INTEGRATED MISSION SIMULATION FOR LONG TERM SPACE FLIGHT

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Introduction

The problems of evaluating pilot performance, pilot training, and the integration of the man-machine system for proper functioning become increasingly difficult as the length of projected space flights increases. Further, actual in-flight experience becomes harder to obtain and the major means for training and evaluation becomes simulation. The first major source of difficulty in any simulation stems from a basic requirement of learning theory: that for increased proficiency of performance to occur within any biologically capable system, the stimuli which are the bases for the expected behavior must be presented in an amenable form to the learner. Further, the sequence of presentation of the pertinent stimuli must be such that the learner can form the appropriate concepts and interactions required for the ultimate use of the learned material. It can then be seen that two basic factors of learning complex skills are:

(1) Fidelity of simulation of pertinent stimuli.

(2) Appropriate sequencing of stimuli during learning for proper concept formation.

The second major source of difficulty stems from the variables involved in the space missions themselves (i.e., the extended periods of the missions, the variety and complexity of system tasks, and the multiman crew). Each of these variables poses special problems for the areas under consideration, since each is unique and apart from our previous experience.

One mode of evaluation which allows for an investigation and manipulation of the two sources of difficulty is integrated mission simulation. This simulation mode is conceptually different from the usual part-task simulations conducted in nonspace systems, but is closely allied to "exercising the system" utilized in large and complex command and control systems. The value of the integrated mission simulation is as follows:

(1) It treats the man as a functioning element within the overall system, thereby providing meaningful data on this man-machine system.

(2) It provides an evaluation of crew performance and the integration of the system in real mission time. Such variables as length of flight, mission phase and spacecraft habitability may be investigated and manipulated.

(3) It provides an evaluation of the complexity of a variety of tasks which must be performed in the operation of the system or in the accomplishment of the mission. It not only allows an investigation of individual tasks, but also an investigation of the sequence in which tasks must be performed.

(4) It allows for a general evaluation and verification of crew status during a complete mission. Further, it provides an end point for the verification of past selection and training criteria.

(5) It allows for an evaluation of pilot performance during various possible abort or malfunction conditions and an evaluation of the appropriateness of his information displays and controls and vehicle dynamics under a wide variety of conditions.

The values attributed to the integrated mission simulation method have been verified by the results of a number of studies[1 and 2]. However, criticism of this approach also should be mentioned. First, it has been suggested that only with the actual displays and vehicle dynamics can usable results be obtained on pilot performance. Wind tunnel tests simulate an environment similar to, but not exactly like, the environment found in actual flight. However, the use of wind tunnel data in the design of high performance aircraft and in spacecraft has been extensive. The heat resistance of metals has been in the past and is now being tested under simulated conditions which only approach the real environment. However, these simulations are used extensively. The fidelity of the displays is, of course, an important variable, although it is not the actual display hardware itself, but the information which is displayed and the mode of displaying the information which are the critical factors. If adequate information is provided in a simulation, pilot performance can be evaluated.

Another criticism was the capability of realistically measuring pilot performance during a mission. Do measurements (root mean square, terminal rates, etc.) taken during such a simulation realistically predict and relate to pilot performance during actual flight? Has the science of performance measurement advanced sufficiently to realistically and adequately measure performance of early system design? Can these data be used to determine crew task assignments and the crew's role? There is some justification in this criticism, since measurement theory and application of theory have lagged behind other technologies in systems engineering. However, these types of simulations present unique situations which allow for the development of measurement techniques which can later be validated by flight operations. The development of adequate measurement theory for pilot performance and its utility are not limited by any insurmountable technological obstacles, but merely by the level and amount of experimentation conducted. Cross-correlation studies of currently available measures should indicate the relatedness of a variety of measures and their contribution to an estimate of total system performance.

