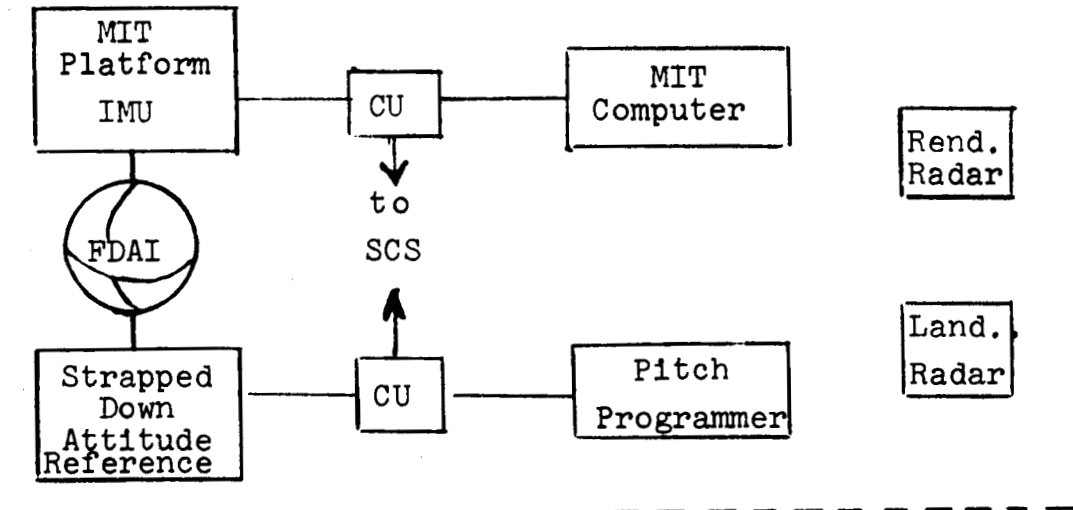
Although the functional capability of each of the configurations in Figure 4 is the same, their reliability may well be different. The strapped down system gives promise of greater reliability than a platform because of its simplicity. When comparing platforms, the MIT platform though heavier than the miniature platform, could well be more reliable. The MIT platform was designed with the reliability requirements of the Apollo mission as a goal rather than attempting to achieve minimum weight.

Thus far in evolving a configuration, very little has been gained in capability when measured against the added weight and complexity. The choice seems to be to add more redundant elements to achieve greater capability or return to a minimum element type of configuration much like the proposed system. Such a choice is illustrated in Figure 5.

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PRIMARY ABORT



PRIMARY - BACKUP - ABORT

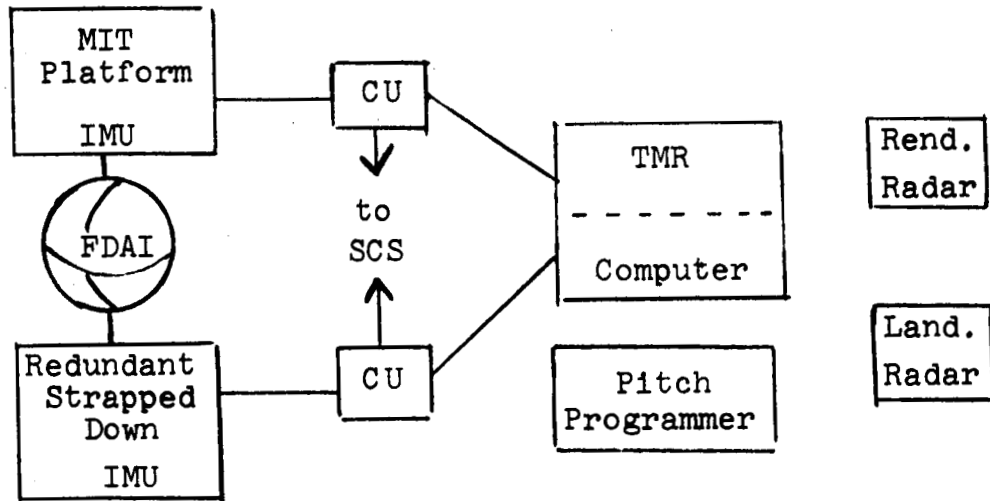


Figure 5

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The configuration in Figure 5, labeled "primary abort", differs from the proposed configuration only in the use of a strapped down system for the abort attitude reference and the implication of few, if any, computer spares. The gain, if any, in reliability of this arrangement as compared to the proposed system depends on the strapped down attitude reference being more reliable than the miniature platform.