A third category of criticism concerns the value of such simulation, since the complete environment contained in manned space flight cannot be realistically reproduced. For example, weightlessness appears impossible to duplicate; such hazards as radiation and acceleration, in most cases, are both costly and dangerous. Furthermore, the psychological environment, including anxiety, motivation, excitement, etc., is contained within an actual flight and can never be reproduced. The truth of these statements cannot be denied; however, the extent to which they affect the obtained data is not as great as it might initially appear. Primary in this consideration is the fact that certain types of tasks have an inherent stability or instability irrespective of the environment. Moreover, our available knowledge on many aspects of the environment indicates that the physiological aspects of the environment may be generalized without complete reproduction in a simulation study. Such factors as motivation or the anxiety and excitement of an actual flight pose special problems. However, the intrinsic excitement of preparing for the simulation after a period of training does to some extent aid in providing excitement, though not comparable to an actual flight. Further the choice of the crew and design of the simulator also aid in providing motivation to ensure high performance.

The last major category of criticism concerns the training periods involved prior to an actual extended simulation. For anticipated long term flights, the training periods of the crew will range close to five years, and it is unrealistic to assume that a crew may be trained for periods longer than two months for any particular simulation. However, with the proper design of the experiment and the use of the statistical verification techniques, the proficiency of the crew may be determined prior to a flight, and these results compared with in-flight proficiency. The obtained results would yield useful design information and indicate areas where training should be increased, or task allocations changed.

Each of the criticisms has some validity. However, none are sufficient to eliminate consideration of the integrated mission simulation in terms of the value which will accrue as a result of the simulation. It should be noted that the integrated mission simulation merely attempts to approach the actual mission and to provide as much fidelity of the conditions as considered possible or necessary.

The remainder of this paper will present some of the requirements for long term simulation and a discussion of some simulations already conducted. Concluding remarks will present some future applications of extended mission applications.

Requirement for Integrated Mission Simulation

Fidelity of Simulation

Basic to any discussion of integrated mission simulation requirements for space flight is the problem of the fidelity of the mechanics of simulation. Generally, it would be advisable to attempt to provide the highest degree of fidelity possible, with all terms in the equations of motion for flight control complete. Such high fidelity would certainly be a requirement for preflight training on flight control tasks.

The degree to which the fidelity of a particular flight control task can be simulated is generally limited by both the physical quality and quantity of available computer hardware. In addition to the governing necessity for overall reliability and continuity in long term simulation, these latter requirements are, by their very nature, incompatible with massive and complicated computer "hookups" wherein comparatively large amounts of time and attention must be devoted to continuously checking and adjusting the equipment. In simulation situations lasting over a period of days or weeks, and involving many phases (an Apollo-type mission), it is often necessary, in order to limit the computer equipment involvement, to employ the computer in somewhat of a serial fashion. This generally means that major changes in the computer programs take place between successive phases within the simulation. These changes must be executed with a minimum of checkout, inasmuch as the main control panel in the capsule cannot be used in the check process. There are then a number of interfaces which will not be checked or exercised until the actual mission phase begins. Hence, the emphasis upon simplicity and reliability[2].

There are many instances in which the task to be simulated requires extensive computer involvement. This type of task usually involves controlling the motions of a body about its own axes and the resulting effect on the flight trajectory--a six-degree-of-freedom simulation. However, there is a distinct difference between the type of simulation study embracing the detailed investigation of the design of a vehicle control or guidance system and that concerned with evaluating crew performance. The former is concerned with the development of a particular system, and the simulation detail, therefore, is very important insofar as synthesis of a desirable set of responses or a particular reaction is concerned. In the study of crew performance, the only concern is that the response of the particular system being exercised reacts the same as the physical hardware, regardless of how the simulation is managed. This would suggest that a number of simplifications could be made in the computer programs to simplify the programming and switching requirements, as well as the amount of hardware involved, without sacrificing simulation fidelity.

The extensive, yet judicious, employment of function generators can save large amounts of equipment, while the elimination of cross-coupling terms, for example, in the programmed moment equations, can greatly reduce computer requirements. It may be argued, of course, that this simplification degrades the fidelity of the simulation, but the fact remains that, unless the crew can actually detect or sense the effect of its deletion, its addition adds nothing insofar as realism is concerned. This statement should not be construed as suggesting that all high order and coupling terms be disregarded. On the contrary, an important measure of crew performance can be obtained by noting the response to dynamic situations in which coupling and higher order effects complicate the control task; however, if such situations are not able to be detected by the crew, they only serve to complicate the programming task.

A class of variables, to which the crew responds quite positively, centers around the handling characteristics of the particular vehicle under investigation.[2] Mass and inertia changes require "exact" simulation, inasmuch as the crew's ability to accomplish a specific control task adequately depends upon their ability to "predict" the behavior of a given system. These areas become especially important when abort or contingency situations are to be investigated, since any abnormal handling characteristics are most likely to appear during these periods. Any situations producing asymmetric or intermittent control require detailed representation and, therefore, demand a concise definition of exactly what level of detail is to be simulated during the mission.

Another factor of critical importance in the fidelity of simulation concerning flight control tasks is the procedural tasks associated with each flight control phase. In most systems, the control task is relatively short, while the "setting-up" of the systems to operate and the choice of systems consume a larger portion of the time. Further, the success of the flight control behavior is predicated upon the successful completion of the preceding procedural tasks. Therefore, those procedural tasks which are associated with flight control must have a high fidelity of simulation.

The fidelity of simulation of other tasks, such as switching, monitoring, and procedural (not associated with flight control) must also be simulated with high fidelity. One reason for this is the apparent sensitivity of these tasks to a whole variety of stresses which might occur during a flight and which do not affect the flight control tasks.[1 and 2] Further, many times in order to gain sufficient data on tasks which occur infrequently, a change is made in the number of presentations of pertinent signals so that the performance evaluation is based upon poor simulation realism even though upon a large number of data points. Such tasks as switching associated with system and monitoring tasks fall into this category. Therefore, it is important to place these types of tasks into proper perspective in the experimental design. Since the realism of these tasks is quite important, some tradeoff must be made in the experimental design so as not to compromise either the realism or the statistical validity of the data collected.

Choice of Population and Crew Tasks

It has been found that a large amount of the data collected in human performance laboratories within this country is somewhat limited in its application to manned spacecraft systems, primarily because the questions asked by the more basic experimenters are concerned with theoretical issues rather than the precise description of the behavior under operational conditions. Further, because of this general theoretical interest, the task is made simpler to facilitate adequate measurement of the behavior involved. This should not be considered an attack upon proper measurement techniques or experimental design but merely an attempt to point out the obvious differences in measuring performance on a reaction time task in a laboratory compared to measuring performance during a critical flight control maneuver in a simulation. Another factor of importance is that in most laboratory studies the experimenter is primarily concerned with describing a trait within the general population rather than within a specific highly selected subpopulation. In many ways, it is indeed difficult to compare the performance of the college sophomore to the expected performance of the astronaut.

Because of the difficulties in utilizing the data obtained from the basic laboratory studies, extended mission simulation provides an opportunity to evaluate the performance of the task in a more realistic situation. However, it does place certain requirements upon the conduct of the simulation in terms of selection of the crew and their tasks.

Because of motivational aspects, general knowledge of the system, evaluation of performance, and engineering evaluation of the various subsystems, it is a prerequisite to utilize a crew which is representative of the astronaut population. This does not mean that only astronauts are suitable but subjects can include individuals which have similar backgrounds, experiences, and attitudes.

The choice of crew tasks must also be representative of the task to be performed during the actual flight. This requirement is often most difficult to meet, particularly in the case of the non-flight control tasks, because of the relative difficulty of measuring performance due to limited data points and lack of general information on these types of tasks. However, deviation from the use of described systems tasks in their proper sequence within the various mission phases tends to distort the obtained data. It also eliminates one important source of information about the crew's performance capability: the interaction effects. These interactions can relate the effects of mission phases, displays, performance levels as a function of task and time on task, etc. However, these interactions are almost meaningless in their application to the actual man-machine space system, if the tasks utilized in the simulation are not related to the actual system tasks.