The configuration in Figure 5, labeled "primary backup abort", indicates full use of redundancy in the inertial components and the computing function. For inertial measurements there is the MIT platform as well as two strapped down systems connected in a redundant mode. For the computing function there is a TMR computer (or two MIT computers) and a pitch programmer. Assume a switching network that can connect any of the inertial packages to the computer or pitch programmer. Then the computer with any of the three sets of inertial instruments can perform the landing maneuver or the ascent maneuver, (the lunar landing also requires the landing radar). When the pitch programmer is used with the inertial instruments only an ascent to lunar orbit is possible. Thus, with the "primary backup abort" configuration, the mission can be continued with failures in both the computing equipment and the inertial packages.

Since the lunar landing radar is essential to the landing maneuver, it also should be backed up by another equipment to make the system fully redundant. Whether the landing radar function can be adequately backed up by the rendezvous radar or whether it itself can conveniently be made redundant, is as yet an unresolved

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question. It is evident that the reliability arguments supporting the configuration are seriously weakened by by a lack of redundancy in the landing radar function.

In summary, various configurations have been examined from a reliability viewpoint. From the work completed to date, the choice appears to be between a simple primary abort configuration and a much more elaborate configuration featuring redundancy in the major components. The lack of a logical choice between these extremes stems partly from the fact that the major components have nearly the same reliability, and since many components are required, making any single component redundant does not increase the overall reliability significantly.

5.0 WEIGHT ARGUMENTS

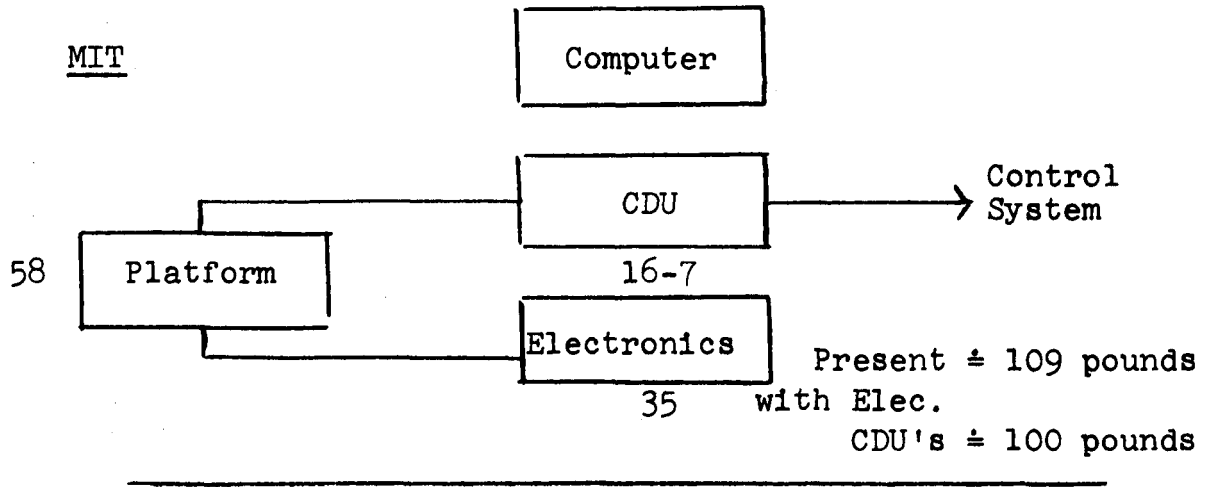
5.1 Introduction

The weight of the LEM Guidance and Navigation system is of particular importance because of its contribution to the total LEM weight. Since the guidance system is located in the ascent stage, each pound added to the guidance system weight requires additional propellants in ascent and descent stage tanks. Each pound added to the ascent stage increases the LEM separation weight by a factor of between 4.5 and 6.4. The lower figure is used if the tanks are designed and the change is in propellant loading only. The upper figure is used for stage design purposes when increased propellant loading requires additional structure and tankage.

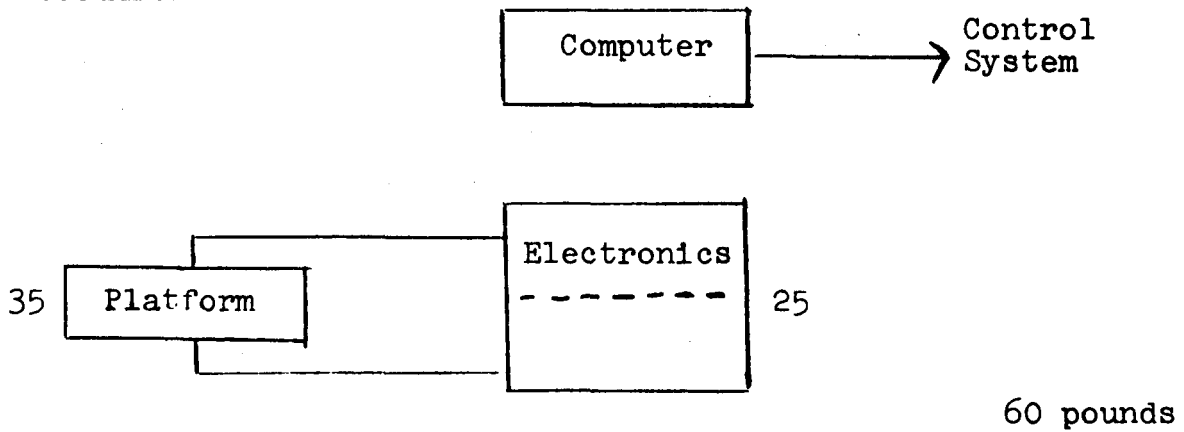
Two points are covered in this section. The first is a comparison of the weight of the MIT platform