In many studies available in the literature concerned with gaining basic information about the effects of certain aspects of the mission environment (duty cycle, confinement, etc.) on general performance, it was acceptable to utilize less complex and easily measured tasks (i.e., reaction time, arithmetic problems, etc.).[3, 4 and 5] However, with the lack of appropriate models which somehow relate or scale the difficulty of one task with another, the performance on these simpler tasks does not appear to adequately describe performance on more complex tasks. Perhaps future research and the development of appropriate models will allow scaled relationships to be made; however, this is not the case at present.

We therefore believe that the best approach and the best source of data may be obtained from a variety of measurements on tasks which are directly representative of tasks to be performed on an actual space mission. Further, in the design of the simulation, we have indicated the importance of the proper sequencing of the tasks in terms of each mission phase. These task requirements, plus the utilization of an appropriate population sample, ensure more applicability of the simulation to actual system problems. An example of some of the crew tasks which require simulation for the lunar landing mission is given in Table 1.

TABLE 1

Categories of Crew Tasks

Procedural Systems Tasks	Switching	Vehicle Control
Communication	Data entry into computer	Transfer to excursion vehicle
Log check	Switch to different mode of systems operation	Firing initiation
Record data	Enable systems	Attitude control
Systems check	Alignment	Translation control
Obtain trajectory information	Star fix	
Determine trajectory		
Compare data from onboard and ground sources		

Displays

One area which we consider most important in determining whether a particular simulation was worth performing is that of flight displays. This is particularly true for a fixed-base simulator with its attendant lack of physical cues. Inasmuch as the crew can communicate with the control hardware only to the extent allowed by the onboard information displays, it is not surprising that the value of a simulation is determined by this factor. It is, of course, highly desirable that duplicate hardware (the same as that used in the flight vehicle) be employed wherever possible. If this is not possible, extreme care should be exercised in choosing a substitute and in installing the particular instrument so that it will provide the proper information in its proper position. The importance of this statement cannot be overemphasized.

The lack of actual hardware cannot be avoided and neither can other problems associated with the display panel in early simulations. Their effects can be minimized by pre-testing with experienced personnel and making available adequate time and effort in the checkout and operation of the onboard display system. Peripheral areas in the man-machine relationship such as seating position, lighting conditions, etc., should also be given the same type of consideration prior to extended mission use.

Given this approach, and ensuring, by various analytical methods, that the information being displayed is pertinent and usable and that the control response is adequate, the integrated mission simulation will allow for the evaluation of the adequacy or inadequacy of a particular display approach. Further, the integrated mission simulation aids in determining the display system layout considering all crew tasks, all mission phases, and the time of confinement in the vehicle. These data cannot be obtained as readily from a part-task simulation.

Results of Integrated Mission Simulation

Thus far, we have presented the pros and cons of integrated mission simulation studies. Further, we have discussed, in some detail, three requirements for this type of simulation: fidelity of simulation, selection of the crew and crew tasks, and displays. Other requirements and variables could be discussed, including environmental factors, internal arrangement factors, measurement of performance, etc. We are cognizant of the importance of these factors and have not discussed them in the interest of time. Further, the extensiveness of the requirements for integrated mission simulation is dependent upon the type of problem attacked and the stage of development of the particular system under consideration.

We have conducted a number integrated mission simulations of the lunar landing mission. A brief description of the purpose, the conduct and some of the results may serve as an example of the utility of these types of simulations.

Over a 10-month period in 1961 and 1962, four integrated mission simulations were conducted. Two of these were of 7 days duration and two of 3-1/2 days duration. We will restrict our discussion to the last 7-day simulations.[2]

This simulation was based upon a complete lunar landing mission. The simulator, control room, and other pertinent simulation variables had developed over a period of time ranging from a simple mockup with static instrumentation to a simulator which had instrumentations controlled by simple electronic circuits to the present one. Testing and evaluation in each of these phases provided valuable information. The basic purpose of this last simulation was to provide a gross evaluation of pilot performance as a function of the restrictive volumes of the spacecraft simulator.

The simulation facility consisted of a 350-cubic foot command module vehicle, which was connected to a one-man lunar excursion module (approximately 35 cubic feet) via a tunnel. All mission phases of the lunar landing mission were simulated, as were most of the pertinent tasks (see Table 1). The experimental design utilized in this simulation deviated from mission realism in that each of the crew members was required to perform a lunar deorbit, lunar ascent, rendezvous, docking, and earth re-entry. Time to accomplish these extra phases was appropriated from the translunar and transearth inactive coast phases in order to keep within a 7-day mission. Figure 1 presents a view of the exterior of the simulator and interior flight deck, indicating the display system. The simulator contained other differentiated functional areas: a sleeping area, an off-duty area (Fig. 2), a sanitation area, and a galley.

The flight control tasks were mechanized to provide feedback by use of a 262-amplifier analog computer facility. Equations of motion, representative of all mission phases, were delineated with at least three degrees of freedom. The trajectories flown in all phases were realistic and representative of the lunar mission. System weight, engine size, gravity terms, etc., were included in the equations of motion. The performance of flight control tasks was also done in real time. All other simulator inputs and outputs were monitored via a control room (Fig. 3). All pertinent displays were activated either by control of the computers or from the control room.

The three crew members who participated in the simulation were all qualified experimental test pilots with extensive flight experience, and each held a degree in engineering. Their ages ranged from 31 to 37 years. All crew members received training in the simulator operation procedures, for an 8-week period, and after training, baseline data were collected on each crew member prior to simulation to be compared to later mission performance.

The results of this simulation, which used gross measures of pilot performance, indicated no apparent effects on crew performance from confinement in the restrictive environment. Performance on tasks associated with flight control, switching and general system procedures was within acceptable tolerance ranges and compared well with baseline performance. An example of the performance of the crew is given below.

One flight control task performed by the crew was the rendezvous of the excursion module with the command module. The pilot's task was to initially acquire the command module by using a starfield background. Once the excursion module was aligned with the command module, the pilot utilized a PPI-radar-displayed indication of the command module's relative location. After the command module was centered on the display with the rates nulled, a finer look angle was selected. Relative vertical distance to the command module was shown by the size of a circle on the display; the circle grew larger as the two vehicles came closer together. Figure 4 presents the result of pilot performance on the rendezvous tasks. The scores are the averaged mean distance along the three axes at rendezvous termination for each pilot. The two baseline conditions--collected 6 and 11 days, respectively, before the simulated rendezvous--are the best terminal conditions obtained during this period. Figure 4 shows that the performance of the pilots after 3-1/2 days of confinement when the rendezvous was conducted is comparable to the baseline performance and well within the tolerance limitations of the systems and the simulation hardware.

Pilot performance on the other tasks (procedural and switching) was found to be adequate. However, it should be noted that, during the simulation, a number of errors associated with switching or procedural tasks did occur which could have compromised the mission. It was suggested that these errors were a result of "forgetting" mission sequences between the last training period and the occurrence of the task during the simulation. Because no empirical verification of this hypothesis was performed, it must be considered as tentative.

Generally, the importance of the display system on pilot performance was considered to be a major factor in the simulation results. Although a majority of the displays were realistic, items such as scan pattern and display-control positioning could have been improved based upon pilot comments at the termination of the study. The lack of any gross indication of performance detriment (particularly on the flight control tasks) even with a less than optimum display system, is a further indication of the lack of reactivity of the crew to the restrictive environment.