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PLATFORM WEIGHT COMPARISON



LIGHTWEIGHT SYSTEMS



IMPORTANT DIFFERENCE IS 23 POUNDS IN PLATFORM WEIGHT

Figure 6

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with a typical miniature platform. The second is an estimate of the weight difference between the primary-abort and the primary-backup-abort configurations shown in Figure 5.

5.2 Platform Weight Comparison

Much has been said in recent months about miniature platforms with the same performance and reliability as the MIT platform, but half the weight. As part of this study, miniature platforms under development by several manufacturers have been investigated and compared with the MIT platform.

A block diagram of the MIT platform and a typical miniature platform together with their associated electronics and the manner in which they are connected in a guidance system is shown in Figure 6. The number beside a block in the diagram indicates the component weight.

Notice first that part of the function performed by the CDU's (Coupling Display Unit) in the MIT arrangement is performed by the computer in the lightweight system. Having CDU's does provide a convenient means for the astronaut to set the LEM attitude manually. If the CDU's are a requirement they should appear in both systems. Surely in a weight comparison, the MIT system should not be penalized for their presence.

Consider next the platform electronics. MIT uses discrete components and provides generous heat sinks where required. Competing lightweight systems employ micro-electronics and thereby effect a weight saving. It is not obvious that in the electronic circuits associated with stable platforms that micro-electronic circuits are the best choice from a reliability point of view at their present state of development.

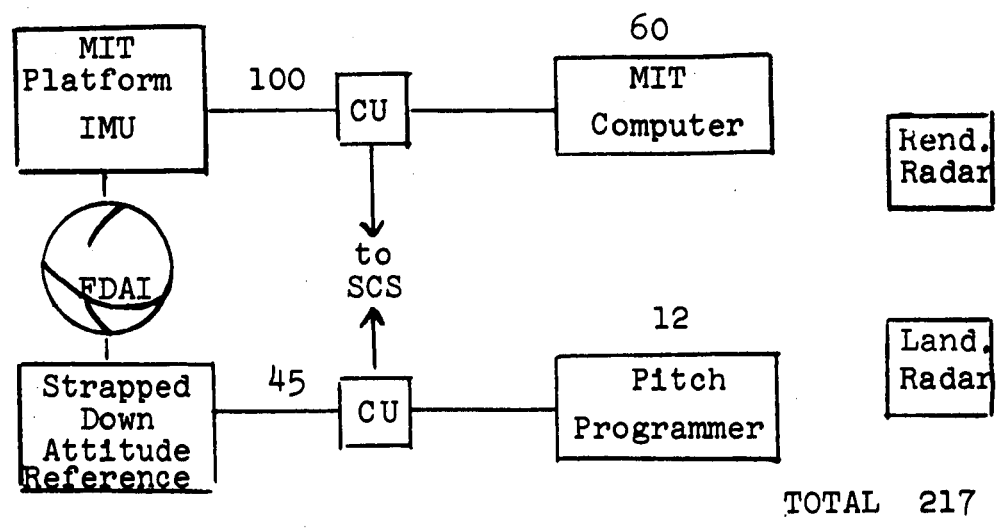
The weight situation therefore, with regard to the CDU's and platform electronics, is that the weight differences arise because of differences in design ground rules. The circuit diagrams used for both systems are very much alike and do not lead to a weight advantage of one system over the other. If it is imperative to save weight, the MIT platform electronics could probably be redesigned using micro-electronics but this may lead to less reliability in these circuits.

The weight difference between the MIT platform and a typical miniature platform is judged to be about 23 pounds. The weight of a stable platform is governed mainly by; (a) the size of the gyros and accelerometers, (b) the size of the gimbal angle pick-offs and torquers on the gimbal axes, (c) the size and number of gimbals, and (d) the environment for which the platform has been designed.

The MIT design is greater in weight mainly because of the larger inertial instruments and the ruggedness of the mechanical design. No firm evidence has been established in this study to justify MIT's heavier design; on the other hand, it is the only design that has been executed with Apollo requirements as a goal.