A more detailed description of the results of the studies are available[2]. However, we believe that the above brief description of the results has indicated the type of data which can be collected. The display system concept, with its many ensuing parameters (scan patterns, etc.), was evaluated for its feasibility. The effects of the restrictive volume of vehicle was found not to cause difficulty in vehicle control. Trained, experienced test pilots could perform the other tasks associated with a lunar mission with minor difficulty. The difficulty which was noted was concerned with crew reliability in switching tasks, duty cycle and other factors associated with the habitability of the vehicle.

In consideration of a perfect flight mechanics simulation, this particular simulation was crude; and certainly, its results could not be used for detailed hardware design. However, it did provide information on the environment, display, and anticipated crew performance problem areas long before other more sophisticated simulators could be developed and the actual vehicle flown. In this manner, integrated mission simulations did contribute to the overall design of the lunar landing mission.

Concluding Remarks

We have attempted to present a brief picture of the value of integrated mission simulation with some of the requirements for its conduct and design. An example was given of such a simulation with the lunar landing mission. As indicated earlier, other areas of interest may be explored with this method of simulation, provided that the requirements can be met.

One such area is the man-machine reliability problem. Great effort is currently being directed toward the evaluation of reliability models which can be applied toward systems under consideration. However, the majority of these models consider only the machine portion of the system with variable reliability characteristics, while the manned portion usually has a constant value which is not obtained under the same precise conditions as the machine component. One reason for this is the lack of applicable data obtained under realistic or quasi-realistic conditions. Some of the reasons given in our discussion of choice of task apply here also. Whether the reliability of man is 1.000 or something less is important. The use of the integrated mission simulation technique can provide this type of data with the proper experimental design and measurement techniques.

As stated earlier, integrated mission simulations are most taxing on computer equipment because of the long periods of operating time involved and, generally, the limited amount of computing hardware available. Because of the sequential nature of a typical extended flight simulation (i.e., launch, staging, orbital insertion, translunar injection, lunar landing, lunar ascent, rendezvous, etc.), there is often little or no time available for reprogramming to account for gross weight, guidance or control changes. Although optimum programming (in this sense meaning a program general enough to encompass many flight phases) in conjunction with large arrays of stepping switches can accomplish this task with a minimum of hardware expenditure, this approach is somewhat restrictive and does not allow the maximum flexibility required for complex, large-scale simulations. The ultimate and logical answer to this problem is the application of "Hybrid" computer techniques.

The "Hybrid" or combination analog-digital type computer combines the speed and flexibility of the analog computer with the accuracy and bookkeeping qualities of the digital computer. The result is a computer which answers many of the questions asked when large-scale simulations are contemplated. The problem of changing large numbers of coefficients to account for the configurational changes which occur during steps from one phase into another can be efficiently handled by the digital portion of the computer. This capability should also be exploited when it comes to required scale changes for the many instruments and displays present in a simulation similar to that used in the seven-day study reported in this paper.

Of great importance also is the requirement for rapid static or even dynamic checks of each simulation model (a single phase). It is quite possible to program the digital computer to accomplish this task many times prior to the time that the actual model will be employed. This capability should greatly enhance both the fidelity and the realism associated with a particular simulation.[6]

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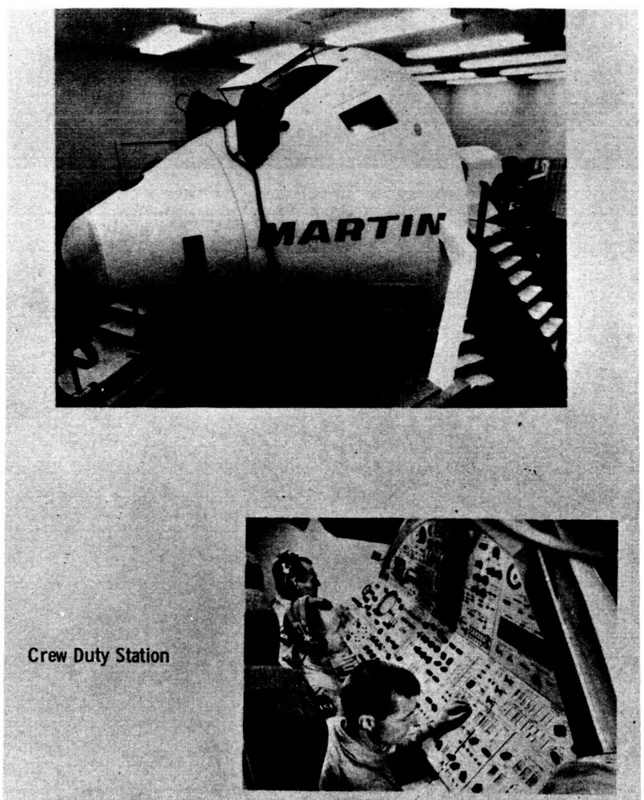

Fig. 1. External and Internal Views of Lunar Landing Simulator

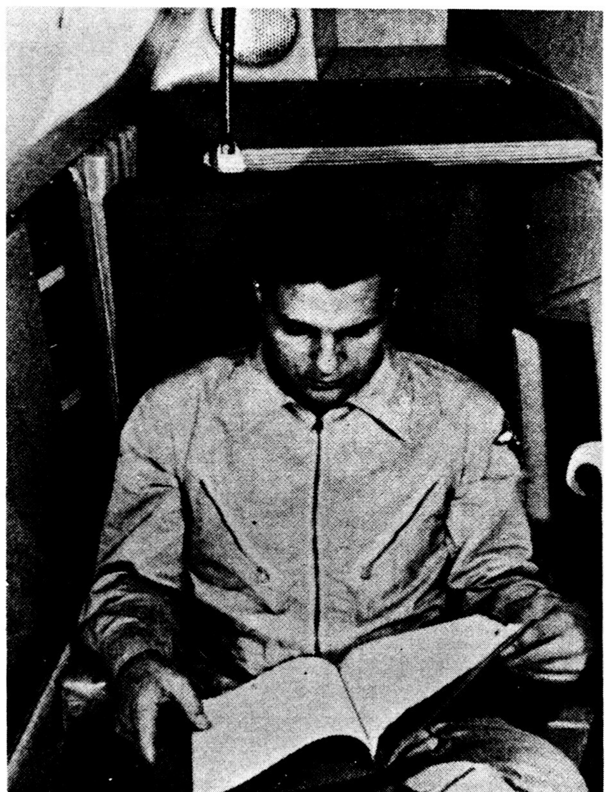

Fig. 2. Command Module Off-Duty Area