Summarizing the weight discussion thus far, if the same design ground rules are applied, particularly with regard to the electronics, the weight difference between the MIT inertial unit and competing lightweight systems may be in the neighborhood of 23 pounds.

PRIMARY ABORT



PRIMARY - BACKUP - ABORT

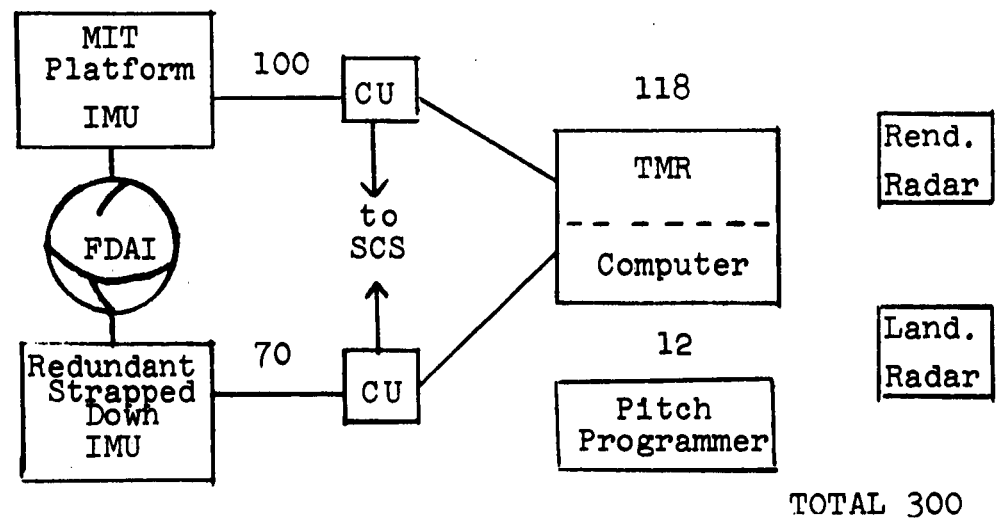


Figure 7

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In Figure 7, the primary abort and primary backup abort configurations using the equipment suggested in Figure 5 are compared on the basis of weight. The number adjacent to a block in the diagram indicates the weight estimate of the equipment represented. Notice that the redundant strapped down IMU is less than twice the weight of a single unit. Weight saving in mounting and packaging the redundant unit make this possible. Weight estimates for cabling, displays and controls, cooling, etc., and equipment common to both systems (e.g., optics) are not included in the total weight numbers.

The estimated weight difference in the configurations is 83 pounds. This difference is, of course, only an approximation. No spares are counted in the weight of the primary abort configuration; and the weight for the additional cabling, displays and controls, cooling equipment, etc., required in the primary backup abort configuration is not considered. With the 83 pound figure as the weight required to add the backup capability and a LEM weight growth factor of 4.5, the increase in LEM separation weight is 373 pounds. This, therefore, is an "in-the-neighborhood" estimate of the weight penalty paid in going from a primary abort to a primary backup abort configuration.

6.0 SUMMARY AND CONCLUSIONS

The main points, in summary, are:

- (a) The Apollo System Specification gives the requirement for an abort system and the design goal of providing a backup capability so that the system may survive a single failure without necessitating abort.

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- (b) Various configurations have been examined from a reliability viewpoint. From the work completed to date, the choice appears to be between a simple primary-abort configuration and a much more elaborate configuration featuring redundancy in the major components.
- (c) If the same design ground rules are applied, particularly with regard to the use of micro-electronics, the weight difference between the MIT design and competing lightweight inertial units may be in the neighborhood of 23 pounds.
- (d) The weight penalty for modifying the configuration by adding backup capability in both the inertial measurement devices and the computing function is in the neighborhood of 83 pounds which would increase the LEM separation weight by 373 pounds.

The firm conclusions that can be drawn from the study work completed at this time are:

- (a) The miniature platforms and associated platform electronics offer but small weight advantages as compared with the MIT design and may be less reliable.
- (b) The use of a configuration consisting of two complete G&N systems, Figure 3, adds very little as compared with the proposed configuration in ability to survive failures and continue the mission.

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- (c) The use of a strapped-down system as the inertial measurement unit in the abort system offers the promise of greater reliability and a saving in weight as compared with a gimballed platform.

7.0 RECOMMENDATIONS

It is recommended that:

- (a) The MIT system be the primary LEM Guidance and Navigation System.

This recommendation does not include an endorsement of the MIT computer.

(There are arguments for using the same guidance computer in the LEM and CM).

- (b) That configuration of the primary and abort system be such as to permit adding backup capability to the degree permissible by overall LEM weight constraints.

This recommendation recognizes that additional study is required before a complete LEM Guidance and Navigation System can be defined.

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