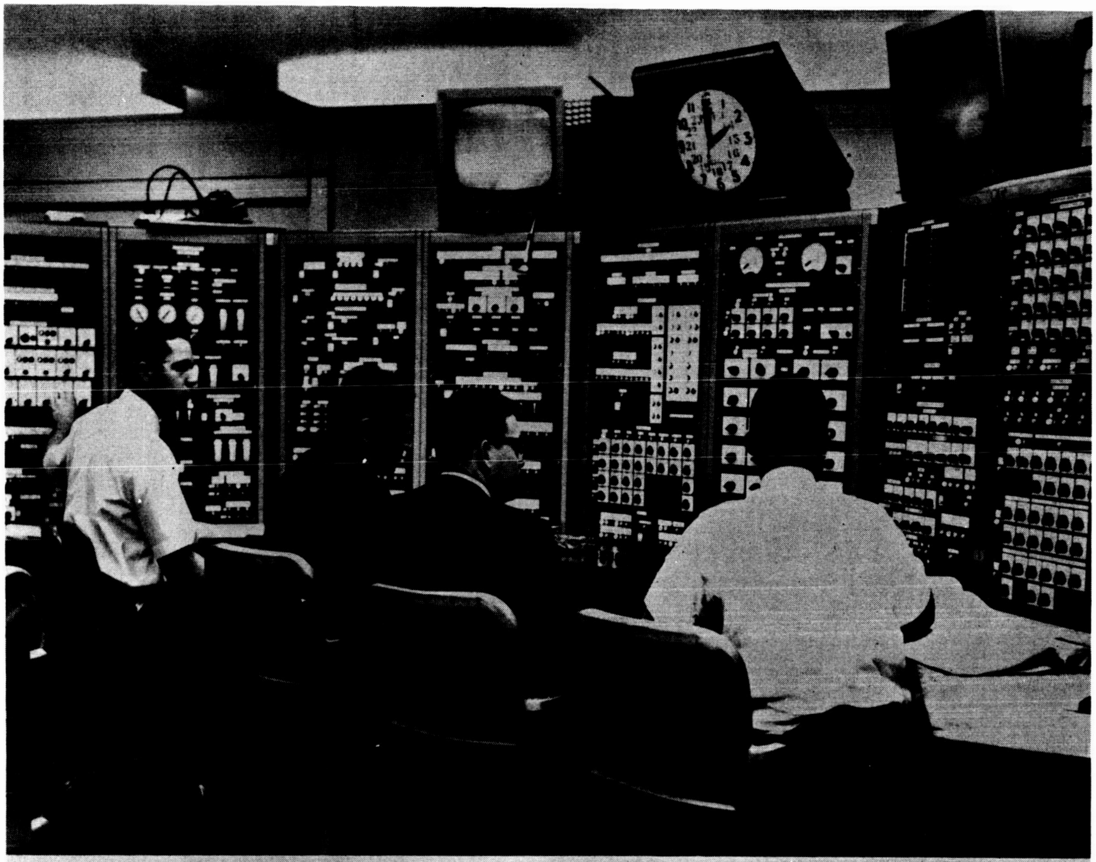

Fig. 3. Lunar Landing Simulation Control Room

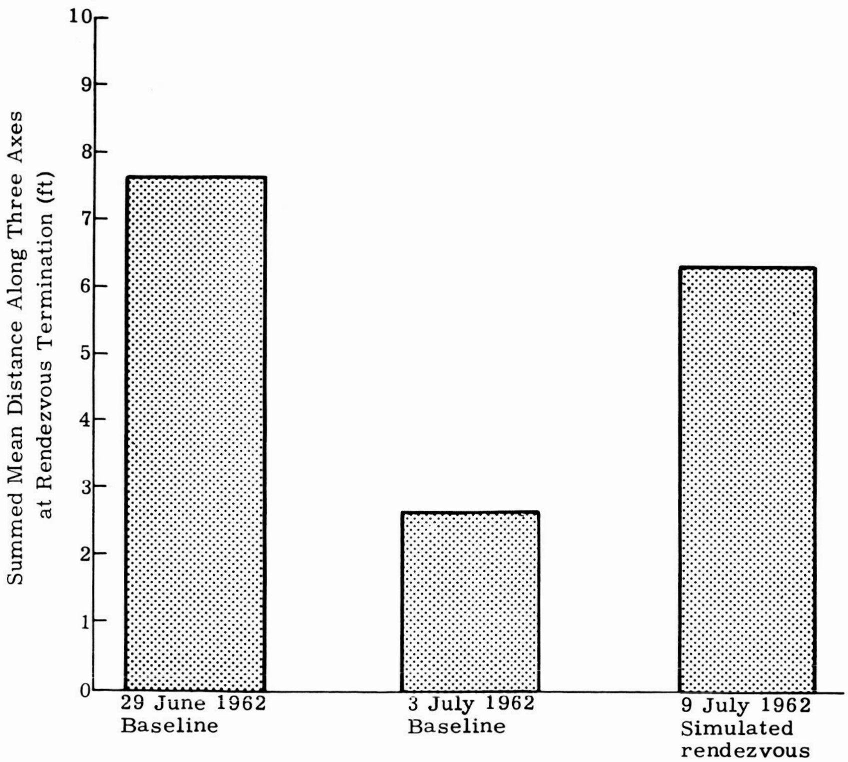

Fig. 4. Comparison of Rendezvous Performance